Report of

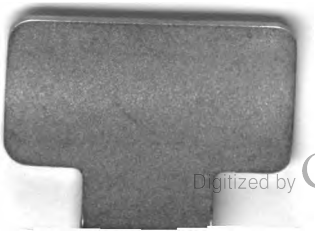
THE SKYLINE CONFERENCE On The Design And Conduct Of Experiments In Weather Modification

National Academy of Sciences–
National Research Council

Publication 742

The search for Truth is in one way hard and in another easy. For it is evident that no one can master it fully nor miss it wholly. But each adds a little to our knowledge of Nature, and from all the facts assembled there arises a certain grandeur.

—ARISTOTLE



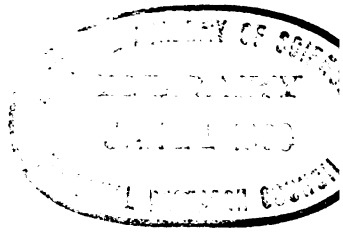
Report of

THE SKYLINE CONFERENCE
On The Design And Conduct Of Experiments In Weather Modification

May 1-3, 1959
Shenandoah National Park, Virginia

Organized by the
DIVISION OF MATHEMATICS

Sponsored by the
NATIONAL SCIENCE FOUNDATION



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Foreword

The advancement of knowledge in the fundamental physical and chemical processes in the atmosphere is the foundation upon which progress in the new field of weather modification is based. In return, experiments in rain-making and other weather modification programs have contributed substantially to the understanding of basic mechanisms within the atmosphere.

The degree of success so far achieved by various research programs in weather modification is, in large measure, due to detailed and skilled analysis of the data which combines sound statistical techniques and enlightened meteorological insight. Such programs must rely upon sound physical principles and valid statistical techniques, both in designing experiments and in properly evaluating the data which come from these experiments. The modest successes of the past presage a continuing and growing effort in such studies, not only because of the needed growth of knowledge of atmospheric processes, but also because of the tremendous economic consequences which controlled modification of the weather may have.

A number of prominent meteorologists and statisticians believed it would be useful to evaluate jointly the basic requirements for the proper design and conduct of meteorological research programs involving experimental control of meteorological factors. These discussions grew out of a suggestion of Earl G. Droessler that such a conference be held to acquaint research scientists with a new National Science Foundation program on weather modification and to stimulate research ideas and discussion on the planning of experiments in this field. Strong encouragement was received from Dr. Paul E. Klopsteg, Chairman of the Committee on Atmospheric Sciences of the National Academy of Sciences—National Research Council, for joint discussion of these problems by meteorologists and statisticians.

Accordingly, the Division of Mathematics of the National Academy of Sciences—National Research Council arranged a Conference on the Design and Conduct of Experiments in Weather Modification. Support for the Conference, which was held on May 1-3, 1959 at Big Meadows Lodge on the Skyline Drive of the Shenandoah National Park, Virginia, was provided by a grant (G-7660) from the Atmospheric Sciences Program of the National Science Foundation. A total of thirty-one meteorologists and statisticians, whose names are listed at the end of this report, participated in the Conference.

The Conference was planned and organized by a Steering Committee consisting of John W. Tukey, Chairman, John R. Sievers, Executive Secretary, Eugene Bollay, Roscoe R. Braham, Jr., Glenn W. Brier and Max A. Woodbury.

The program of the Conference focused on informal sessions designed to inform and provoke discussions among the conferees on the design and analysis of experiments and tests for various weather modification programs and basic research studies

of chemical, physical, and electrical phenomena of clouds and cloud-free air.

The first session was led by Glenn Brier. Current and recent weather modification programs were discussed by individual conference participants. These ranged from experiments on warm and cold stratus decks and fogs, to experiments on orographic and non-orographic cumuli. They included investigations of Hatteras and West Coast storms, of hail and lightning suppression, of hurricanes and of periodic seeding.

The next session was devoted to discussions of statistical evaluations and analysis which have been applied to, or might be suitable for application to, certain weather modification research programs. This session, under the leadership of Roscoe Braham, developed several issues of an interdisciplinary nature, and made it evident that both the meteorologists and statisticians have a considerable collaborative task ahead of them in designing and evaluating experiments in weather modification research programs.

On the second day, discussion of meteorological and statistical problems was vigorously pursued in morning and afternoon sessions, under the chairmanships of Max Woodbury and Eugene Bollay, respectively. The evening session was devoted to the preliminary formulation of conclusions and recommendations for guidance in the design and conduct of future research efforts in weather modification.

The final session, under the dual leadership of Samuel S. Wilks and Horace R. Byers, was devoted to formulating the sense of the conference on various major points and to final consideration of conclusions and recommendations which the conferees felt should be the nucleus of a report. The chairmen of the various discussion sessions were assisted by Arnold Court, Robert D. Elliott, W. Ferguson Hall and Herbert C. S. Thom, each of whom served as a reporter during one of the discussion sessions.

The experience of the Skyline Conference clearly indicates that the main value of holding such "scientific retreats" lies in the opportunity it provides for scientists—in this case scientists from two different fields—to meet and exchange views on the issues pertaining to the theme of the conference in an atmosphere of cordiality and informality.

One note of regret to all participants was that Dr. Tukey, who guided the planning of the conference and who was to serve as the General Chairman of the Conference, was unable to participate because of the death of his father on May 1, 1959.

The present report is the formal outcome of the Skyline Conference. It was prepared by the Steering Committee with the cooperation of the reporters and other participants of the Conference. The informal outcome of the Conference, which is probably of greater importance, is the broadened understanding and insight of the participants concerning the problems of weather modification.

The chairman of the Division of Mathematics wishes to take this opportunity to express appreciation, both on behalf of the Division and on his own behalf, to the members of the Steering Committee, to the reporters and to each of the participants of the Conference for their cooperation in organizing the Conference, carrying out its function, and preparing this report.

SAMUEL S. WILKS, *Chairman*
Division of Mathematics

Washington, D. C.
December 1, 1959

Contents

I. Introduction

The atmosphere has been described as the "ocean at every man's door." We have become so accustomed to this "ocean" that most people regard its storms and its calms as inevitable, uncontrollable features of our geophysical environment. We consider it as something to accept as we find it, to utilize when it is to our advantage to do so, and to defend ourselves against when it is not. We have developed economic, cultural, and social patterns which allow for the vagaries of the weather, but thus far we have made very little effort to adapt the atmosphere, or its weather, to the needs of man.

