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METEOROLOGICAL OBSERVATIONS REQUIRED FOR FUTURE WEATHER MODIFICATION PROGRAMS

By: K. R. Biswas and A. S. Dennis

Prepared for:

National Aeronautics and Space Administration
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Institute of Atmospheric Sciences
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ABSTRACT

A survey has been made of the literature on weather modification experiments carried out in several countries on a scientific basis. An attempt has been made to bring out the pertinent meteorological variables that were found most useful in conducting and evaluating the experiments for particular types of cloud systems and for the particular regions concerned. Emphasis has been placed on specifying the meteorological observations required as input data for computer models describing weather modification experiments, as it seems that future weather modification experiments will rely heavily upon numerical models. Such judgment has been used to specify permissible error in the observations, as there is still no acceptable error criterion for numerical model input data.

The chapters are organized by various weather systems, ranging from a stratus cloud to a hurricane, and discuss the techniques developed so far for modification of these weather systems. The observations required for successful modification of each of these systems, including those variables that determine the response to the system to modification treatments, have been identified.

Each chapter concludes with one or more tables showing, on a priority basis, meteorological observations required for successful modification of the systems considered in that chapter. Wherever possible, figures and tables from the concerned literature have been used for further exemplification. Observations on the mesoscale have been found to be the principal requirement for a majority of modification experiments.

The facts that have emerged from the present study are: (1) certain meteorological variables must be observed in all types of weather modification projects and spatial resolution requirements do not vary greatly with the objective; (2) the observations required are, in general, those required for accurate forecasting of the meteorological phenomena being treated except that increased emphasis must be placed upon condensation and ice nuclei and the composition of clouds; (3) the requirements go far beyond what can be achieved with existing networks in terms of spacing and frequency of observations.

The exact manner in which the various required observed observations will be acquired or how the vast amount of resultant data will be handled are points that are beyond the scope of this report, but it appears that new types of sensors and the most modern data-processing equipment will be required if costs are to be kept within reason.

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1. INTRODUCTION

1.1 Purpose of Report

This report has been prepared as part of a three-year research project to identify possible matches between the meteorological observations required in future weather modification programs and the sensors and data handling equipment developed in this country's space program. An earlier report[†] under the contract summarized the wide variety of sensors available and gave a brief description of each of the various types. This report will be limited to a description of the meteorological observations required for future weather modification programs. No consideration is given to the difficulty of securing a given observation; rather, an attempt is made to identify those atmospheric parameters whose measurement would be valuable in the planning, conduct and evaluation of weather modification projects.

1.2 Historical Review

An overview of the history of weather modification is given in Fig. 1.1. The scientific era of weather modification is usually considered to date from Schaefer's experiments of 1946, in which he dropped dry ice into supercooled clouds to produce a fall of snow accompanied by dissipation of part of the cloud deck (4)*. This was, in a sense, the first experimental confirmation of the hypothesis, advanced by Wegener (6) in 1911 and elaborated by Bergeron (1) in 1933, that ice crystals in supercooled clouds grow rapidly by sublimation to precipitation size. Subsequently Vonnegut discovered that vaporization and subsequent quenching of silver iodide in cold air produces many crystals capable of acting as ice nuclei (5). Introduction of silver iodide smoke into natural clouds produces marked effects, including almost complete glaciation of small clouds where the temperature is below -10 or -15C.

Much of the cloud seeding conducted in the United States and other countries during the late 1940's and 1950's was based on the premise that the introduction of ice crystals into supercooled clouds and their subsequent growth to snowflake size would lead to increases in rainfall or snowfall at the ground. Some thought was given to dynamic effects associated with the release of latent heat which necessarily accompanies the freezing of supercooled cloud water; indeed, one of the first seeding experiments in Australia had given spectacular evidence of dynamic cloud growth produced by seeding.

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*References are listed at the end of each chapter.

[†] "A Survey of NASA Meteorological Technology for Application to Weather Modification Research and Operations" by C. W. Andersen (Raven Industries, Inc.). Report 69-14. South Dakota School of Mines and Technology. First Annual Report under NASA Grant NGL42-001-004.

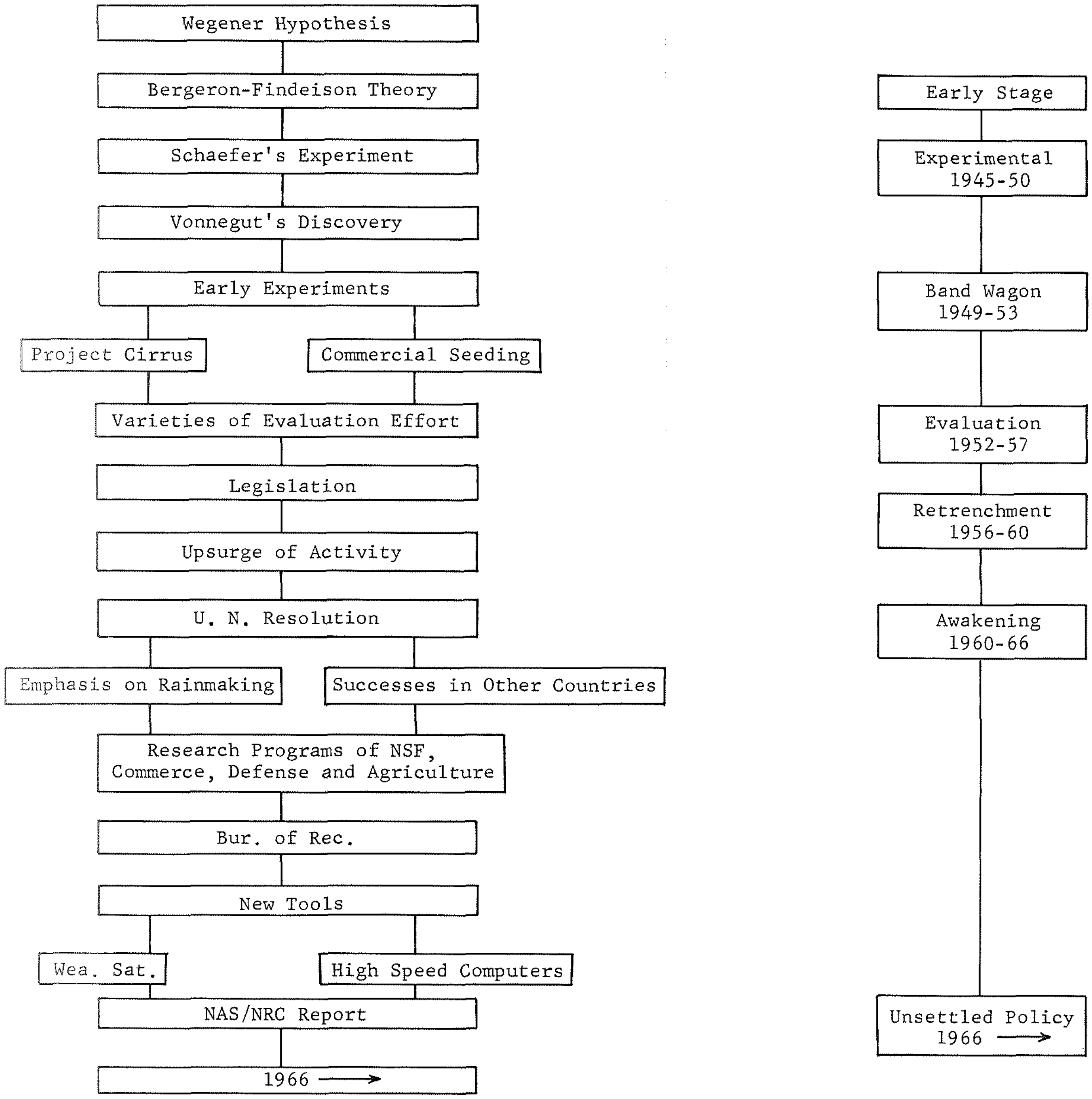

Fig. 1.1. Historical Stages in Weather Modification.

However, the observational and computational facilities required to evaluate this effect properly were beyond the reach of most research groups and of commercial cloud seeders at that time.

During the 1960's there was a considerable upsurge of activity in the field of weather modification in the United States, stimulated in part by reports of successful rain stimulation and hail suppression activities by scientists in the Soviet Union and other foreign countries. The research programs of the National Science Foundation and of the Departments of Commerce, Defense, and Agriculture continued throughout the decade, while an extensive new program (Project Skywater) was begun by the U. S. Bureau of Reclamation. A new approach to weather modification was evidenced by a RAND Corporation report in 1962 which pointed out that newly available tools, namely, weather satellites and high speed computers might serve to make tractable problems which could not be solved previously (2). Further evidence of new optimism within the scientific community concerning weather modification was the appearance in 1966 of a report by the National Academy of Science - National Research Council on the prospects for weather modification research and application (3). It provided a useful review of the situation to that date and suggested areas requiring further investigation.

1.3 Variety of Modification Effects

It is now generally realized by persons engaged in weather modification experiments that the systems being treated are very complicated and involve processes on several size scales ranging from cloud microphysics to large-scale interactions of convective cloud populations with the general circulation. Many different responses to modification treatments are possible, depending upon the clouds and the modification treatments applied. It is not possible to treat all cases in a long series of experiments as though they were drawn from a single population unless observation shows that the cases were in fact similar and the seeding treatments were standardized. Evaluation of field experiments with careful data stratification and experiments run on computers show that cloud seeding can produce both increases and decreases in precipitation and can affect hail, lightning, and wind also.

In the above paragraph we have discussed cloud seeding specifically, although this is by no means the only weather modification technique available. Modification of the earth's surface to affect its radiation balance, for instance, by spreading black powder over snow or ice fields, could produce significant modifications in local weather conditions, as could the dispersal of large quantities of absorbent or reflective aerosols at selected levels within the atmosphere itself. Because the effects might be undesirable, it would be preferable to limit such experiments initially to computer simulation studies. One can also visualize computer simulation to study in advance changes in local climate produced by introduction of irrigation water to a desert valley or by the replacement of a forest by an urban development. Much of the weather modification research effort of the next few decades may be devoted to such inadvertent weather modification effects.

1.4 Method of Approach

Our general approach has been to review the literature on weather modification experiments up to early 1970 with a view to determining the meteorological variables that were measured or whose measurement was considered desirable to conduct and evaluate the experiments. In some cases, the meteorological observations required can be considered as input data for computer models describing the experiments. This approach is desirable because the numerical modelers have advanced further than those of their colleagues who have limited themselves to field projects in defining the types and amount of input data required to predict the outcome of an experiment. However, because of the large computer time required, it has not been possible to run a large number of experiments to determine exactly the error acceptable in the input data. Therefore subjective judgment has been used to specify the permissible errors in the observations.

The chapters have been organized by various weather systems, ranging in complexity from stratus clouds to hurricanes and discuss the techniques developed so far and the observations required for successful modification of these weather systems. The principal meteorological variables are presented in tables at the end of each chapter in order of priority with respect to needs for modification of the particular weather systems along with desired observational frequency, accuracy and spacing. In preparing these tables, our subjective judgment has been used along with the suggestions in the literature concerning those variables which determine the response of the system to modification treatment.

The tables have been reviewed by personnel of the Institute of Atmospheric Sciences, including R. A. Schleusener, P. L. Smith, Jr., J. H. Hirsch and A. Koscielski, who along with the authors represent a combined total of more than 50 years of personal experiences in different weather modification experiments, and by H. D. Orville and D. J. Musil of the Institute's numerical modeling group. Their comments and suggestions have been incorporated to bring out a unified view on observation requirements for different modification experiments on the various weather systems. The priority numbers are still somewhat arbitrary but listings by other investigators should not show differences of more than one or two steps from those given for each variable. The figures on required resolution, accuracy and spacing are also somewhat arbitrary but they are considered good within a factor of two.

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2. SEEDING OF STRATIFORM CLOUD SYSTEMS

2.1 Dissipation of Fog and Low Stratus

2.1.1 Supercooled Fog

The most clear-cut evidence of artificially induced changes in clouds has been obtained in experiments on supercooled fog and stratus. In these stable and persistent cloud systems effects of seeding are limited to cloud microphysics and the spread of seeding effects is limited to transport by the wind and turbulent diffusion. The small amounts of latent heat released by artificial glaciation induce little atmospheric motion due to the stable conditions. As the winds and turbulence are often light, seeding effects are limited in certain instances to distances of only a few hundred meters for an hour or more after seeding, so that comparisons between the seeded portion of the cloud deck and the nearby unseeded portions are readily made. It is this combination of circumstances that makes possible such experiments as the cutting of figures in supercooled cloud decks (Fig. 2.1).

A number of techniques have been used to dissipate supercooled fog, including silver iodide seeding and spraying liquid propane into the air, but the dropping of dry ice pellets from aircraft remains the most commonly used technique (1). The effectiveness of the treatment decreases somewhat as the ambient temperature rises, but visibility improvements have been achieved with surface temperatures close to 0C (Fig. 2.2).

In the conduct of a particular operation, the input data required include the height of the top of the fog layer, the temperature throughout the fog layer, and the wind direction and speed at enough points (perhaps 5 to 10 in an area 10 km across) to define the rate at which fresh fog would be advected over the cleared area. Knowledge of the wind speed would also affect the seeding patterns to be employed. Very light winds and associated lack of turbulent diffusion would necessitate spacings as low as a few hundred meters between dry ice drops.

Scientists in the Soviet Union have conducted field experiments in which supercooled stratus clouds have been dissipated by dry ice seeding with the purpose of permitting sunlight to reach the earth's surface. The additional heating thus produced can be considered a beneficial end result in a cold region and has the additional effect of tending to break up temperature inversions near the surface, thus aiding in the dispersion of pollutants. Information required for the conduct of such an experiment would include the height of the base and top of the supercooled cloud layer, the associated temperatures, and a measure of the wind at the height of the cloud layer.

Fig. 2.1. Dissipation of supercooled clouds by seeding with dry ice - demonstrated in tests near Goose Bay, Labrador, conducted by U. S. Air Force Cambridge Research Laboratories (2).

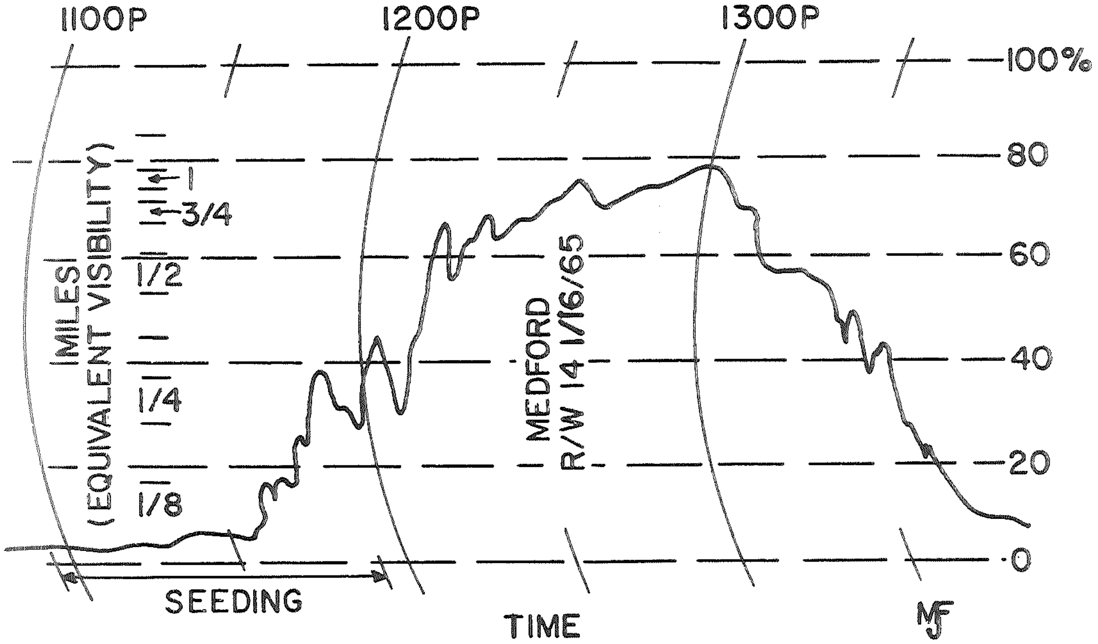

Fig. 2.2. Transmissometer trace associated with seeding of supercooled fog. Visibility improvement occurred 30 min after the first seeding run began. The seeded area held the improved visibility for more than an hour before the residual effect wore off and conditions again deteriorated. On this operation surface temperature was 1C and 415 lbs of dry ice were dropped to effect the change noted under what was a marginal condition for seeding (2).

Numerical modeling of the dissipation of supercooled fog and stratus is simple as the conversion of supercooled water to ice crystals in the affected cloud region is sudden and complete and the spreading of the effects is controlled by wind and turbulent diffusion. Empirical data from large numbers of experiments conducted by the U. S. Air Force, commercial airlines, and others can be inserted into the model to permit good estimates of how seeding effects will spread in a given situation.

2.1.2 Warm Fog

Warm fog dissipation techniques attempted in recent years have included heating and stirring the air by running up jet engines on the ground, but the most commonly used technique is the dropping of hygroscopic materials from aircraft. The hygroscopic agent, frequently finely powdered sodium chloride, settles toward the ground collecting cloud droplets by gravitational coalescence. In a typical operation release of several hundred pounds of salt at a height of 300 to 500 feet is followed by an improvement in visibility at the ground 5 to 20 minutes later (Fig. 2.3).

Numerical models of the warm-fog dissipation process have been developed which differ somewhat in their details (23). Principal input data required include the liquid water content and drop size spectra in the fog and the size spectrum of the seeding agent. In addition, knowledge of the local wind field is required in actual operations to allow for drift of the seeded volume toward the region of interest, which is usually an airport runway.

In addition to ability to determine ambient conditions for controlling fog clearing operations, it is important to monitor conditions to verify and control such experiments. Verification to date has usually been obtained with visual observations or transmissometers. Laser devices now being developed to monitor droplet sizes and concentrations should provide considerable improvement in our ability to monitor fog clearing operations. As many as a dozen such instruments could be profitably used at various locations along and near an airport runway during an operation.

2.2 Stimulation of Precipitation in Orographic Clouds

2.2.1 Advantages of Seeding Orographic Clouds

Supercooled stratus clouds existing over flat country offer little potential for increased precipitation by cloud seeding. Complete deposition on the ground of the water contained in a typical stratus layer would result in only a trace of precipitation being recorded. Only active cloud systems in which fresh water vapor is being condensed offer much potential for increases in precipitation. The stratiform clouds formed by the orographic lifting of moist air

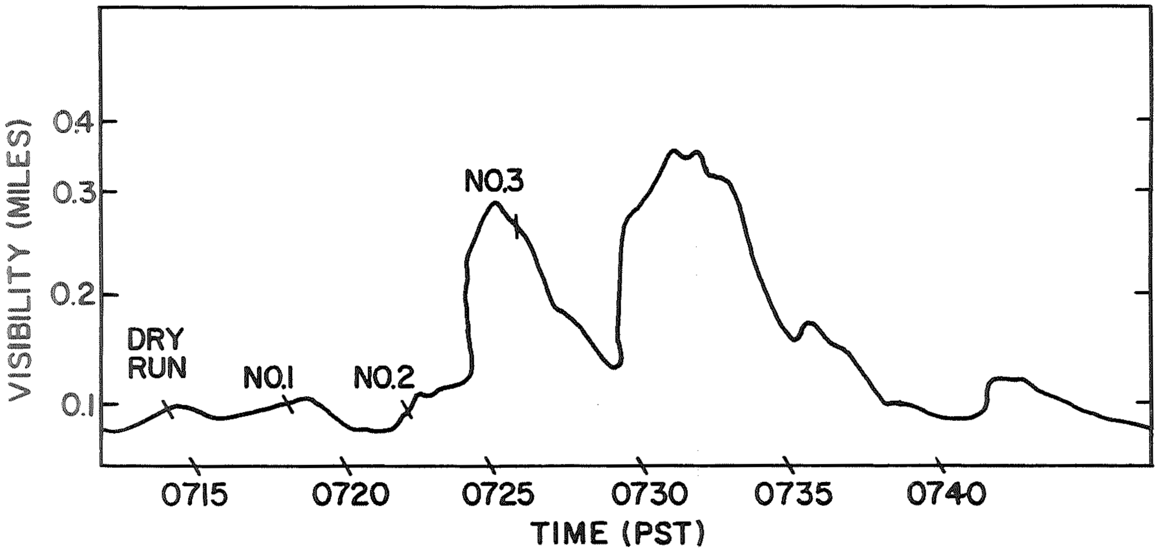

Fig. 2.3. An example of increase of visibility in warm fog by salt treatment (Noyo River Valley, California site). Visibility has increased in 10 min to about 0.3 mi from less than 0.1 mi after three runs of 500 lb each. First release was insufficient to remove appreciable water at the ground level for any visibility improvement. A second release apparently removed some of the remaining water in the fog so that a cumulative effect is apparent (23).

masses over mountain barriers have this characteristic, so it is not surprising that cloud seeding has been applied extensively to orographic cloud systems.

