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ARTIFICIAL MODIFICATION OF CLOUDS AND PRECIPITATION

by

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PREFACE

Control of the weather, because of the strong depend- of man's activities and indeed his well-being on fluctuations of rainfall, wind and temperature, has ays been high among the aspirations of man. One the main objectives of early religions was to obtain intervention of the deities to provide favourable ditions for crops, rain for growth and sun for harvest. With the rise of science, possibilities of human efforts modify the natural weather processes were proposed. rly in the history of meteorology, proposals were de for producing rain artificially by building huge nfires to induce convection under appropriate condi- ns and by other procedures. In the first decades of present century, attempts were made to stimulate cipitation by Wegener in Germany, Vitkevitch in U.S.S.R., and Veraart in the Netherlands. For tematic studies of the problem, the Artificial Rain titute, later renamed the Institute for Experimental teorology, was established in the U.S.S.R. in 1932 der V. N. Obolensky. Increased attention to the oblem in other countries followed the presentation Tor Bergeron in 1933 of his conclusion that the multaneous presence of ice crystals and supercooled ter drops was essential for the formation of rain. ndeisen in Germany, in particular, was active in the arch for means of artificially introducing the ice phase d thereby initiating precipitation in supercooled ouds. It was not, however, until Schaefer discovered 1946 that solid carbon dioxide (dry ice) produced ice ystals in great numbers in clouds of supercooled water ops; and, later that year, Vonnegut found that silver dide and lead iodide could also do so, that artificial mulation of precipitation was considered generally be within reach. Langmuir immediately recognized weather modification implications of Schaefer's covery, and from then on the number of persons d agencies involved in weather experimentation in- eased rapidly.

The widespread interest and economic and social portance of artificial stimulation of rain were reflected the fact that the very first Technical Note of the WMO was on this subject, and shortly afterwards a ore extensive publication, Technical Note No. 13—*tificial Control of Clouds and Hydrometeors*, was ued in 1955. The present publication is essentially revision and up-dating of the latter Note, which is of print. In addition to making available again statement by the WMO for guidance of Member nations and individuals, it attempts to bring to their attention the advances on the subject which have resulted from research and operational attempts during the intervening 13 years. It will be seen that while much new data have become available, the fundamental concepts regarding physical processes in clouds have not been affected, the evidence regarding the effectiveness of modification attempts has been only slightly clarified, and the conclusions remain essentially the same.

Briefly, these conclusions are that seeding of supercooled liquid clouds with dry ice or silver iodide will modify their structure, transforming them to ice clouds, that depending on circumstances this may cause the cloud to dissipate or to intensify, and may lead to increase or to decrease of the amount of precipitation over that which would otherwise reach the ground, but the exact nature of the circumstances leading to one or the other effect in most instances is not determinate *a priori* from present knowledge. The value of the consequences of being able to identify the circumstances and thereby to control the effects is so great that increased research is strongly needed. In the meantime, the decision to undertake operational attempts to produce specific results must be made with the awareness of the risk that effects opposite to those desired may occur; e.g. decrease in precipitation when increases are wanted, and on the basis of an evaluation of the cost-benefit relationship for the risk involved.

Exceptions to this uncertainty include the dissipation of supercooled liquid fog, which can be carried out under conditions and by techniques which are known well enough to warrant operational use. Claims have been made for similar success in hail suppression using silver iodide in artillery shells directed by radar, but objective evaluation of these claims has not yet been published.

Since the material in Technical Note No. 13 remains largely pertinent but is no longer readily available, the present discussion will be based on it to some extent, and large sections will be quoted from it in modified form without attribution. In a considerable degree, therefore, the authors of that Note may be regarded as major contributors to this one. Since there will be differences, mostly in emphasis but in some cases in statement of fact, responsibility for all opinions, and particularly for all errors, must be assumed by the present writer.

MORRIS NEIBURGER

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FOREWORD

In 1955, a working group of the Commission for Aerology (now Commission for Atmospheric Sciences) prepared Technical Note No. 13—*The Artificial Control of Clouds and Hydrometeors*. At its fourth session (1965), the Commission decided that a revised version of this Note should be prepared. At the request of the Secretary-General, Professor Morris Neiburger of U.S.A. thereupon undertook to perform this task. The first draft was reviewed by the members of the Commission's Working Group on Cloud Physics (Dr. Cunningham (U.S.A.), Chairman; Professor Krastanov (Bulgaria); Mr. Nikandrov (U.S.S.R.); Dr. Ohta (Japan); Mr. Ramana Murty (India). Mr. J. S. Sawyer, the Acting President of the Commission, approved the Note and informed the Executive Committee at its twenty-first session (1969) of its contents. The Committee expressed great interest in this work and agreed that the material should be published in the Technical Note series without delay.

The views expressed in the present Technical Note are those of the author and/or the members of the working group, and not necessarily those of the World Meteorological Organization.

I should like to express my gratitude to Professor Neiburger, who, as the author of this Note, has succeeded in presenting material on this complex and controversial subject in a very clear and explicit manner. Thanks are also due to the members of the working group mentioned above for having reviewed the original text.

D. A. Davies.

D. A. Davies
Secretary-General

SUMMARY

n Chapter I the nature of the problem of weather dification is discussed and the present (end of 1968) tus of the subject reviewed. In a way this chapter ents a summarization of the rest of the report. pter II explains in physical terms the reasons why nd seeding may be expected to have an effect on ud and precipitation, and why the effect on precipi- on may in some instances be an increase, in ers a decrease. The methods by which attempts ncrease precipitation may be evaluated are reviewed Chapter III, and the results of a number of such mpts are presented there. In Chapter IV attempts to reduce fog, hail and lightning are reviewed. Chapter V presents the recommendations which are drawn as consequences of the information presented in the previous chapters.

References to source material in the literature are made where pertinent, but these references are by no means exhaustive. A list of general references and bibliographies is appended for those desiring to investigate more thoroughly any of the aspects of weather modification, and also lists of recent publications by Japanese and Russian investigators, furnished by the members of the working group from those countries.

RÉSUMÉ

Le chapitre premier expose la nature du problème de modification artificielle du temps et fait le point de situation en la matière (à la fin de 1968). Il résume quelque sorte les autres parties du rapport. Dans le apitre II, l'auteur indique, en s'appuyant sur des notions physique, les raisons pour lesquelles on peut s'attendre l'ensemencement des nuages exerce des effets sur structure de ces derniers et sur les précipitations, et urquoi il peut en résulter, dans certains cas, un accroisment, et, dans d'autres cas, une diminution des pré- pitations. Le chapitre III passe en revue les méthodes mettant d'évaluer les tentatives faites en vue d'accroître précipitations, ainsi que les résultats d'un certain nombre d'entre elles. Le chapitre IV traite des essais entrepris pour réduire le brouillard, la grêle et les éclairs. Le chapitre V présente les recommandations qui découlent des renseignements contenus dans les chapitres précédents.

Lorsque cela lui semble judicieux, l'auteur mentionne ses sources, mais celles-ci sont loin d'être toutes signalées. Le lecteur désireux d'étudier plus avant tel ou tel aspect de la modification artificielle du temps trouvera à la fin de la Note technique une liste d'ouvrages de référence d'ordre général et de bibliographies, ainsi que des listes de publications récentes de chercheurs japonais et russes, communiquées par les membres du groupe de travail appartenant à ces pays.

CHAPTER 1

INTRODUCTION: THE SCALES AND STATUS OF WEATHER MODIFICATION

The familiar weather phenomena—rain, snow, hail, cold and warm spells, gales and thunderstorms—are the result of the interaction of atmospheric processes ranging in scale from the global circulations of the air in response to differences in radiation arriving from the sun in equatorial and polar regions down to the exchanges of molecules of water at the surfaces of tiny drops or ice crystals in clouds. Between these extremes are the large-scale disturbances, of the order of thousands of kilometres in extent, such as the moving cyclones and anticyclones which constitute the major weather systems of temperate and higher latitudes and the monsoonal winds responding to seasonal variations in heating and cooling of major portions of continents at low latitudes; the intermediate-scale phenomena, of the order of hundreds of kilometres, including tropical storms, typhoons and hurricanes; and the relatively small circulations measuring tens of kilometres or less, such as land-and-sea breezes, and the flow systems associated with individual convective clouds, thunderstorms and tornadoes.

Modification of the weather or climate on all these scales has been proposed, but only on the smaller scales has it appeared feasible to make practical attempts to do so. At the largest scale, proposals have included the modification of the radiational budget of the earth by the introduction of clouds of soot or ice crystals into the atmosphere at particular latitudes and heights, and coating with carbon black the snow and ice surfaces at high latitudes. Both because of the uncertainty of the probable effects of these actions and because of the tremendous logistic problems, such large-scale experiments have remained the subject of vague speculations. The possibility of controlling the large-scale weather systems of temperate and higher latitudes remains likewise almost exclusively in the sphere of conjecture. Some promise of the development of methods for evaluating the possibilities of changing the large- and medium-scale circulations of the atmosphere has arisen with the increasing success of numerical models of the global circulation and numerical prediction methods using high-speed digital computers. When these models become sufficiently realistic, it will become possible to test what the effect would be of a prescribed change in the initial conditions in altering the consequent development of weather conditions. The improvements of the observational system which are being undertaken in the World Weather Watch and the Global Atmospheric Research Programme (GARP) will contribute to the achievement of this goal.

Near the opposite end of the scale, in the range of the microclimate of plants, control measures have been part of standard agricultural practice for many years, with considerable success. Protection of crops from wind damage through the use of rows of trees as windbreaks, and protection from frost and freezing temperatures by means of orchard heaters and wind machines are the most conspicuous examples, but there have also been attempts to alter the local radiational balance and improve crop growth by covering the ground with carbon black and by other means.

The control of cloud and precipitation, which is the subject of this Technical Note, is intermediate in the degree of certainty with which it can be achieved as well as in the magnitude of the task it presents. It has been established by experiments both in the laboratory and in the field that the character of certain types of cloud, specifically those consisting of liquid drops at temperatures lower than 0°C, can be transformed. Whether the consequences of this transformation produce the effects aimed at constitutes a question which in most applications remains unanswered. For dissipation of supercooled fog or stratus cloud for short periods, to permit landing of aircraft, the answer usually is favourable. For increase or decrease of precipitation, suppression of hail, reduction of lightning, or decrease of destructive winds accompanying thunderstorms, the evidence is either contradictory or uncertain.

One of the factors which contribute to this uncertainty about effects on the amount of precipitation is the fact that the quantity of precipitation is governed not only by the microphysics of individual clouds, but also by the dynamic processes involved in the larger-scale circulations. The amount of water substance in a vertical air column is usually of the order of two or three grammes per square centimetre. One can expect the processes of condensation and drop growth to lead to precipitation of only a small fraction of this amount, so that unless there are processes which are constantly replenishing the supply of water vapour and leading to further condensation and drop growth, only a few millimetres of precipitation at most would result. To influence the amount of precipitation to any extent, it would appear necessary to change the flow patterns which determine the amount of moisture being fed into the system and control the cloud-forming processes.

In general, the amounts of energy involved in the smallest of these cloud-forming circulations is so large that it is not economically feasible to introduce similar amounts of energy to alter them artificially. However, there appear to be circumstances when small amounts of energy applied at the right time and place may change the circulations from one mode to another.

In addition, there are strong indications that the efficiency with which precipitation is released may depend on the microphysical processes as well as on the dynamic ones. For a given dynamically controlled flow system, the amount of precipitation reaching the ground may be large or small, according to such factors as the width of the drop-size spectrum in the cloud and the number and effectiveness of ice-forming nuclei.

The attempt to modify the amount of precipitation is based on the possibility that the dynamic state or the efficiency of the precipitation process may be affected by introducing substances which alter the microphysical processes in the clouds. The uncertainty is due to the fact that the consequences desired are not the primary changes in cloud structure, but instead are indirect results of a chain of events.

When the desired effect is the direct and immediate consequence of the treatment, as in the instance of fog dissipation, it may be possible to determine unequivocally the success or failure of the attempt. Even in this case, the question whether the observed change was the consequence of the treatment or would have occurred without it must be considered, but often the answer is obvious. For instance, supercooled layer clouds have been seeded in particular patterns, such as a Γ-shape, and cloud-free areas of corresponding shapes have appeared in the places where the reagents were sown. But for effects on the amount of precipitation reaching the ground, such direct and conclusive observations are not possible. The comparison between the observed amounts and those which would have occurred without the treatment cannot be made, since the latter quantities are unknown. Consequently, it is necessary to turn to statistical procedures to try to determine the effects.

Various statistical procedures have been used to evaluate attempts to augment precipitation. Because of the high variability of precipitation in space and time, and because its distribution departs from the normal distribution on which most statistical tests are based, long series of experiments are required and special evaluation techniques must be used for convincing demonstration of success in increasing (or decreasing) precipitation artificially. Most of the attempts to modify the weather have not been designed to meet rigorous standards of statistical validity. A considerable amount of controversy has resulted, with the enthusiasts and the commercial firms which carry out seeding operations being convinced of success by evaluations which were not considered by critics and statisticians to be valid. The latter group has maintained that definite conclusions can be drawn only when experiments are designed in accord with the principles established many years ago by R. A. Fisher in connexion with the testing of agricultural treatments (Fisher, 1936; Neyman and Scott, 1967a). The key aspect of the design is randomization to enable evaluation of the effect of variation not related to the treatment.

