RANDOMIZED CLOUD SEEDING IN THE UNITED STATES

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1. Introduction

Randomized experimentation in weather modification is like the weather itself: many people talk about it, but few actually do it. In the 17 years since the artificial nucleation of supercooled cloud was first demonstrated, only 15 randomized field experiments on the consequences of such nucleation have been conducted in the United States. Of these, eight have not been completed, and two others ended so recently that full reports are not yet available. Locations of the 15 experiments, with methods of treatment indicated, are shown in figure 1; dates, institutions, purposes, and some experimental details are given in table I.

Randomization, however, is not the only requirement for a valid experiment in weather modification. Other basic requirements of any experimental design in this field are the subject of this paper, in which the randomized experiments completed thus far are described in the light of these requirements. First to be discussed is the method of treatment, which is so variable and uncontrollable that the actual intensity of treatment cannot be specified even as to order of magnitude. Thus the relevant experiments cannot be used to estimate treatment effects, but must be analyzed as tests of hypotheses.

The hypotheses to be tested in weather modification experiments will be shown to depend primarily on the intent of the experimenter, and also on all the other important foreseeable consequences of any effort to modify weather. After discussion of the experiments thus far completed, and some still in progress on which adequate information is available, the conclusion is reached that no definitive experiment has yet been performed in the field. Some speculations will be offered for this lamentable lack.

To be considered are only those experiments attempting cloud glaciation, by the introduction of solid carbon dioxide ("dry ice") or silver iodide, and not efforts at weather modification by altering electrical fields, surface albedo, or other properties. No attempt has been made to survey the half dozen or more randomized field experiments in other countries, nor laboratory experiments on threshold temperatures and other properties of nucleating agents, even though some of these have been randomized. References are given only to published articles and books, and not to the innumerable contract reports, progress reports, and papers presented at meetings, although some of these are quoted.