The combination of supercooled clouds in a fixed location and orographic lifting to carry silver iodide or other artificial nucleants into the supercooled cloud regions made the systems appear ideal for seeding by ground-based generators (3). Silver iodide seeding from the ground to increase precipitation over the mountains of the western United States began as early as 1950. It was upon the basis of rainfall anomalies associated with these projects that the Advisory Committee on Weather Control reported in 1957 that seeding was associated with apparent precipitation increases of 10 to 15% in winter storms in the western United States (27).

It is convenient to distinguish between purely orographic projects, in which mountains extend to temperatures colder than -5C, and semi-orographic projects, in which they do not. In the latter case, orographic lifting can carry silver iodide crystals only part way to the region where they are effective, so some other mechanisms must be relied upon to complete the process. Large numbers of both types of projects have been conducted all over the world, including experiments in the United States, Mexico, Australia, France, and Israel. However, it is only since the completion of some carefully planned experiments in the past few years that conditions governing success or failure for the purely orographic projects have been clearly defined.

2.2.2 Purely Orographic Situations

Perhaps the most thoroughly documented experiment on orographic clouds is that conducted at Climax, Colorado by Colorado State University (17). Silver iodide generators were operated upwind of target areas near the Continental Divide. Modeling of the airflow over the target and observations of snow within the cloud by radar aided in generator placement and interpretation of results. Detailed analyses of the first five years of record suggested that snowfall increases were associated with particular temperatures in the snow-producing cloud. This hypothesis has been confirmed by several additional years of experiment (18).

The results can be stratified in terms of the temperature at the 500-mb level, which is usually within the snow-producing cloud (Table 2-1). The increases in snowfall amount to over 100% for 500-mb temperatures between -12C and -20C but fall off to zero at both higher and lower temperatures. The results can be given a plausible explanation. Natural ice nuclei are scarce at temperatures above -20C. Silver iodide seeding increases the number of ice nuclei (Fig. 2.4) and hence of precipitation embryos provided the temperature

PERCENTAGE DIFFERENCE IN PRECIPITATION IN CLIMAX (TARGET), BETWEEN
SEEDED AND NONSEEDED CASES AS A FUNCTION OF 500 mb
(NEAR CLOUD TOP) TEMPERATURE

Adjusted for control, control average of eight storms, target
average two highest elevation stations.

( )* number of cases

500 mb Temp. (°C, Lowest Exp. Day)			
39 – 24	T	$\frac{T_s - T_{ns}}{T_{ns}} = \frac{.177(74)^* - .189(80)^*}{.189} = \frac{-.012}{.189} = -6.3\%$	
	C	$\frac{C_s - C_{ns}}{C_{ns}} = \frac{.128(74)^* - .118(80)^*}{.118} = \frac{.010}{.118} = +8.5\%$	
		Avg. Diff. T - Avg. Diff. C = 6.3% - (+8.5%) =	-14.8%
23 – 21	T	$\frac{T_s - T_{ns}}{T_{ns}} = \frac{.143(31)^* - .143(31)^*}{.143} = 0$	
	C	$\frac{C_s - C_{ns}}{C_{ns}} = \frac{.078(31)^* - .089(31)^*}{.089} = -\frac{.011}{.089} = -12.3\%$	
		Avg. Diff. T - Avg. Diff. C = 0 - (-12.3%) =	+12.3%
20 – 12	T	$\frac{T_s - T_{ns}}{T_{ns}} = \frac{.173(30)^* - .090(33)^*}{.090} = \frac{.083}{.090} = +92.2\%$	
	C	$\frac{C_s - C_{ns}}{C_{ns}} = \frac{.095(30)^* - .069(33)^*}{.069} = \frac{.016}{.069} = +37.7\%$	
		Avg. Diff. T - Avg. Diff. C = +92.2% -37.7% =	+54.5%

TABLE 2-1

In some orographic situations, temperature at 500 mb (near cloud top) could be a good indicator in stratifying the situations for which seeding would be most effective. The table illustrates the seeding results at Climax, Colorado, in terms of percentage difference of precipitation between seeded and non-seeded cases stratified according to 500 mb temperature (T-target precipitation, C-control precipitation, subscript s-seeded, ns-not seeded). Seeding seems to be more effective when the temperature is warmer than -20C (17).

is lower than about -12C, so seeding increases the snowfall at temperatures between -12C and -25C. At some temperature around -25C the concentration of natural ice crystals reaches the optimum for the cloudwater concentration present. Additional ice crystals induced by seeding reduce the efficiency of the system by producing snowflakes too small to fall out in the target area, a condition known as overseeding. The small snowflakes may fall out further downwind but this possibility has not yet been investigated.

The Colorado State University results have been essentially confirmed in a separate project in the Park Range of Colorado (21).

It may well be that the cloud top temperature, if available, would be a better predictor of seeding effects than the 500-mb temperature. Presumably in some cases the cloud top extends above the 500-mb level and natural ice crystals are present even though the 500-mb temperature is relatively high; on the other hand, shallow clouds not extending to the 500-mb level may have a shortage of ice crystals even though the 500-mb temperature is well below -12C. Comparison of results for sites separated by some tens of miles shows differences in response to seeding which may be related to differences in cloud top height. The degree of spatial resolution and the frequency of observations required to determine cloud top temperatures would not be great. It appears that determination of cloud top temperature with a resolution of 10 to 20 km would be adequate. This is well within the capabilities of a high resolution infrared satellite system.

An experiment in the northern Sierra Nevada has also shown variations in snowfall increases due to seeding which can be related to the prevailing weather conditions (19). Seeding was accomplished using silver iodide generators on the ground. It was found that warm storms with southerly winds showed little response but that snowfall increases could be induced during cold periods with northwesterly winds. It appears that either wind direction or temperature at some selected level (say 700 mb) would be a suitable criterion for a seed/no-seed decision in this situation.

Obtaining wind measurements to determine the general weather situation would not be difficult. Measuring winds to determine where generators should be operated to influence a specific target area would be more difficult, as winds near the ground in mountainous areas are erratic. Measurements would have to be taken at points not more than 10 to 20 km apart and once every two or three hours to accomplish the latter objective.

More recently scientists of the University of Wyoming have studied the numerical modeling of airflow over Elk Mountain, Wyoming

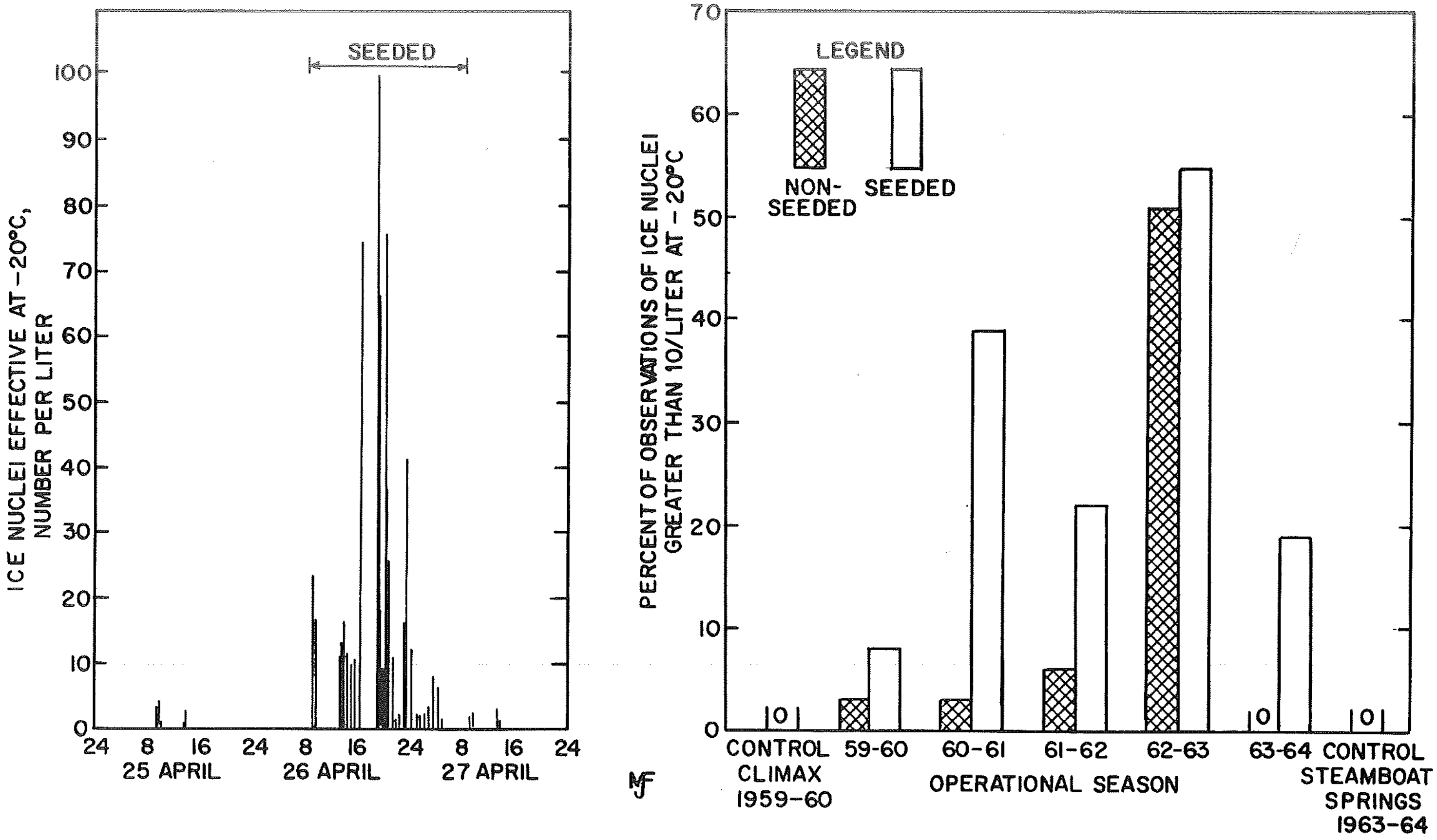

Fig. 2.4. Measurements of ice nucleus concentrations can be a good indication of the behavior of seeding materials. As an example, (A) 26 April 1964 (at Climax, Colorado) a seeded day shows very high concentrations throughout the day in comparison to previous or following day. High concentration measurements can also indicate contamination of no-seed day (control) as seen in the case of 1962-63 (17).

during cap-cloud conditions. Cap clouds are lenticular clouds produced by orographic lifting over isolated peaks. The model has shown promise in predicting flow patterns around the mountain (7). It is an adaptation of one developed for studying airflow over Lake Erie and the resultant snowfall distribution along the south side of that lake (16). The model is applicable when there is an unstable layer of air next to the ground capped by an inversion with more stable air aloft. Input data for the model include the wind field in the unstable air, the height of the inversion surface, the temperature structure and moisture content of the unstable layer, and the temperature structure above the inversion. Horizontal resolution of perhaps 5 km is required for successful application of the model.

In view of the fact that orographic seeding depends upon the introduction of artificial ice nuclei to supercooled clouds some information on background ice nuclei concentrations should be available to any operational project. It appears that the information could be obtained by operating one or two sampling sites on the mountain slopes in each project area. As it is not likely that local sources would be important in the mountains, one could assume that the background nuclei were distributed widely and throughout a considerable depth of the atmosphere in a roughly uniform fashion. Thus there would be no requirement for extensive three-dimensional mapping of the background ice nuclei concentrations.

2.2.3 Semi-orographic Situations

As noted above the term "semi-orographic" describes situations where orographic lifting carries cloud seeding agents only part way to the desired level and some other mechanism must be relied upon to carry them into the regions where they become effective. Convective currents often serve as the transporting mechanism for the seeding agents, as these cloud systems frequently contain active convective cells. However, they are treated here rather than in Chapter 3 below because the convective cells are usually embedded in stratiform cloud decks and the clouds' responses to seeding treatments agree better with those observed in the purely orographic situations than with those observed in convective clouds over flat country.

Semi-orographic seeding projects have been carried out in many parts of the world. Discussion will be limited to three sets of experiments, in Australia, Israel and California, which typify the methods and results.

Australia. The large scale Australian experiments have involved silver iodide releases from airborne generators. Most of the Australian semi-orographic experiments have been conducted over three regions: Snowy Mountains (24), New England (25), and Warragamba Catchment (26). All the regions are in southeast Australia, the topography of which is dominated by the Great Dividing Range (Fig. 2.5). The prevailing winds are westerly.

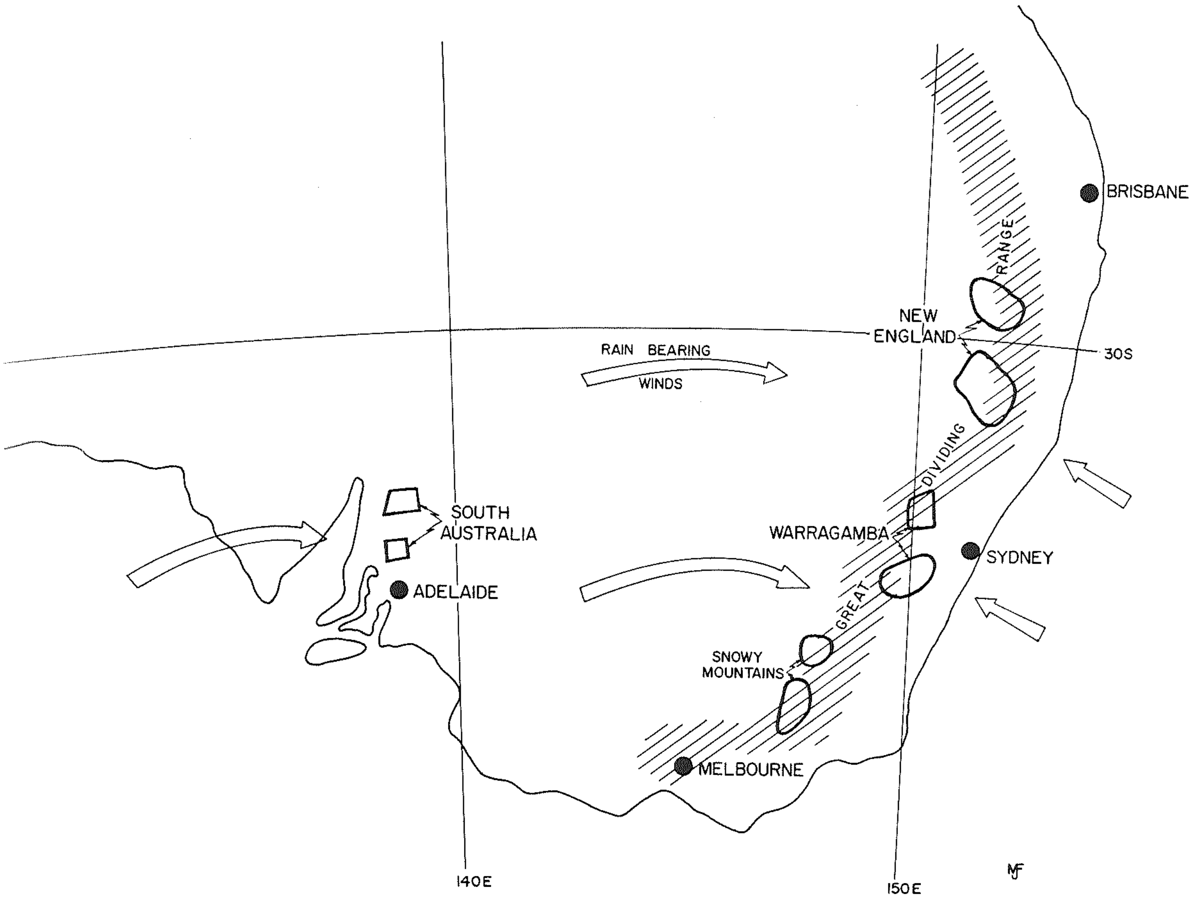

Fig. 2.5. The majority of the Australian experiments have been conducted in the Southeast, where topography is dominated by the Great Dividing Range and the situation is semi-orographic (26).

The Snowy Mountains and New England experiments were similar as both were on the western slopes of the dividing range and were expected to have mainly continental airstreams. The Warragamba experiment, situated towards the eastern side of the range, received some maritime and some continental type weather. Operational objectives were to seed both cumulus and stratiform supercooled clouds. Early results from the Snowy Mountains and New England were extremely promising but Warragamba showed no detectable effects of seeding. In the final results, although Snowy Mountains and New England gave positive results, they were only marginally significant, and results from Warragamba were negative. The deterioration of results has been tentatively attributed to persistence of seeding effect. It was observed that the ice nucleus concentration in a seeded area increased when seeding commenced and remained high for several months after seeding stopped. The detrimental effect of persistence on the results of a randomized seeding experiment has been described by Bowen (4), (Fig. 2.6).

The Australian experiments, which have shown the considerable potentiality of silver iodide seeding, have also revealed that the effects are not simple. Investigations are now being conducted into the physical processes of glaciation, nucleation, etc. on which cloud seeding depends. New series of experiments are also being conducted to determine the amount by which silver iodide released from an aircraft can increase the rain over specified areas and to detect persistent effects of seeding.

In order to overcome uncertainties, as in the case of Australian experiments, it is essential to have more critical and frequent measurements and observations of meteorological parameters. This would enable proper selection of situation, choice of clouds to be seeded and also permit one to stratify the results so as to isolate the circumstances which are not favorable for operation.

Israel. The experiments in Israel (12), (13), (Fig. 2.7), with more or less similar design to those of Australia, have shown significant positive results over a long period (1961-67). This region, which lies on the eastern side of the Mediterranean, is influenced by continental airmasses for the most part. The mountain ranges are only a few thousand feet high and oriented from north to south. The winter is the main rainy season. Southwesterly winds from the North African deserts or the northern part of the Negev desert to the south usually prevail when a low pressure system approaches the eastern Mediterranean coast. Rainfall amounts are generally light.