A recent review of all available data (Neyman and Scott, 1968) showed that 23 experiments meet the requirements of statistical designs and adequate duration to produce significant results. Of these, only six definitely indicated larger amounts of precipitation when seeding took place than would have occurred in its absence. Seven of the other experiments were indefinite, showing an increase or a decrease, depending on the portion of the target studied or the methods of evaluation used. The remaining ten experiments indicated a definite decrease in precipitation with seeding below that which would have been expected without it.

There are physical reasons why one would expect that under some circumstances cloud seeding would decrease precipitation rather than increase it. If the dynamical processes are affected in such a way as to reduce the total upward flow and thus the amount of water condensed, or if the microphysical processes are affected in such a way that the efficiency of the precipitation is reduced, the total rain reaching the ground will be smaller than in the absence of seeding. While we have a fairly clear understanding of these processes in qualitative terms, adequate theories and observational data for quantitative evaluation of the rates at which these processes go on naturally and the way these rates would be affected by seeding are not available. Consequently, we cannot tell whether the natural process in a given instance would proceed at optimum efficiency or whether a particular change, say by cloud seeding, will lead to an increase or a decrease.

In the following sections we shall first review the physical processes of cloud and precipitation formation as a background for understanding the various factors on which the possibility of cloud modification is based and the reasons why in some instances increases, and in other instances decreases, might be expected. Next, a résumé of the structure of clouds and cloud systems the forms of precipitation accompanying them will esented. The problem of evaluating modification pts will be discussed, especially in terms of the of weather-modification experiments. A review results of various attempts to augment precipitation, decrease hail, etc., as reported in the literature, will be presented as a basis for appraising the present status of the subject. Finally, recommendations will be made regarding further research required, and guidance presented regarding decisions for practical applications.

CHAPTER 2

THE PHYSICAL BASIS FOR CLOUD AND PRECIPITATION MODIFICATION

As a foundation for discussion and evaluation of proposed methods for weather modification, a brief review of the physical processes involved in the formation of natural clouds and precipitation will be presented. Since some readers may not be at all acquainted with meteorological processes, the presentation will presume no previous knowledge. The readers who are familiar with them are invited to skip over the next few sections of this chapter.

A. Humidity and condensation

Clouds in the atmosphere form by condensation of water vapour on particles of other materials. To describe how this condensation takes place, it is necessary to review first the concept of *humidity*.

Water vapour, although relatively small in amount, occupies a special distinction among the gases of which air is comprised because of its variability and because it gives rise to many of the phenomena we call weather. The other components are practically constant in their proportions; taken together, they are called *dry air*; and correspondingly, the air including water vapour is called *moist air*. The part of the total air pressure due to the molecules of water vapour is called the *vapour pressure*.

Moist air which can exist in equilibrium over a plane surface of pure liquid water at the same temperature is said to be *saturated*. The vapour pressure of saturated air depends only on its temperature, approximately doubling its value for every 10°C increase in temperature. The *relative humidity* of moist air is the ratio, usually expressed as a percentage, of the actual vapour pressure to the vapour pressure of saturated air at the same temperature. Saturated air therefore has a relative humidity of 100 per cent.

In the absence of surfaces, the vapour pressure can exceed the saturation value several-fold before condensation begins. If the relative humidity exceeds 100 per cent, the excess is called the amount of *supersaturation*.

Moist (unsaturated) air can be brought to saturation either by adding water vapour—e.g. by evaporation—to raise the vapour pressure to the saturation value at the same temperature, or by cooling the air so that its saturation vapour pressure is reduced to the actual vapour pressure. If the cooling of air is carried out at constant pressure, the temperature at which saturation is reached is called the *dew point*. Further addition of water vapour or further cooling produces supersaturation. In the presence of a plane liquid water surface, it would result in condensation onto the surface. In the absence of such a surface, condensation in the form of droplets is obstructed because the vapour pressure over a curved liquid surface exceeds the saturation vapour pressure by an amount which increases with the curvature. In air devoid of other particles, droplet condensation begins only if it is sufficiently supersaturated for the vapour pressure to exceed the value in equilibrium with the largest aggregates of liquid phase produced by chance molecular collisions, a supersaturation of several hundred per cent. Because the atmosphere always contains suspended particles (condensation nuclei) which present surfaces on which condensation can take place, these high supersaturations never occur in the free air. Usually condensation begins even before saturation is reached because many of the particles in the atmosphere contain hygroscopic substances which take up water molecules and exist as solution droplets with equilibrium vapour pressures lower than the saturation vapour pressure. For a given quantity of solute in a solution droplet, there is an equilibrium size at which the effect of hygroscopicity in lowering the equilibrium vapour pressure just offsets the effect of surface curvature in raising it, to give exactly the existing vapour pressure. Hygroscopic particles thus are efficient *condensation nuclei*, which grow with increasing humidity even before saturation is reached. However, for relative humidities below 100 per cent, even hygroscopic nuclei grow to an equilibrium size only a few times the size of the dry particle. For unlimited growth a slight supersaturation is necessary, though by an amount which is less for a hygroscopic nucleus of a given size than for an insoluble particle, and for a larger nucleus than for a smaller one. Once this amount of supersaturation is exceeded, the drops grow until the excess water vapour is used up, at first rapidly in radius, then more slowly, since the increase in mass is proportional to the third power of the radius, but the diffusion of water vapour is proportional to the surface area of the drop, and thus the second power. Because of the large number of nuclei the individual vertical motions have a scale much smaller than the convective motions, but are distributed more or less uniformly over large areas. A category which bridges these scales is that of *orographic clouds*, in which the upward motion of the air is produced by flow over hills or mountains, and the size depends on the dimensions of the obstacles, from single small clouds over isolated peaks to cloud systems associated with mountain ranges thousands of kilometres long.

Both for convective clouds and for orographic clouds, the speed of upward movement of the air may range from one to ten metres per second. In stratiform clouds, the vertical motions are usually very much slower, in the range of one to ten centimetres per second. In some instances, convective instability may be released within a region of general convergence and the rapid up-and-down motions of convective currents, with associated cumuliform cloudiness, may be superposed on the widespread layer-type cloudiness. In these situations, upward and downward motions with speeds of metres per second occur within the widespread regions of sustained upward speeds of the order of centimetres per second.

In contrast to the occurrence of areas of convective activity within regions of stratiform cloud, horizontal divergence and downward subsidence of air sometimes take place over large areas. In these situations, the convective activity is inhibited or limited to small heights. Examples of such areas are the central and eastern portions of anticyclones, particularly the semi-permanent anticyclones of subtropical latitudes. In these areas, the general stability of the air is such that heating at the ground can produce instability only in the lowest kilometre or two, not sufficient to give rise to clouds deep enough to produce precipitation.

The size of the cloud particles which form by condensation depends on the rate and duration of the vertical motion. For a given distribution of sizes and nature of condensation nuclei, the greater the total upward displacement of the air, the larger the drop which forms. In cumuliform clouds the vertical motions are sustained for short periods, of the order of 30 minutes. During that period, air parcels may be subjected to several up-and-down oscillations, but some of them may be displaced upward as much as five kilometres, or even ten kilometres or more in severe thunderstorms. In stratiform clouds at fronts or in cyclones, a parcel of air may flow upwards more or less continuously for a day or more, so that even with the much smaller speeds the displacement may be nearly as large as in convective clouds. Except for the longer time in which the drops can fall relative to the air the size of drops in convective and stratiform clouds may be expected to be much the same at the same heights; and indeed the observations that are available indicate that the spectra of drop sizes in clouds depend more on the number and size of nuclei in the rising air, as reflected by the air mass source, than on the type of cloud. Thus, maritime clouds, whether stratiform or cumuliform, have fewer drops per cubic centimetre, with larger model sizes and broader size spectra, than clouds in continental air masses.

C. Formation of precipitation

1. *The difference between cloud and precipitation*

When drops form by condensation on nuclei during the ascent of moist air, their radii are mostly in the range between 1 and 20 microns. Drops of this size fall with speeds between 0.01 and 5 cm/sec, and the upward flow of the air forming the clouds more than offsets the downward motion of the drops, keeping them from falling to the ground as rain. If drops of such small sizes do fall out of the cloud into unsaturated air, they very quickly evaporate. In air with 90 per cent relative humidity, they would be vaporized before falling as much as one metre.

For drops to fall faster than the air is rising, and to reach the ground without evaporating, they must be much larger. The smallest precipitation particles, the drops of drizzle, are about 0.1 mm (100 microns) in radius, and raindrops range up to 3 mm in radius. In these sizes, their fall speeds vary from 70 cm/sec for drizzle drops to 9 m/sec for the largest raindrops. These speeds are large enough for the drops to fall through the air faster than the cloudy air is rising, and to pass through the unsaturated air below the cloud base rapidly enough to reach the ground before being completely evaporated, even when the upward velocity of the air is considerable and the humidity of the air below the cloud is low.

The key difference between cloud and precipitation is thus particle size, and the problem which the physics of precipitation must answer is to explain how the particles grow, more than one million times in mass, from cloud-drop size to precipitation size. With the large number of nuclei which are activated, there is not enough water vapour available to form precipitation-sized drops by condensation.

2. *The processes of formation of precipitation*

There are two ways that cloud particles can grow rapidly to precipitation: (1) by collision and coalescence; and (2) by the three-phase, or Bergeron, process. The way the first process acts is obvious. Larger drops falling faster overtake and collect smaller drops in their paths, thereby becoming larger, falling still faster d sweeping up small droplets more rapidly. However, ause of the tendency for the air to carry drops around ch other, the larger drops must exceed some minimum before this process can proceed at any significant It turns out that a broad spectrum of drop sizes, th some drops larger than about 20 microns in radius, ecessary for drop growth by collision and coalescence. The three-phase process occurs because drops remain uid at temperatures below 0°C, and ice crystals, en they form, are much fewer in number than the uid drops. As was pointed out in section A, when crystals are present in a cloud of liquid drops at b-zero temperatures, the drops evaporate and the crystals grow rapidly. Since they are much fewer in mber, the ice crystals become much larger than the existing drops. These crystals then fall relative the remaining small drops and collect them.

Process (2) thus may initiate process (1), and the two ing together can readily lead to the formation of cipitation in sub-freezing clouds. In clouds warmer n 0°C which precipitate, collision and coalescence one must be the activating process.

The warm rain process

When a drop falls, the air ahead of it is pushed out its way and the smaller drops contained in that air ll tend to be carried out of the way by the moving The inertia of the smaller drops reduces their dency to be deflected, and if they are not too small d are close enough to the axis of fall of the larger op, they will be struck by it. The fraction of all the all drops in the path of the larger drop which would collected by it is called its *collection efficiency*. It pends on the sizes of the large and small drops. For ops of radii less than about 19 microns, the collection ficiency is extremely small; some computations indicate at it is zero, but other recent evaluations give it non-o but still very small values. In order that the collision-lescence mechanism operate, there must be some ops which have become larger than 19 microns. These st be produced by condensation. That clouds exist frequently without precipitating is evidence that very ten condensation does not produce these large drops.

For some time, the view was held by many that precip-tion was initiated only by the three-phase process, that clouds would not precipitate unless at least ir upper portions were at sufficiently low temperatures ice crystals to form. Now it is generally accepted t precipitation has frequently been observed to fall m clouds which are entirely warmer than 0°C, and t often convective clouds which in the course of their velopment eventually reach up to heights where the temperature is below freezing have been shown by radar echoes to begin to precipitate before their tops reach those heights.

The occurrence of rain from warm clouds complicates the question of precipitation modification by seeding with dry ice or silver iodide, which is based on the premise that the three-phase process is necessary for precipitation initiation or maximum efficiency of the precipitation process. If circumstances are such that precipitation is initiated by collision and coalescence before the cloud becomes supercooled, there is no possibility of influencing its early stages by methods based on ice-crystal formation. On the other hand, the occurrence of this type of precipitation suggests the use of alternative treatments to initiate drop growth by coalescence. The various proposed methods for precipitation modification will be discussed later.

The development of large drops ($r > 20\ \mu$) by condensation appears to depend principally on the existence in sufficient numbers of "giant" nuclei. Observations suggest that over oceans the number of giant nuclei is relatively large, and over continents they frequently are practically absent. There have been insufficient measurements of the number of giant nuclei to make firm generalizations about their occurrence, and especially to relate their numbers to various types of large-scale weather patterns.

It has been suggested that turbulence within clouds produces fluctuations in the humidity which lead to a broadening of the drop spectrum produced by condensation and the production of some especially large drops. While the theoretical treatment of this problem has established that it will occur, it has not yet shown under what circumstances it will be favoured, nor are observational measurements of turbulent fluctuations in clouds available for identification of these conditions.

Computations of drop growth by coalescence have been carried out using high-speed digital computers, and also analytically with simplified models, for the purpose of finding out how the growth depends on the drop-size distribution in the clouds, and how fast precipitation-sized drops will develop under various assumptions regarding liquid content and drop-size distribution. As expected, these computations show that if there are initially a sufficient number of relatively large drops, a group of the largest ones will grow, at first slowly but later with increasing speed, and reach precipitation size in a time approximating that in which precipitation develops in natural rain. However, critical values of the parameters controlling the rate of development of precipitation have not yet been determined.