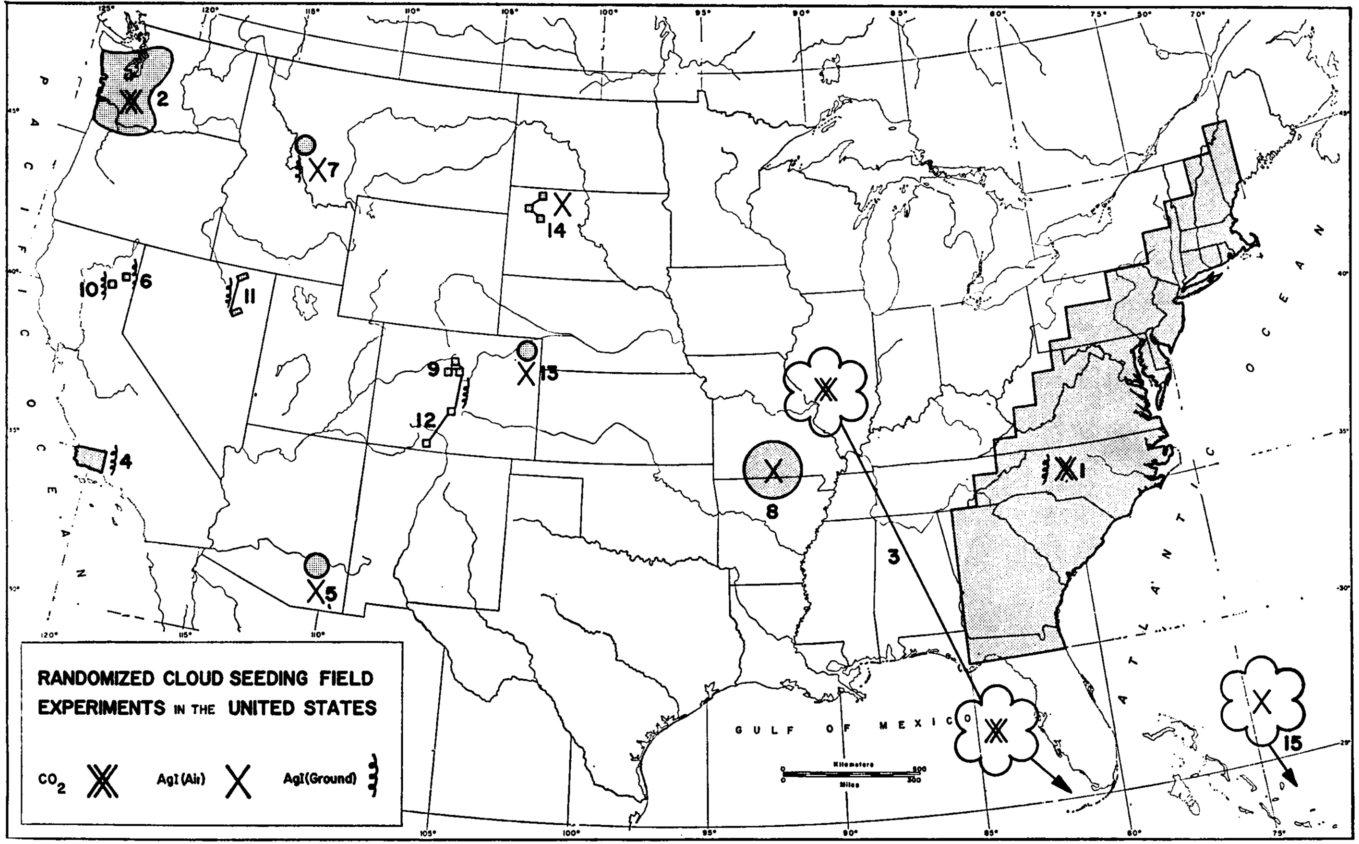

Figure 1

Randomized cloud seeding field experiments in the United States.

TABLE I

CHRONOLOGICAL LIST OF RANDOMIZED FIELD EXPERIMENTS IN CLOUD SEEDING IN THE UNITED STATES

i: Purpose: M, cloud "modification"; R, precipitation increase; L, lightning decrease; H, hail decrease.
ii: Nucleant: C, CO_2 from aircraft; A, AgI from aircraft; G, AgI from ground.
iii: Time interval of randomization; V indicates variable start for interval.
iv: Target for rainfall measurement; W, presumed area of effect based on wind observations; F, fixed target area; X, one of two or more areas in "crossover" experiment.
v: Treatment period, in hours.

Name	Institution	Location	Experimental Period	i	ii	iii	iv	v
1. SCUD	New York Univ.	E. Coast U. S.	Winters 1952–53, 1953–54	M	CG	storm pr	W	24
2. ACN	U. S. Weather Bur.	W. Wash. & Ore.	Mar 1953–May 1954	M	C	days	W	4
3. Cloud Physics	Univ. Chicago	Carib., Cent. U. S.	Aug 1953–Nov 1954	M	C	cld pr	—	—
4. Santa Barbara	Cooperating Groups	California Coast	Jan–Apr, 1957–59	R	G	12 hrs	F	12
5. Tucson	Univ. Arizona	Sta. Catalina Mtns.	Jun–Aug, 1957–62, 1964	R	A	day pr	F	6
6. Eagle	Calif. Div. For.	N.E. California	Jul–Sep, 1958–59	L	G	days	F	9
7. Skyfire	U. S. Forest Svc.	Western Montana	Jun–Aug, 1960–61, 1965—	L	AG	day pr	F	6
8. Whitetop	Univ. Chicago	Central Missouri	Jun–Aug, 1960–64	R	A	days	W	6
9. Climax 1	Colo. State Univ.	Colorado Rockies	Winter, 1960—	R	G	days	F	24
10. Almanor	Pacific Gas & Elec.	N.E. California	Nov–Apr, 1962—	R	G	12 hr V	X	12
11. N.A.R.P.	Univ. Nevada	N.E. Nevada	Nov–May, 1963—	R	G	18 hr V	X	18
12. Climax 2	Colo. State Univ.	Colorado Rockies	Dec–May, 1963—	R	G	winter	X	—
13. Colorado Hail	Colo. State Univ.	N.E. Colo. Plains	Summer, 1964—	L	A	cld pr	—	—
14. South Dakota	S. Dak. Sch. Mines	N.W. S. Dak. Plains	Summer, 1965—	R	A	5 days	X	?
15. Stormfury	U. S. Weather Bur.	Caribbean	Summer, 1965—	M	A	cld pr	—	—

Before the detailed discussion of the problems of experimental design in weather modification, some significant trends in such experimentation can be found in the 15 randomized experiments. These concern the nucleant and its method of dispersal, and the size and definition of the presumed or intended area of effect. Carbon dioxide was the chief nucleating agent in the first three experiments, in 1952–54, with AgI used supplementally in SCUD. Since then, CO_2 has not been used in any randomized field trial, nor is it used generally in precipitation increase operations. However, CO_2 seems so directly effective in fog dispersal and stratus dissipation that no randomized experiments have been required in this aspect of weather modification.