The Israeli investigators realized the importance of trying to identify synoptic conditions particularly favorable or unfavorable to seeding effects. This allows for rational allocation of seeding efforts and also avoidance of negative seeding effects. The data

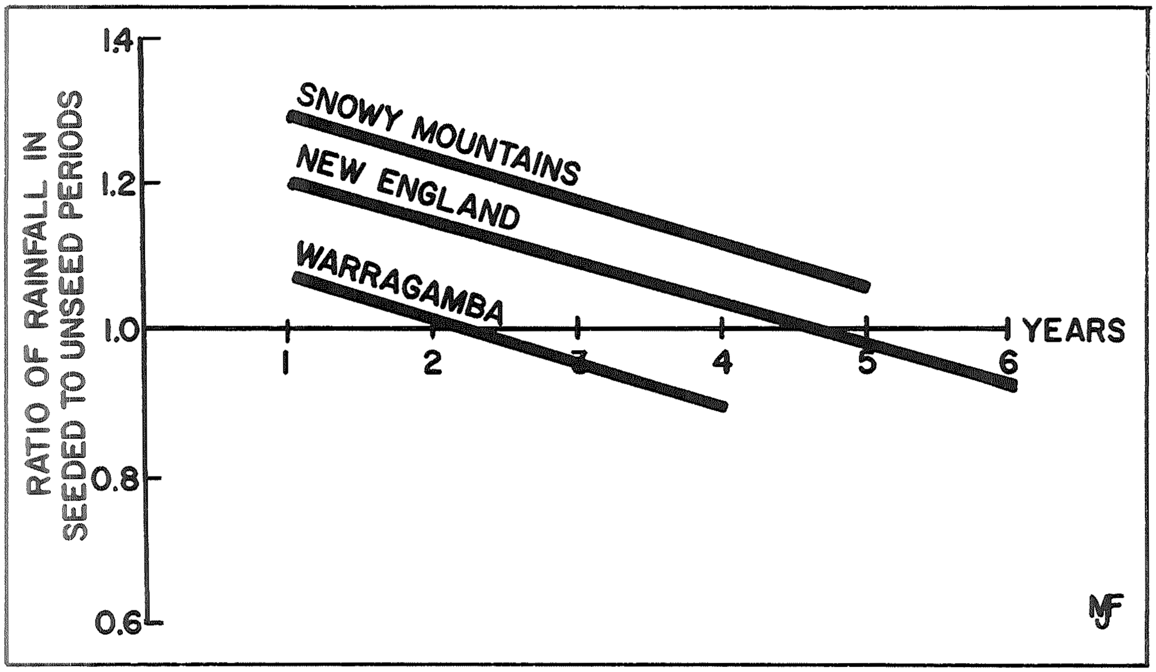

Fig. 2.6. Total amount of rain which fell during cloud seeding experiments in eastern Australia was well above normal. However, the statistic used in the experiment, namely, the ratio of the rainfall in seeded periods to the rainfall in unseeded periods appeared to decrease as seeding progressed because the effect of seeding persisted from the seeded into the unseeded period. Graph shows annual decrease of this ratio in different regions (5).

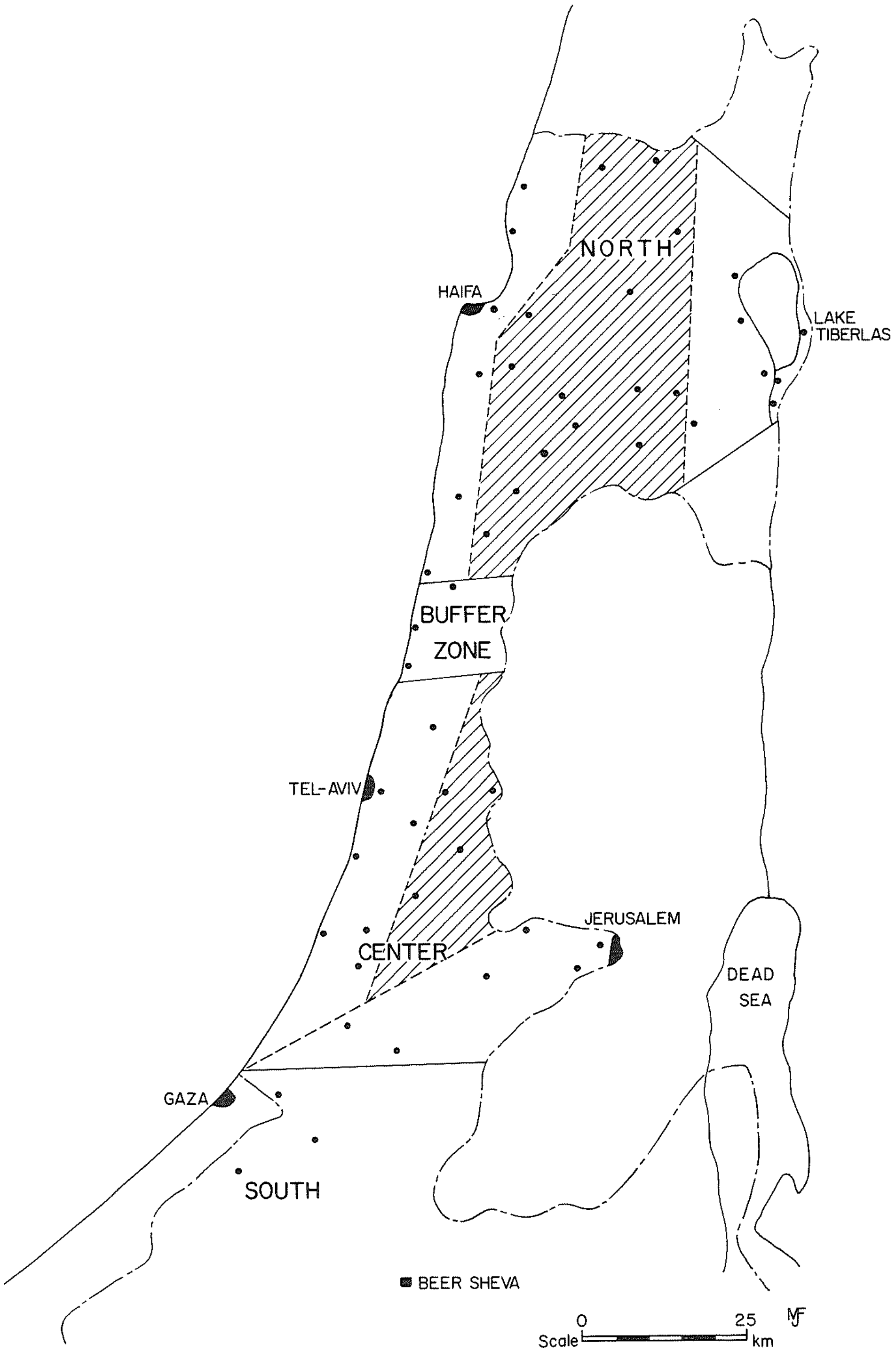

Fig. 2.7. Map of Israel showing both experimental areas and the interior areas (shaded). Dots indicate raingages used in analysis (12).

were stratified in terms of season, month, and length of spell of rainfall as well as different meteorological parameters obtained from radiosonde observations, such as temperature at 700-mb level, wind direction and speed at 500-mb level, stability index, and precipitable water from surface to 500-mb level. Significantly enough, the persistence effect observed in Australia was completely absent in the Israeli experiment (14).

It is quite obvious that close soundings (at spacing of about 15 km) at shorter intervals (about 3 hrs) of time, giving particularly the temperature profile, precipitable water and winds are of primary importance along with observations of clouds for a region like this. Since the seeding agent is artificial ice nuclei, information on natural ice nuclei is essential for careful evaluation of seeding experiments. Measurements of ice nuclei over several winters have been conducted, although the results are not yet conclusive (15). It is also essential to have the background counts while conducting experiments.

California. Semi-orographic situations exist over the California coast ranges during most winter storms. Operational seeding of these storms began in 1951 in both Santa Clara County and Santa Barbara County. Both of these projects were considered by Thom in his analysis of semi-orographic projects for the Advisory Committee on Weather Control (27).

The Santa Barbara Project was converted to a randomized seeding experiment in the fall of 1956. The results of this experiment were inconclusive but seeding has continued in Santa Barbara County since that time with apparent success (9).

Considerable effort has been devoted to studies of the structure of coastal storms in central California. Elliott described the characteristics of a relatively simple storm model with a single front (8). He noted that the precipitation was concentrated in a band of convective showers preceding or accompanying the front or trough line.

> "The system is discussed as a steady-state mechanism whereby the generation of liquid moisture in vertical currents is balanced by its removal through precipitation, primarily in the instability zone near the surface front, and by evaporation, primarily in the altostratus zone in advance of the instability zone . . . It is shown that in this storm model efficiencies are normally well below 100 percent, and that the introduction of artificial ice-forming nuclei can raise this efficiency markedly."

Larger storms often contain several bands of convective instability (6). The bands of convective clouds are readily identified on radar through the sharp-edged echoes from the precipitation cells, but are not so readily apparent to visual observers because of the extensive stratiform cloud systems which sometimes fill the regions between them. Some of the bands are large enough to be detectable in a mesoscale analysis. Surface winds typically back in advance of a convective band and veer by 30 to 90 degrees at the time of its passage. The bands are typically several hours apart in time.

Experience on both the Santa Barbara and Santa Clara Projects led to the tentative conclusion that cloud seeding was most effective during the passage of the convective bands (6, 9). This would appear reasonable in view of the updrafts to 5 m sec^{-1} in the cells, which would carry silver iodide aloft from the surface mixing layer, and the abundance of supercooled water in the cells above the 0C level. Increases in rainfall of 50 to 100% are suggested in some cases. Elliott suggests that the release of latent heat by seeding intensifies the convective currents in the bands and the energy of the bands themselves and leads to an increase in the amount of water processed (10).

Experiments are presently underway in the Santa Barbara area in which convective bands are being seeded on a randomized basis in an attempt to better define the seeding effects. A numerical model is used to help determine where seeding effects should occur. Preliminary results for these experiments indicate that silver iodide seeding of the bands yields significant increases in rainfall up to 100 km downwind of the release of the seeding agent (11).

It is apparent that a reliable method of timing the passage of the convective bands (Fig. 2.8) would be a useful input to the operation and evaluation of cloud seeding experiments in the coastal regions of California. The question immediately arises as to whether or not the convective bands exist as recognizable entities offshore. Evidence that they do is provided by detailed studies of the mesostructure of large storms in the eastern Pacific. Nagle and Serebreny, using satellite photographs and radar data, showed one large storm to be a very complex system involving five different air masses and with convective bands concentrated south and southeast of the center (20).

Possible techniques for tracking the bands include the examination of cloud photographs, a search for wind shift lines, and the use of X-band radiometer data to detect the concentrations of large precipitation particles in the convective cells. Although the supercooled cumuliform clouds in the bands may sometimes be overlain by cirrus clouds, the results in hand suggest that the offshore bands can be tracked adequately on the basis of satellite cloud photographs. Once the bands cross the coast, land-based radar sets provide supplementary data permitting them to be tracked inland and seeded. Seeding material

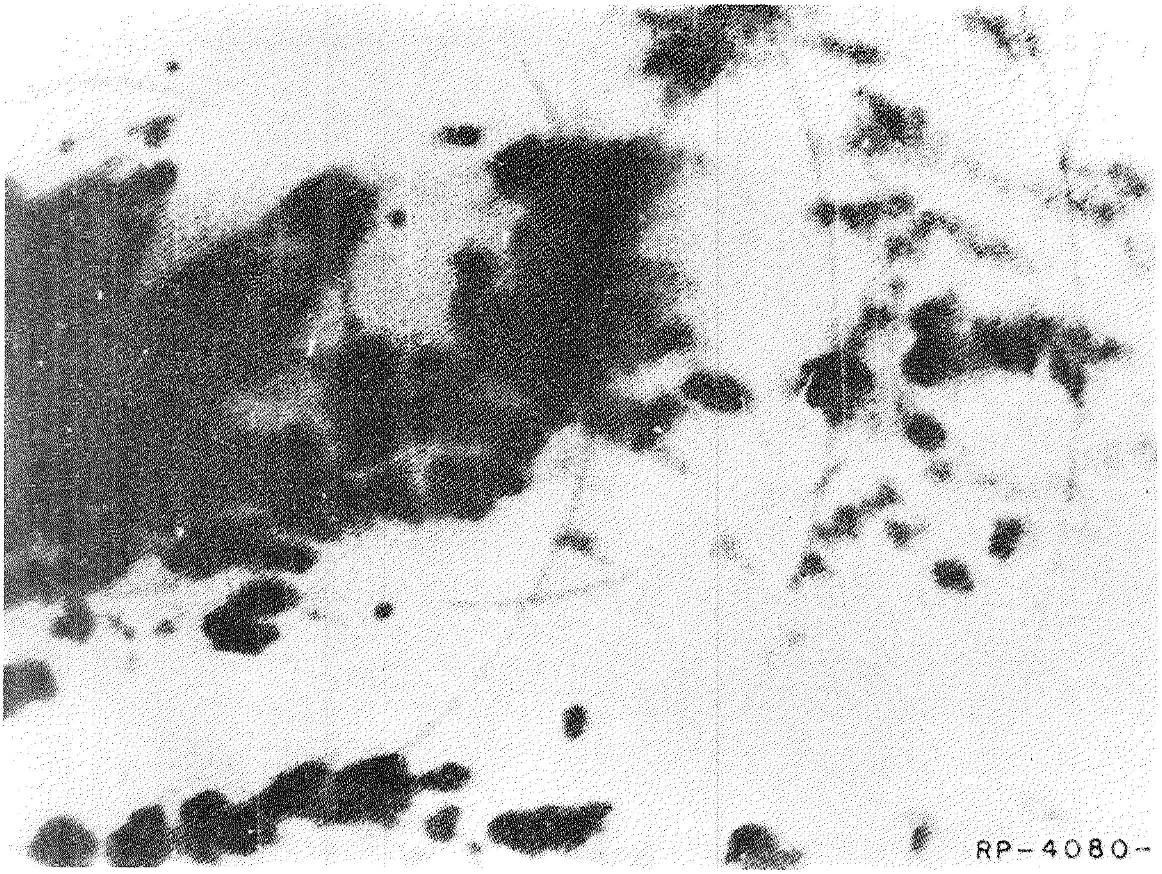

Fig. 2.8. For the operation and evaluation of seeding experiments in semi-orographic regions, the identification of the banded rain structure by radar could be most useful.

released just ahead of them from mountain peaks or aircraft is readily carried upward. Detailed measurements of the associated wind fields can be made for experiments but would not be essential in an operational project.

2.3 Conclusions

This subsection summarizes with the aid of tables the observational requirements for the various types of projects discussed above.

The measurements required to conduct and monitor a supercooled fog and stratus cloud dispersion program are shown in Tables 2-2 and 2-3. It is believed that the tables are self-explanatory and require no comments here.

The measurement required to conduct and control a warm fog dissipation program are shown in Table 2-4. The liquid water content and median drop diameter, which are given as first and second priority measurements, can be considered as a measure of visibility. However, they are much more than this, as they provide information on the optimum quantity and size distribution of the fog clearing agents to be introduced.

The meteorological measurements required for control and evaluation of orographic seeding projects are summarized in Table 2-5. All of them have been discussed above except the snowfall rate. This could be obtained conveniently by a weather radar or by telemetry from remote snow rate sensors. An elaborate network using the latter approach has been set up by Utah State University in a mountainous region east of Great Salt Lake.

The measurements required for a semi-orographic cloud modification project are summarized in Table 2-6. Top priority is assigned to the location of convective bands within large storms. It appears that this could be most readily accomplished by radar observations of the precipitation cells, although other possibilities exist. Temperature observations to determine vertical stability would identify those areas in which ground based seeding equipment could be used. Wind and pressure data would be used principally as an aid in precise location of the convective bands and in projecting their movement. Measurements of cloud top height and updraft speeds would be useful principally in assessing the intensity of individual convective bands and could be used to tailor the amount of seeding material to the quantities of water being processed in each band.

TABLE 2-2

Primary Measurements for Modification of Supercooled Fog

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Visibility	± 20%	0.2	--	1	
2	Temperature through fog layer	± 0.5C	0.5	50	10	For most operations one sounding is enough
3	Fog depth	± 50 m	0.2	--	10	
4	Wind					
	Direction	± 10°	0.2	50	1	
	Speed	± 0.5 m sec^{-1}	0.2	50	1	

TABLE 2-3

Stratus Cloud Modification

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Height of base and top of cloud layer	± 50 m	1	--	15	
2	Temperature	± 0.5C	1	100	15	
3	Wind					
	Direction	± 10°	1	100	10	
	Speed	± 0.5 m/sec	1	100	10	

TABLE 2-4

Measurements in Warm Fog Dissipation

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Liquid water content	± 0.1 g/m^3	0.1	100	1	
2	Median drop diameter and spread	± 1 μ	0.1	100	1	
3	Wind:					
	Direction	± 10°	0.1	100	1	
	Speed	± 0.1 km/hr	0.1	100	1	
4	Fog depth	± 50 m	1	--	1	
5	Temperature	± 0.5C	1	100	10	

TABLE 2-5

Measurements for Orographic Cloud Modification

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Cloud top height	± 100 m	1	--	10	
2	Temperature	± 0.5C	1	100	50	Also determine 500 mb temperature and inversion surface, if any
3	Wind					
	Speed	± 0.5 m sec^{-1}	1	100	10	Spacing as low as 2 km may be required for running cap cloud models
	Direction	± 10°				
4	Snowfall rate	Factor of 2	0.25	--	10	
5	Ice nucleus count	Factor of 2	1	500	10	

TABLE 2-6

Measurements for Semi-orographic Cloud Modification

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Rainfall rate	Factor of 2	0.2	--	5	Obtainable by radar identification of bands in large storms
2	Temperature	± 0.5C	3	100	50	To determine vertical stability
3	Wind:					
	Speed	± 0.5 m sec^{-1}	1	100	10	
	Direction	± 10°	1	100	10	
4	Pressure	± 0.5 mb	3	100	50	
5	Cloud top height	± 500 m	3	--	50	Best done by IR technique, crude estimate possible from photographs
6	Updraft speeds	± 1 m sec^{-1}	1	1000	--	In selected precip cells

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3. MODIFICATION OF CONVECTIVE CLOUD SYSTEMS

3.1 Nature of Convective Clouds

3.1.1 Introduction

The discovery of techniques for modifying physical processes within natural clouds gave great impetus in the mid-forties to that portion of physical meteorology concerned with the physics of clouds and precipitation. Although the early spectacular demonstrations of modifying clouds (59) were done over stable stratiform clouds, the majority of the work that has followed for the last two decades has gone over to the convective systems and justifiably so, as most of the world's rainfall and severe weather phenomena come from the convective systems. The complexities and uncertainties regarding weather modification results started with this change in emphasis. Considering the areal extent and impact of convective phenomena, the potential value of control techniques over convective systems is also very high. The central problem in the field of weather modification has been and still is, how should we approach control of convective clouds and when do we reap the benefits?

The ability to monitor artificial changes in convective cloud systems has increased with development of weather radars, doppler radar, computers and automatic weather stations, although much remains to be done in automating data collection, handling and reduction. The theoretical development has reached a point where mathematical simulation is already providing a crude insight into the possible changes in cloud physics and cumulus dynamics. In the future we must rely heavily on improved modeling techniques coupled with improved systems of observation, without which adequate simulation would be impossible.

The vigorous activity in cloud physics and weather modification in the last two decades has produced a number of interesting revelations, the most pervasive of which is the astounding complexity, not previously fully appreciated, of the physical processes in the atmosphere. Natural variability is the big obstacle in obtaining quick answers to any questions of weather modification and, to conclude in the words of Dr. Thomas Malone, "A long and winding road lies ahead with the outcome still uncertain" (52).