It is significant that many competent scientists have come to regard the atmosphere as a natural resource of enormous magnitude. These scientists believe that the greatest obstacle to using the atmosphere is a lack of basic understanding of the physical-chemical-electrical-hydrodynamical processes that operate within it. Present efforts to acquire this understanding seem infinitesimal compared with potential benefits which may be gained therefrom.

The past few years have seen a growing awareness of the need for improving our knowledge about the atmosphere. At the same time new tools of physics, mathematics, and engineering have been developed which make the atmosphere more accessible for scientific inquiry.

An ever-increasing effort has gone into the study of clouds and of the possibilities for modifying them in usable ways. These studies have progressed slowly because of (a) our lack of understanding of the basic physical processes involved; (b) our inability to duplicate the larger scale atmospheric phenomena for study within the laboratory, and (c) the great natural variability of weather phenomena for study in the field. Many false starts have been caused by a lack of appreciation of these factors and the consequences of conducting experiments which do not properly take them into account.

It is now quite generally recognized that modern statistical principles designed to cope with the natural variability must play a key role in the conduct and evaluation of experiments in weather modification. It is fitting therefore that a conference should be held to provide a common meeting ground between meteorologists involved in weather modification experiments and statisticians skilled in experimental design and evaluation. Some general conclusions and recommendations have resulted from the Conference which may be useful to those scientists and administrators responsible for future weather modification research and testing.

II. Summary of Conclusions and Recommendations

After more than two days of discussion of topics concerning the physical basis of weather modification, current and recent weather modification programs, and problems of designing present and future experiments in this field, the Conference participants agreed unanimously on the conclusions and recommendations given below. Further discussion of these topics appears in the remaining sections of this report.

1. Statistical Design of Weather Modification Experiments.

Weather modification efforts at the present time are characterized by high meteorological variability and by the possibility of a large economic payoff for relatively small effects. Scientifically designed weather modification *experiments* are difficult to conduct, but are extremely important for increasing our knowledge of natural and artificially stimulated precipitation processes. Such experiments should be carefully planned. Proper consideration should be given to modern statistical techniques of experimental design, including the principles of randomization in comparative experiments. It is extremely important to obtain the advice and cooperation of competent statisticians in the planning phase, as well as in the conduct and analysis of these experiments. Field experiments should be designed with a broad approach to the problem so as to yield information on a number of important questions. Thus, many hypotheses should be formulated and tested, involving the various conceivable effects of the modification effort on the timing, duration, and intensity of rain, raindrop size and temperature, and other characteristics in addition to amount of precipitation. Field experiments should be coordinated with laboratory and theoretical studies, wherever appropriate.

2. Longevity of Experimental Programs.

Most field experiments in weather modification need to be operated on a well-planned basis for several years in order to produce enough information to be conclusive. Longevity in each program is therefore essential. Very few experiments thus far conducted in the United States have had sufficient duration and continuity.

3. Replication of Experiments.

To ensure an adequate basis for generalization of results to a specified class of meteorological and other atmospheric conditions, replication of experiments in space as well as in time is needed. Insofar as possible, experimental procedures should be standardized between experiments conducted at different locations, whether by the same group or by different groups, in order to provide the kind of replication suggested here.

4. Non-Scientific Nature of Many Commercial Weather Modification Operations.

Many attempts at practical weather modification are made on a commercial

basis. Very few of these operations are designed as scientific experiments, and hence it is virtually impossible to make a sound scientific assessment of their effectiveness. Financial support of weather modification experiments for developing scientific knowledge should be channeled into investigations of relevant basic atmospheric processes and of modification techniques which employ scientific methodology and modern principles of statistical experimental design.

5. Basic Research.

Basic research programs in atmospheric physics, chemistry, and electricity should be considerably augmented. Laboratory studies should extend into such areas as solid state physics, crystallography, surface chemistry, electron miscroscopy, etc. Field studies might well begin in each instance in places where atmospheric behavior is relatively free of complexity. Particular attention should be given to research on nucleation and precipitation processes which attempts to discover critical conditions under which intervention may be effective. Seeding agents might be used as one tool to initiate cloud reactions in order to establish observable effects. Whenever specific effects seem to be indicated, well-designed experiments should be conducted to examine them rigorously.

Basic studies of specific weather systems, such as shower clouds, orographic clouds, hailstorms, lightning storms and full scale cyclonic systems are needed in order to develop effective approaches to their modification. The natural processes in these systems must be better understood if attempts at altering them are to be successful.

6. Small-Scale Research Efforts.

Many investigations of questions relating to weather modification can be carried out by the research efforts of an individual or a small group of scientists. This is especially true for laboratory studies, but field work also is possible for small groups. Typical examples of field problems which can be effectively treated are (*a*) determination of the relation between lightning and cloud top temperature, (*b*) determination of easily measured cloud parameters in various types of clouds, (*c*) certain cloud modification programs involving small geographical areas or individual clouds. Such relatively small-scale efforts should be encouraged and supported. These projects will be largely of an exploratory nature and the results, if promising, may lead to further experimentation and statistical analysis on a much larger scale.

In connection with (*c*) it is to be noted that experiments intended to test the effects of cloud seeding on precipitation actually reaching the ground usually require substantial organizational effort, an extensive installation of equipment, etc., and cannot be treated as small-scale projects.

7. Cooperation Between Meteorologists and Statisticians.

Cooperation between meteorological and statistical research groups is highly important for the advancement of knowledge in the field of weather modification, particularly in connection with large-scale tests and experiments. In order to stimulate this cooperation special attention should be given to

(*a*) Strengthening meteorological and statistical research groups or departments in those universities or research institutions where effective cooperation between meteorologists and statisticians already exists or is promising. In some institutions, where a strong research group exists in one of these fields, consideration should be given to establishing a research group in

the other. The establishment of such groups should allow the development of fellowship programs and other methods for attracting able young scientists into these areas.

(*b*) Establishing summer study groups, summer institutes, and other conferences and seminars whose membership combines meteorologists, statisticians and other scientists interested in weather modication.