Despite laboratory investigation of other nucleants, AgI is the only one that has been used in randomized field experiments in the past decade. Dispersal was from the ground in half the experiments and from aircraft in the other half, all of which were on summer cumulus and cumulonimbus.

Another trend, suggested by figure 1, is a general reduction in experimental area over the years. Whereas the first three experiments were grandiose, and the next several still involved 10^3 to 10^4 square kilometers, the eight randomized experiments still in progress are concerned with areas of hundreds of square kilometers, or less. This trend cannot be documented precisely, because some early experiments defined the study area after the experiment, from estimates of where wind would have carried the nucleant. Of the later studies, only Whitetop has used such a wind defined target, although in two others the method of analysis is wind dependent.

Also notable are the crossover designs in four of the last six experiments; the other two are aimed at cloud modification, and do not need target areas for rainfall measurement.

2. Nucleation

Nucleants are introduced into supercooled clouds, or at least towards them, to alter their properties or behavior in some detectable manner. The first consequence is expected to be the creation of ice crystals at warmer temperatures ($-5°$ C to $-15°$ C) than those at which crystals would occur naturally ($-15°$ to $-25°$ C). Thereupon the cloud is glaciated by the three phase process, in which cloud droplets evaporate while ice crystals grow through vapor deposition.

Typically, a cubic meter of nonprecipitating cloud has some 10^7 to 10^9 droplets [5]. In cumulus clouds their volume median diameter is 20 to 50 microns and the total water content about 1 gram, while in stratus clouds droplets are smaller, 10 microns, and water content less, 0.5 gram. At temperatures of $-10°$ to $-15°$ C, any droplet that freezes will grow rapidly by vapor deposition while the surrounding droplets evaporate. Under some conditions, freezing of a droplet causes it to splinter into many crystals, each then growing rapidly. Depending on the actual temperature, motion, and size distribution of the cloud droplets, complete glaciation requires the initial freezing of between 1 and 1000 droplets in each cubic meter.

Thus, artificial glaciation requires the introduction of 1 to 1000 ice nuclei, effective at the existing temperature, and 10^3 freezing nuclei per cubic meter often is considered the lower limit for effective nucleation to induce or increase precipitation. Hence, of the order of 10^{12} freezing nuclei, more or less uniformly dispersed, start the conversion of a cubic kilometer of supercooled cloud into ice crystals that can grow large enough to fall and eventually produce rain.

Initially, the cloud is formed by the cooling resulting from expansion in upward motion at the rate of some 100 meters per minute. In such motion, a cubic kilometer displaces its own length in ten minutes, during which it cools by some 6° C. To convert such a cubic kilometer of supercooled cloud into ice crystals earlier, and lower, than would occur naturally requires 10^{12} nuclei per square kilometer during ten minutes, or 10^{11} nuclei per square kilometer per minute.

Around 10^{16} crystals can be produced from one gram of silver iodide [10], but their size distribution, from even the most efficient ice nucleus generator, is such that perhaps only 10^{15} of them would be effective as ice nuclei at $-20°$ C, only 10^{14} at $-15°$ C, and only 10^{13} at $-10°$ C [11]. Many generators in actual use vaporize slightly less than one gram per second, and are not completely efficient, so that the actual number of effective nuclei emitted is one or two orders of magnitude less, at a given temperature. Characteristic outputs in many cloud seeding operations are 10^{11} to 10^{13} nuclei per second, effective at $-10°$ C, or perhaps 10^{14} per minute. These would provide the desired concentration of 10^{11} nuclei per square kilometer per minute to some 10^3 square kilometers.