3.1.2 Dimension, Dynamics and Physics

Experimental and theoretical developments in cumulus dynamics and physics up to the last decade have been well treated by Mason (54) and Fletcher (35). These developments have clarified to a considerable

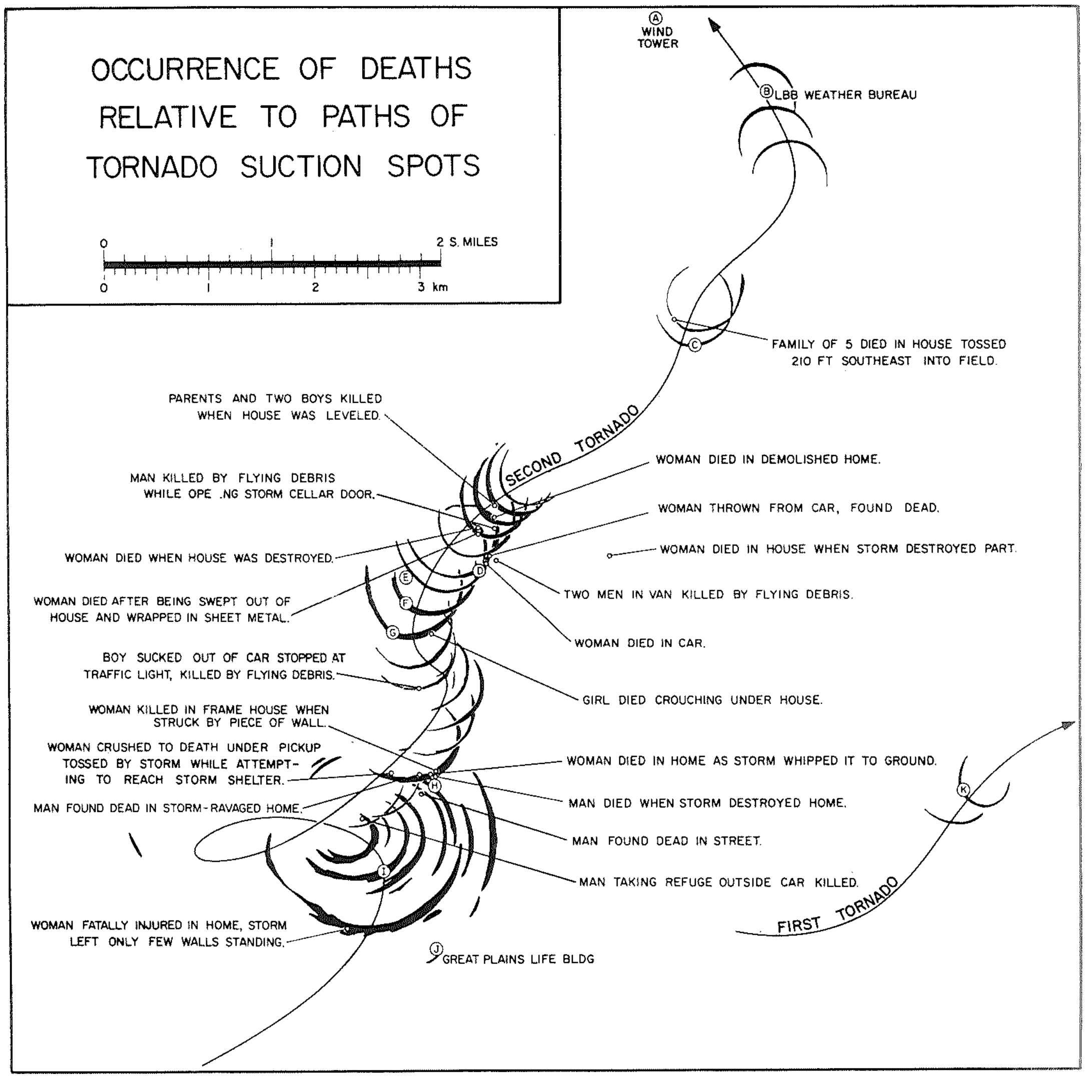
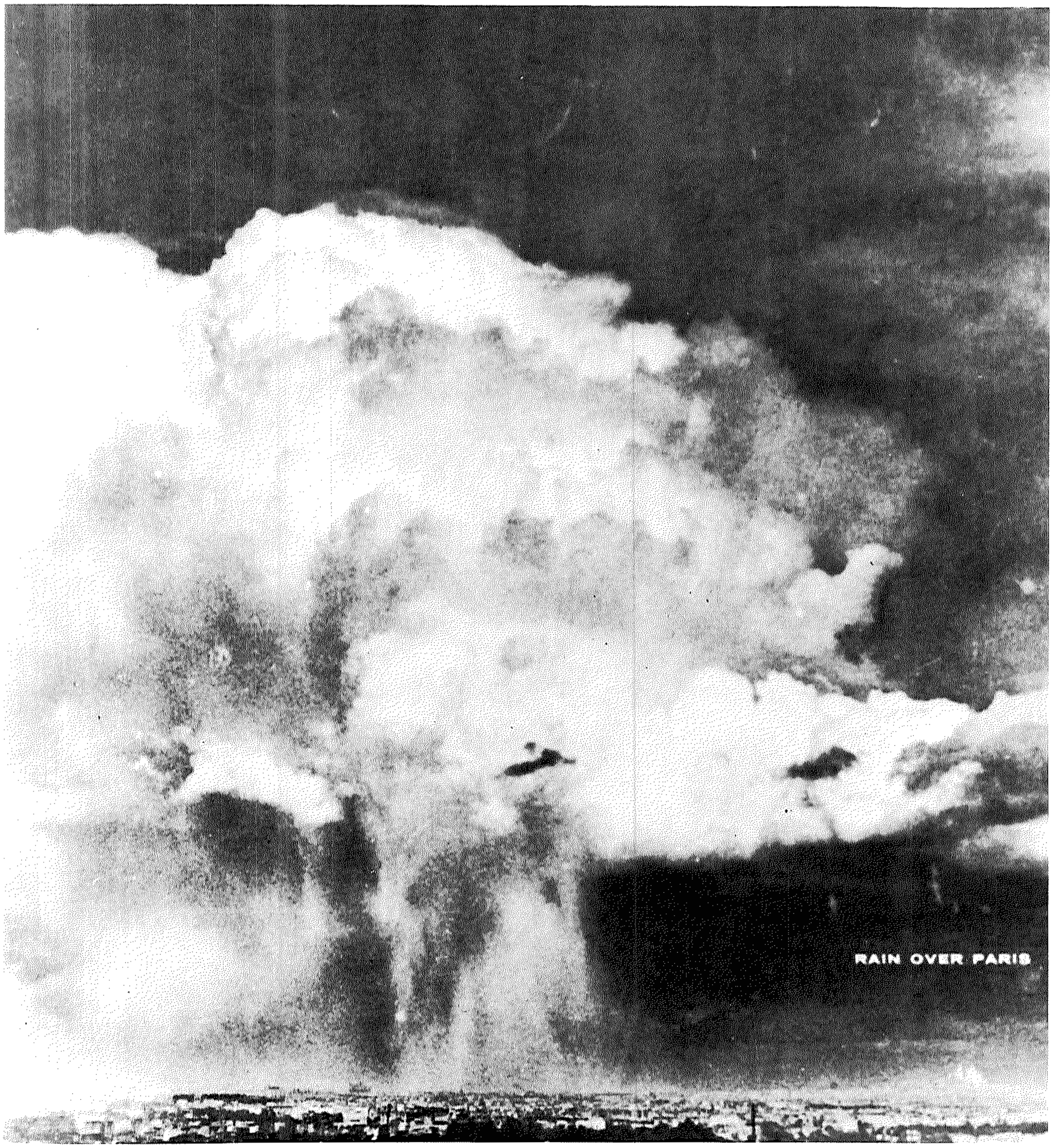


Fig. 3.1. One of the severest manifestations of convection is the tornado. Although confined to a narrow width it can do a great havoc as evidenced in the above illustration showing 26 deaths from the recent case at Lubbock, Texas on May 11, 1970. Rotational speed might have been between 145 and 290 m.p.h. (37).



Convection on a grand scale.

Fig. 3.2. This photograph permits one to see the outcome of rain formation processes that extend from the ice crystal level of the upper troposphere down to the ground. At the uppermost level a pileus cloud, usually associated with thunderstorm formation, can still be seen even though the cloud mass has begun to lose its characteristic cumuliform. The photograph strikingly illustrates the torrential downpour of rain in the downdraft region characteristic of large cumulonimbus clouds (53).

degree the role of temperature and humidity lapse rates, lateral entrainment, updraft, and penetrative down draft from cloud top upon the development of individual cumulus clouds. The role of wind shear near the top of thunderstorms in converting them to severe local storms has also been recognized recently (30).

The primary energy of ascending currents in convective systems is derived from atmospheric instability that can develop fair weather cumulus a few hundred meters deep with low vertical velocities (1 m/sec or so) and lasting for a few minutes, cumulonimbus clouds extending to the stratosphere with vertical velocities up to 40 m sec^{-1} and lasting for several hours and releasing a few inches of rain, roaring hurricanes with chimneys of cumulonimbus lasting for days, or tornadoes (Fig. 3.1). The wide variation in both time and space makes the convective system not only difficult to understand but also to observe (Fig. 3.2).

The tendency of initial condensation growth in clouds is to lead to droplets of nearly the same size (45) but, in reality, turbulent mixing leads to droplet spectrum broadening. In maritime cumuli droplet concentrations are near 50 cm^{-3} and rarely go above 100 cm^{-3} (72), (3), whereas in cumuli growing over continental interiors, droplet concentrations usually run from several hundred to as many as thousands per cubic centimeter with a typical value of 400 cm^{-3}. As cloud liquid water does not differ greatly, this characteristic difference is usually attributed to certain differences in the population of condensation nuclei found over sea and land, although differences in typical updraft play a minor role (75). Further growth of these drops to precipitation size always involves a collision and coalescence (accretion) process. The precipitation embryos [large drops that form around unusually large condensation nuclei known as giant nuclei (32), as a result of chance coalescence among cloud droplets, or through the introduction of ice nuclei in the supercooled portion of the cloud] grow by overtaking and sweeping up smaller cloud droplets, although in the initial stages in supercooled cloud the growth of ice crystals by sublimation is more rapid (13), (32). It may further be mentioned that the collision of two drops does not necessarily lead to their coalescence into single drops (74), (16), although experimental cases have been reported (41) of complete coalescence for certain pairs of drop radii. Weak external electrostatic fields and net charges borne by the colliding drops do have some role. It may be said that we scarcely understand the barest essentials of highly complex phenomena controlling coalescence of colliding drops (Fig. 3.3).

All thunderstorms and even many cumuli not producing visible lightning emit radio waves over a wide range of frequencies (58). A number of observers have noted (76) rapid appearance of rain in large cumulonimbus clouds immediately following lightning discharges. Electrical phenomena in tornadoes have been well documented by Vonnegut (77), and recently sferics have been

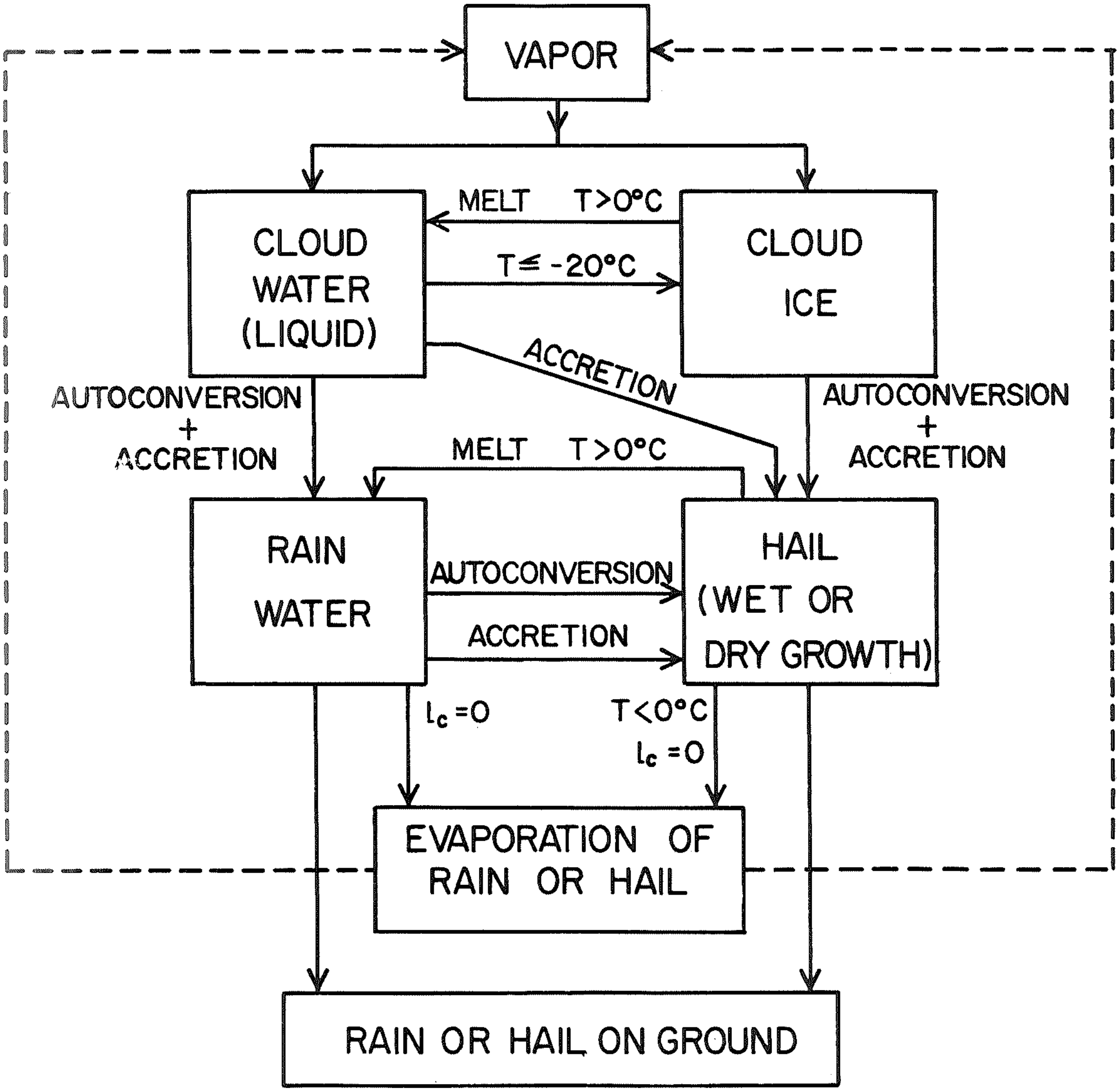


Fig. 3.3. Complexities in cloud physic processes in convective systems can be visualized from the above schematic drawn for modeling precipitation growth in cumulonimbus (56).

utilized for detection of tornadoes by TV sets (15). All these lead us to believe that electrical forces may be more important than hitherto supposed and that electricity may produce significant effects on the formation of precipitation and on the circulation within storms.

3.1.3 Mechanism and Basic Difference in Convective Cloud Modification

The amount of agreement concerning results of weather modification diminishes as one proceeds from stratiform to orographic to purely convective cloud systems. In contrast to stratus clouds, convective clouds show little continuity in time and space. The lifetime of an individual convective system is comparable to that required for seeding material to act upon its water content. Convective clouds change so rapidly that the clouds under treatment may develop, in a few hours, from scattered cumulus to giant cumulonimbus with consequent changes in water content, temperature and drop size. The treatment may also have to be applied at varying distances from the cloud or at least from its point of effectiveness, and actual treatment intensity and characteristics of treated clouds vary markedly from point to point. The subject and treatment can be specified in general terms only and the degree to which the experiment can be described and reproduced is limited, making it extremely difficult to differentiate artificially produced changes. Seeding, in general, influences convective clouds in three different ways. First, seeding changes the microphysics. This may be done by changing the initial droplet spectrum or by glaciation of supercooled portions of the cloud and can lead to the production of precipitation particles in an otherwise inactive region of the cloud. Secondly, the latent heat release by glaciation may influence the cloud dynamics and thereby the total amount of rain produced. Thirdly, effects may be produced in neighboring clouds. This question is more complex and quantitative estimates of such effects are only beginning to emerge.

3.2 Review of Experiments: Rainfall Increases

As the complexities of the precipitation mechanism were revealed in different cloud physics studies and weather modification programs, the desirability of measuring more meteorological parameters with increased accuracy, closer spacing and at shorter time intervals was also realized. This realization was strengthened with the advent of numerical modeling. A survey of a few of these past experiments is perhaps worthwhile before we make estimates of measurements and observations required for the purpose.

Numerous experiments on seeding of convective clouds have been carried out since the days of Schaefer's experiment and the discovery of silver iodide crystals as freezing nuclei by Vonnegut. Most of these experiments have involved generation of silver iodide crystals to act as artificial ice nuclei, although other techniques, using dry ice, salt particles and water spray, have also been used. These projects, which have been carried out in many countries, range from well designed experiments to commercial attempts to exploit the technology for immediate economic benefit. Each country's research program has been directed towards the solution of its own weather problems. Thus, projects in Australia, Israel, Mexico, and India have been mainly for rainfall increases; those of Argentina, Soviet Union, and Switzerland have been for hail suppression. Researches in the United States have been for increase of rainfall, suppression of hail, and decrease of lightning strikes. We are limiting our discussion in this chapter to a few recent experiments with sound scientific design, primarily on the convective systems of nontropical regions using freezing nuclei as the main seeding agent. A few interesting experiments on convective clouds in the American tropics are dealt with in the following chapter.

3.2.1 Australia

Among the long term experiments conducted outside the United States are those of Australia. Early experiments (Fig. 3.4) were done with dry ice (68) (71), but the method was found expensive. Subsequently, following preliminary trials with silver iodide (78), randomized trials were undertaken with this material. Test clouds were supercooled, reasonably isolated, deep, of long duration, without excessive shear, with no other cloud raining or glaciated within 30 km, and with no appreciable rain from nearby clouds within 30 minutes of seeding. The suitability of a cloud which was specified for seeding was determined by visual observation and required estimation of dimension, shear, rain and glaciation.

The importance of measurements of different meteorological variables such as cloud top and environment temperature, depth of cloud, base and top height, etc., was realized from the beginning. Rainfall was estimated from the permanent impression of drops on a raindrop impactor flown under the densest part of the cloud and through rain. For clouds whose tops were -10C or colder the results indicated that the seeded ones had more rain than the unseeded ones, the difference being statistically significant (Fig. 3.5).

The majority of the Australian experiments on larger areas were done on semi-orographic regions and have been discussed earlier. The experiment in South Australia (69) was the only one over flat low-lying land. Most of the rain here falls during winter, and the incidence of clouds and rainfall in this area is usually associated with passage of lows. Prefrontal altostratus moving in from the northeast is replaced on the passage of a cold front by large cumulus degenerating to smaller cumulus. Both altostratus and cumulus clouds were seeded, the criterion being that cloud top be colder than -5C. Experiments were conducted using the randomized crossover design; but the results yielded no evidence that cloud seeding influenced the mean precipitation. The

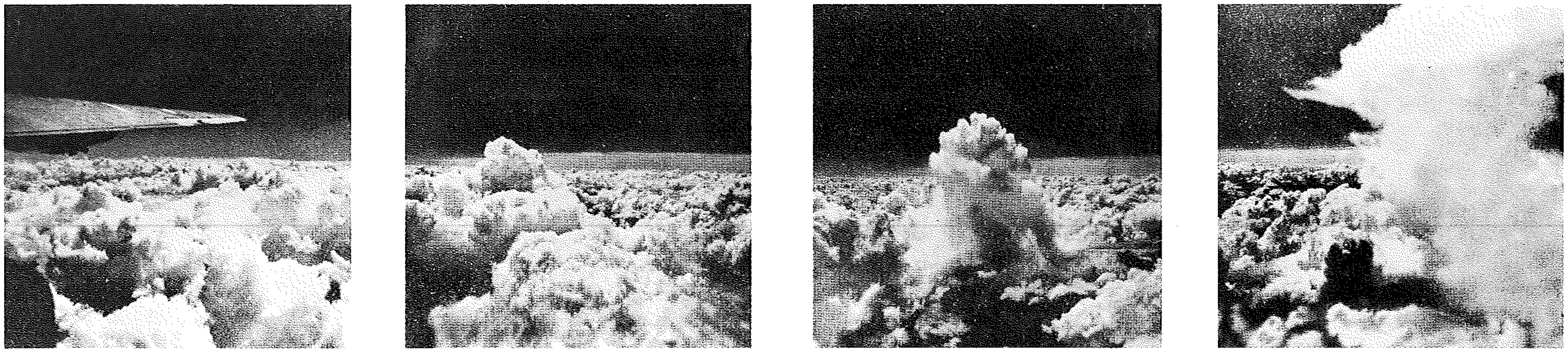


Fig. 3.4. Seeding experiment on individual cumulus cloud in Australia. Above is one of the striking examples of dynamic effect of seeding from the experiment over Blue Mountains, on February 5, 1947. Clouds prior to seeding (1st picture) had base 3300 meters, top 7000 meters with freezing level at 5500 meters. After 100 kg of dry ice dropped in one cloud, radar echo was observed nine minutes later and the cloud started to rise above others (2nd picture) after thirteen minutes cloud had reached 9000 meters (3rd picture). A few minutes later heavy rain started to fall from base. The cloud eventually spread out and formed anvil with height between 9000 and 12,000 meters (last picture) (17).