Factors of definite importance are the cloud thickness and duration of updraft. Computations show that it would take about 50 minutes for a 30-micron radius drop to grow by coalescence to 300 microns (0.3 mm) in a typical cloud (average drop size, 7.5 microns; liquid content, 1 g/m^3). In this time, it would fall about 2 km relative to the cloud. This suggests the general time scale and cloud thickness required for precipitation to form by the warm process. For larger drops to form, the clouds must be correspondingly thicker.

When drops grow sufficiently large they tend to shatter. Large raindrops are distorted from their spherical shape by the air flow as they fall, and drops exceeding about 3 mm equivalent radius break up into a number of smaller drops, of which about ten have a radius of about 1 mm. In a vigorous cumulus updraft, there can be a chain reaction of raindrop multiplication, in which drops grow by collision with smaller drops until they disrupt, producing several small drops for each original growing drop, which in turn grow and break up. Depending on the concentration of liquid water in the cloud, this multiplication of the number of precipitating drops can produce a tenfold increase every five to ten minutes. In addition to augmenting the number of raindrops formed by the warm process and thus the rate of precipitation, this process could contribute to the charge generation in thunderstorms. However, observations suggest that the ice phase is involved in the production of the large separation of charges associated with thunderstorms, and the most generally accepted theories are based on mechanisms involving freezing.

4. *The three-phase (Bergeron) process*

The number of ice nuclei and the temperatures at which they are effective have been measured extensively only in recent years. Earlier, their scarcity was inferred from frequent observations of the existence of supercooled liquid clouds. The occurrence of liquid clouds at sub-zero (Celsius) temperatures is responsible for the icing of aircraft, which constituted a serious hazard to aviation until methods of preventing it were developed. In connexion with investigations of aircraft icing, statistics were accumulated on the frequency of occurrence of supercooled clouds. Recently, extensive observations were made in the U.S.S.R. of the phase of cloud particles (Borovikov, 1968). It was found that some clouds containing liquid drops occur at temperatures as low as −40°C. More than 80 per cent of the clouds warmer than −10°C contained liquid, but about half of them were mixed liquid and ice. By −20°C, only 10 per cent were liquid clouds, although 30 per cent contained both supercooled drops and ice crystals. This distribution is understandable in terms of the frequency and effectiveness of natural ice nuclei.

Although many ice nucleus counts have been made at various places over the earth, a consistent pattern of their distribution and behaviour has not emerged. This is in part due to differences in technique used. Recently, there has been a move towards standardizing the procedures, and it is hoped that with increased reliability, a more consistent relationship will be established between the number of ice nuclei and the occurrence of ice crystals in clouds.

Certain facts about the frequency and behaviour of ice nuclei are known. The number effective at a given temperature increases exponentially with the amount of supercooling in such fashion that there is approximately a tenfold increase for each 5°C drop in temperature. As rough averages, there are 10 natural ice nuclei per cubic metre active at −10°C, and one per litre at −20°C in clean maritime air. In continental air subject to pollution, the concentrations may range from one or two orders of magnitude higher. Natural ice nuclei appear mainly to be soil particles, of which some clays seem to be the most effective. Industrial pollutants, including some metal particles, appear also to be active ice nucleants.

The optimum concentration of ice nuclei for the formation of precipitation depends on temperature and speed of updraft. For usual conditions, it is estimated that about 100 nuclei per cubic metre result in growth of ice crystals at a rate sufficiently rapid to fall out at the same rate as water vapour is provided for condensation by the adiabatic cooling of the lifted air. If the nuclei concentration is much smaller, as occurs naturally at temperatures of −10°C and above, the few precipitation-sized particles which are produced are not adequate to saturate the air below the cloud and reach the ground. If there are as many ice nuclei as there are cloud drops, as at very low temperatures, the cloud will be transformed to ice crystals too small to precipitate.

Thus, the question whether a cloud will precipitate depends on the number of ice crystal nuclei present, the temperatures at which they are effective, and the temperature in the cloud. Since the temperature of the cloudy air depends on the height to which it is lifted, it is to be expected that precipitation will develop in clouds extending upward to high enough levels, but the height required will depend on the number and the nature of the ice nuclei present. Usually, clouds reaching a few hundred metres above the level where the temperature is −10°C will develop precipitation. The liquid content of cumulus clouds of warm weather having bases well below the 0°C level and extending above the −10°C level is large, and showers develop rapidly, with crystals growing to hailstones of one cm by accretion within ten minutes if strong updrafts are present. For cumulus clouds with colder bases, the growth of ice crystals is slower, and it may be necessary for the cloud to extend above the −20°C level before precipitation develops.

The rate of growth of ice crystals in layer clouds similarly depends on the liquid content of the cloud as well as the number of ice nuclei effective at the prevailing temperature. The growth of crystals to precipitation size proceeds rapidly in air which is saturated with respect to liquid drops at temperatures between −10°C and −30°C. These conditions enable crystals large enough to fall faster than the small upward speeds of the air in stratiform clouds to be formed in less than five minutes. Even shallow clouds developing at these low temperatures are therefore likely to produce virgae, or trails of falling ice crystals.

Once the crystals reach a size large enough to fall relative to the cloudy air, their growth may be enhanced by their collecting cloud droplets or smaller ice crystals in their path. The collection leads to formation of graupel, small hail, or snowflakes. However, precipitation is frequently found to consist of single crystals. This is the case, for instance, in winter-time orographic snowfalls in the Rocky Mountains of the U.S.A.

If the precipitating ice crystals fall to levels where the temperature is above 0°C, they will melt. If still in cloud, the raindrops thus formed will continue growing by collecting cloud drops, and will be subject to possible multiplication by disruption if they grow too large.

There has been the suggestion that ice crystals are also subject to a multiplying action. This suggestion arose to explain the fact that the number of ice particles in clouds frequently are found to be an order of magnitude larger than the number of ice nuclei effective at the prevailing temperature. The action proposed is a splintering, in which a freezing drop, when nucleated, shoots off some small fragments which then act as nuclei for growth of other ice crystals or freezing of other drops. At first, laboratory experiments seemed to corroborate the existence of this action, but subsequent investigations showed that splintering under natural conditions is so slight that it cannot explain the observed rate of multiplication.

A further unexplained phenomenon is the occurrence of ice particles observed in some instances of cumulus cloud which did not extend above the −4°C level. A possible explanation is the preactivation of nuclei. It is suggested that nuclei which have grown to ice crystals at high levels and low temperatures may retain within irregularities in their surface small amounts of ice, even after falling through several kilometres of clear air; this ice then can nucleate freezing or sublimation in clouds with temperatures only slightly below 0°C.

D. The ways that clouds and precipitation may be modified

The above discussion shows that the formation and structure of clouds and the development, form and amount of precipitation could be influenced in two ways: (1) by altering the dynamic processes—that is, the airflow leading to cloud formation, and (2) by altering the microphysical processes of formation and growth of cloud and precipitation particles. It can be demonstrated that direct influence of the flow patterns would require amounts of energy so large that it is not feasible except in a few special circumstances. However, altering the microphysical processes may under some circumstances produce large changes in the dynamic processes. The possibilities of producing weather modifications by utilizing dynamic consequences of microphysical changes will be discussed in connexion with the presentation of the possibilities of their direct action.

Whether the objective is to alter the cloud structure and thereby cause it to dissipate, as in dispersing fog at airports, or to change the form or amount of precipitation, as in hail suppression or precipitation augmentation, in order to influence the microphysical processes it is necessary to introduce into the clouds materials (seeding agents) which change the size distribution or nature (phase) of the cloud particles, thereby affecting the growth processes which are responsible for the stability of the cloud and for the amount and nature of precipitation from it.

1. *Seeding of non-supercooled droplet clouds*

The drop-size distribution of liquid clouds might be modified by (1) changing the concentration, size and nature of the condensation nuclei; (2) addition of water drops of other (larger) sizes; or (3) introduction of substances which alter the surface properties of the drops. All three of these methods have been attempted. For instance, the introduction of additional giant condensation nuclei and the introduction of large water drops by spraying have been tried for augmentation of precipitation from cumulus clouds. These attempts have been less frequent than those based on the seeding of supercooled clouds to initiate ice-crystal formation.

The expectation that seeding of clouds with giant hygroscopic nuclei or with water spray will have an effect is based on the premise that the large drops thereby introduced, being larger than the droplets previously present, will grow by collision and coalescence sufficiently rapidly to lead to precipitation in a cloud which would otherwise produce no precipitation or produce precipitation at a later time. It is assumed by those wishing to augment precipitation that by initiating precipitation earlier, the total amount reaching the ground will be greater than otherwise, and not merely displaced in time or decreased because of reduction of the subsequent rate of precipitation from what it would have been.

For any particular cloud composition and dynamical structure, there will be an optimum size and concentration of seeding particles and an optimum time and region for their introduction to obtain the most efficient result. In layer clouds, which contain feeble updrafts, the particles might best be sprayed into the cloud tops, as happens naturally when rain is augmented by falling from higher clouds through low-level layer clouds. To cause a warm fog to dissipate, this would be the appropriate procedure. For substantial increases of rain received at the ground, layer clouds too thin to produce natural precipitation are negligible, since they contain too little available water and have no innate regenerating mechanism.

Cumuliform clouds are more promising subjects for precipitation augmentation by these methods, since it is probable that many fail to yield appreciable showers by a narrow margin. The seeding agents may be introduced into these clouds near the cloud base, or even injected into the updrafts from the ground, with the size selected so that they will be carried upward into the upper parts of the cloud before they become large enough to fall back through the cloud, thus growing on both the upward and the downward traverses of the cloud. Recently, attempts have been made to compute the amount of effect of various treatments to augment warm cloud precipitation from schematic models of cumulus clouds, using high-speed digital computers. In one such computation (Peterman, 1968), the effect upon growth of precipitation-sized drops produced by various treatments with hygroscopic particles was evaluated for different constant updraft speeds for 10–minute periods of growth. It was found that different treatments might either increase or decrease the amount of rain developing in a given time, but with some treatments there might be as much as a fivefold increase. For effective treatment, the mass of salt introduced had to exceed 10^{-6} grammes per cubic metre, and the particle size required ranged from about five to 20 microns. It must be emphasized that this computation was based on a simplified model. The results are therefore indicative of the general range of effects to be expected, and do not give definite consequences of particular treatments. The theory and the method of computation will have to be improved considerably to achieve such definitive results.

2. *Seeding of supercooled clouds with ice crystals*

Clouds of liquid droplets could of course also be seeded with giant hygroscopic nuclei or water spray when they extend to levels where the temperature is below 0°C. In this case, however, the introduction of ice nuclei to utilize the three-phase process of precipitation development presents a more favourable possibility. If ice nuclei are introduced which are effective in larger numbers at higher temperatures than the existing natural nuclei, the height at which crystals occur in concentrations significant for the production of precipitation will be lowered. In the case of cumulus clouds, for instance, this would result in precipitation beginning at an earlier stage in their convective growth. On the other hand, if the cloud already contains sufficient natural nuclei for maximum precipitation efficiency, the introduction of more ice nuclei may produce "overseeding", and thereby reduce the precipitation or inhibit it completely. Thus, seeding with ice nuclei could result in an earlier initiation of precipitation and an increase in the total amount, or a decrease or elimination of it.

To know the direction of the effect to be expected, it would be necessary to know the natural ice nucleus content of the cloud, and to be able to compute the effect of the introduction of particular treatments. Unfortunately, it is not easy to make counts of nuclei under field conditions, and it is doubtful that the numbers observed by the measuring techniques which involve rapid cooling are the same as the numbers of ice crystals forming in the atmosphere at the much slower cooling rates which occur naturally. In addition, it is difficult to regulate the rate of introduction of nuclei so that a specified concentration will be produced at a particular place in the cloud. The prediction of the character and amount of influence seeding would produce is limited by the fact that the present state of the theory does not enable computation of precipitation rates even if the exact concentrations of ice nuclei are known. The theory enables only broad qualitative estimates to be made of the effects of seeding.

With these limitations in mind, we shall discuss briefly the effects to be expected by seeding various types of cloud with ice nuclei.

The introduction of ice nuclei (in not too great numbers) into supercooled fog or stratus cloud results in the rapid conversion of the cloud to ice crystals which fall out, leaving gaps in the cloud where the seeding took place. This effect is so direct as to leave no question that it is due to seeding. If the cloud regenerating mechanism or drifting (advection) is not too rapid, the resulting dispersal of low cloud or fog is adequate to permit aircraft operations, and this method is being used successfully to reduce the number of hours airports are closed by low ceilings and visibility. The amount of precipitation reaching the ground from such clouds oo small to be of significance in programmes aimed ncreasing the water supply.

or significant increases of precipitation reaching ground, one should have continuous upward flow ir regenerating the cloud as it precipitates, or con- ous advection of new moisture-laden clouds to ace the ones which have precipitated. The types cloud which meet one or the other of these require- ts include winter frontal clouds, orographic clouds, warm-season convective cumulus.

is probable that the widespread layers of clouds ociated with cyclonic convergence and frontal lift- usually have precipitation initiated naturally by the they reach any given location with sufficient thickness significant amounts of precipitation to fall from m. Data are not available on the frequency with ich conditions favourable for accelerating the precipi- on process by seeding occur in these clouds—i.e., how quently thick layers of supercooled wholly and pre- minantly liquid clouds are present in these sys- ms.