But all these approximations are not valid even as to order of magnitude, so that a generator at peak efficiency conceivably could nucleate far more than a thousand square kilometers of cold cloud in one day, and possibly not even affect one square kilometer of slightly warmer cloud another day, or later the same day. Also highly uncertain is the fraction of nuclei released from the ground that actually is carried aloft and into the cloud; depending on atmospheric conditions, this fraction can range from 0 to perhaps 90 per cent. Even nuclei released from airborne generators suffer some attrition before reaching their intended target droplets.

The uncertainties of several orders of magnitude in the level of treatment attained in weather modification experiments preclude the direct estimation, in such experiments, of treatment effects. Instead, all such field experiments, at least insofar as they concern precipitation and other effects on the ground, must be considered as tests of hypotheses, carefully formulated according to the experimental intent and method of operation.

In some experiments, including a few that were randomized, the primary interest was in the nucleation action itself, or in its immediate consequences; these include changes in electrical properties or increases in vertical motion because of the increased buoyancy from the release of latent heat of fusion. In other experiments, on supercooled stratus clouds, the desired result of nucleation was the dissipation of the cloud, especially when low enough to be classed as fog. In still others, on cumulus clouds, the nucleation was intended to modify the cloud properties and processes so as to reduce the amount of lightning, or of large hailstones, emerging from it. But, in the vast majority of nonrandomized practical or commercial operations, and in many of the randomized experiments, the primary interest was the inducement of greater amounts of precipitation from the cloud than otherwise would have occurred.

3. Fertilization

As a putative precipitation producer, silver iodide, or any other cloud treatment, is simply a *fertilizer:* "an enriching material used to increase productivity," to abstract one dictionary definition. Ideally, all experiments to determine the increased yield due to fertilization should be designed in the same way; such weather modification experiments are analogous to agricultural field trials of fertilizers, or tests of dietary additives on animal growth. But several almost insuperable difficulties preclude close parallelism between tests of yield increases of cloud and field fertilizers.

In a classic field trial, both subject (crop) and treatment (fertilizer) are controlled (specified), and noncontrollable effects of weather and soil are eliminated by randomization. Seeds of a homogeneous strain are planted in a prescribed manner, and the treatment is applied in given strength at so many tons per acre or hectare, at a specified time, such as 30 days after planting. Similarly, in a nutrition experiment, animals from the same litter, herd, or flock are kept in identical pens or fields, and all fed the same diet; a specified dietary additive of so many grams or ounces per day is given to a group of animals, selected at random to eliminate response variations due to heredity and environment.

Clouds, however, cannot be selected to be as similar as corn or cows. Furthermore, clouds change during the course of the experiment: in a few hours, the clouds under treatment may develop from scattered cumulus to giant cumulonimbus, with great changes in water content, temperature, and drop size. Worse yet, the treatment must be applied at varying distances from the cloud, or at least from its point of effectiveness. Thus, both the actual treatment intensity, and the characteristics of the treated cloud vary markedly from point to point. Neither subject nor treatment can be specified in any but the most general terms, limiting drastically the degree to which the experiment is describable and hence reproducible.

Understandably, in some experiments more attention has been given to the characteristics of the clouds than to the results of treatment. Although clouds cannot be selected in advance for homogeneity, they can be grouped afterwards, on the basis of such measurements, and treatment effects for each class estimated separately [21]. But when such classes are established afterwards, rather than specified in the experimental design, some loss of confidence results.

The great variation in both subject and treatment prevents any weather modification experiment from being purely objective; cloud seeding is more an art than a science. No weather modification experiment can be assessed simply in terms of the result of applying a specified treatment to a selected subject. Instead, it is largely a determination of the degree to which a competent meteorologist, expert in cloud physics, has accomplished his intent—a test of a hypothesis, or a verification of a forecast.

Although the statistical analysis of a precipitation increasing experiment is more closely related to forecast verification than to estimation of treatment effects of fertilizer or diet supplement, some parallels remain with agricultural and dietary trials. A treatment intended to increase fruit size should not be castigated because plant height is not increased, nor should a diet supplement intended to improve laying frequency or milk production be branded as ineffective for lack of body weight increase.

Similarly, cloud nucleation to prevent lightning or hail should not be assessed primarily in terms of precipitation increase. For such purposes, higher nucleant concentrations are desired (whether achieved or not) and the time and place of nucleant release may differ substantially from that used for precipitation increase. Project Stormfury is trying to cause cumulonimbus clouds to "explode" from the rapid release of latent heat, and is "not attempting to increase precipitation" [20]. The cloud nucleation is by pyrotechnic rockets, estimated to provide more than 10^7 nuclei per cubic meter—a thousand times the concentration generally sought in rainmaking.