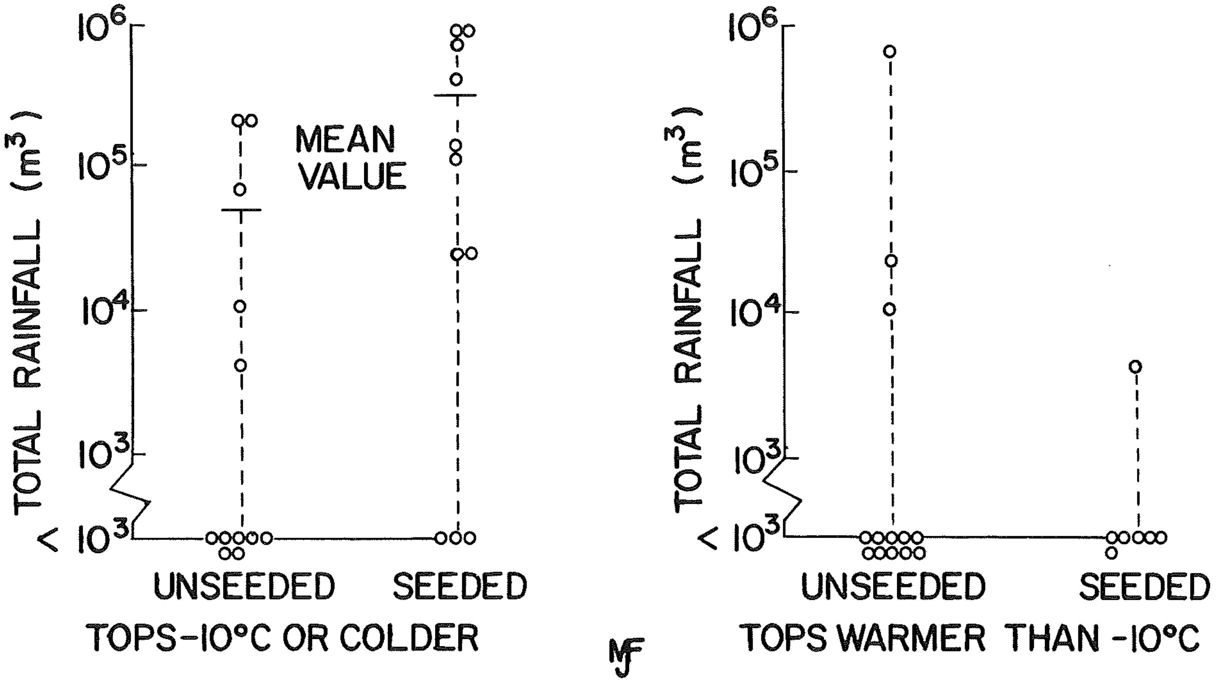


Fig. 3.5. Sometimes stratification of rainfall data according to cloud top temperature can give us greater insight as to the effectiveness of modification treatment or otherwise. As in the above illustration from Australian experiments with individual clouds, the effect of seeding with silver iodide is quite apparent for clouds with tops colder than -10C, where as for those with warmer tops, no conclusion could be drawn (70).

inconclusive result has been attributed to infrequent occurrence of clouds suitable for seeding and the predominance, in the maritime situations encountered, of rain formation by the coalescence process.

3.2.2 Chicago Group

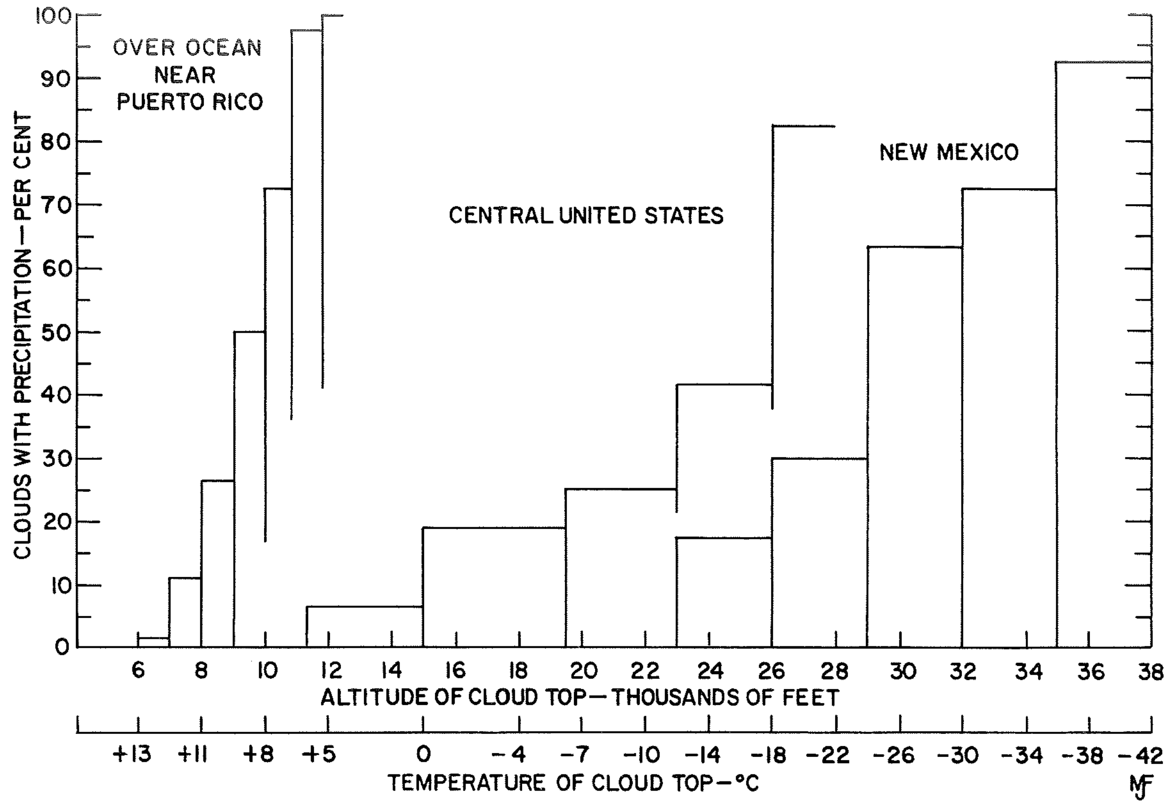
Many experiments have been conducted on convective clouds or embedded convective systems in the United States. One of the earlier experiments, involving randomized dry ice seeding for initiating precipitation in individual cumulus clouds in the central United States, was undertaken by the University of Chicago Cloud Physics Laboratory (18) (19). Seeding was carried out at temperatures slightly colder than OC in the hope that early release of latent heat of fusion might add buoyancy in such a manner as to stimulate cloud growth and favor development of precipitation. The results did not indicate (contrary to Australians) that this seeding produced detectable difference in the formation of radar precipitation echoes, (52). The initial computational studies also failed to give any better understanding but the necessity of continued observation and measurements in field and laboratory were realized. Simultaneous experiments on individual clouds were also carried out over Caribbean tropical cumulus and it was shown that precipitation develops there from all water condensation--coalescence mechanism. The most important outcome of these experiments of the Chicago group is the realization of importance of the coalescence mechanism for a region like the central United States as well as the tropics.

The most important measurements that were required were: (a) the temperature of free air in and around clouds with an accuracy of ±0.1C; (b) the humidity in the cloud environment; (c) cloud droplet concentration, size and size distribution at discrete points inside the cloud; (d) liquid water content of the cloud; (e) the electrostatic field, thought to be important in droplet coalescence; (f) major drafts and turbulence assessed from airspeed and altitude measurements; and (g) photographs made of visual clouds. Heights of cloud tops were measured and the clouds were checked for echoes with calibrated radar. This was done to determine the precipitation probability as a function of cloud height (Fig. 3.6), cloud thickness and cloud top temperature (27). Most of the instruments required for the measurements were airborne, including the aircraft nose radar.

As the artificial nucleation of a cloud can result in changing the time of precipitation initiation a computational work was also carried out to find time and level of echo formation.

3.2.3 University of Arizona Experiments

The seeding of orographic summer convective clouds on a randomized basis was undertaken in 1957 in Arizona (5), (4).



Relation of Precipitation Development to Cloud Height

Fig. 3.6. Census was taken of cumulus clouds in three geographically different regions indicated A cloud census of the type illustrated can be very useful in determining the primary type of seeding treatment for a region. Natural precipitation develops in every cumulus cloud in the Carribbean (Puerto Rico), before they grow to heights for ice crystal process to be involved and seeding treatment involving this method may not be very effective as precipitation is unlikely to develop before the clouds reach freezing level (20).

A striking feature of the weather of southeastern Arizona is the sudden change of air mass in the early part of July. The dry air prevalent during the month of June is replaced by moist air within which convective clouds and thunderstorms form with a high frequency. Once this "Arizona monsoon" has started, one can expect showers in southeastern Arizona during most days of July and August.

The convective showers have a diurnal variability with a distinct minimum during the morning hours. When convection begins, the clouds form first over the mountains during the late morning or early afternoon. As the day progresses, clouds may appear over the valleys but for the large part of the cloudy period the valley around Tucson remains relatively clear. Earlier studies (7) had revealed that the building cumuli here were generally supercooled to levels colder than -10C and there are 40 to 50 days each summer that have large convective clouds, most of which do not rain naturally. It was reasoned that introduction of silver iodide into growing convective clouds might produce important effects. Days with precipitable water exceeding 1.10 inches were considered seedable. Apart from the routine meteorological measurements based on soundings, etc., the important observations that were carried out were (a) properties of visual clouds (with aid of time-lapse camera and a pair of aerial cameras giving accurate cloud top heights); (b) precipitation formation as revealed by radar. (It was possible to study the location of the initial precipitation echoes, the rates of spread of precipitation and the frequency of large convective clouds from the film records of radar scope); and (c) lightning. (This was mainly done with visual observation of cloud to ground lightning strokes although an electric field meter and a lightning counter were installed).

Out of the four years of the first phase of the program, the first two years' results (6) were encouraging (Fig. 3.7), both from rainfall measurements, radar echo heights and cloud top temperature, although results were not very significant, but the subsequent two years' result was negative (7). At the end of the four years the experiment failed to show that silver iodide particles released from an airplane at -6C level caused detectable changes in the quantity of precipitation, lateral spread of precipitation, frequency of large thunderstorms or the frequency of cloud-to-ground lightning strokes, although evidence was there to suggest that silver iodide particles caused the formation of precipitation echoes in clouds which would not have developed echo naturally.

As the results of the first phase suggested that the microphysics of clouds play a much smaller role than previously thought in determining the quantity of rainfall, a new series of experiments (10), (11), (12) was started to test the value of silver iodide particles for modification of convective clouds. The most important changes were: reducing the seeding flight altitude to 1000 to 2000 feet below

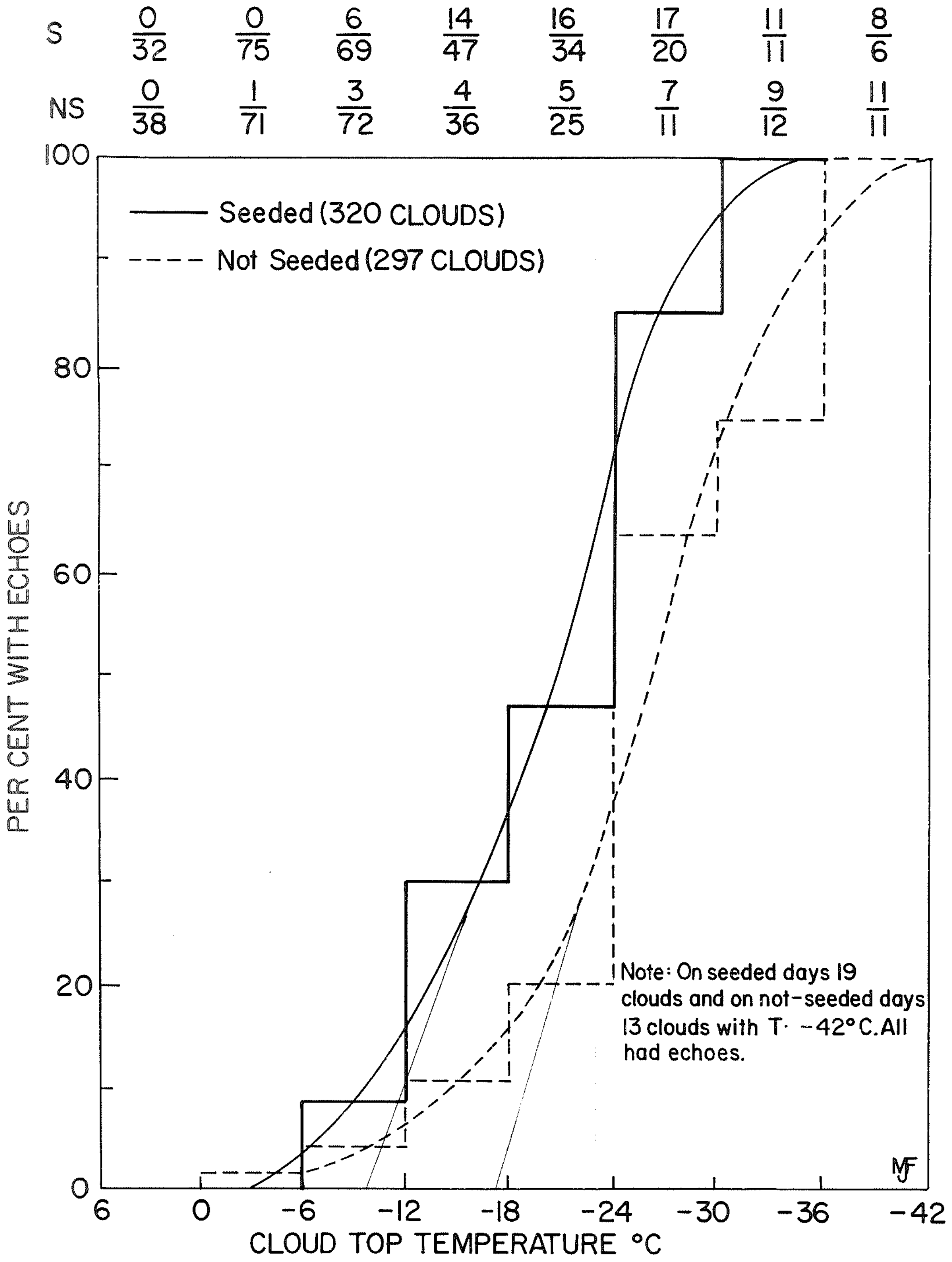


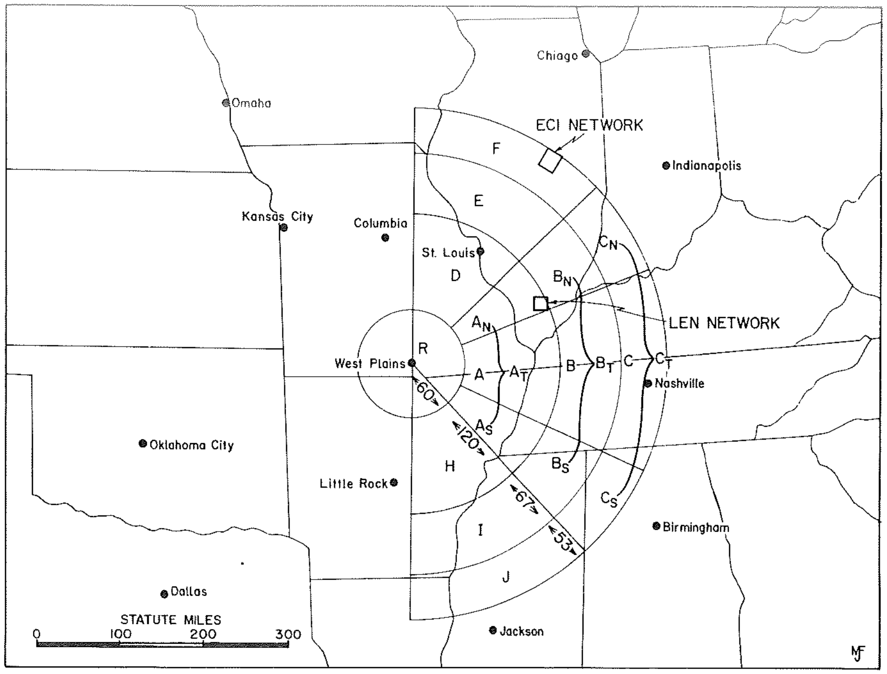
Fig. 3.7. In some orographic cumulus, cloud top temperature can be good indicators in stratifying the situations where AgI seeding would be most effective. The figure shows summary of observations made during 1957-1958 with seeding orographic cumuli seeding in Arizona. As seen the likelihood of precipitation was greater on seeded days than on non-seeded days with the same cloud-top temperature (6).

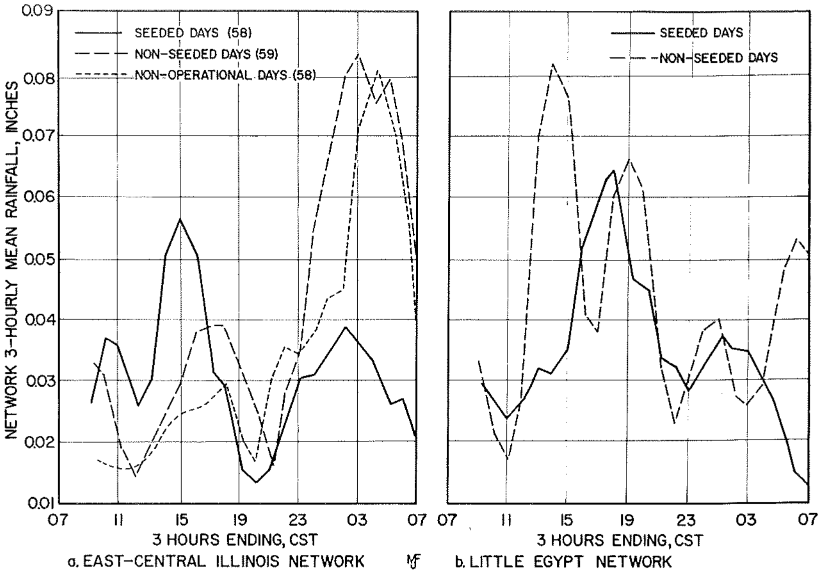
cloud base along a line upwind, increasing the number of raingages for better sensitivity and selecting "seedable" days with more restriction. The overall results based on rainfall measurements were again negative but were not significant enough to attribute the apparent decrease to seeding effects. It should be recognized that these tests used a specific type of seeding on a specific class of clouds and the results as such cannot be directly extrapolated to other techniques, other regions or even other clouds of similar appearance. A number of studies (1), (2), (21), (8), based on measurements of cloud base, altitude of initial radar echo, echo heights and cloud base temperature, have revealed that the dominant precipitation initiation mechanism in convective clouds in Arizona is the coalescence process. Perhaps techniques involving this process may be more effective for this region, although there are many clouds in this region in which precipitation initiation can be influenced by ice-nuclei seeding and some of which may not develop precipitation particles by the coalescence process alone.