Orographic clouds, particularly those resulting from w of moist-air masses over extensive mountain ranges, r the most promising opportunities for precipitation mentation by cloud seeding. The continuous lift- of the air is assured, so that new water substance ndenses as the old is removed by precipitation; it nown that the clouds frequently are composed of percooled liquid drops, particularly in winter, and the ice nucleus concentration is not sufficient for ximum natural production of precipitation the intro- ction of additional nuclei should be expected to rease the precipitation. Since there is no likelihood t seeding will modify the vertical air motion (as may cur with cumulus convection) the only danger of oducing a decrease rather than an increase lies in possibility of overseeding.

Cumulus clouds formed by convection also are charac- ized by vertical motions of sufficient magnitude and ration to produce significant amounts of precipitation. equently they occur with tops extending to levels ere the temperature is −20°C or lower without ecipitating, indicating that the natural ice nuclei ective at these temperatures are not present in sufficient mbers to produce precipitation. In this case, the roduction of the appropriate concentrations of ice clei may start precipitation before it would begin turally. Furthermore, it is reasonable to believe at even in instances in which natural ice nuclei are fficient to initiate precipitation, they may not be esent in large enough numbers to produce the maximum te of precipitation, and the addition of artificial nuclei ll increase the rate of precipitation.

In addition to the possibility of starting the precipitation earlier and improving its efficiency, seeding cumulus clouds may augment the vertical motion and thereby increase the amount of water vapour condensed and made available for precipitation. This possibility arises because the buoyancy of the rising air currents is augmented when the drops are converted to ice, thereby releasing the latent heat of fusion. In some cases, this might result in de-stabilizing a stable layer that convection had been unable to penetrate, resulting in a large upward surge of the cloud top. If this happens, a large increase in precipitation may occur. In addition, the enhanced growth of one cumulus tower might lead to growth of neighbouring ones which are seeded by ice crystal residues of the seeded one, thereby promoting propagation of a self-sustaining shower which may be considerably more enduring and extensive than the seeding which initiated it.

If, however, the precipitation process has already started naturally and is proceeding at approximately 100 per cent efficiency, addition of ice nuclei may result in the formation of so many ice crystals that precipitation is retarded or prevented. Furthermore, in some instances when seeding initiates precipitation before it would occur naturally, the earlier beginning of precipitation may decrease the level to which convection extends and thereby decrease the duration and intensity of the shower. Such a limitation of convection might be due, for example, to the earlier development of downdrafts associated with the precipitation.

The possibility that overseeding can limit the growth of precipitation has led to attempts to reduce the formation of crop-damaging hail by cloud seeding. In these attempts, the seeding with ice nuclei is intended to convert the cloud to ice early enough so that the hailstones, which grow by collection of liquid drops, no longer have water drops to feed on and cannot grow large enough to do damage.

The seeding of clouds to reduce the occurrence of lightning which causes forest fires has also been proposed and tried. The premise in this case is that the electrification of thunderclouds will be reduced by earlier conversion of the cloud to ice crystals, either because the charge-mechanism is diminished or because the total growth of the cumulonimbus cloud is limited.

Other possible effects include the redistribution of precipitation. Thus heavy snowfalls which occur at the downwind end of open bodies of water—warm, large lakes or seas—might be reduced in depth and spread over larger areas if the number of ice nuclei in the clouds were increased so that the snow crystals were more numerous but smaller, and thus were carried farther inland by the wind as they fell.

The possibility of reducing the total amount of precipitation in flood-producing rains also might be achieved by appropriate measures of overseeding. Practical ways of insuring overseeding over extensive areas have not yet been suggested.

E. Conclusion

The present understanding of the physical theory of cloud structure and precipitation formation suggests that under some circumstances they may be subject to modification. Neither the available observational data nor the status of the theory is adequate to predict definitely their natural behaviour or the effect of treatment attempting to modify or control them. The immediate need is to gather more detailed and extensive observational data, and to render quantitative the theories of cloud and precipitation formation. Much current research effort is being applied to these tasks, but increased activity is desirable.

Until such improved observations and theory are available, the question whether precipitation will occur naturally at optimum rates cannot be answered adequately either in general or in a specific situation. There does not yet exist a co-ordinated theory which would enable estimation of the number and sizes of condensation nuclei and of ice nuclei effective at various temperatures which would lead to maximum precipitation for a given distribution of temperature, humidity and vertical velocity, or the effect of the growth of cloud and precipitation on the vertical velocity. At present, only guesses or at best rough estimates can be made regarding the direction and amount of effect of introducing additional nuclei. As discussed in the preceding sections, either growth or dissipation of clouds, and either increase or decrease of precipitation, can be expected to result from seeding, depending on circumstances which are not yet well understood.

The lack of complete understanding and predictability has not deterred various agencies from undertaking field operations. In some cases these operations have been intended to test the practicability of achieving desired objectives by cloud seeding; in others the purpose was to meet specific needs; practicability being assumed. The records of these operations over a period of more than 20 years might be expected to be adequate to demonstrate whether or not seeding achieves the desired results. However, although for some effects, particularly the dispersal of supercooled fog, the results are clearly demonstrable, for others the answers are not so clear, primarily because the natural variability of precipitation is so great that it is difficult to determine whether the observed occurrences were due to the treatments or would have been the same in their absence.

A considerable amount of controversy has occurred through the years concerning the efficacy of various techniques of cloud seeding, particularly with respect to increasing precipitation. The source of the different views, which are still present, lies in the interpretation of the significance of various ways in which the results of various operations have been evaluated. Before proceeding to a review of the cloud seeding operations and their results, we shall, in the next chapter, discuss the problem of their evaluation.

CHAPTER 3

THE EVALUATION OF ATTEMPTS TO INCREASE PRECIPITATION

Background

The possibility of putting some of the potentialities discussed from the theoretical standpoint in the preceding chapter into actual practice came with the discovery by Vincent Schaefer in 1946 that dry ice (solid carbon dioxide) created large numbers of ice crystal embryos (ice nuclei) in a supercooled cloud (Schaefer, 1946). These experiments were carried out in clouds he produced in a food freezer. The dry ice chilled the saturated air in its vicinity below −40°C, the threshold temperature for homogeneous ice nucleation. Dr. Irving Langmuir, with whom Schaefer was associated at the General Electric Company, immediately recognized the implications of this effect for the structure of atmospheric clouds and enabled Schaefer to carry out experiments by airplane which demonstrated that supercooled clouds occurring in the atmosphere changed to ice crystals when seeded with dry ice pellets. Schaefer reported that in these experiments a supercooled altocumulus cloud was converted to snow-crystal streamers, a valley fog was transformed to ice crystals which fell out, clearing the fog, grooves were produced in a stratus cloud along the line of flight, and isolated towering supercooled cumulus were made to produce localized snow showers (see Schaefer, 1968). The changes were conspicuous, and appeared to be so clearly associated with the seeding as to leave no question in the experimenter's mind that they were the consequences of it. In some cases, for instance the occurrence of T-shaped grooves in supercooled stratus seeded in that pattern, no one could doubt it; in others, such as the clearing of the valley fog, the possibility that other factors were at work cannot be completely dismissed.

Shortly afterward, another of Dr. Langmuir's associates, Dr. Bernard Vonnegut, found that silver iodide was an effective ice nucleating agent, with a nucleation threshold of −4°C (Vonnegut, 1947). He developed generators for production silver iodide smoke, including a type similar to the one commonly used at present, which burns a solution of silver iodide and potassium iodide in acetone.

With these seeding agents available, great interest developed in the possibility that seeding operations might increase substantially the precipitation in arid regions or regions affected by drought, or increase the snowpack on mountains for additional power and irrigation water. A number of cloud-seeding operations were begun in various parts of the world. Some of these operations were intended as tests to establish whether results of practical importance could be obtained, but many of the operations were conducted almost from the start to achieve specific benefits in the form of increased rainfall. Commercial cloud-seeding firms entered the field and actively promoted rainmaking or rain-increasing programmes. Some of these firms claimed astonishing success, increases of several hundred per cent. With the passage of time these claims have been modified, and now the most optimistic of these firms claim average increases of only about 10 to 20 per cent, amounts which are consistent with estimates made by some independent or governmental bodies, but are so small that they are almost impossible to determine, even though they are large enough to be economically important.

The largest amount of rainmaking activity took place in the U.S.A. Although some of the operations there were sponsored by power companies, irrigation groups or local governmental units concerned with their water supply, the largest activity was carried out under the aegis of groups of farmers or ranchers. In some cases, the seeding was carried out by employees of the sponsoring agency. Generally, however, the seeding operations were carried out by cloud-seeding firms under contract with the sponsoring group. Projects sponsored by farmers encompassed large fractions of a state, and it is estimated that by 1951 approximately one-third of the United States west of the Mississippi River was covered by rainmaking contracts amounting to three to five million dollars per year. To quote Vincent Schaefer (1963): "The rash of entrepreneurs and 'rainmakers' which developed shortly after these experiments were announced, and their expansive claims and brash attitudes, played on the relative ignorance and desperate situation of groups of farmers and ranchers, mulcting them of hundreds of thousands of dollars, at the same time putting the entire field of experimental meteorology in disrepute."

Partly as a result of disillusionment, and partly because in some of the areas involved a period of wet years followed the period of drought, there was a considerable decline in the extent of rainmaking operations in the

1950s. Some power companies and other agencies have maintained continuous programmes from the early years, but for the most part the clientele of rainmaking firms has changed as the interest and needs of some declined and those of others arose. At present, some 200,000 square kilometres are being treated in the United States.

It is interesting to note that in spite of the more definite evidence of the efficacy of seeding in dispersing supercooled fog, little attention was given to its practical application for improving visibility at airports during the first few years. More recently, systematic use has been made of this application.

The discovery of the seeding effect of dry ice and silver iodide smoke, followed by claims of its usefulness in rainmaking, led to pressures on governmental agencies to investigate their practicality.

In 1948 and 1949, the U.S. Weather Bureau undertook tests of the effectiveness of seeding with dry ice dispersed from airplanes for increasing precipitation (Coons *et al.*, 1948, 1949). Seeding of various kinds of clouds in different locations and seasons were carried out using airplanes which were fully equipped to make meteorological measurements and radar observations, and measurements of precipitation and radar echoes were made at the ground. The results showed that the seeding rarely produced precipitation reaching the ground unless unseeded clouds in the vicinity were also precipitating, and that the seeded clouds usually tended to dissipate rather than regenerate or grow. The conclusion drawn from these experiments was that seeding could either augment or diminish precipitation, depending on other factors. There was severe criticism of the Weather Bureau for its "negative attitude" as a result of a conservative policy based on these results.

Tests carried out in other countries were similar in showing clear-cut effects on individual clouds and ambiguous conclusions with respect to increases of precipitation reaching the ground. In one of the earliest of these, a large supercooled cumulus cloud seeded over Australia with 70 kg of dry ice grew 5 km higher than surrounding unseeded clouds, and heavy rain was subsequently observed to be falling from its base (Kraus and Squires, 1947). Other trials in Australia were believed to have produced showers in 15 out of 20 cases of seeding cumulus clouds. In South Africa during the summer of 1947/48, dry ice was dropped into the tops of 36 supercooled cumulus clouds, and the results observed by radar at the ground. Precipitation echoes were observed to develop in 24 of the seeded clouds, but in some of them the echoes were of short duration, and in others they did not develop until more than an hour and a half after the seeding, and thus probably could not be attributed to it. In 1948, a series of experiments was conducted in Canada, in which 12 of 35 supercooled cumulus clouds which were seeded with dry ice produced precipitation which reached the ground, and 11 showed virgae. (For a review of these and other early seeding tests, with references, see Mason, 1952, chapter VII.)

The early experiments with dry ice thus corroborated the theoretical implications, that under some circumstances seeding could initiate or promote precipitation and in others it might inhibit cloud growth and diminish precipitation. The evidence was not interpreted in those terms by most interested parties. Instead, they divided into enthusiasts who maintained that precipitation could be increased by seeding at every opportunity, and the detractors who said the evidence had not demonstrated this capability. Because the circumstances favourable for increasing precipitation were not known, most operators seeded on every occasion favourable for natural precipitation. Because of the greater ease and smaller cost than seeding with dry ice from airplanes, most commercial operators used ground-based silver iodide generators.

The uncertainty whether effects are produced by seeding is magnified when the seeding is carried out using silver iodide generators operated at the ground, for in addition to questions regarding the influence of the seeding agent on the cloud, there are the questions of whether the silver iodide reaches the clouds over the target area and at what concentrations, and whether it may have been deactivated before reaching them. It is assumed that the upward air currents which give rise to formation of the clouds will carry the silver iodide smoke into them. The few attempts to trace the smoke plumes from silver-iodide generators suggest that the nuclei are carried downwind distances of the order of tens of kilometres in fairly high concentrations, but that in conditions of normal atmospheric stability the diffusion upward may not be rapid enough to carry them into the clouds.