4. Consequences

Field experiments on the consequences of cloud nucleation have been decried, over the years, by some meteorologists and other physicists as premature, prior to elucidation of the precise mechanism by which such nucleation can operate. Such a shortsighted pseudoscientific attitude in other fields would deny mankind the advantages of most modern fertilizers, drugs, machines, and other benefits. Biochemists are still uncertain about the exact sequence by which nitrogen makes plants grow, or aspirin reduces pain, or most other chemical treatments accomplish a desired result in man, animal, or plant. Watt did not understand the thermodynamics of his steam engine, nor did Edison comprehend electron excitation as the source of his incandescent light.

Science progresses by establishing first the existence of an effect, and only thereafter by discovering its true cause. Eventually the actual mechanism may be found to differ markedly from that vaguely assumed by the first developer of the treatment, process, or device; then improvements and refinements ensue. But verification of a treatment effect is not dependent on any understanding of its *modus operandi*.

However, all possible effects, and not merely the one desired, must be investigated. New drugs should not be used until *all* their consequences have been found acceptable; violation of the principle can be disastrous, as in the recent thalidomide scandal, or the current furor about the long term effects of pesticides. Assessment of the efficacy of a nucleant in causing more rain must be accompanied by study of what else it does—and no weather modification experiments, randomized or not, have met this criterion.

". . . Rainfall is not beneficial if it is so heavy that it washes out the fields and silts up the reservoir, or so gentle and protracted that crops become insect infested. Good visibility at an airport is undesirable if it is accompanied by crosswinds so strong as to make landing unsafe. Hail prevention is not worthwhile if it is accomplished by causing a cloudburst—or creating a drouth."

This was part of my suggestions, in 1954, to the Advisory Committee on Weather Control, which had solicited advice from some two dozen persons. Many of those contributions, which were never published but kept "administratively confidential," are equally valid today. In 1959 the Weather Modification Conference of the American Society of Civil Engineers was told [7]:

"Wind accompanying the rain may be affected by the treatment. Just like the surgeon who claimed that the operation was successful even though the patient died, a cloud seeder conceivably could provide enough rain to save a crop—and a strong wind to blow it flat on the ground . . . Meteorologists have been surprisingly unimaginative in outlining the probable results of any successful alteration of natural precipitation mechanisms . . . After a dozen years of spasmodic experimentation and commercial exploitation, cloud seeding really should be evaluated from all aspects."

The "requirements for valid and efficient experimentation" set forth by the 1959 Skyline Conference on the Design and Conduct of Experiments in Weather Modification ([16], p. 19) said:

". . . Efficiency demands that an experiment be designed to answer several questions. For example, the amount of precipitation cannot be altered without changing either the intensity or the duration of the precipitation, or both . . ."

None of the six randomized experiments begun before 1959 was designed to study rainfall intensity or duration, nor has any of the nine begun since then announced such hypotheses in the experimental design. However, after completion of some experiments, intensity increases attributable to treatment have been found [9]. In some areas where cloud nucleation is attempted in hopes of increasing rainfall, notably in Southern California, increased rainfall intensity on steep, highly erodible soils may cause more damage than any benefit accruing from additional rain. Certainly such possible deleterious consequences of treatment must be investigated in any field experiment on weather modification.

Also of concern throughout the history of cloud seeding are the possible effects outside and beyond the area of operations. Does California cloud seeding steal Nevada's water? In some commercial operations, and one or two randomized experiments, downwind effects have been sought in the collected data, but no hypotheses concerning them have been incorporated into experimental designs. Certainly tests of such consequences are worth specifying in advance.

5. The first decade

Within months after the first demonstration of cloud nucleation, on 13 November 1946, two large research studies were organized to study this new phenomenon, primarily in the clouds. Randomization was not even considered for Project Cirrus, directed by Irving Langmuir, and was rejected for the Cloud Physics Project of the Weather Bureau, aided by the Air Force and N.A.C.A., as unnecessary in view of "the control exercised by the use of several observational aircraft and, especially, of a rain sensitive radar" [6].