3.2.4 Missouri (Project Whitetop)

The Project Whitetop seeding (1960-1964) on Missouri (23), (24), (36), (25) summer cumuli was a randomized cloud seeding experiment with a detailed study of natural rain mechanisms in cumulus clouds. One of the main considerations for selecting southern Missouri was the occurrence of a high frequency of non-orographic summer convective clouds in an area of uncontrolled airspace large enough to accommodate the project research flights. Emphasis was placed upon physical measurements. The reasoning behind these measurements was that under suitable meteorological conditions seeding would detectably alter convective clouds and that fundamental research in cloud physics was required to identify the suitable conditions. The main measuring tools were ground based RHI radar, instrumented aircraft for cloud physics measurements and hydrometeor sampling, cameras for cloud and stereophotography, ice nuclei counters, a network of recording rain gages, and pilot balloon observations every two hours for plume mapping. Criteria for an operational day were based upon precipitable water up to the 500-mb level and winds at 4000 ft MSL. Local winds were used to estimate the downwind transport of silver iodide and to divide the research area into a plume, where it was thought that there should be wind-transported silver iodide, and a non-plume area, free of silver iodide.

The primary results from the data, which were stratified according to different weather conditions (wind direction and echo heights), indicate an overall negative effect of seeding. The days with low-level south winds show a strong negative effect. On these storm days, both seeded and non-seeded, high concentrations of ice particles and snow pellets were found in many clouds at temperatures as warm as -5C to -10C (22). These clouds evidently contain a natural ice mechanism





a. EAST-CENTRAL ILLINOIS NETWORK

b. LITTLE EGYPT NETWORK

OFF TARGET EFFECTS

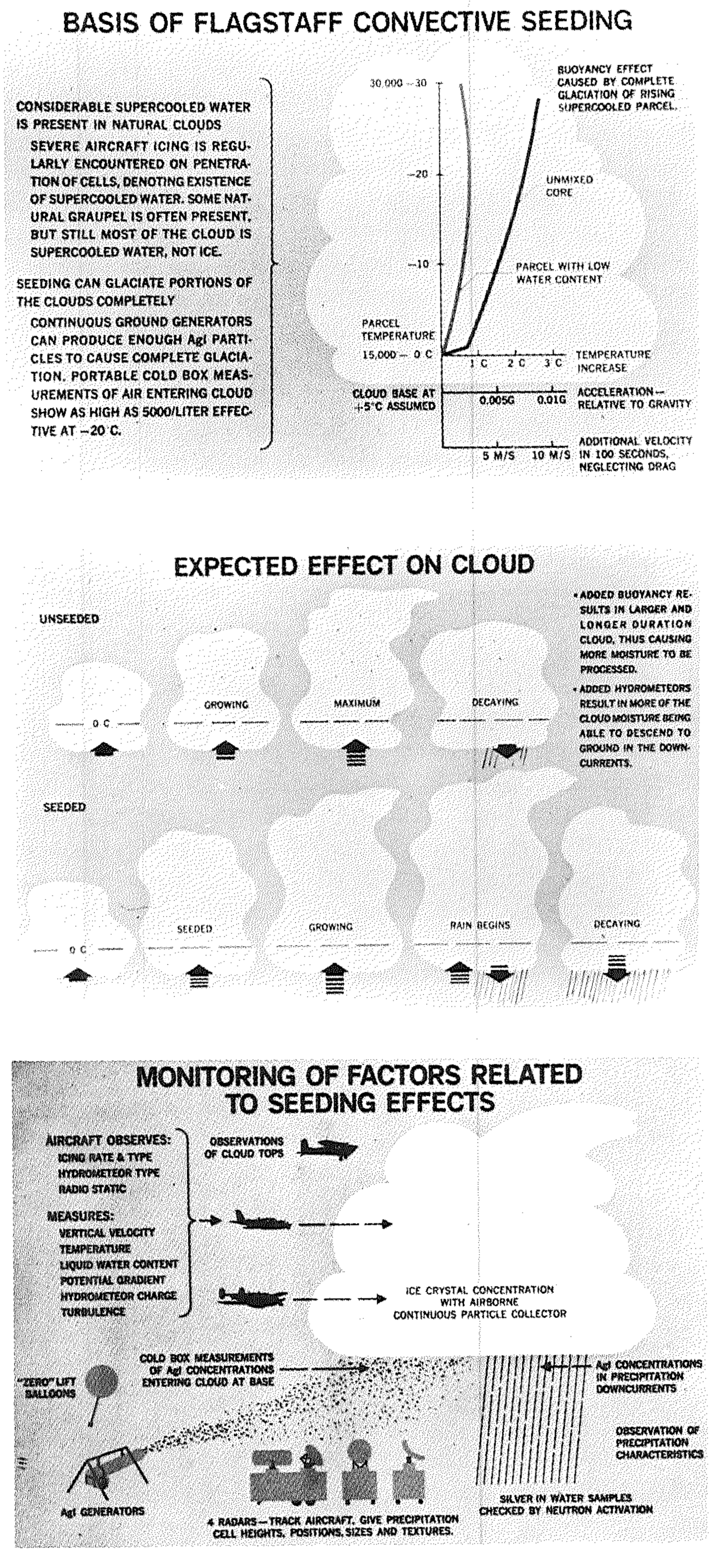
Fig. 3.8. Detailed analysis of Project Whitetop data has revealed number of complexities that can come out of weather modification programs. One such is the downwind effect of seeding beyond the area of normal target. For example, East Central Illinois network (E. C. I. - 1st figure), which is about 290 miles away, showed definite decreases of rainfall (2nd figure) in the next early morning following seeding which was also the expected time for seeding material to reach there. But pronounced downwind seeding effects were also found in Little Egypt network (LEN - 1st figure) 175 miles away immediately following starting time of Whitetop seeding (2nd figure), which could not be explained and raised the question that ECI early morning effect may also be due to sampling vagary (60).

effective at the temperature threshold for silver iodide. Evidence also indicates that these ice particles perhaps arose from heterogeneous freezing of raindrops that formed by coalescence, and that the area seeding resulted in overseeding with a negative effect. There is strong evidence from Project Whitetop experiments that on the storm days with south wind particle growth in cloud is dominated by coalescence processes and perhaps summer cumuli in Missouri grow in air masses that contain essentially maritime condensation nuclei. The days with low-level west winds showed evidence of positive effects during seeding hours, especially on days with maximum echo height between 20,000 and 40,000 ft MSL.

The complexities (Fig. 3.8) of precipitation mechanisms revealed by the Missouri experiments demand more study on all the variables in order to improve substantially our ability to produce useful modification of cumuli.

3.2.5 Flagstaff (Arizona)

A randomized seeding experiment was conducted in recent years in Flagstaff, Arizona (80), (50), (51), on isolated cumulus clouds. The project was a part of Project Skywater, sponsored by the Bureau of Reclamation to develop quantitative seeding techniques which can have economic benefit when applied to various locations. The most significant result of this experiment was that of demonstrating seeding effects on isolated cumulus clouds with the help of a simple numerical model incorporating both microphysics and dynamics, with initial emphasis on dynamics (Fig. 3.9). The results of the experiment indicated that the seeded clouds had significantly higher visual tops, radar top, duration and rainfall, as revealed by examination of the observations alone and also by examination of the seeding cases with the model aiding in supplying control information. The model (79) helped in selecting test clouds for which dynamic effects were expected to be large, as well as in evaluation of results. The clouds were carefully selected to fit the requirements of the limited model. The model predicted three gross factors which could be measured - the maximum height, the rainfall amount, and the rainfall duration. The basic inputs into the model are the environmental lapse rates of temperature and humidity, the updraft radius, the cloud base height and assumed temperatures for natural and artificial glaciation. The numerical model was used with the early morning sounding to select ranges of cloud base diameters which would be expected to be particularly responsive to seeding, the final selection being done on the basis of aircraft-measured base size and existence of upcurrents. Data obtained during 1967 and 1968 on microphysical processes indicate that in this region also the warm rain process initiates precipitation. Initial ice phase originates in the decaying cloud regions and precipitation development occurs during the clouds' dissipating stage. Seeding with silver iodide produces nuclei that act primarily by contact. The principal effect of seeding is dynamic and related to latent heat release.



BASIS OF FLAGSTAFF CONVECTIVE SEEDING

CONSIDERABLE SUPERCOOLED WATER IS PRESENT IN NATURAL CLOUDS

SEVERE AIRCRAFT ICING IS REGULARLY ENCOUNTERED ON PENETRATION OF CELLS, DENOTING EXISTENCE OF SUPERCOOLED WATER. SOME NATURAL GRAUPEL IS OFTEN PRESENT, BUT STILL MOST OF THE CLOUD IS SUPERCOOLED WATER, NOT ICE.

SEEDING CAN GLACIATE PORTIONS OF THE CLOUDS COMPLETELY

CONTINUOUS GROUND GENERATORS CAN PRODUCE ENOUGH AgI PARTICLES TO CAUSE COMPLETE GLACIATION. PORTABLE COLD BOX MEASUREMENTS OF AIR ENTERING CLOUD SHOW AS HIGH AS 5000/LITER EFFECTIVE AT −20 C.

BUOYANCY EFFECT CAUSED BY COMPLETE GLACIATION OF RISING SUPERCOOLED PARCEL.

EXPECTED EFFECT ON CLOUD

- ADDED BUOYANCY RESULTS IN LARGER AND LONGER DURATION CLOUD, THUS CAUSING MORE MOISTURE TO BE PROCESSED.
- ADDED HYDROMETEORS RESULT IN MORE OF THE CLOUD MOISTURE BEING ABLE TO DESCEND TO GROUND IN THE DOWNCURRENTS.

MONITORING OF FACTORS RELATED TO SEEDING EFFECTS

Fig. 3.9. Schematics of Arizona (Flagstaff) convective seeding plan.

Average rainfall per gage per test case (in inches) and seed/no-seed ratios in target areas for all days of given type.

Shower days	SW-flow	NW-flow
North area, Seed N	0.039	0.036
Seed S	0.027	0.025
Seed/no-seed ratio	1.4	1.4
South area, Seed S	0.072	0.045
Seed N	0.012	0.004
Seed/no-seed ratio	6.0	11

Storm days	SW-flow	NW-flow
North area, Seed N	0.086	0.035
Seed S	0.111	0.170
Seed/no-seed ratio	0.77	0.21
South area, Seed S	0.093	0.054
Seed N	0.117	0.125
Seed/no-seed ratio	0.79	0.43

TABLE 3-1

Summary results of the seeding experiment in South Dakota, showing definite increase of rainfall for shower days. But for storm days with northwest flow, there seems decreases of rainfall on seed days and for southwest flow it is not conclusive (29).

3.2.6 South Dakota

In another part of Project Skywater a randomized crossover area seeding experiment was conducted near Rapid City, South Dakota (29), (47) to test effects of artificial nucleation upon supercooled spring and summer convective clouds. The location was selected to take advantage of the reliable supply of convective clouds forming over the Black Hills during daylight hours and drifting over the plains. There are two distinct patterns of shower occurrences near the Black Hills. In one the showers move from the southwest under the influence of southwesterly wind aloft while in the other showers move from west or northwest under the influence of northwesterly wind aloft. Accordingly, two pairs of target areas were set up in order to reduce cross-target contamination. The test days were stratified in accordance with the criteria of precipitable water up to 500-mb level, wind speed and direction at 850-mb level, and vorticity advection around the project area, into four categories of (a) very little rain, (b) stratiform cloud days, (c) shower days, and (d) storm days. The seeding, which was restricted mostly to shower days and storm days, was conducted on the basis of opportunity in the updrafts under convective clouds containing large quantities of supercooled water rather than along fixed tracks or at fixed times (c.f. Whitetop). Seeding operation was coordinated from a radar facility with six radars, (for directing seeding, locating seeding aircraft, time lapse scope photography and providing quantitative signal intensity data).

Usually there were higher concentrations of ice nuclei in the seeded target than in the unseeded target, but under certain wind regime there was evidence of cross-contamination. Instrumented aircraft penetration of clouds near the -10C level indicated abundant ice crystals and snowflakes in seeded areas and large quantities of supercooled water in unseeded areas. Results (Table 3-1) indicated more rainfall in the seeded target area on shower days, but rainfall was lighter in seeded target areas on storm days.

3.3 Review of Experiments: Hail Suppression

The basic conditions required for a hailstorm are: (1) Sufficiently high updraft velocities to support the stones during their growth, (2) accumulation of supercooled liquid water, and (3) a persistent updraft to permit the stones sufficient time to grow. The present approaches to hail modification are to produce more minute ice particles by adding freezing nuclei and thus promote the growth of more hailstones of smaller size, or to overseed as much as possible of the supercooled part of the cloud in order to prevent the growth of hail by accretion of supercooled droplets. The experiments in hail suppression may broadly be classified in two phases, that of earlier experiments with indirect assessment of results with seeding done from ground, and the second phase with the advent of radar for monitoring storms and the use of aircraft for seeding and measurements.

3.3.1 Early Experiments

France: The French hail suppression effort began in 1951 and was conducted on an operational basis using ground based silver iodide generators (31). In 1959 the experiment was reorganized and the charcoal silver iodide burners used previously were replaced by burners consuming silver iodide in acetone solution. The generators were distributed over the southwestern part of France, where most damaging hailstorms occur. The project was non-randomized and the effect was estimated by comparing the ratio of the hail insurance losses paid out to the insured capital for the period seeded with the ratio in the past. The analysis indicated a reduction in hail damage for the seeded period as compared to earlier periods, but a comparison by another investigator of the same ratio with that in regions outside the seeded area indicated hail damage increases in the target area. An analysis on a statistical basis (26) has also yielded inconclusive results. It has been emphasized that verification of physical effects must also be done for such parameters as number of ice nuclei, ice crystals and hail embryos, water content and updraft velocity.

Argentina: The randomized experiment conducted over the province of Mendoza (40), (46) for five seasons (1959-64) was aimed at finding if cloud seeding can significantly reduce the hail damages sustained by vineyards in this area. The seeding was conducted with silver iodide generators on the ground and the result, analyzed on average percent damage, indicated less hail on days with frontal storms but more days with isolated hail. The primary meteorological data utilized to forecast hail were the vertical stability index and potential stability index (temperature difference between environment and parcel at 500-mb level and corresponding difference of equivalent potential temperature) and the vertical wind shear.

Switzerland: The main Swiss hail suppression experiment "Grossversuch III" (67) was a long one, conducted for seven years (1957-63) with ground based silver iodide generators on a randomized basis on selected test days. Results indicated that seeding was effective in increasing the number of hail days, even when data were stratified according to different zones from the plains to the high Alps. Additional classification according to weather situation (no storm, cold front, local thunderstorm, barrage situation and more than one storm situation) again indicated more hail days with seeding than without seeding on all types of days. Further classification according to maximum wind at 5500 m above sea level also indicated an increase of hail days associated with high wind velocities on seeded days (Table 3-2). No analysis was done on the basis of damage inflicted. Analyses of duration, areal extent and intensity of hailfall indicated no significant change by seeding, but there were strong indications of rainfall increases with the

HAIL INCIDENCE ON SEEDED AND NOT SEEDED TEST DAYS

Section	No. of Observers	No. of Hail Days Without Seeding	No. of Hail Days With Seeding	Total	$P(\chi^2)$
A	2	7	8	15	--
B	4	14	15	29	--
C	5	5	14	19	<.06
D	9	9	19	28	<.07
Total test Area	20	23	38	61	<.04
Total no. of test days		147	145		

FREQUENCIES OF DAYS WITH HAIL IN TOTAL TEST AREA IN DIFFERENT KINDS OF GENERAL WEATHER SITUATIONS

General Weather Situation	Without Seeding No. of Test Days	Without Seeding Hail Days No.	Without Seeding Hail Days Frequency	With Seeding No. of Test Days	With Seeding Hail Days No.	With Seeding Hail Days Frequency
No storm situation	24	0	0.00	22	0	0.00
Cold front	45	5	0.11	45	6	0.13
Local thunderstorms	28	6	0.21	31	10	0.32
Barrage situation	30	2	0.07	22	5	0.23
More than one storm situation	20	10	0.50	25	17	0.68
Total	147	23	0.16	145	38	0.26

FREQUENCIES OF DAYS WITH HAIL IN TOTAL TEST AREA ACCORDING TO DIFFERENT WIND VELOCITIES AT 5500 m ABOVE SEA LEVEL

Max. Wind Velocity km/h	Without Seeding No. Exp. Days	Without Seeding No. Hail Days	Without Seeding Frequency	With Seeding No. Exp. Days	With Seeding No. Hail Days	With Seeding Frequency
0-40	41	5	0.12	36	8	0.22
40-80	60	5	0.08	72	15	0.21
>80	46	13	0.28	37	15	0.41
Total	147	23		145	38	

TABLE 3-2

Swiss hail suppression experiment indicated increase of hail days even when the data are stratified, according to different zones from plains to hills (1st table), or according to weather situation (2nd table), or according to maximum wind velocity at 5500 m A.S.L. (3rd table) (67).

seeding. The rainfall increases were statistically significant on days with cold front and barrage days in all sections but not on days with local thunderstorms or more than one storm situation.

3.3.2 Advent of Radar and Aircraft Seeding

Kenya: The Kericho area of Kenya (Fig. 3.10) may have the highest hail incidence of any location in the world. Of about 200 thunderstorm days per year, 85% of the cases have hail. The experimental region is close to the equator and is actually in the tropics but because of the elevation, which is nowhere less than 6000 ft, it has a temperate climate. There is very little fluctuation of temperature, which seldom exceeds 85F.

Studies on cloud development here have indicated that hail production can be explained in the majority of cases by a hailstorm model similar to an air mass thunderstorm. In its simple form, the air which rises to the hail formation zone is along the trailing edge of the main cloud mass under the fresh turrets that have varying degrees of vertical development. There is another type in which single cumulus cells organize themselves into systems which exhibit squall line characteristics. In this case, the main inflow is along the leading edge (Fig. 3.11).

An earlier experiment in this area (57) with Italian anti-hail rockets suggested reduction in hail intensity estimated on the records of damage to the tea crops. Further experiments from 1967, (44), (42), (43) were conducted by Atmospherics, Incorporated, California, U. S. A., with aircraft seeding by silver iodide pyrotechnic devices. The average loss in made tea per hail instance on seed days was 41% of the average damage due to unseeded storms. Comparison with historic period also indicated much reduction of losses on seeded instances.

The radar data suggest that well defined and high intensity precipitation zones of untreated storms often spread out and produce less intense precipitation for a longer period subsequent to seeding. The radar has proven an indispensable tool that supplies information on the birth areas of thunderstorms, rates of growth, speed and direction of movement, inflow area, areas of hailstone growth, positions of high reflectivity, duration of precipitation and areal distribution of hail on the ground.