Silver iodide particles are subject to photolytic action in sunlight. Experiments indicate that the number effective is reduced to about one-tenth every half hour. Thus, the smoke must be generated in high enough concentrations that after dilution during travel and after photolytic decay the number reaching the clouds is still sufficient to initiate the precipitation process.

A further complication is suggested by recent experiments concerning the way in which silver iodide nuclei act to initiate crystallization. It has been found that when a silver iodide particle enters a water droplet at temperatures above 0°C, freezing will not begin until the drop is cooled below −10°C, whereas if the drop is first cooled to −5°C and then the silver iodide particle is introduced, the drop freezes immediately. This suggests that if the cloud base is at temperatures higher than —5°C, seeding from the ground will be less effective than if the nuclei are roduced by airplane or rocket into the cloud at the el where the temperature is $-5°C$.

The uncertainties regarding the intermediate physical ocesses taking place during cloud seeding operations uld be dismissed if there was definite evidence that the al result desired—namely, the increase in amount of ecipitation—was achieved. However, it is impossible to ve such evidence, for one cannot know how much rain r snow) would have fallen in the absence of seeding. imilarly, if the purpose is some other objective, such as e dispersal of fog or the reduction of hail, one could not ow how long the fog would have lasted or how much il would have fallen in the absence of seeding.) If one d a firm quantitative physical theory and the necessary servations, one would be able to make such a predicon; but, as has already been stated, only the broad tlines of the theory are available; quantitative details ait further research.

Because of this situation it is necessary to turn to statiscal procedures to arrive at estimates of the probable fect produced by seeding. Various procedures have en used, but only a few are considered by statisticians being capable of giving unambiguous indications of the ccess or failure of the treatment.

Evaluation methods

The basic question in evaluating a cloud seeding eration is whether or not the process of seeding prouced the desired change from the condition which would ave occurred in its absence. For purposes of discussion, e shall consider operations for increasing rain over a ecified area; the application to other objectives by alogy will be obvious.

The question is, then, did more rain or snow fall over e target with the cloud seeding than would have if there ad been no seeding? And if so, how much more?

To answer these questions, it would be necessary to now how much would have fallen in the absence of eding, and the main problem of evaluation is to estimate his amount. The problem of determining how much ctually fell with seeding is not a negligible one, however. The deficiencies of raingauge measurements are well nown and need not be discussed in detail here. In ddition to the failure of raingauges to collect all of the ain falling in their vicinity and the non-representativeness f the catch due to exposure and location relative to opographic features, the density of raingauges in the sual climatological network is quite sparse in relation to he scale of the precipitation patterns and its large variability both in space and time, particularly if short periods re involved. Thus, the precipitation records give a ather crude estimate of the total precipitation over an rea. Air mass showers and thunderstorms in particular may give a large amount in the position of a raingauge and a very small amount a short distance away, or vice versa. For valid measurement of the amount of precipitation, very dense networks are required. By using longer periods and larger areas (containing more raingauges), this uncertainty of measurement can be reduced. Using longer time periods as units of observation, however, reduces the number of samples in the statistical population, and the inclusion of larger areas may involve logistic and other practical difficulties in a cloud-seeding operation.

Radar observations provide an alternative to raingauges for measuring precipitation. While the intensity of echoes is more strongly influenced by the size of the drops than by their number, and thus in principle is an ambiguous measure of precipitation intensity, the drop size distribution in rain is related to the rainfall rate with sufficient regularity for fairly good correlations to have been found between strength of radar echoes and precipitations rates. The degree of precision does not appear to be great enough to detect the 10 to 20 per cent increases in total precipitation currently claimed, and the use of radar in cloud seeding evaluations so far has been largely limited to determining whether precipitation echoes have been initiated and at what heights they have occurred.

Radar measurements of rainfall intensity cannot be used in methods of evaluation which depend on historical records of rainfall, such as the target-control regression procedure described below. They may be applied, with reservations, in randomized seeding experiments. The reservations involve the fact that radar measures the intensity of precipitation (with the ambiguity referred to above) as it falls through the air—not the amount reaching the ground. Since the view radar takes is along the line of sight, the intensity is measured at higher elevations at larger distances from the position where the radar equipment is located.

In mountain regions where the objective is to increase the water stored in the snow and released to reservoirs and power stations by melting in the spring, snow surveys provide a reasonable basis for evaluation of seeding effects. In these surveys, the depth of snow on the ground and its water content are measured periodically along prescribed paths or "courses". Accumulated snow cover may not represent accurately the total precipitation at a particular course, because of losses due to evaporation and runoff. In addition, the courses are located in more accessible areas and may not be fully representative of the snowpack in more rugged terrain.

Stream-flow data have been used as a means of integrating the precipitation over area and time. The area involved is frequently an appropriate one for operations whose purpose is to increase the water supply in a particular drainage basin. The time units required are at least a season, or usually a year, and even for these the ground storage may contribute a considerable amount of uncertainty to the data.

The estimation of the precipitation which would have fallen in the absence of seeding is much harder than measuring the amount which did fall. Because of the very large variability of amounts of precipitation from year to year one cannot use climatological normals. Various predictive devices have been used, of which the target-control area regression is an example. In this procedure, an area near the target and otherwise resembling it as much as possible is selected for comparison. It is assumed that the natural variations of precipitation at the control area are closely similar to those at the target area, so that the amount which would have fallen at the target in the absence of seeding can be estimated from the precipitation which fell at the control area during the period of seeding. It is further assumed that the seeding does not spread into the control area and "contaminate" it.

To utilize the regression technique, records of precipitation for the target and control areas are required for long periods, in order to establish the correlation between them. The statistical analysis usually assumes that the precipitation amounts in the two areas are drawn from stationary and normally distributed time series. Actually, precipitation data satisfy neither of these characteristics. To correct the departure from normal distribution, transformations of variable have been used—for instance, taking the logarithm or the square root of the precipitation amounts. It has been shown that the distribution of precipitation is closely approximated by an incomplete gamma function; the transformation based on this finding has rarely been used in regression analysis so far. The transformation to normality of the precipitation variables enables the calculation of the significance of a particular departure of the precipitation in the target from that expected on the basis of the precipitation observed at the control—i.e., the probability that it could have happened due to chance variations in the relationship.

The difficulty of non-normally distributed variables can be overcome by using non-parametric tests which do not require a knowledge of the distribution of the test variables.

The target-control regression technique has been subjected to severe criticisms by statisticians who regard it as subject to various kinds of bias. In the first place there is what has been called the storm-type bias. Weather patterns are known to occur in spells or cycles. During one spell lasting perhaps for several years, the pattern might be predominantly such as to favour heavier precipitation at one area, say the control area, than at the target area; in a succeeding period the reverse might tend to be true. If the historical regression were based on a period when the first type of spell predominated and the seeding period was one when other occurred, false indications of the influence of seeding would be inferred. A further bias is possible if the seeding periods are selected by an operator of a cloud-seeding project whose objective is to demonstrate that seeding produces increases in precipitation. He can influence the results favourably by using weather forecasting to select for seeding only those situations in which more precipitation is likely to occur naturally over the target area. Other biases pertain to the time of starting and stopping cloud-seeding operations. Such operations are usually begun after a period of drought, and are stopped after a series of adequate rains have occurred on the target. Consequently, the precipitation data for the operation do not represent a sample taken from the entire population of precipitation data. This sampling error has been shown to lead to fictitious apparent increases of five to ten per cent when applied to monthly precipitation units.

In operations in which a control area could not readily be selected, attempts were made, particularly in the early days of rainmaking, to evaluate the effectiveness of the seeding by comparing the precipitation observed in the seeded period with past records over the same area. It was demonstrated (H. C. S. Thom, 1957) that because of the large variability of precipitation, the precipitation would have to be increased to three times its average value to demonstrate with a reasonable degree of significance that the change was due to the seeding. Without any other basis for prediction of the amount of precipitation which would have occurred in the absence of seeding than the past records, it is clear that demonstration of precipitation increases due to cloud seeding at the level currently claimed—10 to 20 per cent—is impossible.

Randomization offers a procedure for eliminating the sources of bias attributed to the target-control regression method, and for eliminating need for a control area or other independent predictive device if none is readily available. (It should be added at once that if a predictive device is available, its inclusion in the design of a randomized experiment greatly increases its power.) In a randomized experiment, the possible occasions for seeding are divided into two groups on the basis of pure chance, such as the tossing of a coin or the selection of a random number. One of the groups receives the treatment, and the other does not. The evaluation of the effect of the treatment is based on the difference between the precipitation for the seeded and non-seeded groups.

The assumption of randomization is that all other factors than the treatment are distributed equally, within identifiable limits of variation, in the two groups, so that e observed effect can be attributed to the treatment with degree of significance which can be computed with ecision from the observed variability of the data.

The power of a randomized experiment to yield signi-ant results in the shortest possible time is increased if is combined with predictive devices. The most straight-rward is the target-control cross-over procedure, in which two areas are utilized—one of them seeded and the ther not—on each cloud-seeding opportunity, the ecision which one is to be seeded being made on the sis of a random event. The procedure would be as llows: on the basis of meteorological information, a tuation is selected as suitable for cloud seeding as dicated by the hypothesis being tested. The random xperiment is then carried out to determine which of the wo areas is chosen for the target; the other remains as ontrol for that particular situation. In the course of the ntire experiment, one obtains data on a series in which rea *A* is seeded and *B* is not, and another series in which rea *B* is seeded and *A* is not. Thus, data on which to base a conclusion are accumulated twice as fast as in a imple randomization experiment. If the precipitation in the two areas is strongly correlated, the amount of the ata required is further reduced.

Of course, a necessary feature of the randomized rossover experiment is that there be no contamination —i.e., when area *A* is seeded none of the seeding agent or its influence would reach area *B*, and vice versa. Because of the variability of wind, this feature may be difficult to achieve in operations using ground-based ilver-iodide generators.

In all statistical techniques of evaluation, it turns out that large quantities of data are required unless the magnitude of the effect is quite large, in order to establish the conclusions with acceptable significance. Consequently, a long time is needed for an experiment to test whether a cloud-seeding procedure produces an increase of precipitation, usually about five years or more. This long duration of a test, with the accompanying high cost, has led to the consequence that very few experiments yielding significant conclusions have been conducted so far.

C. Results of evaluations

The need for careful statistical analysis of the results of attempts to increase precipitation by cloud seeding was not recognized at first. Perhaps not all advocates were as brazen as one head of a rainmaking firm, who would show prospective customers a picture of an empty reservoir purportedly taken before a seeding operation and another picture with water up to the top of the reservoir, like the before-and-after pictures in the advertisements of hair nostrums, and ask what more proof was needed. Generally, however, the attitude was that the increases would be large enough to be self-evident.

The controversy in the United States in the early 1950s led to the statistical analysis of some of the results of commercial cloud seeding both by the cloud seeders and by independent groups, usually by means of the target-control area regression technique. The dependence of the conclusions on the choice of target and control areas and the length of record used soon became evident. For example, in one evaluation of a four-month seeding operation in central Arizona using twenty years of data at 13 stations in the target area and 39 stations in the control area, increases of 15 to 54 per cent were indicated; an independent evaluation using 30 years of record, for which data at only 11 of the target stations and 26 of the control stations were available, showed no significant increase. Similarly, commercial operations carried out in 1950–54 in Oregon for which the operator claimed significant increases were analysed by an independent group which found indicated increases of six per cent, while at least a 15 per cent change would have been needed for the result to be regarded as unlikely to have occurred by chance.

An attempt to settle the dispute was made by a committee appointed for the purpose by the President of the United States, acting under authority of an act of Congress. The report of this Advisory Committee for Weather Control, issued in 1957, contains a careful study of the problem of evaluation by the target-control regression technique. From it, the report concluded that "the seeding of winter-type storm clouds in mountainous areas of the United States produced an average increase in precipitation of 10 to 15 per cent from seeded storms, with heavy odds that this increase was not the result of natural variations of rainfall". For types of precipitation other than winter orographic precipitation, no significant effects were found, but it was stated: "This does not mean that effects may not have been produced. The greater variability of rainfall patterns in non-mountainous areas made the techniques less sensitive for picking up small changes which might have occurred there than when applied to the mountainous regions."

The conclusions of the Advisory Committee report regarding orographic precipitation were severely criticized by statisticians who pointed out the various possible sources of bias in the target-control regression technique (Brownlee, 1960; Neyman and Scott, 1961). Some of these had been considered and guarded against in the analysis which was conducted on behalf of the Advisory Committee. The critics, however, were emphatic in their insistence that the only way to eliminate the possibility of bias was by means of randomization. Previous to the Advisory Committee report, the advocates of randomized experiments had been gaining ground, and a few randomized experiments had been started. The reaction to the report gave an added impetus to randomized testing.

Because randomization requires that approximately one-half of the situations judged suitable for seeding be left unseeded, commercial operators and their clients have for the most part been unwilling to pass up opportunities for increased yield of precipitation, and randomized tests have been conducted almost exclusively by or for government agencies interested in determining whether precipitation can be enhanced. To date, approximately 25 randomized experiments useful for this purpose have been completed in the world.