III. Physical Basis for Weather Modification Efforts.

1. General Remarks.

The term "weather modification" properly extends to the alteration or amelioration of any and all weather elements, including temperature, precipitation, severe storms, etc. During the last decade, however, most of the emphasis has centered on those changes in the natural precipitation processes which would provide benefits from increases or decreases in rain and other related weather elements such as lightning and hail. The reasons for this emphasis are largely historical in nature, reflecting the interest, especially to agriculture and water power, in the initial discovery by Schaefer in 1946, that under suitable conditions non-raining clouds can be made to precipitate. The economic value of obtaining even a small degree of control over rainfall has created undesirable pressures, which have tended to dilute the scientific quality of some weather modification experiments. There are strong scientific reasons, apart from economic value, for concentrating initial research efforts along the lines of precipitation control. Any technique which offers a means for controlling the amount of precipitation reaching the ground may in turn offer means for modifying the energy balance in weather systems. The first step in seeking such a technique is to develop an understanding of the processes which lead to natural precipitation. As a result of extensive studies in the past ten years we now have a usable, although incomplete, understanding of natural rain formation. These studies help to explain the variability of natural rain, and show that no single seeding technique will be suitable for all kinds of clouds, nor will a single experimental design be suitable for all geographical regions and meteorological conditions.

2. Precipitation Mechanisms.

For the benefit of the reader who has not been involved in studies of natural rain mechanisms it may be useful to give a brief discussion of the subject at this point. Further details can be found in the writings of Braham (1956, 1959), Houghton (1959), and Mason (1955, 1957).

Precipitation formation depends on mechanisms by which it is possible for nature to bring together a million or more cloud droplets, initially spaced many diameters apart, to form a single raindrop. The basic difference between cloud particles (cloud droplets) and precipitation particles (rain drops) is that of size.

Cloud droplets are very small, their diameters ranging in size from less than 5 microns to more than 100 microns. Within an average cloud they are spaced at great distances relative to their diameters.

On the other hand raindrops are relatively large, with diameters ranging from something like 1 mm to 5 mm (from 1000 to 5000 microns). A raindrop thus represents the water equivalent of 10^6 to 10^8 cloud droplets. Raindrops occur in concentrations ranging from 50 to 200 per m^3, while concentrations of cloud droplets range from 10 to 1,000 droplets per cm^3

with a value of 100 per cm^3 (10^8 per m^3) typical of an average cloud.

For almost a century it has been known that clouds are formed through the condensation of water vapor onto dust and other small particles in the atmosphere. It was originally thought that precipitation particles were the end product of continued growth of cloud droplets by a condensation process. It is now known that very little of the precipitation which falls to the earth's surface is formed by this process alone. Studies of the time required to produce raindrops by the condensation process alone show that it is very unlikely that precipitation other than light drizzle can occur in this manner, except possibly in those clouds which are stable over periods of many hours or even days, e.g., stratus.

In the more generally accepted theories, the processes which initiate the formation of rain drops differ from those which lead to cloud droplets with regard to the number, kind and mode of action of the nuclei on which the initial growth begins. The production of a particle much larger than the average cloud droplet, in a time period that is short compared to the lifetime of the cloud, is usually brought about by a nucleus of a special type.

There are two types of these special nuclei. One induces the formation of ice crystals and the other leads to giant solution droplets within the clouds. Bergeron (1935) has shown that because of vapor pressure differences, ice crystals in a subcooled cloud will grow quickly to a size larger than an average cloud droplet. Giant solution droplets can form on certain atmospheric particles which are favored both because of their large size compared with normal condensation nuclei and because of their specific hygroscopic nature. Condensation nuclei of the type which lead to average cloud droplets are always present in the atmosphere in numbers sufficient to produce clouds whenever dynamic processes lead to adequate vapor pressures. However, the number of the ice-forming or large solution-droplet-forming nuclei is vastly smaller. The possibility exists that under some conditions precipitation may be hindered by an inadequate supply of these precipitation nuclei.

The presence of a few cloud particles many times larger than the average cloud droplet initiates a process in which these larger particles collide with, and sweep out, the smaller cloud droplets as they fall. This process of collision and coalescence marks the essential difference between cloud formation and precipitation formation. Condensation on a few giant condensation nuclei leads to the formation of a few giant cloud droplets which fall through the body of the cloud, sweeping up and coalescing the other cloud droplets to produce drizzle. These drizzle-size particles, after further growth, may become large enough to be classified as rain.

Regardless of the number of effective giant condensation nuclei, any cloud which continues to grow upward until it passes through about the $-10°C$ temperature level is likely to contain ice-forming nuclei which will become active. Once this has occurred growth leads to ice crystals. Under some conditions these ice crystals will clump together, producing snow flakes which may fall to the ground as snow, or may fall through the melting level to become raindrops. In cumulus type clouds, the ice crystals often fall through the body of the cloud, sweeping out the cloud droplets to produce snow pellets. These snow pellets change to rain as they fall through the melting layer.

3. Incompleteness of Knowledge of Details of Precipitation Mechanisms.

While some of the general features of the precipitation mechanisms are now un-

derstood, there are many areas of ignorance concerning details of the processes. This general knowledge cannot be readily applied to an assessment of the role of the condensation-coalescence mechanism versus the sublimation-coalescence mechanism in the production of natural rainfall.

Many features of the condensation and sublimation processes are understood. Laboratory studies support the theoretical considerations concerning the rates of growth of droplets and ice crystals provided by these processes. The rates at which the various embryonic precipitation particles coalesce with cloud droplets to form precipitation particles are poorly understood. Our knowledge of the collection process which involves collision, coalescence, clumping, and riming efficiencies is very incomplete. Data are needed concerning the falling speeds of snow particles, the density of snowflakes and snow pellets, the size distribution of cloud droplets, and the total liquid-water content of clouds under various conditions, to mention a few of the important parameters.

4. Possibilities of Artificial Modification of Precipitation Processes.

On the basis of the discussions in the preceding paragraphs it is easy to see how it might be possible, in principle, to influence the precipitation processes in useful ways by utilizing artificial cloud-seeding agents such as dry ice, liquid water and silver iodide. We shall briefly consider some of these possibilities.

Experiments to increase rainfall. Maximum amounts of rain result from favorable combinations of incipient precipitation particles (ice nuclei or giant condensation nuclei), cloud depth, cloud water content, cloud duration and updraft speed. If, for example, ice nuclei are too scarce to be effective, these can be supplied artificially. It may also be possible to alter the cloud updraft speed, cloud depth, and cloud duration by increasing the number of ice crystals in a subcooled cloud top, thus affecting the release of latent heat of fusion. Each of these has been cited as an objective to be obtained by cloud seeding.