Colorado: Northeastern Colorado is near the center of maximum hailstorm frequency in the United States, which is located at the junction of the borders of Colorado, Wyoming and Nebraska. A program for reducing hail was conducted as early as 1951 and again in 1958 but without any clear-cut evidence of effectiveness. In 1959, (61), (62) a program was initiated by the Northeast Colorado Hail

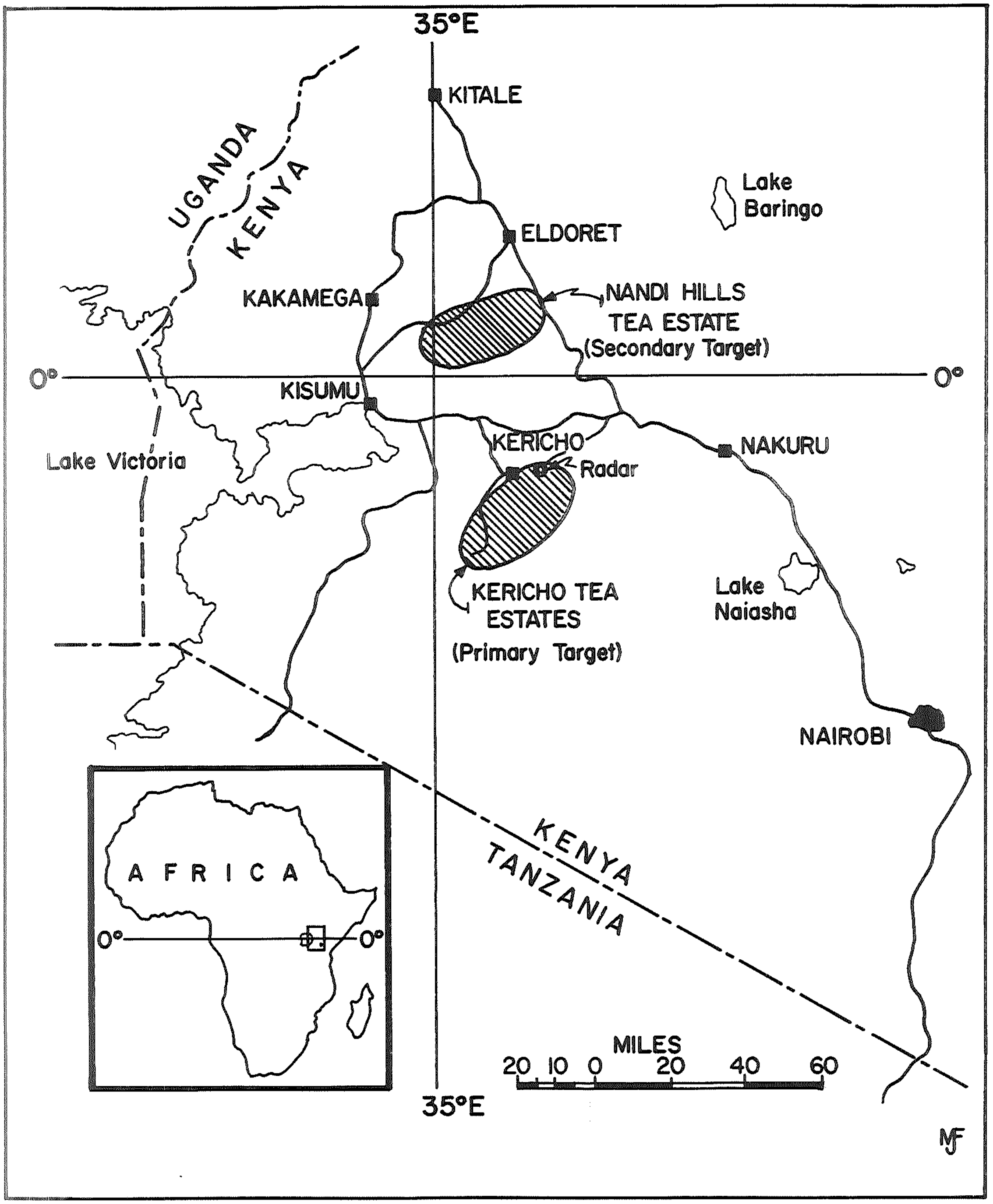


Fig. 3.10. Location of the hail suppression project in Kenya (43).

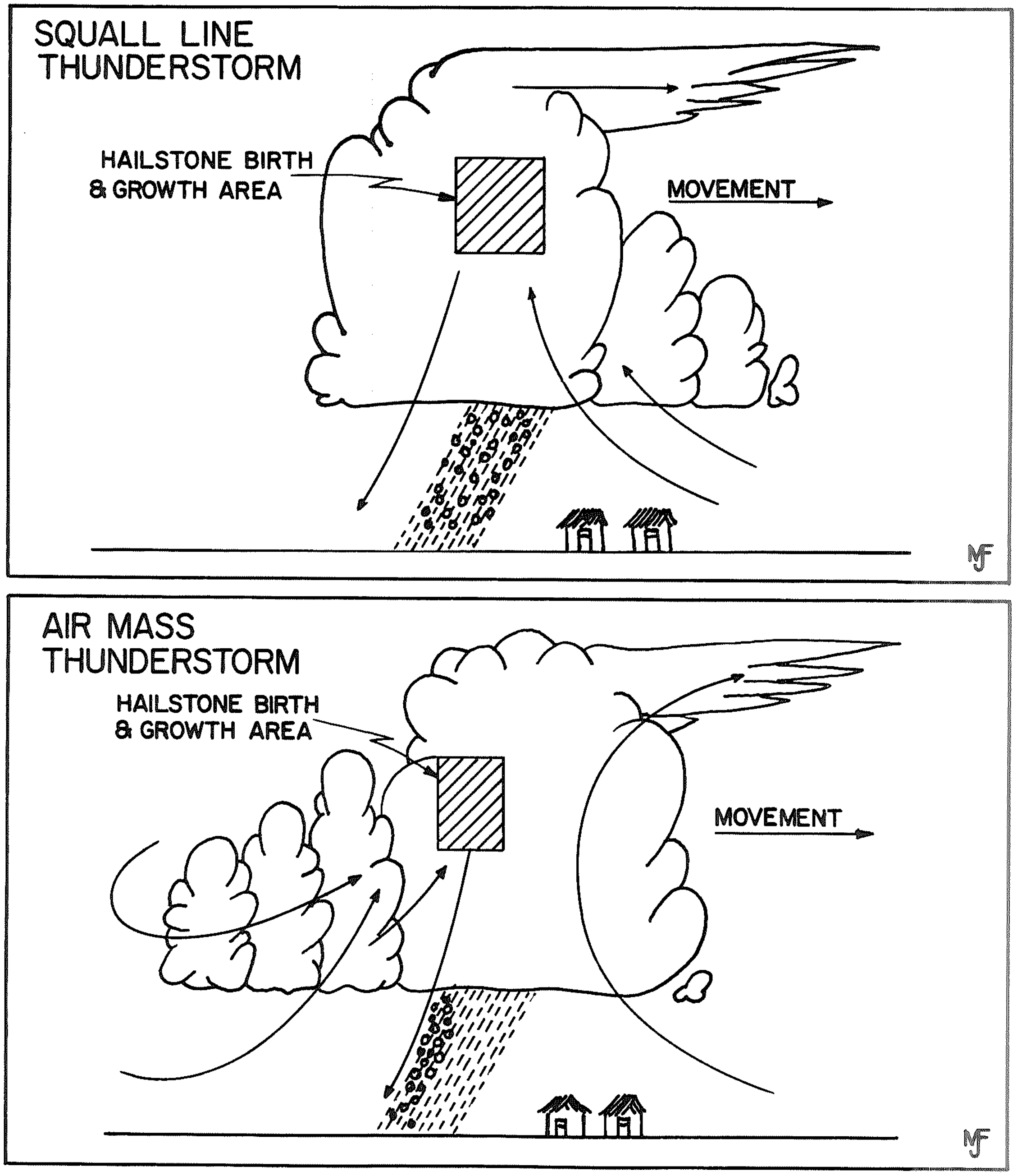


Fig. 3.11. Simplified drawings showing inflow and outflow of the air mass and squall line thunderstorm, the two major types producing hail in Kenya. They are similar to the hail producing thunderstorms of the Great Plains of the United States (43).

Suppression Association to determine if an operational program of hail suppression was effective in reducing hail occurrences and also to determine the effect on precipitation amounts of the cloud seeding measures taken during the program. The data indicated apparently favorable results from the cloud seeding on some occasions. There were also some cases with an apparently unfavorable effect on hail associated with the cloud seeding. A comparison of hail events indicated reduction in hail impact energy associated with seeding although not very significant.

A further hail suppression program using randomization was taken up during 1962, 1963 and 1964, (63) by Colorado State University. Test cases available were too limited to permit any conclusion concerning effectiveness of cloud seeding in reducing hail damage, but there was a difference between seed and no-seed cases in most occasions. The principal observations carried out from the ground were radar echo top, maximum radar reflectivity, height of maximum reflectivity and areal coverage (Table 3-3). Photographic observations on clouds were done by conventional and time-lapse cameras. Extent and intensity of hail and the maximum size of stones were determined by field surveys. Pilot balloon observations were carried out to determine airflow. In addition to the photographic observations on clouds, measurements from aircraft gave outside air temperature, vertical speed and nuclei count.

Northern Great Plains: Experiments conducted around the Rapid City area of South Dakota with Project Hailswath (64) indicated that the area covered by hail and the impact energy from hail were decreased by seeding but that the total rainfall and volume of small hail were increased. Further analysis (65, (66) was done with hail days associated with other projects during the period of 1966 to 1969 to test effects of silver iodide seeding upon convective storms. The analysis based on hail impact energy estimated from passive indicators suggested that seeded hailstorms were less intense and fewer in number than unseeded storms. The seeding was generally conducted by releasing 300 gm silver iodide per hour below the bases of small storms and in organized updrafts ahead of large storms.

Feeder clouds (Fig. 3.12) are one of the striking phenomena associated with the hailstorms of this region. Each feeder cloud grows rapidly as it approaches and merges with the main cumulonimbus cloud mass, usually at its southwest side. Radar echoes are usually noticed in a feeder cloud just before its merger and the merger generally is followed by an upsurge of storm activity with a burst of heavy rain and hail at the ground. Simple computer modeling of hailstone growth in feeder clouds has been done (55). Basic inputs for the model were temperature, pressure and mixing ratio profile, liquid water content and updrafts. The model indicated hail formation

Test Case Characteristics	Prior to test case				During test case				After test case			
	Mean	No. Days	No. Data	Standard Deviation	Mean	No. Days	No. Data	Standard Deviation	Mean	No. Days	No. Data	Standard Deviation
Maximum diameter hail, inches	0.70	11	11	0.60	0.61	8	8	0.44	0.38	4	4	0.42
Maximum energy no., ft-lb/ft^2	370	6	6	630	60	5	5	50	140	3	3	280
Radar tops K-ft MSL, M-33	44,800	3	12	16,000	44,600	4	29	14,500	38,100	3	11	11,800
Radar tops K-ft MSL, CPS-9	37,300	9	12	8,600	36,800	10	18	6,300	37,900	7	10	5,800
Radar tops K-ft MSL, NRR	36,300	11	15	6,100	35,600	10	22	9,800	37,900	7	13	11,100
CPS-9 radar reflectivity Z_{30}	35	7	9	9	36	9	15	9	35	6	8	6
Area covered by radar echo, mi^2	210	15	16	150	270	13	19	200	280	15	16	240
Rainfall-volume, acre-ft	13.9	--	14	8.5	14.4	--	13	9.1	15.9	--	12	9.9
Maximum updraft, ft/min	800	11	35	500	500	10	39	400	400	8	25	400

TABLE 3-3

Colorado Hail Suppression

Summary of nine parameters for test case days during 1962, 1963 and 1964. With the limited number of test cases, no conclusions have been drawn concerning the effectiveness of seeding in reducing hail damage. This method of analysis with pertinent measurements taken is a means by which the dynamic and physical factors governing the generation and growth of thunderstorms can be studied in detail (63).

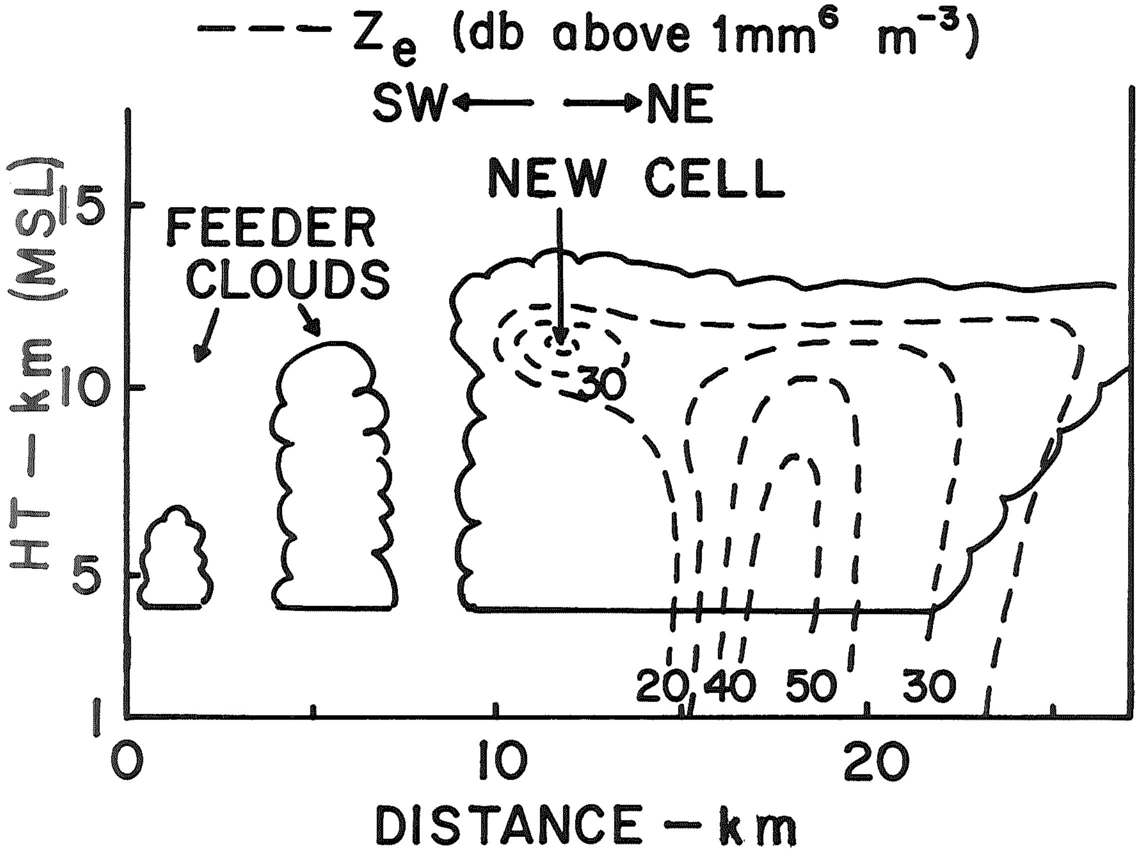


Fig. 3.12. An ENE-WSW cross-section through typical hailstorms of western South Dakota. Hail of sufficient size to reach ground is likely whenever Z_e as shown on figure exceeds 50 dBz (28).

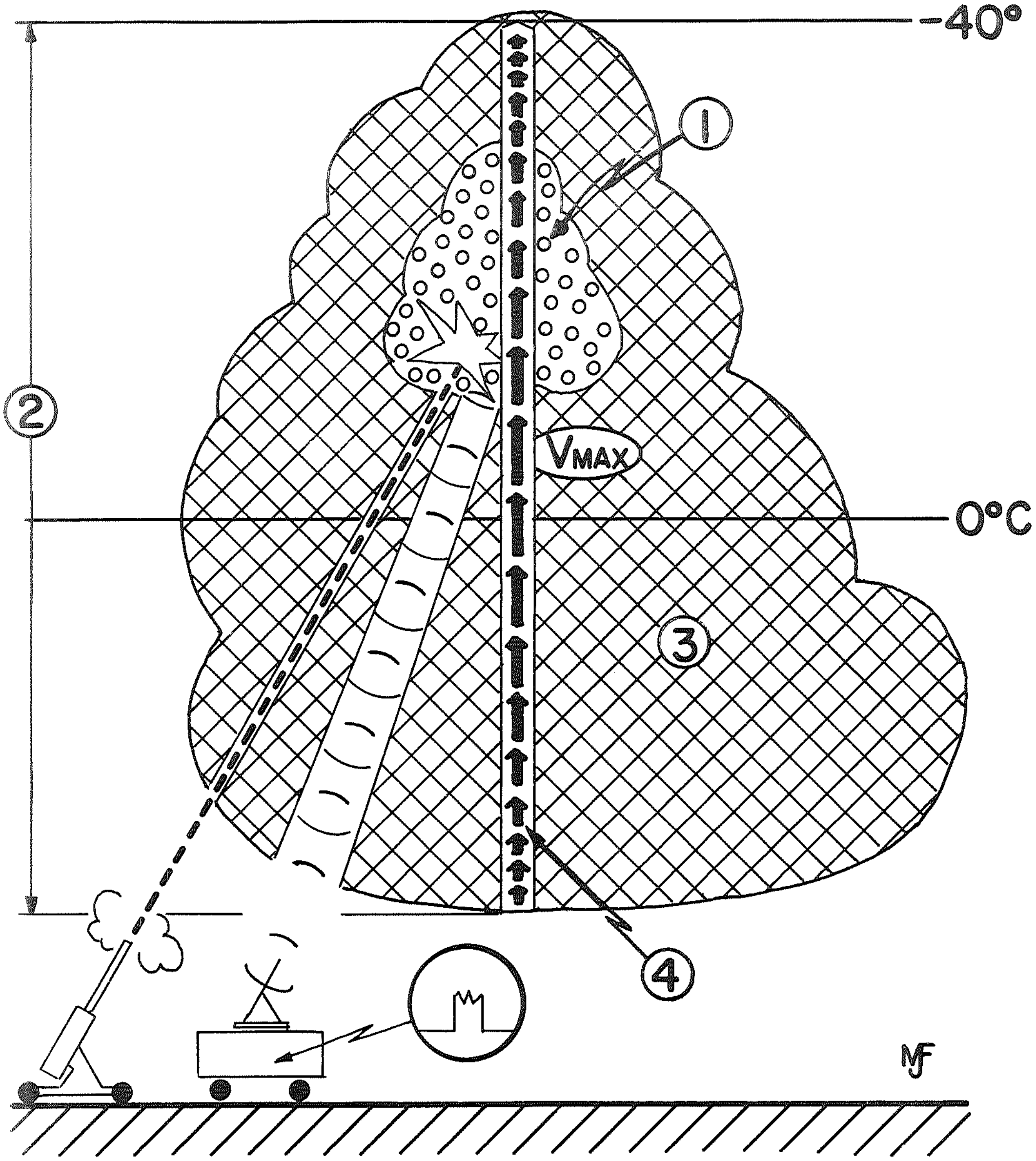
for updrafts greater than 12 m/sec; storm rotation, sloping updraft, and strong wind shear, which are observed sometimes in hailstorms, are not essential for formation of hail.

3.3.3 Experiments in the Soviet Union

The greatest enthusiasm for hail suppression emanates from the U.S.S.R. Their experiments (9), (73) have attracted wide attention because of their large magnitude and the special seeding technique of shooting silver iodide directly into hail clouds. The hail control experiments are carried out in the Alazan Valley of Georgia and the Kabardinian-Balkarian region. Their approach is to identify precisely the region in a convective cloud where hail is beginning to form, and then place silver iodide crystals in that spot by means of artillery shells (Fig. 3.13). Their prediction method is based on the concept that a great accumulation of supercooled water is required for hail formation. Radar observations have indicated updraft maxima in the middle level of hail clouds and decreases upward, a velocity profile that is said to favor storage of supercooled water above the maximum updraft. Identifying such regions with radar, they have claimed 97% accuracy in detecting the clouds that are producing hailstones.

Most of the hail modification work in the U.S.S.R. has been based on a cloud model that requires as essential conditions for hail formation, (i) thermal instability through 3 to 4 km depth of atmosphere, (ii) large vertical extent of cloud of 6 to 8 km, (iii) development of clouds to temperature level of -12 to -16C and, (iv) strong vertical velocities of 10 to 20 m $\sec^{-1}$ lasting long enough to allow large quantities of liquid water to accumulate above the level of maximum updraft speed. Some of their studies indicate that hail can be forecast on the basis of radar observations that indicate reflectivities greater than some fixed value, high reflectivity areas exceeding 3 km in depth and located in the upper part of clouds and mostly in the region of temperature less than 0C, and the echo top exceeding 9 km with a thickness of more than 6 km.

The experimental design (non-randomized) does not allow for adequate statistical evaluation but the empirical evidence has convinced them that the results are highly effective in reducing hail losses to crops. It is claimed that there has been no experiment with negative results (hail increase). The effects are manifested by (i) the decrease of radar reflectivity of the hail formation zone; (ii) a few minutes after the projectile explosion in the cloud, the hail formation zone thins out, expands in its lower parts, top of the reflection zone descends, and in some cases, completely collapses; (iii) in some cases, visual observations indicate rifts or disintegration of treated clouds; and (iv) in the region of



Experiment in U.S.S.R.