The results of these randomized projects were analysed recently by Neyman and Scott (1968). They found that of the 23 experiments for which they were able to obtain data, only six showed increases of precipitation ascribable to seeding which were at a level of statistical significance. Seven showed increases according to some methods of analysis or for some parts of the target, and decreases for others. The remaining ten experiments showed statistically significant decreases in precipitation.

In contrast to the results of the randomized experiments, a new analysis by a panel of the U.S. National Academy of Sciences of 18 commercial seeding operations showed increases of 5 to 57 per cent in 17 of them, with only one of them resulting in no increase. From these data and other evidence, the panel concluded that: "Despite the impossibility of rigorous quantitative evaluation of all these operational results, when taken together and supported by the tentative results of some experimental projects, they appear to us to suggest that precipitation increases of the order of 10 per cent may be stimulated, under certain meteorological conditions, by silver iodide seeding."

The appropriateness of basing this conclusion on the results of a selected group of commercial operations has been seriously questioned (Brownlee, 1967; Neyman, 1967). Brownlee points out that there are many sources of possible bias, some of which might account for the 10 per cent increase attributed to seeding.

A more detailed discussion of the results of some of the randomized experiments will be given in the next section. It can be pointed out at once, however, that the conclusions of the panel of the U.S. National Academy of Sciences, when taken verbatim, are not contradicted by the randomized experiments. These experiments also show that "precipitation increases ... may be stimulated *under certain meteorological conditions* by silver iodide seeding." But they show that under other meteorological conditions decreases may be stimulated. The task which is facing the meteorologist is to find out how to discriminate between the two types of meteorological conditions. Only if those conditions favourable to increases can be selected for seeding and those likely to produce decreases omitted will consistent augmentation of precipitation result. At present, the inability to distinguish the two types of conditions leads to cancellation of the increases occurring on some occasions of seeding by decreases on others, with net changes so small as to be difficult to detect.

D. Randomized experiments on precipitation augmentation

In conducting a test by a random selection process, it is necessary that the hypothesis being tested be stated explicitly in advance. Additional information may be drawn from analysis of the results, but *post facto* examination cannot produce conclusions with the same validity as tests of the *a priori* hypothesis.

In practically all randomized rain-augmentation experiments, the hypothesis being tested was that a particular seeding technique applied to situations selected in a particular way in a particular locality would result in greater precipitation than the amount which would have occurred without seeding. The consequence is that the results are not necessarily indicative of what would happen with other seeding methods, in other meteorological conditions, and in other places. It is desirable, in discussing experimental results, to group them according to type of weather situation, such as summer convective clouds and winter orographic precipitation. While there are obvious advantages to such a grouping, the experiments do not all fit nicely into such categories. We shall follow the simpler procedure of grouping the experiments by country in which they were performed.

1. Randomized cloud-seeding experiments in Australia

Cloud-seeding experiments began in Australia in 1947 immediately after Schaefer's pioneering work. Early tests indicated that supercooled clouds favourable for seeding occurred frequently, but that dry-ice seeding was too costly for use in seeding large areas and silver iodide smoke released from the ground decayed before reaching the cloud. In the tests of seeding effects over large areas, the seeding was therefore carried out with silver iodide smoke released from airplanes. The silver iodide was introduced into as many as possible of the deep supercooled clouds passing over the target areas, cumulus being seeded at the base and stratiform clouds at levels where the temperature was between −5° and −10°C.

Experiments were conducted in four locations, using two slightly different procedures. In the Snowy Moun-

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to the published reports (E. J. Smith, 1967)
ipated before the experiment started that
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or the first two years seemed to support this
but in the subsequent years the results did
The final evaluation showed an increase of
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uld have occurred by chance. A fifth experi-
l out for two years at Darling Downs, showed
decrease of 13 per cent due to seeding, with
significance 0.03. The conclusion by E. J.
principal scientific officer in charge of the
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and did not justify any definite statement
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alysis indicated that the deterioration of the
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iodide cannot remain effective, it was sug-
his persistence may be due to such factors as
of previous rains (augmented by seeding) on
pour flux, the radiation balance and temper-
area, and the number of condensation nuclei
the ground. A more optimistic view of the
e Australian experiments has been presented
. Bowen (1967).

li artificial rainfall stimulation experiment

e Australian experience, a randomized experi-
l has given consistent indications of increases
tion due to seeding, with positive effects
uring 1961–1966, and an over-all indicated
8 per cent with a significance level of 0.027.

The seeding was carried out by airplane in a fashion similar to the Australian experiments, the silver iodide being released just below the base of the clouds in an area upwind of the target after the cloud-seeding officer determined that the cloud top extended above the −5°C level. The experiment used the cross-over target-control technique. Two areas of Israel, designated North and Centre, separated by a buffer zone to avoid contamination of one when the other was being seeded, were designated as potential targets. One or the other of the areas was designated by random selection at the start of the season, for seeding on each day. Thus, about one-half of the days were designated for North seeding, and the rest for the Centre area to be seeded.

The already highly significant increase described above is still greater, 27 per cent, significance level 0.004, when the analysis is restricted to the interior of the areas. Justification of this restriction exists in terms of the limitations on the flight of the seeding plane imposed by navigational and political considerations. While this selection of a limited area for analysis is subject to some question because it was suggested after the results of the first two and one-half years were available, the persistence in subsequent years of the pattern of larger increases there indicates that it is valid.

An analysis of the meteorological conditions associated with the Israeli experiment was carried out to find out what the conditions were which led to increases there and not in other experiments conducted in similar fashion. The principal difference between days with large and small amounts of precipitation was the ice-nucleus count. On the basis of this analysis, it was suggested that the precipitation that occurs in Israel is predominantly initiated by the three-phase process, with the amounts of precipitation being larger if the natural ice nuclei are plentiful or are augmented by seeding. In other areas, where silver-iodide seeding from planes has not produced increases, it has been suggested that precipitation was initiated by the collision-coalescence process before the ice-crystal process stimulated by the seeding could play a role.

3. Randomized cloud-seeding experiments in the United States

In the United States, the first randomized project, SCUD, which was conducted by New York University in conjunction with the U.S. Navy in the winters of 1952/53, and 1953/54, had as its objective to test whether cloud seeding would influence the development of temperate latitude cyclones (J. Spar, 1957). Since the hypothesis was that cyclogenesis off the east coast of the United States might be influenced by the release of latent heat during the augmentation of precipitation, the effect on precipitation was evaluated. The seeding was carried out both by dry ice dispersed from aircraft and by silver iodide smoke from 17 generators installed at stations extending over an area from Florida to New York. The precipitation was averaged over an area extending along the east coast of the U.S. from Florida to Massachusetts, another large area to the north-east of the first one, and a third area adjusted according to the probable drift of the seeding agents. The target areas thus were much larger than those of other experiments. Randomization was by storm, the initiation of each period being based on a forecast of cyclogenesis.

The evaluation of the precipitation effects showed smaller amounts with seeded storms than with unseeded, but at a level of significance which made it likely that they were due to chance variations.

In the same years, an experiment, known as the Weather Bureau ACN Project, was conducted to evaluate the "seeding potential" of clouds over western Washington and Oregon (F. Hall, 1957). Seeding was carried out using dry ice dispensed from aircraft flying along lines 20 to 40 miles long perpendicular to the direction of advancing storms. Seeding opportunities were selected on the basis of synoptic data and observations made by aircraft, and two-thirds of them were seeded on a random basis. The targets were identified on the basis of the location the winds would carry the seeded clouds. The results indicated that there had been increases in precipitation, but at such a low level of significance that the investigator stated that there was "no strong evidence to support a conclusion that the seeding produced measurable changes in rainfall".

An experiment was conducted in Santa Barbara County, California, in 1957–1960, to test whether precipitation from winter storms could be increased by seeding with ground-based silver iodide generators (State of California Department of Water Resources, 1960). Some aspects of this experiment have been criticized severely by one of the statistical groups which participated (Neymann, Scott and Vasilevskij, 1960). For one thing, there is a strong likelihood that there was contamination from seeding by a commercial operation in a neighbouring area. Large increases in precipitation were indicated the first year of the experiment, but for the experiment as a whole the effects were below the level of statistical significance. Analysis of the physical characteristics of the storms during the experiment (T. B. Smith, 1962) showed that part of the difficulty was inadequate selection of "seedable" storms.

Two experiments were conducted to examine the possibility of increasing the precipitation from cumulus clouds which form almost daily in summer over the Santa Catalina Mountains near Tucson, Arizona (J. L. Battan, 1966; Battan and Kassander, 1967). In these experiments, the seeding was randomized by pairs of days—that is, when a forecast based on objective criteria indicated that the following two days would have clouds suitable for seeding, the decision whether the first or the second day of the pair should be seeded was made by a random process. In the first experiment, in 1957–1960, the seeding was carried out with silver iodide smoke from an airplane flown at the —6°C level along a line perpendicular to the wind upwind of the target. Rainfall was measured at a network of 29 recording raingauges. The seeding flights lasted two to four hours, and the rainfall during a five-hour period embracing the seeding period was used for testing the effect. Increases were indicated during the first two years of the experiment, and larger decreases during the latter two years, with the over-all indication a 30 per cent decrease at a level of significance which showed the result could have occurred by chance.

Following the preliminary analysis of the first experiment, a new experiment was started using a more restrictive criterion for selecting the pairs of days, to reduce the frequency of experimental days with zero rainfall, and doing the seeding from an altitude 300 to 600 metres below the cloud bases, instead of at the −6°C level. The target was made smaller, and the number of raingauges in it was increased. The new experiment was carried out in 1961, 1962 and 1964. Its result was the same as the first, an indicated net decrease of 30 per cent, with a strong likelihood that it could have occurred by chance.

The remaining randomized experiment which has been completed is *Project Whitetop*, which was conducted by the Cloud Physics Laboratory of the University of Chicago over a circular research area 60 miles in radius in the State of Missouri (Braham, 1966). The project was conducted during the summers of 1960–1964 for the purpose of testing the precipitation effects of seeding non-orographic summer cumulus with silver iodide by airplane at the same time as measurements were made of the physical properties of the seeded and non-seeded clouds.

In *Project Whitetop*, the days were identified as seedable on the basis of objective criteria indicating likelihood of instability showers. If the amount of precipitable water shown by the morning soundings at two nearby radiosonde stations, Little Rock (Arkansas) and Columbia (Missouri), exceeded 1.30 inches and 1.05 inches, respectively, and the wind direction at 1,300 m was between 170° and 340°, the day was designated operational, and a random process determined whether it should be seeded or not. Prior to the random decision a seeding line 30 miles long, about 45 miles upwind of a central radar site, was selected. On days which were selected for seeding, the plane flew back and forth along this line at the level of the cloud base from noon to 1800 CST (90th meriian time), with its silver iodide generators operating. On both seeded and unseeded days this line was used to define "plume" positions on the basis of the most divergent winds between the seeding level and 4,500 m. This defined the "Chicago plumes". Narrower plumes, based on the winds at the seeding level, were called the "Missouri plumes". The target area was considered the area covered by these plumes, and comparisons were made between the precipitation in the plumes on seeded and non-seeded days, and between the plume and non-plume precipitation.

Rainfall measurements were obtained from the regular Weather Bureau network of raingauges supplemented by additional gauges installed for the experiment. While the network is sparse (one raingauge per 700 square kilometres), it represents the only data available concerning the rainfall reaching the ground. Radar records were obtained but, as stated previously, these cannot be considered suitable for quantitative evaluation of precipitation effects.

The precipitation records for *Project Whitetop* have been analysed by statistical groups at the University of Missouri (Decker and Schickedanz, 1967) the University of Chicago (Flueck, 1968), and the University of California (Neyman, Scott and Smith, 1969). All the analyses, although treating the data differently and applying different tests of significance, agree that there was a significant *decrease* in the precipitation on seeded days as opposed to *unseeded* days both in the Missouri plume and in the Chicago plume, amounting to 60 per cent and 40 per cent respectively. There was also a decrease in non-plume precipitation on seeded days, but at a lower level of significance. The evidence appears conclusive that in the conditions of the *Whitetop* experiment, seeding produces decreases rather than increases, and Professor R. R. Braham, the director of the project, in discussing the project at hearings of the United States Senate Committee on Commerce in 1966 stated: "We now come to realize that indeed there may be periods in the weather, certain weather situations in southern Missouri, in which our seeding, using standard techniques, resulted in decreases in the precipitation in that region." The indication is also that the seeding agent spread more widely than estimated on the basis of the winds, producing decreases in the so-called non-plume areas as well.

In addition to the analyses of the precipitation records, Professor Braham conducted some investigations of the distribution of radar echoes. By a complicated series of manipulations of the data in order to eliminate topographic and other extraneous influences, he concluded that there was a five to ten per cent increase in radar echoes on seeded days in the region immediately downwind of the seeding arc, a negative effect of the same magnitude farther downwind, and another positive effect at a still larger distance downwind. The positive effects shown in the radar echoes did not appear to have associated with them areas of increases in precipitation measured at the ground.

In summary, of the experiments which have been completed in the United States, almost all involved seeding from aircraft, and almost all gave indications of decrease of precipitation in so far as the results attained statistical significance. Guided by these results, a number of new tests have been designed and are under way. Preliminary results of some of them indicate increases in precipitation attributable to seeding. In view of previous experiments in which such indications did not hold up, one is reluctant to put any importance on them until the experiments have been completed and the final results have been evaluated.