It has been observed that, on occasion, the water content of a cloud is in the form of exceedingly small ice crystals. The possibility that a cloud might be artificially converted to this state by "overseeding" has been cited as a means of decreasing precipitation since such small particles do not grow or fall to the ground. Overseeding has been observed locally in a few experiments, but the affected area usually disappeared rapidly by mixing with the general environment. Large resources would have to be devoted to large scale overseeding (e.g., 10^{18} particles are needed for 10 cu. km. to attain a concentration of 10^{8} particles per m^3).

Experiments directed toward increasing or decreasing rain are enormously hampered by that fact that any given weather situation may contain clouds differing widely in size, duration, water content, etc. Furthermore, it is difficult to measure cloud parameters adequately, and such measurements are rarely attempted.

Experiments to modify hail and lightning. Although the logic of rain-increasing experiments is fairly straightforward, the physical foundations for attempts at decreasing hail and lightning are much more obscure. The effects of seeding on these phenomena are not clearly understood, and contradictory theories are held concerning the effects.

It is commonly thought that hail forms from the accelerated growth of snow pellets in regions of high water content. This being so, it is reasoned that the amount and severity of hail might be reduced by increasing the number of ice nuclei to the

point of glaciating the entire subcooled cloud region. On the other hand the logistical problem of overseeding has been mentioned, and less than complete seeding might conceivably lead to substantial increases in hail. Also the suggestion has been made of increasing the number of giant condensation nuclei to the point where a substantial fraction of the cloud will "rain-out" before reaching the subcooled stage. Both kinds of experiments have been attempted, but neither has been adequately tested.

There are two schools of thought regarding lightning formation. It has been generally believed that lightning is associated in some way with the presence of a mixed ice and liquid-water cloud. Under these circumstances the amount of lightning might be grossly affected by silver-iodide or carbon-dioxide seeding. However, a small group of meteorologists regard the presence of the ice phase as being only incidental, and believe that lightning fields can develop in a cloud entirely warmer than freezing. In such warm clouds it is hard to see how ice nuclei seeding could play any role whatsoever. Many further experiments, both basic and applied, are needed to disentangle the strands of this problem.

IV. Recent and Current Efforts in Weather Modification Research

1. Scope of Efforts Discussed at Conference.

The modern era of weather modification began in November 1946, when Schaefer scattered dry ice from an airplane into supercooled clouds over western Massachusetts. The pronounced visual changes in the clouds produced by this and later experiments led some to believe that research in weather modication was simply a matter of treating clouds or the atmosphere with a suitable substance and watching for unusual or unexpected results.

Within the next few years, many such experiments were performed and numerous spectacular results were reported. However, the validity of many of the claims made was questioned by many scientists, since the events observed following seeding tests might have happened as a consequence of natural processes only. No adequate experimental "controls" were provided in these experiments, thus making it extremely difficult to arrive at a sound scientific inference. In view of the large natural variability and almost total unpredictability of cloud processes, it was soon recognized that the problem of evaluating weather modification experiments at this stage is heavily dependent upon statistical techniques.

In more recent years, a number of field projects were organized which made use of some modern statistical principles of experimental design. Several of the best known and more important of these projects were described by individual conference participants, who had a close association or familiarity with a specific project. Many other worthwhile and important projects were not discussed, but the examples chosen for discussion at the Conference provide an adequate description of the range of recent and current weather modification research efforts.

No attempt was made at the Conference to review the various laboratory and other experiments which had as their primary objective the understanding of basic physical processes such as coalescence of raindrops, ice crystal growth, droplet electrification, collection efficiencies, etc. Also omitted from consideration at the Conference were those commercial cloud seeding operations which are sometimes called experiments but which, in reality, have no scientific value. Space does not permit more than a brief mention here of the individual projects discussed at the Conference. Details of some projects are given in published reports (see Petterssen and others (1957)).

2. Australian Orographic Clouds.

Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia.

The Australian Snowy Mountain project began in 1955 and is still continuing, thus being the longest weather modification experiment to date. This experiment involves two areas: a target area and a nearby control area. The target area is either seeded with silver iodide by aircraft during a given storm, or left unseeded during that storm,

the choice being made at random, while the control area is never seeded at all. Preliminary results based on four years of operation of this experiment indicate precipitation increases of about 10-15 per-cent, which are just marginally significant statistically.

Further experiments under the auspices of CSIRO are under way in four other regions, each of these involving pairs of similar and adjacent areas of a few thousand square miles. In these latter projects the area of a pair to be seeded, by silver iodide from aircraft, is chosen at random for each storm. Separations between storms are identified by the passage of a ridge or wedge of high pressure across the east coast of Australia.

The northernmost pair of areas, during one summer of operation (in the New England Section of Australia), indicated a 40 per cent increase in rainfall, while two winters of operation in South Australia showed no effect. This latter result was thought to result from the presence of a persistent inversion, effectively limiting vertical development of clouds. These latter four experiments make use of a random cross-over design (see Section V), which gives substantial increase in experimental sensitivity and should reduce the length of time required to reach a predetermined level of accuracy by a factor between one half and one quarter.

All treatments involved silver iodide released through a high-efficiency burner mounted on an aircraft flying either just below cloud base or at −5° or −6°C. Precipitation was measured in ordinary rain gauges read daily at 9 a.m. or, in the Snowy Mountain project, was estimated from isohyets based on snow surveys and some precipitation gauges. Bowen and others (1957) have given a summary of details of these experiments and references to the full reports. These experiments are continuing.

3. Orographic Summer Cumuli in Arizona.

University of Arizona. Summers of 1957 and 1958.

This began as a cooperative project of the University of Arizona and the University of Chicago to study the natural processes of summer precipitation over the Santa Catalina Mountains near Tucson. Several years of study had preceded the first summer (1957) of silver iodide treatment.

Days were taken in pairs, a suitable day being one on which the precipitable water shown by the morning radiosonde ascent at Tucson exceeded 1.1 inches. If the following day was also suitable, the two formed a pair; if it was not suitable (having less than 1.1 inch precipitable water or being a Sunday) but the next day was suitable, those two formed a pair; if neither the second or third day was suitable, the first day was eliminated from the record, and the selection of a new pair was started with the first suitable day thereafter.

On a treated day, selected at random from each pair, an aircraft flying at the −6°C level dispensed silver iodide for four hours upwind of the Santa Catalina mountains, where 29 recording rain gauges and a two-man observation station were installed. A vertically-scanning radar was located 20 miles away. Stereo-photographs were obtained from synchronized cameras three miles apart. Sixteen pairs of days were obtained in each of two years.