The first three randomized experiments (table I) were part of the six conducted in 1952 and 1953 on the recommendation of the ACN Advisory Group, the first committee in the field to include nongovernment experts and the first to include a mathematical statistician. In the preface to the report on these three projects, the chairman [19] recalled that:

"Since it is rarely possible in individual cases to separate artificial influences from natural atmospheric processes, emphasis was placed on randomization with adequate statistical control and services. Although little information was available, the Advisory Group estimated that if any appreciable modification were feasible, it should be possible to provide within a period of one or two years a *tentative* answer to the question of success or failure in cloud and weather modification."

However, none of the six projects was designed specifically to determine the ground effects of changes in precipitation amount or character. The University of Chicago group [4], under Air Force contracts, studied the effects on a cloud, randomly selected from a pair of similar clouds, when treated with water or dry ice; precipitation was not and could not be measured.

ACN Project SCUD of New York University [22], supported by ONR, used both carbon dioxide dispensed by aircraft and ground released silver iodide in an effort to initiate or modify cyclogenesis (the development of new low pressure storm centers) off the east coast of the United States; randomization was by storm period. Precipitation caught in the existing raingage network was divided into presumed seeded and nonseeded areas, which differed from storm to storm. "The null hypothesis with regard to precipitation cannot be rejected," nor could it be rejected with regard to pressure changes, the major subject of study.

The Weather Bureau ACN project in western Washington and Oregon [15] was intended primarily to assess the "seeding potential" of winter storms off the Pacific by measuring their moisture content and their deficiency, if any, in ice nuclei, and then randomly treating two thirds of them with dry ice; for a secondary hypothesis, 100 recording raingages were distributed over the operation area, but six different methods of comparing the precipitation in the presumed area of effect gave six different answers, with "no strong evidence to support a conclusion that the seeding produced measurable changes in the rainfall," although increases of as much as 15 per cent could not have been detected.

While the ACN projects were in full swing, Congress [23] created the Advisory Committee on Weather Control to make "a complete study and evaluation of public and private experiments in weather control . . ." The *Final Report* of the Advisory Committee [1] says:

"From the outset the Committee was well aware that within its statutory authorization it could undertake a program of only limited scope: It could not, for lack of sufficient time, carry on long-range research, desirable if not essential to evaluation, such as scientifically-designed, randomized cloud seeding experiments . . ."

This regret at a presumed inability to sponsor randomized experiments may have been more in retrospect than "from the outset." Randomization was not mentioned in the guiding principles adopted at the first Committee meeting on 18 December 1953, which recognized needs "for additional basic research dealing with processes related to rain, snow, and cloud phenomena" and also "to develop ways and means of providing methods for reliable evaluation of weather control activities."

Despite its professed inability to conduct long term research, the Committee supported, from its half million dollar appropriations, in whole or in part half a dozen assorted field experiments in its "physical evaluation program." None was randomized, or even designed in a statistical sense. Perhaps the Committee's final report was influenced by suggestions and criticisms during its four years of existence, especially those of its Interim Report of February, 1956.

In many ways, the Advisory Committee's activities and report ended an era in weather modification. This decade, 1947–56, contained three periods of field research, including three randomized projects, none primarily designed to determine precipitation increases.

6. The second decade

Three more randomized experiments began early in the second decade of weather modification research. One sought to determine the magnitude of precipitation increase from ground release of AgI into winter storms on California's coast, the other two involved summer cumulus clouds in Arizona (treated from the air to study precipitation processes and increase mountain rainfall) and in northeastern California (treated from the ground in hopes of reducing lightning on dry forests).

The Santa Barbara project [14] was first conceived in Berkeley on 8 May 1956, at a seminar that was the aftermath of the Conference on the Scientific Basis of Weather Modification Studies at Tucson the preceding month. The target was the entire county of Santa Barbara (5478 sq km), divided into subtargets in which were placed about 50 recording raingages, some of which were so remote that helicopters were the only feasible means of servicing them. Operations ran from January through May, 1957–60, supported by the County of Santa Barbara, the State of California, and NSF and ONR, with cooperation of the Forest Service and the Weather Bureau.