4. *The Swiss hail-suppression project "Grossversuch III"*

While, as the above heading says, the objective of *Grossversuch III* was to test whether hail could be decreased or prevented by release of silver iodide from ground-based generators, the method of operation was identical with that used in attempts to stimulate rain, precipitation measurements were systematically collected, and the results with respect to precipitation effects were so interesting that it seems appropriate to discuss the results in this section.

The experiment was fully randomized (Thams *et al.*, 1966). Each afternoon during the months May-September of the seven years 1957–1963, a meteorologist at the Osservatorio Ticinese in Locarno-Monti decided whether the following day should be considered a test day; if he forecast that thunderstorms which might produce hail were likely, the day included in the experiment, and an envelope selected randomly was opened to determine whether seeding should be carried out on that day. In this way, 292 experimental days were selected during the seven years, of which 145 were seeded.

The seeding was carried out by 20 ground-based generators operating from 0730 to 2130 on a pulsating schedule of five minutes on and ten minutes off. The generators were located in and to the south of the target area, a 3,500 square kilometre region on the southern slopes of the Alps, ranging in altitude from 200 to 3,400 metres.

With respect to its purpose, the experiment was a failure in the sense that the results showed no significant difference in duration, areal extent or intensity of hail when it occurred on seeded and unseeded days, and the frequency of hail on seeded days was considerably greater than on unseeded days, with a probability of only four per cent that the difference in frequency could have occurred by chance (Schmid, 1967). In regard to precipitation, on the other hand, the frequency of days with rain was significantly affected, but average rainfall on seeded days was 21 per cent greater than on unseeded days, with a significance level which borders on the acceptable. For the portions of the target at higher elevations, the increase was larger and the level of significance higher.

Neyman and Scott, in analysing the precipitation results of this experiment, made an interesting discovery (Neyman and Scott, 1967 b). They stratified the results according to the forecasters who predicted the suitability of the test days, and found a striking difference between the days selected by the two forecasters who made the largest number of forecasts. When one of them, call him forecaster *A*, selected the experimental days, the precipitation on seeded days was 79 per cent greater than on unseeded days, whereas when forecaster *Z* selected them, the seeded days had 44 per cent less precipitation than the unseeded days. Neyman and Scott hypothesized that inadvertently forecasters *A* and *Z* had based their selections on criteria which discriminated between those weather situations which (for the southern Alps in summer) result in increases when seeded and those which result in decreases. They proposed that by examination of the meteorological conditions on the days for which the two made their forecasts, the two kinds of weather situation could be identified.

A meteorological analysis was carried out as they proposed (Neiburger and Chin, 1969). It turned out that the decrease for days selected by forecaster *Z* was the accidental effect of the particular way the random process selected the days to be seeded. The amount of precipitation on the southern slopes of the Alps is greatly influenced by the wind direction, with southerly winds producing large amounts, and northerly winds very small amounts. It chanced that of the days with northerly flow selected by forecaster *Z*, most of them were seeded, resulting in smaller average precipitation for seeded than for unseeded days. If the days with northerly flow were omitted, the days selected by *Z* showed an increase with seeding, though not as large and significant as those selected by *A*. Days with northerly flow, by themselves, showed larger amounts when seeded than when unseeded by about the same percentage as days with southerly flow, but since the total amounts were so much smaller, the actual amount of increase on days with northerly flow was negligible. The conclusion is that in the southern Alps, where precipitation is plentiful, seeding with silver iodide smoke from ground-based generators produces increases in the amount of precipitation under those conditions favourable to large amounts of natural precipitation.

5. *Canadian cloud-seeding experiments*

A randomized cloud-seeding experiment was conducte in western Quebec province, in Canada, from 1959 t 1963 (Godson, Crozier and Holland, 1966). The cros over technique was used, with one of two test area 32 nautical miles square and separated by 32 nautic miles seeded in each experimental unit, while the othe remained unseeded as a control. Once the weather situation was designated as suitable, the choice of which are was seeded was determined by a random process.

Because of the great variability of precipitation amount from air mass showers, the test was confined to organize weather systems associated with fronts or depression which were expected to affect both areas equally. Operations were limited to the period 15 May to 15 Septembe each year to avoid the difficulties of getting representativ precipitation measurements from snowfalls. The seedin was carried out with silver-iodide generators release from airplanes flying in and around clouds near the −5°C level. The experimental unit was the *storm*, or perio affected by an individual synoptic system.

The mean rainfall for each area for each of the storm was computed, and the "seeding influence index", o ratio between the precipitation in the seeding area and that which would be expected there on the basis of the precipitation in the unseeded area, was computed. The result was an over-all apparent *decrease* of 2.5 per cent in precipitation due to seeding, with a high probability that it could have been due to chance.

E. Seeding of warm cumulus to augment precipitation

There have been few experiments to test the possibility of stimulating the warm (collision-coalescence) process in order to increase precipitation.

Experiments with water sprayed into the base of cumulus clouds in Australia in 1949 showed a tendency for the treated clouds to develop precipitation more rapidly than nearby untreated clouds. Similar tests of water spray seeding of cumulus clouds over the Caribbean and in the central United States, conducted by selecting pairs of clouds suitable for treatment and treating one of the pairs selected by a random process, showed effects, measured by radar echoes, only when the spray was injected at very high rates, about 1,000 litres per kilometre. The high cost of transporting such large quantities of water, with expected yield of at most a factor of 10^4 makes the economic practicality of the water-spray technique questionable.

Seeding with giant hygroscopic nuclei appears logistically more favourable, particularly if the seeding can be carried out from the ground. Ten-micron salt crystals would form droplets more than twice this size while being carried up through the first few hundred metres of the cloud, so that 40 grammes of salt would be equivalent a litre of water dispersed in 50-micron drops. Thus the mass of salt required is of the order of 1/25 the mass of water.

Salt seeding was tried on a few isolated occasions in France in 1949, and in England in 1952, with uncertain results. In an experiment over east Africa, a mixture of sea salt and calcium chloride was carried aloft by balloon and released in the cloud by an explosion of gunpowder set off by a time fuse. The results showed less rain on seeded than unseeded days, with a tendency for the clouds in which the salt particles had been released to disperse rapidly.

A programme to test the effectiveness of dispersing salt particles and salt solution from the ground in increasing rain from shower clouds was conducted in the central Punjab region of Pakistan. The experiment was conducted with two target areas, one level and the other subject to orographic influences. The results were evaluated by comparing the rainfall in the region downwind of the nucleus generators with that in neighbouring areas which were presumed outside the region affected by the seeding. Positive effects were found, particularly in an area where orographic effects were present. Since the experiment was of short duration and was not randomized, limited confidence could be placed on the results.

In India, experiments with warm cloud seeding were conducted between 1957 and 1966, at Delhi, Agra and Jaipur, in the plains of north India, and at Munnar, over the mountain ranges of south India (Murty and Biswas, 1968). The seeding was accomplished by using ground-based generators to spray dilute salt solution or to blow finely powdered salt and soapstone mixture into the air in the expectation that the convection would carry the giant condensation nuclei thus produced up into the clouds. Control and target areas were fixed on the basis of the winds from the surface to 2.5 km, including the 90° sector in the direction of and opposite to the direction of the mean wind through the layer, and extending from a short distance from the generators 15 to 20 miles down (or up) wind. The seedable days were determined on the basis of advice from the weather forecasters, and randomization was carried out using tables of random numbers.

The evaluation was based on the comparison of the ratio of 24-hour rainfall in the target and control areas on seeded and unseeded days. For all stations it was found that the ratio was greater on seeded days in almost all the years of the experiment. Over all, the data suggest about a 40 per cent increase in rainfall due to seeding. However, since days with frequent or continuous rains were excluded from the experiment, this percentage increase cannot be expected to apply to the total seasonal rainfall. It is suggested by the experimenters that an increase of 20 per cent might be expected.

The Indian experiments suggest that seeding with salt nuclei from the ground is effective in increasing the efficiency of the warm rain mechanism in convective showers during the summer monsoon. It is desirable to test this procedure in other areas and under other circumstances, for increasingly it has been suggested that the reason silver iodide seeding does not appear to be effective in summer cumulus in some regions is that the warm process is already at work by the time the top of the clouds becomes supercooled.

CHAPTER 4

REDUCTION OF FOG, HAIL AND LIGHTNING BY CLOUD SEEDING

While the largest emphasis in weather modification experimentation has been placed on the attempt to increase precipitation, much work has also been done in the areas of fog dissipation and hail and lightning suppression. In the case of fog, the efforts have resulted in a considerable amount of success. For hail suppression, the results are more questionable, and with respect to lightning the attempts must be regarded as exploratory so far.

A. Dissipation of supercooled fog

The dissipation of supercooled fog, which was demonstrated in one of Schaefer's very first experiments, has become an operational practice in airports in various parts of the world. It has been applied at airports in the U.S.S.R. since the late 1950s, utilizing dry ice introduced both by airplane and from the ground. At the Orly airport of Paris, the seeding is accomplished by releasing liquid propane through expansion orifices; the cooling by expansion as the propane evaporates produces ice crystals (Serpolay, 1965; Cot, 1964). In the United States, the procedure used is for small seeding planes to be alerted when cold fog is expected, so that they can take off before the fog closes in (Beckwith, 1965). The seeding aircraft releases the dry-ice pellets into the fog at a suitable distance upwind of the runway, and awaits the development of a hole in the fog as the ice crystals grow and fall out. Unless the wind drift carries new fog onto the runway, making additional seeding necessary, the plane lands on the cleared runway, which then is available for take-off and landing of other planes. The propane method has also been tested successfully in the U.S.A. (Hicks, 1967).

Studies by the U.S. Air Force (Vickers and Church, 1966) showed that optimum results in dissipating supercooled stratus cloud and fog were obtained with a seeding rate of 2 kilogrammes per kilometre using 1.5 cc dry-ice pellets. Smaller rates have been found to be adequate when the cloud is colder than −6°C, and larger rates are needed if its temperature is only slightly below 0°C. The size of the pellets used in practice ranges from small grains to grains of about one centimetre in diameter, and the rates vary over an order of magnitude, suggesting that the values used are not critical. Difficulties are encountered when an inversion is present, so that the temperature of the upper part of the fog is above 0°C. In this circumstance, seeding from the ground, as with propane sprayers, is preferable.

B. Dissipation of warm fog

From the standpoint of airport operations, the dissipation of warm fog is more important than that of cold fog, for at most of the busy airports of the world a larger portion of the hours of low visibility occurs at temperatures above freezing. Already in the 1930s the possibility of improving the visibility in fogs by spraying with calcium chloride solution was demonstrated, but because of the large amount of corrosive material which would be required, it was not used in practice. Recently, it has been shown in laboratory tests that improvements in visibility can be achieved by seeding with giant hygroscopic nuclei. This process would involve much smaller quantities of salt than injection of spray. Some field tests of the procedures have been conducted (Jiusto, Pilié and Kochmond, 1968).

In the 1940s, attempts were made to eliminate fog around runways with large quantities of heat produced by burning oil. The combination of the large expense of installation and operation and a relatively frequent inability to cope with the advection of new fog has led to abandonment of this type of approach.

Recently in the United States, tests have been carried out of two procedures for which some degree of success is reported. One method causes the mixing of warm, dry air into the foggy air by flying helicopters slowly across the top surface of the fog (Plank, 1969; Plank and Spatola, 1969). The downwash action of the rotors forces air from above into the fog, where it mixes, producing lower humidity, causing the fog drops to evaporate. Tests were carried out in Florida and Virginia, and in both places cleared areas were produced in the helicopter wakes. The other method (Osmun, 1969) involves seeding with polyelectrolytes, which are expected to cause electric charges to develop on the drops, thereby promoting their coalescence and fallout. Although experiments in fog chambers at Cornell Aeronautical Laboratory have not confirmed that the microphysical effects occur, the reports of the field tests state that at the Sacramento, California, port the method resulted in dissipation of fog in 19 out 27 cases in which it was tried, and equally good results were found elsewhere.

Other techniques which have been tried include the use of high-frequency (ultrasonic) vibrations, injection of ectric charges, and seeding with carbon black to alter the radiative properties and with water to promote the washout by collision and coalescence.

In the U.S.S.R., it has been demonstrated that the plication of mono-molecular films of surface-active ents to surfaces of unfrozen lakes in winter results in aring of the fogs forming over the lakes by reducing the evaporation from them.

It has been estimated that the economic benefits of percooled fog dispersal at U.S. airports are five times s cost (Beckwith, 1966), and that about the same ratio plies in the U.S.S.R. (Gaivoronskij, Krasnovskaia and olovjev, 1968). The large savings that would result if milar success could be achieved with the more frequently curring warm fogs, strongly motivate continued and creased investigation and experimentation in this field.