Preliminary results were that the treated days had 30 per cent more rain ($p = 0.14$, i.e. at a 14% statistical signficance level), heavier rain ($p = 0.08$), greater maximum cloud heights ($p = 0.05$), and a somewhat higher percentage of radar echoes for a given cloud top temperature. More

lightning occurred on treated days, but the number of forest fires from lightning was about the same as on untreated days. Details on the more recent results of these experiments are given by Battan and Kassander (1959). The University of Arizona is continuing this program.

4. Tropical Cumuli near Puerto Rico.

University of Chicago, 1953-54.

In this experiment warm clouds in the Caribbean Sea near Puerto Rico were treated with water sprayed from aircraft. Pairs of clouds were selected and one of each pair, chosen at random, was treated. Initiation of precipitation was determined by radar. Results showed that treated clouds produced radar echoes significantly more frequently than untreated clouds ($p = 0.017$) (see Petterssen and others (1957)).

5. Cold Convective Clouds.

University of Chicago, 1953-54.

Summertime cumulus clouds in Central United States were treated with dry ice. Pairs of clouds were selected and one cloud of each pair, chosen by a random scheme, was treated to determine effect on precipitation initiation as measured by radar echoes. No significant difference was found between precipitation in treated and in untreated clouds, but the sample size was very small (see Petterssen and others (1957)).

6. Lightning-Suppression Experiment in California.

Division of Forestry of the State of California, U. S. Forest Service, and others.

During the summer of 1958 an experiment was conducted in a mountainous region of 3,000 square miles in northeastern California to study the possible effects of silver-iodide seeding on the suppression of lightning. Fifty ground-based, silver-iodide nuclei generators were used. Days of treatment were chosen at random from those for which the U. S. Weather Bureau's fire weather office at Redding forecast thunderstorms in the test area; control days were those not chosen by the random procedure.

Of the 13 treated days, 4 had rain and 7 had fires attributed to lightning, while the 13 control days included 7 with rain and 6 with lightning-caused fires. However, the treated days had more rain ($p=.09$), more lightning counts ($p=.12$), and more lightning fires ($p=.28$) than the untreated ones. These probabilities are based on two-tailed "t" tests. To avoid the assumptions in analysis of variance, a permutation test will be used in the final report, being prepared by Forest Service researchers under contract to the state agency.

7. Lightning Suppression in Western Montana (Project Skyfire).

U. S. Forest Service, Weather Bureau, and others.

This project was carried out in western Montana in 1958 to determine the effects of silver iodide on the growth rate and structure of large cumulus clouds and on the electrical structure of growing cumulus clouds and thunderstorms. A randomization scheme was used to select certain days for no treatment, or for seeding from a network of 30 ground-based generators, or for seeding from an airborne generator. The scheme resulted in three untreated storm periods, two ground-seeded periods, and two aerial-seeded periods. Frequency of lightning strokes and change of electric moment were measured by an experimental network of three synchronized electric field meters.

The data, even though meager, suggest the possibility of a reduction in the change

in electric moment (coulomb-kilometers) per strike in proportion to the quantity of nuclei supplied. No obvious differences were found in the frequency of intra-cloud and cloud-to-ground strikes between seeded and unseeded storms. The two aerial seedings were followed by the largest storms of the season, in which there was nearly a complete absence of lightning.

8. Santa Barbara Cloud Seeding Experiment.

State of California Department of Water Resources, Santa Barbara and Ventura Counties, North American Weather Consultants, Inc., Statistical Laboratory of the University of California at Berkeley, National Science Foundation, Meteorology Research, Inc.

This randomized experiment began in 1957 and is continuing. It is located in the foothills and coastal ranges of Santa Barbara County in southern California, and its objective is to determine the effects of silver-iodide seeding with ground-based generators on precipitation in the watershed of that area during the period January-April. It is the only known commercial type seeding operation in which the seeding days have been chosen by a randomizing scheme, thus permitting a scientific analysis of the results. Increases in precipitation, which appeared to be possibly significant during the 1957 season, were not confirmed by the 1958 results. A summary of details of the first year of this experiment has been given by Reynolds (1957). However, the results were subsequently contradicted, in part, by the Statistical Laboratory of the University of California, Berkeley.

9. Migratory Storm Systems (Artificial Cloud Nucleation Project)

U. S. Weather Bureau 1953-54.

The purpose of this experiment was to determine the effect of dry-ice seeding in modifying rainfall from extensive cloud systems of the Pacific Northwest associated with migratory storms. Storm systems were chosen at random for treatment from systems considered suitable for treatment. Those not chosen by the randomization procedure were used as control storm systems. A number of statistical evaluations were carried out which, considered as a whole, did not show statistically significant results from the seeding (see Petterssen and others (1957)).

10. East Coast Cyclogenesis (Project Scud).

New York University, U. S. Navy 1952-54.

This experiment was conducted in the central and southeast coast of the United States to study primarily the effects of aerial seeding with dry ice and ground seeding with silver iodide on the intensification of large-scale storms, and secondarily the effects of such seeding on rainfall. Storms selected for treatment were chosen at random from those considered suitable for treatment. Storms not chosen for treatment were used as controls. During test periods unseeded storms deepened slightly more than those seeded, and also yielded slightly more rain (neither effect being statistically significant) (see Petterssen and others (1957)).

11. Dissipation of Stratus Clouds.

U. S. Army (Signal Corps Engineering Laboratories), 1952-55.

A series of experiments was conducted in the northeastern section of the United States, Western Germany, and Greenland to determine the effect of aerial seeding with dry ice on the dissipation of stratus clouds. Numerous cases occurred where large holes (50 to 75 square miles) were created in cloud decks, and frequently light snow showers which reached the ground were produced. Seeding rates of ten to

twenty pounds of dry ice per mile were most successful. Dissipating or stagnant decks were most susceptible to treatment; active decks resisted effects or quickly "healed."

12. Periodic Seeding (Project Cirrus).

General Electric Company 1949-51.