This was the first randomized project in which the target was fixed; the two

ACN projects in which precipitation was measured used subtarget areas defined meteorologically, on the basis of wind flow during the precipitation period. In Santa Barbara, randomization was by fixed twelve hour periods, 10 o'clock to 10 o'clock, if they had been declared "seedable" by 9 o'clock.

Despite intensive efforts at data collection and exhaustively careful statistical analysis, results were at best inconclusive; although some comparisons indicated significant increases, they were for samples too small to be convincing meteorologically. "Stratification of the data into convective and stable type storms increases the target-control correlations and thus permits the detection of smaller precipitation increases," but "no striking seeding effect is present in either case," Smith [21] found.

Also begun in 1957 was what was to become a seven year program of aerial seeding of summer cumulus clouds over the Santa Catalina Mountains, east of Tucson, by a University of Arizona group supported by NSF [2]. Randomization was by pairs of days that had been declared seedable by an objective criterion. The basic hypothesis of this experiment was that many clouds did not yield rain because they were not frozen, and that introduction of silver iodide nuclei would cause more clouds to yield rain. Rainfall increases indicated in the first two summers, over a network of 25 recording raingages installed in the mountains, were not found in the next two, so the experiment was modified slightly and continued for three more years; the final report is not yet available. Further details appear in Battan and Kassander's paper in this volume [3].

A year after the Arizona summer cumulus program began, another randomized cumulus seeding program began in northeastern California "to establish the extent to which the incidence of lightning-caused fires can be reduced by cloud seeding at a minimum cost through use of regular field personnel . . . in addition to their other routine duties." The study was initiated and supported entirely by the California (State) Division of Forestry, which contracted with the U. S. Forest Service for assistance in design, operation, and evaluation.

Fifty silver iodide generators, at lookouts and fire stations of the state and federal forest services, burned from 10 a.m. to 7 p.m. on days in July, August, and September randomly selected from those on which target area thunderstorms were forecast by the Weather Bureau; randomization was 50-50, except that runs of treated or untreated days were restricted to three (although only one person knew this). Routine reports of lightning-caused fires over the 8000 sq km target, records of a lightning stroke counter, and data from 29 recording raingages (10 specially installed) indicated "no effect on the number of days with rain, lightning, or lightning-caused fires, but an apparent increase in the amount of rain and number of lightning-strokes and lightning-caused fires" on the 13 treated days compared to the 13 untreated ones.

The following summer (1959), the same design was followed, but the target was reduced to 1400 sq km around Eagle Lake, and in addition ice nuclei were counted in an airborne cold box. More lightning-caused fires but less rain occurred, neither difference having any statistical significance, and a highly significant three fold increase occurred in the relative number of ice nuclei at 3 km; absolute concentrations could not be determined.

7. The third generation

Three more randomized field experiments in weather modification began in 1960. Two involved airborne seeding of summer cumulus, in Montana (Skyfire) to reduce lightning, in Missouri (Whitetop) to study clouds and also any effects on rainfall. The third (Climax 1) attempted to increase winter snows in the Colorado Rockies.

Project Skyfire was begun by the U. S. Forest Service "to determine the effect of silver iodide nuclei treatment on the frequency of lightning flashes from summer thunderstorms in western Montana" with a secondary objective of determining any seeding effects "on the physical and electrical nature of thunderstorms." Five recording raingages were installed as part of the study, but ground precipitation effects were not part of the experimental design.

Two summers gave 18 serial pairs of days on which thunderstorms were forecast. Days randomly selected from each pair for aerial silver iodide treatment had 21 per cent fewer lightning discharges, and 38 per cent fewer cloud to ground strokes, than untreated days, with 1 in 4 significance. The experiment, originally intended to run for four summers, was suspended to develop better seeding techniques, and was resumed in 1965 to run three more years.

Only one other randomized experiment in which ground precipitation is measured has been completed thus far, and only preliminary indications are available as yet. Project Whitetop was conducted each summer (June–August) from 1960 through 1964 in southeastern Missouri by a University of Chicago group supported by NSF. Precipitation effects in a wind defined target were studied together with physical measurements in nonorographic summer cumulus and the possible modification of such cloud properties by aerial introduction of silver iodide.