C. Suppression of hail

Attempts to prevent the occurrence of hail antedate the troduction of seeding with dry ice or silver iodide. For any years, gunfire and rockets have been used extensively in France, Italy and Switzerland. Various theories for the possibility that the anti-hail rockets might be effective have been suggested. One suggestion is that the sound waves from the explosion induce cavitation in the hailstones, causing them to shatter and become "mushy" (Vittori, 1960). Estimates of the effectiveness of rocket firings in Italy, where tens of thousands of rockets are released each year, have been that as much as 80 per cent of the firings have been successful in preventing hail. Since no randomization or control was used in the estimate, its reliability is open to question. In Switzerland, a predecessor of the experiment discussed in Chapter III was conducted to test whether firing rockets of the Italian type reduced damage from hail over the southern slope of the Alps. While the test was not randomized, its results seemed definitely to show that the rockets produced no effect on the frequency or intensity of hail damage. On the other hand, evaluation of a four-year test in Kenya indicated that the use of the Italian anti-hail rockets resulted in a large reduction in damage to tea, with loss in "made tea" in a protected estate only fifteen per cent of that in estates unprotected by rockets (Sansom, 1968).

The proposal that seeding developing convective clouds with silver iodide would convert the cloud to ice early enough to prevent the growth of hailstones led to field tests to see whether the method would work in practice. In addition to the Swiss experiment, *Grossversuch III*, tests using silver iodide have been carried out in France, Italy, Germany, Argentina and the Soviet Union. Of these, only *Grossversuch III* and the Argentine experiment were randomized. Both of them were conducted using ground-based silver-iodide generators. The *Grossversuch III* results have been discussed in the preceding chapter. The Argentine experiment showed no over-all effect of seeding, but this was composed of a decrease of about 70 per cent on days with cold-front passages and an increase of 110 per cent for all other days (Iribarne and Grandoso, 1965).

The tests in Germany were carried out in Bavaria using silver iodide released from rockets and ground generators (Müller, 1967). The rockets attained maximum elevations of only 1,400 m, and as the 0°C level in summer over the region is more than three kilometres, the transport of the seeding agent to levels where it would be effective was dependent on the updrafts in the clouds for the rockets as well as the ground-based generators. The evaluation was based on the comparison of hail damage in the target area with that in control areas upwind of it. The results showed no effect due to the seeding.

In France, a very large-scale programme for protection of agricultural areas from hail is in operation, using ground-based silver-iodide generators. In a region covering 70,000 square kilometres in south-western France, 240 generators are operated during the period between 1 April and 15 October whenever the probability of hail is forecast (J. Dessens, 1968). Estimates made by the director of the project, on the basis of comparison with past data on the ratio of the hail insurance losses paid out to the total insured capital for the period seeded, indicate a reduction of 22.6 per cent in hail damage during the years 1959–1966, as compared with 1944–1958, the period before the beginning of the use of silver iodide seeding. Comparison with the same ratio for the portions of France outside the protected region led another investigator to conclude that the hail damage has increased in the target area relative to the unprotected area.

Extensive programmes for the protection of crops from hail are being carried out in the Soviet Union by the Alpine Geophysical Institute, the Central Aerological Observatory and the Institute of Geophysics of the Georgian S.S.R. Academy of Sciences (Sulakvelidze, 1966 and 1968; Gaivoronskij *et al.*, 1968; Kartsivadze, 1968). They are based on studies of hail-producing storms which have led to a theory regarding the way hail is formed and what part of the storm in which it is produced. The conclusion from this theory is that by injecting very large numbers of ice nuclei in the appropriate place in the cloud—namely, the zone of high liquid water accumulation—hailstones can be prevented from growing.

To accomplish this, the procedure is to use radar to locate the precise position of the storm cloud where the hail production is taking place, and artillery shells or rockets to deliver silver iodide or lead iodide in large quantities quickly and precisely into the hail-producing centre. Refrangible shells and rockets were developed so that the debris falling from the spent projectiles would consist of very small fragments which could do no harm.

The apparent success of the Soviet procedures has led to rapid expansion of the areas under protection, so that there were 320,000 hectares being protected in the Alazan Valley, and 150,000 hectares in the Moldavian S.S.R. in 1967, and 1,960,000 hectares in the north Caucasus and Transcaucasus in 1968. The method of estimating the effectiveness had been comparison of protected and unprotected areas. With extension of the protection to practically all territory subject to hail danger, control areas became progressively more difficult to find. The estimated reductions in hail damage in protected regions range from 50 to 90 per cent. The lack of randomization, of course, adds to the uncertainty due to lack of comparison areas.

In the United States, where hail losses to agriculture are estimated at two hundred million dollars per year, and damage to other property may be equally costly, research into the structure of hailstorms and field experiments aimed at testing methods of suppressing them have expanded in the past few years. The Russian procedures have aroused considerable interest, and tests of modified versions of them are being designed. A review of the experiments in hail suppression which have been carried out so far, including preliminary results of experiments in the U.S. which seem to have some success, suggests that seeding with silver iodide must be carried out at rates higher than 2,000 grammes per hour per storm cloud in order to reduce hail damage, whereas seeding at rates less than 1,000 grammes per hour tends to lead to increases in convective activity and the occurrence of hail (Schleusener, 1968).

D. Suppression of lightning

Lightning is the principal cause of forest fires in the extensive forests of the western and midwestern United States. The suggestion that the charge-separation and discharging of clouds could be affected by cloud seeding received prompt attention by the agencies responsible for conservation of the forests and combating the fires. In 1958 and 1959, a randomized project was carried out by the State of California Division of Forestry to test whether seeding by ground-based silver-iodide generators could reduce the incidence of lightning-caused fires. The results were negative. There was an apparent increase in the number of lightning-caused fires due to seeding, but at a low level of significance. Subsequently, a study was begun by the U.S. Forest Service, with field operations in Montana. Seeding using ground-based generators, but with total output much larger than in the California experiment, gave preliminary indications of a 33 per cent reduction in the number of lightning strokes, but so far the results are not statistically significant.

Another approach to the modification of thunderstorms which is being attempted is the transformation of the discharge from a lightning stroke into a corona discharge by dispensing chaff—metal covered nylon needles—into the cloud. Results of tests of this procedure show that the corona discharge takes place, but practical means of dispersing the chaff throughout the cloud have not yet been developed.

CHAPTER 5

RECOMMENDATIONS

In any decision regarding the advisability of undertaking a weather modification programme, the potentialities for benefit must be weighed against the costs and risks involved. In the present state of uncertainty with respect to the likelihood of success, particularly with respect to precipitation augmentation, it is clear that in addition to the operational costs, the possibility of obtaining the opposite effect from the one desired—e.g. a decrease in precipitation instead of an increase—must be taken into account.

Frequently, an amount of change which is profitable may be much smaller than it is possible to detect by statistical techniques with reasonable amounts of data. For instance, a study for Electricité de France (Bernier, 1967), showed that increases of precipitation as small as one per cent or less over some of the watersheds feeding its power plants would more than pay for the cost of installing the silver-iodide generators and operating them using "standard" rain-augmentation procedures. In such a circumstance, it may be appropriate to risk the expenditure if there appears to be a reasonable chance of success even though the likelihood of being able to demonstrate the achievement is small. Conversely, it would appear that a correspondingly small decrease would represent a sizeable economic loss, and if the probability of increase is not considerably greater than the probability of decrease, the expenditure of the cost of the experiment would surely be unwarranted.

The problem of choosing a course of action thus turns upon the estimation of the chances of success. For some types of weather modification, such as the dissipation of supercooled fog, the estimation can be made fairly simply and reliably. The frequency of fogs at various temperatures, wind directions and wind speeds can be tabulated from past records, and from these data the number of additional hours of operational conditions permitting aircraft landings and take-offs which could be made possible by seeding evaluated. In the case of precipitation, in which the circumstances under which increases can be achieved are unknown, the prudent course would seem to be to strive to determine these circumstances, rather than assuming that they occur more frequently than the (likewise unknown) circumstances under which seeding leads to decreases.

The effort to identify the conditions under which seeding can produce increases and those in which decreases will result requires fundamental studies of the physics of precipitation and also laboratory and field experimentation with weather-modification techniques. Study and experimentation of this type have been going on at an increasing rate, but additional support for them is certainly justified in the light of the benefits which would accrue from control of the precipitation process.

The field experiments should be designed to yield the maximum amount of information. As we have seen, this requires randomization and the specification of the hypotheses to be tested. The question of how restrictive the hypotheses should be in the light of our ignorance of the conditions to be tested is a difficult one to answer. Neyman and Scott (1968) have suggested that the seeding experiments be carried out to explore the effects of a variety of seeding methods, localities, and synoptic situations, instead of attempting to test the efficacy of a particular method in a particular locality under particular meteorological conditions. Many objections can be raised to such a loosely specified experiment, especially the fact that it would require tremendous expenditure of time and money to collect enough data to have a chance of giving significant results. However, since the past experiments have yielded so little information regarding the conditions which will result in seeding effects, the matter of experimental design deserves careful consideration.

To enable full interpretation of the results of seeding experiments, it is important that all physical parameters, including temperature and humidity soundings over the target area, condensation and ice nuclei, and drop size and liquid content of clouds, be measured.

The specifics of statistical design cannot be treated in the abstract. It is essential that in any experiment the assistance of a competent statistician be obtained, and that he and the project meteorologist familiarize themselves with the designs of previous experiments and the deficiencies in them that were revealed by the results. The problem of enlarging the number of parameters which are varied, along the lines suggested by Neyman and Scott, while minimizing the duration and cost of the experiment, is one of the aspects of the design which may best be solved jointly by a meteorologist familiar with the physical aspects and the meteorological conditions of the area, and a statistician well versed in evaluating the power of statistical tests.

In preparation for the proper design of a cloud-seeding experiment, it is necessary to compile a census of the frequency of occurrence of various types of cloud at various temperatures with and without precipitation. This type of survey of cloud population has rarely been made. Yet it is clear that unless one knows the frequency of non-precipitation supercooled clouds in a given location, one cannot know how often there is a possibility of initiating precipitation there by seeding with ice nuclei. It would be advantageous to assemble data on the number of natural ice nuclei and condensation nuclei (particularly giant hygroscopic nuclei) and the drop size and liquid content of the clouds, but these measurements have been made only as parts of special research programmes, and are not generally available, whereas cloud heights (or estimates thereof) and upper-air temperatures are routinely available.

To improve the power of the statistical tests, and thereby reduce the length of the experiment required for significance, predictors which enable estimation of the processes in the absence of treatment are desirable. While such predictors (apart from control-area precipitation) have been used in some tests to select seeding opportunities—e.g. the precipitable water and wind direction in the case of *Project Whitetop*—they have not usually been incorporated into the quantitative evaluation of the experiments. To be effective in this role, of course, the predictors must correlate well with the phenomena they are used to predict, and as persons familiar with the problem of weather forecasting know, the amount of precipitation, as an example, is rarely strongly dependent on the value of a single parameter but is instead the consequence of the interaction of a large number of them.

The need for accurate methods of predicting the rates and amounts of natural precipitation and the probable effects of seeding emphasizes the importance of continued research into the processes of drop and crystal growth by condensation and coalescence, and into the dynamics of clouds and the interaction of dynamic and microphysical processes. Ideally, given the observations of the general meteorological situation and the measurements of condensation and ice nuclei, it should be possible to compute the rate of development of cloud and precipitation. Considerable progress has been made in recent years in developing numerical models which deal with one or another aspect of the over-all problem, but so far these models are highly simplified. In spite of their simplified and piecemeal nature, these models tax the capacity of the largest high-speed digital computers. Thus, in addition to further clarification of theory, accurate prediction of precipitation rates will have to await development of bigger and faster computers.

One can visualize the ultimate state of the weather-control process, in which the observations are automatically fed into computers which process them to formulate predictions of the conditions which will develop without treatment, and on the basis of criteria for social, economic and esthetic benefits, compute the treatment required to produce the optimum weather conditions for the largest number of people, and automatically turn on nucleus generators or other devices to administer the treatment needed. We are far from such a state, and may never achieve it. There is much to be done before we will be able to discriminate between the situations when a particular artificial seeding procedure will increase the precipitation rates and those which will decrease them, and still more to be done in developing means of determining which type of treatment is best in a given situation. But with the promise of much social good and economic benefit resulting from success, the efforts to develop these objectives must be pursued as rapidly as sound scientific methods permit.

Their pursuit will obviously be facilitated by the most active international co-operation. Exchange of information, such as was achieved at the International Conferences on Cloud Physics in Tokyo in 1965 and Toronto in 1968 under the auspices of the IUGG and the WMO, serve to speed the attainment of the goal. Prompt and complete publication of the results of research and experimentation everywhere in the world will enable rapid progress towards it.

In summary,

(1) The decision whether to undertake a weather-modification programme must be made in any specific instance on the basis of weighing the probabilities of benefit against the costs and risks.

(2) In the case of precipitation-augmentation and hail-suppression, it is not known under which circumstances and by what techniques operations will lead to success, and when opposite effects will result.

(3) Consequently, programmes in these areas should be designed to identify favourable circumstances and procedures.

(4) Programmes should be designed carefully to give maximum information with full regard to the validity and significance of the results from the statistical standpoint. Randomization is an essential feature of such design, as is a long enough duration of the programme to compensate for meteorological variability.

(5) Research into the fundamental microphysics and dynamics of clouds and precipitation must be fostered and accelerated, to enable the best possible planning and interpretation of weather-modification experiments.

(6) International co-operation through conferences and publication of reports on activities in this field will accelerate the achievement of the goal of control of clouds and precipitation with the accompanying benefits for all mankind.

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