Silver iodide ground generators were operated in central New Mexico during regularly scheduled periods each week to determine whether a measurable or detectable 7-day periodic component could be induced in local meteorological data. During some months of 1950, pronounced periodicities of about 7 days length in temperature, pressure, and rainfall were observed over large areas in the eastern United States. A statistical analysis by the U. S. Weather Bureau (Brier, 1955) showed that when all the data were included, the pronounced correspondence that had been claimed between the changes in the seeding schedule and the rainfall patterns was not substantiated. Details of the original experiment have been given by Langmuir (1953).

V. Further Research Needs and Problems

1. Introductory Comments.

In the preceding sections most of the discussion has dealt with points raised by Conference participants concerning the physical basis for weather modification experiments and the design and conduct of those experiments in recent and past years. It was clear from the Conference discussion that a great increase in basic knowledge of atmospheric processes is needed in order to make further genuine progress in weather modification research. Many aspects of precipitation processes, both natural and artificial, which should be integral parts of any expanded research effort are noted throughout this report. It is to be emphasized that, if any substantial progress in weather modification research is to be realized within the near future, a multi-phased, energetic, scientific effort to obtain an understanding of the physical and chemical interrelationships leading to natural precipitation phenomena is mandatory.

Of crucial importance are basic physical studies having as their aim the determination of the conditions under which atmospheric processes lend themselves to artificial modification. Once this basic understanding has been achieved, it will then be possible to predict, with greater precision than is now possible, natural precipitation phenomena under a large variety of atmospheric conditions. This ability will in turn enable the scientists engaged in weather modification research to arrive at more definitive evaluations of the scientific and economic feasibility of continued efforts and expenditure of funds directed toward attempts to modify these natural atmospheric processes.

2. Need for Improved Measurements and Objectively Defined Meteorological Categories.

There is a need to develop objective criteria for defining such meteorological categories as "storm," "pairs of comparable cumulus clouds," "pairs of comparable test areas," "cloud suitable for seeding," "day suitable for seeding," etc. Such "suitable" or "comparable" categories are being used as experimental units in weather modification studies, and are apparently the best units now available. It is important that units be as objectively defined as possible without creating a ponderously large number of them. This is a requirement for the improvement of the basic scientific procedures so as to provide data that are more adaptable for making sound comparisons of treated and untreated units, as well as to permit some degree of intra-experiment comparisons, and to facilitate the accumulation of a body of comparable scientific results. It will not be easy, of course, to arrive at objective definitions of such terms. It is recognized that definitions of these terms, and others, must rest largely on the expert meteorological judgment available.

It is necessary to improve the measurement of the amount of precipitation in the test areas in all precipitation modification studies and experiments. Certainly, some measure of reliability of a network of rain

gauges, snow surveys, or radar echoes for determining precipitation amounts, must be devised for all test areas.

There is a need for an active program to develop improved instrumentation for the measurement of such quantities as cloud temperatures, the size and distribution of cloud particles and of liquid and solid precipitation particles within individual clouds or cloud systems, the cloud-air water-vapor content, and the cloud liquid-water content. Similarly, more active research should be undertaken to provide more exact knowledge of the nature, concentration, and rôle of natural condensation and ice nuclei in the atmosphere, as well as of the properties of the output of nuclei generators and the diffusion of these particles. A great deal is yet to be learned about the artificially generated nuclei and their movement and stability in the atmosphere.

Cloud and precipitation physics would be greatly benefited by the development of devices to obtain accurate measurements of the space charge, the charge carried on cloud particles and precipitation elements, and, in general, all electrical processes within a cloud or cloud system. Such research would help elucidate the relationship between the electric field and the formation and subsequent growth of liquid and solid precipitation particles.

3. Basic Laboratory Research Needed.

In concert with the various research activities mentioned above (which in most cases could be conducted as small-scale field experiments), would be the laboratory studies which might extend into such areas as solid state physics, crystallography, surface chemistry, electron microscopy, diffusion cloud chambers, etc. Physicists and chemists have much to contribute to the basic laboratory research activity in these relevant areas, as well as in the field experiments. Laboratory experiments, in which much of the basic physical and chemical research on atmospheric processes will be conducted, may lead to hypotheses suitable for testing in field experiments under natural atmospheric conditions.

4. Value of Exploratory Field Studies.

Progress in any science depends upon exploratory experiments and probes by imaginative and creative scientists under conditions free from commercial, political and other pressures. While some basic physical and chemical research on atmospheric processes can be carried out in small-scale laboratory experiments, and can lead to physical hypotheses to be tested in the field, much exploratory experimentation can be conducted only in the field under natural conditions.

Research of this type is important, if not necessary, for the discovery of effects and the preliminary testing of hypotheses before entering into highly-organized large-scale field tests. This will normally lead to the drawing up of a formal hypothesis regarding the effect of a specific treatment, at such time as apparently encouraging results have been obtained. Exploratory research will often be carried out to increase basic knowledge of atmospheric processes, as discussed above. In the present context, however, we are considering actual experimentation with clouds and other phenomena, searching, for instance, for any indication that a particular cloud treatment is producing an effect.

Many of these exploratory investigations can be carried out as "small-scale" or even "one-man" projects. As emphasized at the Conference, these often are extremely productive and deserve an important place in future research efforts. Such small-scale projects will often relate particularly to basic laboratory or observational research.

However, in many cases, simple and effective cloud treatment tests can be handled on a relatively modest scale. Also, much of the groundwork preceding actual systematic tests can be accomplished in this manner.

The important contributions made through exploratory research are illustrated by the following examples:

(1) Schaefer's cold-box experiment and initial seeding experiment;
(2) The early tests of dry ice seeding of subcooled stratus;
(3) Studies of ice crystal production and growth by seeding subcooled fog.

The foregoing were carried out as rather small-scale projects. Three other exploratory programs on a somewhat larger scale were:

(1) The later phases of Project Cirrus;
(2) The early seeding tests conducted in Australia by CSIRO;
(3) The Weather Bureau—Air Force Cloud Physics Project.

5. Experimental Design in Exploratory Work.

There has been much discussion as to the need for statistical design in carrying out tests and investigations at the exploratory level. On the one hand, the physical scientist is interested in a high degree of flexibility in his work, so that a wide variety of treatments and cloud types can be investigated, and so that attention can be rapidly shifted and focused on only the most promising situations. On the other hand, it has been pointed out that without certain precautions, the unwary scientist may be seriously misled into erroneous preliminary conclusions, both in mistaking natural events for induced effects and in failing to recognize true effects masked by natural variability.