On the 102 treated days, randomly selected from the 198 objectively determined to be seedable, the presumed target downwind of the aircraft seeding track had one half (47/105) to two thirds (61/104) as much rain as the corresponding area on untreated days; the difference depends on whether the plume is defined narrowly (Missouri) or widely (Chicago). When allowance is made for the 66/85 ratio of rain on treated and untreated days outside the wider plume, treated days still show less rain than untreated ones, but neither difference approaches statistical significance.

These plume areas were the only targets specified at the outset of the five year program. No subsidiary hypotheses were formulated concerning subtargets, intensity, time of onset, or any other aspects. Now that the data are collected, the analysts have found many interesting contrasts between treated and untreated days, and the more the data are manipulated by various classifications, rotations, and truncations, the greater the contrasts.

The third experiment begun in 1960, Climax 1 of Colorado State University, operates "hypodermic needle-type silver iodide generators" west of Climax, Colorado, on winter days selected at random from those for which snow is forecast. Snow accumulation in gages and on special snow boards near roads going over three passes, each more than 3 km above sea level, on treated and untreated days will be compared at the conclusion of the experiment, which entered its seventh season in December, 1965; after the first, February–May, 1960, several operating and observational procedures were changed [12], [13], [14].

A related experiment, Climax 2, is randomized seasonally on a crossover basis: two of four designated mountain pass areas are selected at random for a winter long treatment. Snow in gages, on snow boards, and streamflow will be used for analysis of the experiment, which began its second season on November 15, 1965.

The five remaining randomized field experiments listed in table I are also still in progress. Three are intended primarily for precipitation increases, two in winter (in California [8] and in Nevada) and one in summer (in South Dakota), each with crossover design. The other two aim at cloud modification—of hail clouds in northeastern Colorado and of cumulus clouds and hurricanes in the Caribbean.

8. Conclusion

Randomization, rejected for the first large scale field experiments in weather modification, now provides the framework for many experiments. But other aspects of experimental design, some even more important, have been sadly neglected. In few, if any, experiments have specific hypotheses been formulated in advance, and methods established for testing them. Most experiments still follow the philosophy of "try it and see what happens," with randomization as the only concession to proper design.

Many experimenters even feel that formulation of a hypothesis about the effect of cloud seeding, such as precipitation increase of a certain amount or percentage, is somehow unethical, and would prejudge the case. And no investigators have formulated, in advance, hypotheses concerning all the important possible consequences of weather modification efforts—on rainfall amount, intensity, timing and duration, both within and beyond the experimental area, on wind, lightning, cloudiness, and other aspects of the weather.

Why was the principle of randomization accepted so slowly in weather modification research, and why have other aspects of proper design been ignored even more? First, because meteorologists are so imbued with the tradition that theirs is a nonexperimental science, working with an uncontrollable atmosphere, that they are unprepared by training and outlook to capitalize on the promise of controlling one atmospheric variable (ice nucleus concentration). Second, because the statisticians who were consulted about experimental design did not realize fully that the gross uncertainty in treatment intensity and procedure makes each experiment a test of intent (hypothesis) rather than a problem in estimating treatment effect. Third, neither the meteorologists nor the statisticians considered carefully the many possible consequences of weather modification efforts, and hence formulated no hypotheses, or even measurements, concerning these important side effects.

In other ways, too, statisticians have ignored the inherent differences in between experiments on agricultural and atmospheric fertilizers. Randomization of plots helps reduce fertility gradients and weather differences, so that responses are considered additive, and each response is a random measurement of the same quality. Randomization of time periods for treatment with atmospheric fertilizers, however, does not work the same magic, and does nothing to equalize precipitation over the experimental area.

Each raingage measures precipitation appropriate to its location, and the great variation of rainfall with distance imposes uncertainty on any estimate of total or average rainfall over an area. Furthermore, even if the rainfall over an area were uniform, so that each gage reading could be considered as an estimate of that true areal value, the readings of individual gages are strongly correlated. Thus the precision of an estimate of area rainfall, taken as the average of n raingage readings, increases much more slowly than $n^{-1/2}$.

Randomization of itself, therefore, does not guarantee that a weather modification experiment is properly designed, and will give usable results. Hypotheses concerning the principal result anticipated, as well as other significant consequences, must be formulated, and tests for them devised, and measurements for the tests planned and made. Such are the requirements for the statistical design of an experiment in weather modification.

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