In some instances, such as the generation of large holes in decks of stratus clouds with dry ice seeding, the results of exploratory experiments are so reproducibly spectacular that no special analysis is required to establish cause and effect relationships. Here the uniformity and persistence of the clouds, together with a knowledge of the seeding path (and even its shape), provide adequate experimental control.

On the other hand, in many phenomena subject to exploratory field experimentation the natural variability is so great that effects, if any, are far from being obviously reproducible. This situation will usually arise in cases where the treatment is intended to supplement a natural occurrence, as for example, increasing the intensity of naturally falling rain. An example of a situation where an effect was believed to have been caused, but which was apparently a natural phenomenon, was the unwarranted conclusion regarding the effects of periodic seeding mentioned in Section IV-12.

There is no general rule that can state the design requirement for all types of exploratory experiments; too much will depend upon the physical characteristics of each particular case. The objective should be, of course, to maximize the amount of reliable information obtained from any given research effort, and this can be done by adjusting the rigor of design in accordance with the difficulty of detecting the effect of treatment in the presence of natural variability. In cases where this variability is large compared with the magnitude of experimentally induced effects, special attention must be given to the problem of designing the experiments so that effects can be isolated and measured if they, in fact, exist. Modern statistical methods, including the principles of randomization, provide the most effective known approach to this

problem. One example of such design is given in the next section.

6. Capitalizing on "Unique" Effects.

Certain seeding effects are quite unique in the atmosphere, and offer a means of detecting the presence of a seeding agent, the strength of a particular treatment, and the existence of cloud and atmospheric conditions susceptible to treatment. The holes and troughs cut into subcooled stratus clouds thus provide a visual indication of the location of the seeded portion of the cloud, as well as the extent of the cloud reaction to the particular treatment employed. Such situations can thus be used as trial grounds for studying rates of seeding, rates of growth of induced ice crystals, and the extent of spread of seeding effects. Newly developed seeding agents could be readily tested on such cloud decks. Since, however, the reaction of these clouds is not always the same for a given treatment, depending upon such factors as temperature and active or stagnant nature of the cloud, it would be desirable to compare the effect of the new agent against that produced by dry ice, for example. Then, since even stratus decks are not entirely uniform or changeless with time, a randomization procedure could well be employed similar to that used in agricultural experiments where seeding with the two varieties is carried out in rows or squares selected at random. Also, since clouds change with time, the order in which the two agents are dispensed should also be randomized.

Other rather unique seeding effects which might be useful in different cases include condensation trails, especially those produced by dry ice or silver iodide in cold air supersaturated with respect to ice but not water, ice crystal fogs produced in subcooled fogs by dry-ice or silver-iodide seeding, and numerous optical phenomena resulting from artificially produced ice crystals.

7. Field Surveys Preceding Formal Testing.

The effectiveness of formal testing programs can be greatly enhanced by carefully conducted preliminary studies of cloud and other atmospheric conditions prevailing in a proposed test area. The importance of adequately defining experimental test "units" of the atmosphere is mentioned elsewhere in this report. As a prelude to systematic testing, it usually will be found desirable to establish these units in the course of the preliminary surveys. This will require the careful observation and measurement of the proposed "units"—for example, clouds of a particular type—to determine their *seedability* and natural habit, and to isolate as many of the factors bearing on their behavior as possible. Such a survey will often include a "census" of clouds which will include a measure of the probability of natural rain (in the case of cumulus) as dependent upon certain cloud characteristics such as height, lateral dimensions, rate of growth, etc. Internal cloud measurements will also be of importance, particularly as regards those features which it is hoped will be altered by the seeding or other treatment.

Such studies and surveys will assist furthermore in estimating the duration of the testing program necessary to reach specific conclusions, and will often direct the effort toward treatment of the most favorable cloud types.

Preliminary studies will also be appropriate to assure that the intended treatment will be realized in practice during the test program. Two aspects are important: first, the performance of the treatment generator or dispenser, to be certain of the quantity, quality, and reliability of the output; second, the adequacy of the distribution of the treatment or seeding

agent within the treated cloud (it will be necessary to make certain that other control clouds or areas are not contaminated). Aircraft dispensing will be employed in most future research projects to assure more positive control of the location of the treatment. Whether the seeding agent is dispersed from the air or from the ground, it will be most important to make an extensive study of the diffusive properties of the atmosphere, and the probability that the seeding agent will be carried to the proper portions of the clouds in the proper amount. The upward diffusion of smoke from ground generators or low flying planes is dependent upon atmospheric stability in the layers of interest and can be completely inhibited by inversions. For example, in connection with the Santa Barbara experiment, the silver iodide from the ground generators probably failed to reach proper cloud height in approximately one fourth of the storm situations due to atmospheric stability. These considerations will be of even greater concern if one attempts to extrapolate the yield from aircraft seeding at cloud level to that which might be obtained under the same conditions from ground generator seeding.

8. Systematic Weather Modification Tests.

Once an effect has been established or hypothesized on the basis of physical theory, laboratory results or small-scale exploratory experimentation, interest is generated in testing for the effect under wider conditions. Such testing, whether directed toward practical military or economic application, or toward increasing our scientific understanding of the atmosphere, often tends to become a large-scale technological testing problem involving considerable organization and expenditure of funds. If such a test is to have any scientific value, the importance of careful planning, design and execution of the test, as well as sound analysis of results cannot be overemphasized.

The variability of atmospheric conditions is so great compared with most effects which might have been induced to date by weather modification efforts, that it is all too easy to make the mistake of "inferring" an effect which does not, in fact, exist, or to overlook one which does. To avoid these difficulties *entirely* is impossible, since the variability in nature cannot be eliminated. However, the effect of this variability can be reduced by the use of modern principles of experimentation. As mentioned above, these principles are often important even in exploratory work; in formal testing programs they are indispensable. Therefore, it is proper to discuss some of the major requirements of a valid and efficient experiment. The reader interested in further information on the principles of experimental design is referred to Cochran and Cox (1957), Cox (1958), Fisher (1951), and Kempthorne (1952).

9. Requirements for Valid and Efficient Experimentation.

In order to carry out effective research in the field, it is necessary that every effort be exerted to locate the best areas for conducting the field tests. The choice of the individual experimental unit may be a single cloud, for example, or a geographical area with its weather pattern. These units must be sufficiently homogeneous and numerous to provide occasions both for the application of the treatments as well as omission of the treatment for the purpose of a "control." These units must be sufficiently independent of each other, in time and space, so that the effect of a treatment on one of them will not "spill" over to the untreated units. The careful choice of these experimental units permits the repetition of an experiment, and thus

reduces the effects due to the atmospheric variability discussed earlier. With sufficient repetitions even relatively small effects may be detected. Even if effects are large, repetition is necessary if results of scientific or technological importance are to be demonstrated. However, the *reproducibility of a result* will depend not only on the availability of additional similar experimental units but even more, perhaps, on the *reproducibility of treatments.*

To illustrate what is meant by this, consider the case of seeding, in which one uses ground or airborne generators at, let us say, 10 miles from the center of the target in an "area" experiment. Precise evaluation of treatments imposed on the clouds over the target area for the specified period, such as 12 hours, would indicate great variability in the intensity of the imposed treatment. To appeal to statistical mechanics and statements of the type that 10^x (x large) particles are poured out per minute is of little help in determining the actual concentration of the seeding agent in the cloud system, *because of the variability of air currents.* The special weakness of many commercial operations in this connection must be recognized in interpreting any statements based on a statistical analysis of such operations.

To meet the requirements for a reasonable reproducibility of treatment on a number of comparable experimental units, an extensive program covering a considerable period of time may be necessary. In very few of the experiments discussed in Section IV was the duration of the series of experiments sufficient to produce convincing evidence for genuine effects due to treatments. This points up the need for experiments with greater longevity than has generally been true of weather modification experiments in the United States. In contrast, some of the Australian experiments have been running, or are scheduled to run 5 years and more. Areas for experimentation should be selected with the help of meteorologists and climatologists, making use of the historical data. A statistical investigation could then be made on the problem of how long a randomized experiment would have to be conducted in order to detect such a precipitation increase as, say, 5, 10, or 25 per cent.

While increase of precipitation has been a major objective of many weather modification efforts, evaluation of the results of many experiments has often been hampered by vagueness as to the actual objectives. 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. Usually the investigator has a choice among a number of measurements of "yield" or response. The measurements to be used for rigorous confirmatory statistical tests should be specified in advance, but this requirement should not discourage the investigator from examining the results for unexpected effects or clues. Such examination provides an important source for new knowledge and additional hypotheses for further experimentation; special care, of course, must be taken in applying ordinary significance tests to such selected "findings."

Sometimes preliminary results from partially completed experiments may suggest abandonment or modification of the original design. The investigator must use extreme caution in taking such action lest he find his efforts scattered in too many directions. A useful alternative plan might be the use of sequential experiments in which case the length of the experiment is not fixed in advance but is determined by the application of a prescribed rule to the

results obtained as the experiment progresses.

As mentioned earlier, our lack of understanding of atmospheric processes prevents us from treating weather modification attempts from the point of view of straightforward physical evaluation without statistical analysis. If accurate predictions of weather events, based either upon physical principles or detailed empirical experience could be made, then the effect of seeding, for example, could be determined directly by comparing what actually happened after an experimental treatment with what should have happened as indicated by the physical prediction. The high variability and unpredictability of atmospheric conditions have so far prevented this, and have made it necessary to resort to indirect methods of estimating treatment effects by using comparative experiments. No immediate change in this situation is foreseen.

By using carefully defined experimental units and principles of randomization, it is possible to design the experiment so that it can be conducted within relatively homogeneous classes of atmospheric conditions, with the result that the variability of conditions within these classes is greatly reduced without, at the same time, reducing the magnitude of the effects under study. An integral part of such a design is the size of the experiment in terms of the number of comparisons which can be made between treated and untreated units. In the present state of the art of designing weather modification experiments, these classes of atmospheric conditions are determined in most cases by selecting pairs of experimental units (e.g. clouds, days, storms, geographical areas) which are as nearly alike as possible. One member of each pair is chosen by a random process to receive the treatment while the other does not, and hence serves as a control.

The sensitivity of an experiment like that described above, or its capacity for detecting effects that actually exist, depends in part upon the number of pairs incorporated in the design. For instance, an experiment involving only four pairs of units which is to be judged on the basis of how many of the treated units show up "better" than their respective untreated partners, is too small to produce convincing evidence of a treatment effect. Even if all four treated units turn out the same way, this is not convincing evidence, since even if the treatment had absolutely no effect, this event would happen by chance one time in sixteen. So large a probability, equivalent to that of obtaining a head four times in a row when tossing a coin, is not considered significant in standard statistical practice.

The sensitivity of such an experiment may be increased either by using more pairs or by analyzing the amounts, on some continuous scale, by which the treated units are "better" than the corresponding controls. Under some conditions, variables related to the measurement of yield can be used through statistical regression methods to increase the efficiency of the experiment. In dealing with large scale tests, in which the experimental units are periods of time several days long, the use of time distribution of rain within periods can be used to increase the efficiency of the experiment.

One of the most commonly used designs in weather modification is the use of a fixed target area A, which is seeded on about one half of the favorable opportunities on a random basis. The nearby control area B is never seeded but the precipitation (or other measurements in the area) is used as an auxiliary variable. This design can be modified and made more effective by using a crossover pattern where area B (chosen to be meteorologically comparable to A) is seeded during

the periods when A is not seeded. The use of crossover tests in weather modification experiments has been discussed by Moran (1959).

Experimental designs involving pairs of experimental units are among the simplest used in scientific experiments. More complex designs, such as those found in Cochran and Cox (1957), are available, but are not likely to be required in weather modification studies until meteorological experimentation has progressed to a more highly quantified stage.

10. Concluding Remarks.

Recognition by meteorologists of the importance of carefully designed weather modification experiments is laudable and necessary. This step alone, however, will not be sufficient to overcome the difficulties that now stand in the path of further progress in weather modification research. Further cooperation between meteorologists and statisticians is highly important, particularly in the more complex field experiments and large-scale weather modification tests, where every effort must be made to design the experiments and tests so as to strip away as much of the variability contributed by nature as possible and to obtain a clearer picture of the existence and size of treatment effects.

In weather modification experiments, the role of randomization is important and was recognized as such at the Conference. However, randomization is no universal panacea, for no statistical refinement can be a substitute for a poorly designed physical experiment. Since man is not perfect, as someone pointed out at the Conference, it is not surprising that his experimental designs will not always be perfect. The real problem is to get "good," not necessarily "optimal," designs. With these, effective tests can be made of statistical hypotheses formulated as a result of enlightened meteorological insight. By such careful planning and experimentation, further progress can be assured.

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