Fig. 3.13. In one set of Soviet experiments, it was aimed at preventing hail formation by seeding early in the life of the cloud. The artillery shells were fired into the cloud at about the -6C level, the region of the cloud where supercooled liquid water was expected to be concentrated in the form of large drops.

① Large droplet zone; ② height of cloud; ③ small droplet fraction, and ④ velocity of updraft; (9).

explosion of the projectiles, the hailfall stops and precipitation reaches the ground as graupel or rain. Verification of this last effect constitutes the basic method of checking.

As can be seen, extensive use has been made of radar in studying the process of cloud development and precipitation. Both X-band and dual wavelength radar (X- and S-band) have been used. These determined the velocities of ascending currents, location of hail centers in convective clouds with proper coordinates for control, dimensions and evolution of reflection zone and size of hail particles in cloud and their concentrations.

3.3.4 Current Plans

Several groups in the United States are participating in the National Hail Research Experiment, a field experiment in northeastern Colorado. The primary aims of the project are: (i) testing the prediction of numerical models with field observations, (parameters for such comparison will be cloud base, cloud top, cloud temperature, updraft velocity, updraft radius, cloud water, hydrometeors, radar reflectivity and height of maximum reflectivity); (ii) study of radar reflectivity profile using different wavelength radars, (iii) study of updraft profile in thunderstorms using observations from aircraft and dropsondes; (iv) hailfall evaluation and mapping by infrared radiometer or time lapse camera; and (v) study of correlation between ice nuclei temperature spectrum and hail incidence. The program is expected to yield greater insight into hail formation processes and the effects of modification treatment.

3.4 Review of Experiments: Lightning Suppression

Lightning is the outstanding cause of forest fires in the forested areas of the western and midwestern United States. These fires, aside from threatening human life and property, damage the resources of the forest including timber, forage, water, wildlife and recreation. There have been two approaches to lightning suppression; one is the modification of the electrical structure of thunderstorms by means of silver iodide seeding and the other is modification of a lightning discharge into a corona discharge. Only the former type of experiment is described here.

3.4.1 Montana (Skyfire)

The experiment in this region (39), (38) was intended to investigate the possibility of preventing or reducing the number of lightning fires (Fig. 3.14) and to obtain a better understanding of the occurrence and characteristics of lightning storms and lightning fires in the northern Rocky Mountain region. There are not yet any satisfactory hypotheses for lightning modification and, although we have some descriptions of physical processes involved in lightning discharges,

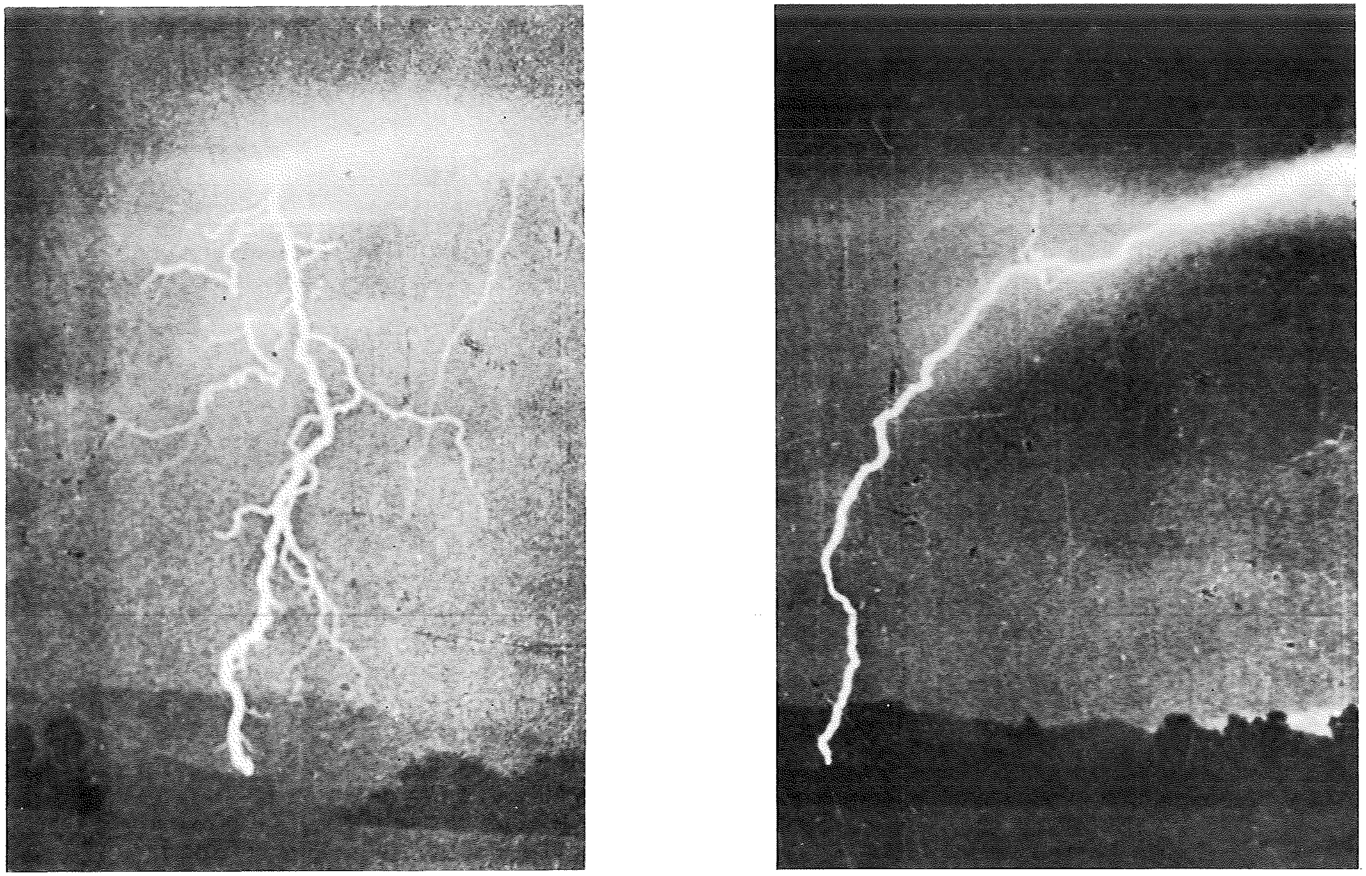


Fig. 3.14. Photograph of typical discrete (left) and hybrid (right) cloud to ground lightning discharge, the important cause of forest fires (39).

there is no explanation as yet of the effect of hydrometeors on the discharge processes. There is strong evidence that total lightning activity within a thunderstorm is closely associated with precipitation, which in turn is correlated with storm development. There were hypotheses based on laboratory experiments that conversion of supercooled drops to ice crystals could initiate corona discharge and limit the maximum potential gradient within clouds and thus inhibit the start of a cloud-to-ground discharge.

The results from the individual storm data indicate a decrease of flashing rates and of stroke duration that could be attributed to seeding, suggesting strongly that massive seeding with ice forming nuclei alters the frequency and character of lightning in mountain thunderstorms. The primary measurements were of electric fields, luminosity, and lightning photography. For better analysis the observed and calculated parameters desirable were: frequency of cloud, cloud-to-ground and total lightning; electric moment of cloud-to-ground discharge; electric charge transferred by cloud-to-ground discharges; height of negative charge center; number of strokes within a flash; electric moment of strokes; number of discharges with a persistent current flow; height of initial radar echo; rate of growth of radar echo; maximum height of visible cloud tops and rate of growth of visible cloud tops; of which only a few could be tested in the experiment conducted. Along with the experiment simple numerical models were tested and modified to include lightning as one of the predicted variables.

3.5 Conclusion

The history of weather modification is mainly the history of attempts to modify convective clouds. An enormous amount of work has been done on precipitation mechanisms in convective systems and their modification, of which only a few interesting cases have been cited here, but our understanding is still far short of what is required to modify clouds in truly intelligent fashion. The knowledge gained is opening up the era of simple numerical model computation, which is advancing our understanding of convective systems and the effects of modification processes upon them. The numerical models have the capability to define more precisely the measurements required of different meteorological parameters and can also test new systems of observations before any costly program is undertaken on a large scale.

The experimental procedure in different regions varies widely depending upon the objective, geographic location, local weather, and available facilities. Emphasis on different meteorological measurements and cloud observations vary accordingly. Although the overall synoptic situations cannot be ignored, the mesoscale systems usually play the primary role (Fig. 3.16). In some cases local features may dominate.

Fig. 3.15. Looking down on scattered cumulus clouds from an altitude of about 60,000 ft. High resolution cloud data could be used to monitor the effect of man's attempt to modify cloud and weather (33), (48).

Photo: National Severe Storm Lab. ESSA, Norman, Oklahoma

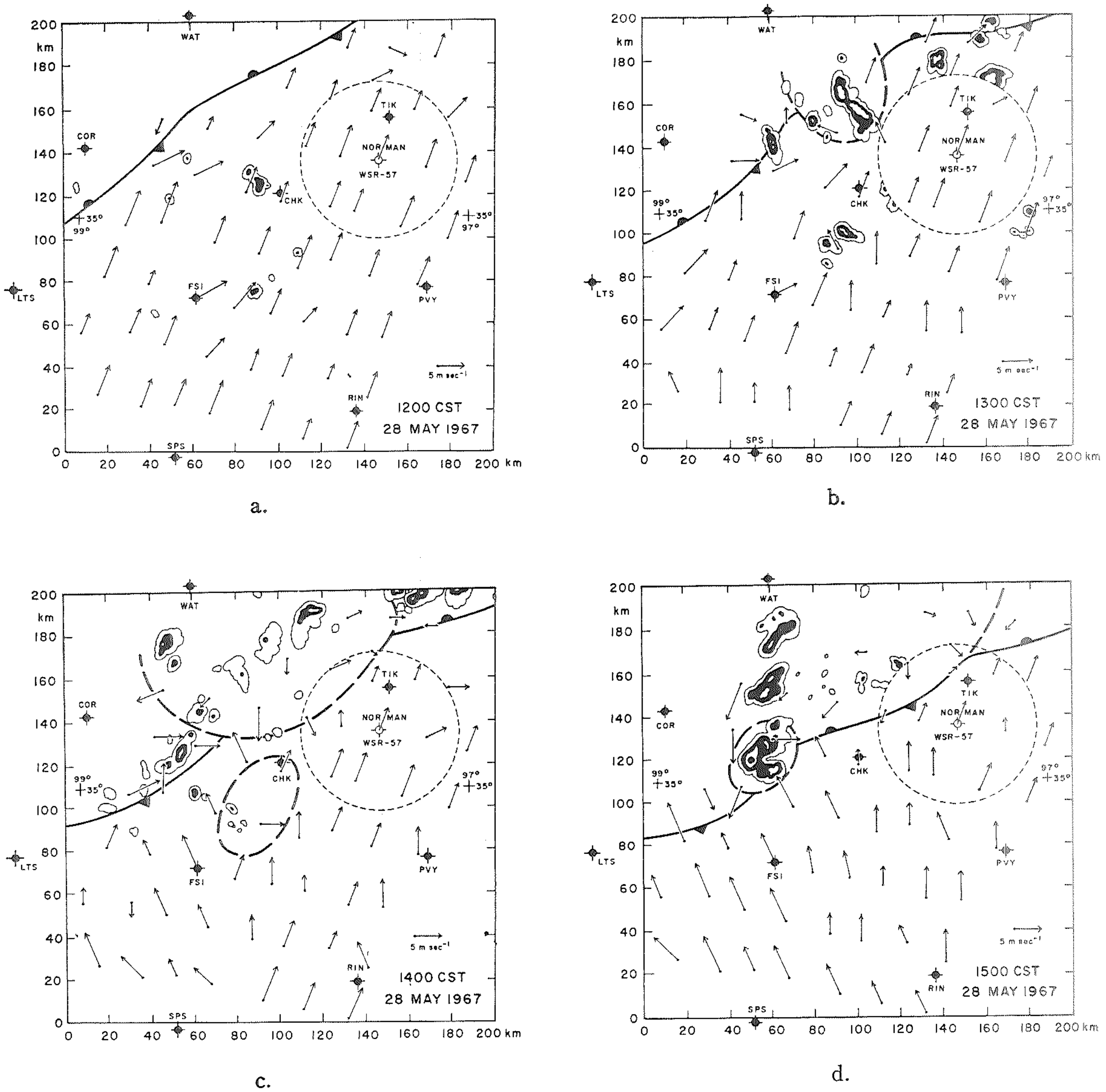


Fig. 3.16. An adequate description of atmospheric variables at an appropriate scale is essential for the understanding and modification of convective systems. The conventional synoptic networks are completely inadequate for the purpose and the mesoscale network is an approach to solve this problem. Above is an example from National Severe Storm Laboratory network showing hourly frontal (heavy solid) and meso-system (heavy dashed) boundaries, radar echo position and intensity (contour interval 10 db) and surface winds (May 28, 1967). Bold dots designate rawinsonde sites. Dashed circle indicates lower range limit in radar (34).

Soundings at close spacing at frequent intervals during the whole period of an experiment would be the primary need. This would include temperature and humidity profiles of the whole troposphere and wind aloft. Observations on clouds has next priority, (Fig. 3.15); they would include amount and type of cloud together with horizontal and vertical dimensions, temperature of top and base, growth rate, and the type and rate of precipitation. Finally, identification of updraft regions and measurement of their strength will determine the seeding treatment employed.

Irrespective of the cloud parameters that one considers, there is urgent need for better measurements of each parameter such as humidity, temperature, vertical velocity, nuclei characteristics, drop size distribution, liquid water content and the cloud-electrical parameters, which also demands better vehicles and platforms for carrying instruments.

In the table following we have tried to outline the measurements and observations of principal meteorological parameters with expected accuracy and frequency as visualized presently.

Most of these observations are obtained at present by visual, photographic, radar, radiosonde and other types of sounding, pilot balloons, rain gages, hailpads and hail sensors, aircraft penetration by instrumented aircraft, etc. Doppler radar are providing a new category of detailed observational data on cloud kinematics in the field of indirect probing. Laser techniques as well as new optical techniques are also being tried that measure drop sizes without distortion by collecting surfaces.

TABLE 3-4

Principal Measurements for Modification of Convective Clouds

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Temperature	± 0.5C	3	100	10	Requirement in some cases may demand observations every hour. Numerical models may require observations at intervals of 0.2 hr similar to cloud updraft or total water content.
2	Precipitable water or	±1 mm	3	1000	10	
	humidity lapse rate	±0.5C	3	100	10	
3	Wind aloft					
	a. Direction	±10°	3	500	15	
	b. Speed	±0.2 m sec^{-1}	3	500	15	
4	Height of top of cloud	±50 m	0.2	--	1	Could be selective directed sampling of single cloud done with temperature sensors.
5	Precipitation					
	a. Type	--	0.2	--	1	In cases continuous record preferred.
	b. Rate	25%	0.2	--	1	
6	Cloud updraft	±1 m sec^{-1}	0.2	100	--	Identification of region of updraft and its dimension is required.
7	Cloud phase	±0.1	0.05	100	0.1	Made in active growth region

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
8	Total water content	±0.1 gm m^{-3}	0.2	100	0.1	
9	Cloud particle size (Modal diameter and spread)	±1 micron	1	100	15	
10	Aerosol measurements					
	a. Giant condensation nuclei	±0.01/liter	6	1000	30	
	b. Freezing nuclei	±1/liter	6	1000	30	
11	Low level upcurrent	±0.1 m sec^{-1}	1	100	15	Required only for operation with ground generators.
12	Hail					
	a. Size	0.5 mm	--	--	1	Spacing required may be quite low depending on hailswath
	b. Energy	±1 ft-lb/ft^2	--	--	1	
13	Electrical activities					
	a. Lightning strokes	±10%	Continuous	--	15	
	b. Sferics frequency and strength					
	c. Space charge					
	d. Field strength change					
	e. Electric field					

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4. MODIFICATIONS OF TROPICAL CLOUD SYSTEMS

4.1 Introduction

The two basic features that distinguish the formation of clouds and precipitation in the tropics are the high temperature and the high humidity. As a result, when condensation occurs, the clouds have a high liquid water content, which is important in initiating precipitation through coalescence and in promoting heavier rainfall. The frequency with which rain occurs from clouds only a few hundred feet deep is often remarkable to visitors to the tropics (19). There are indications also that a high percentage of clouds in the tropics produce rain without the aid of the ice phase, contrary to the earlier belief that the ice mechanism was the only one that could initiate precipitation. These features lead us to suspect that attempts to modify weather artificially in the tropics could yield spectacular results. However, it has been apparent to persons engaged in weather modification on a scientific basis that because of the complex nature of local weather, of cloud microphysics and of precipitation formation, in any tropical region, it is difficult to say that the results observed would not have occurred naturally. These complexities gradually have led to more and more detailed measurements of different cloud and weather parameters, with more precision, in an effort to understand the processes of cloud and precipitation formation.

Weather men all over the world, including those in the tropics, were enthusiastic to experiment on weather modification and artificial rainmaking following Schaefer's unique experiment in 1946. Subsequently, there were experiments conducted in 1948 and 1949 (11, 12) in the Hawaiian tropics, and also over the tropical regions of East Africa, India, Central and South America and Hawaii.

For a better understanding of the requirements for measuring different meteorological parameters and the precision with which they should be measured for future weather modification programs, it is worthwhile to glance briefly over a few of the experiments and examine how the measurements of different meteorological parameters have come up in the execution and subsequent evaluation of these experiments.

4.2 Review of Experiments

4.2.1 East Africa

From 1951 to 1956 trials were made by the East African Meteorological Department at a number of places in the East African tropical region (2, 3, 4, 5, 6, 22). They were mostly initiated because of natural calamities caused by lack of rain. Most of the experiments had short lives with variations in technique and seeding material from time to

Place	Country	Year	Period		Technique and Material
Kongwa	Tanganyika	1951	Jan-Apr	(i) (ii)	Silver iodide acetone solution in ground charcoal burner Balloon bom with charge impregnated with silver iodide acetone solution
Kongwa	Tanganyika	1952	Jan-Apr	(i) (ii)	silver iodide balloon bomb Balloon bomb with charge of Hygroscopic mixture (90% sea salt + 10% $CaCl_2$)
Amboseli	Kenya	1953	Oct-Dec		Balloon bomb with hygroscopic charge only
Dodoma	Tanganyika	1954	Jan-Mar		------ Do -----
Mitiyana	Uganda	1954	Sept-Dec		------ Do -----
Tobora	Tanganyika	1956	Nov-Dec		Hygroscopic charge dispersed with rocket

TABLE 4-1

Early East African Experiments

time (Table 4-1). In the majority of these experiments finely powdered salt was used as the seeding material. The methods adopted for its dispersal in cloud included balloons and rockets. The rocket technique of dispersal of salt powder in cloud appeared more effective. None of the experiments were very conclusive, although in a number of cases there was an apparent increase of rainfall downwind.

Measurements were made on cloud amount, wind, height of cloud base and temperature. Synoptic situations proved of great importance in these regions. The synoptic situation, as defined by the Intertropical Convergence Zone (ITCZ) and the westerlies that bring an even flow of moist air from the Indian Ocean, controls the rainy periods of the year. During the season the synoptic situation changes several times and the periods have to be stratified accordingly for analysis of seeding results. In regions like these, closer networks of weather observation than now exist are required for predicting the movement of ITCZ and the westerlies. Soundings close to the time of experiment at spacing of 10 to 15 miles would be required for better design of the experiment.

Measurements of height of cloud base and top and the associated temperature would indicate whether or not a cloud had sufficient depth to be affected by hygroscopic materials. The measurement of updrafts below the cloud base would indicate the effectiveness of chain reactions for precipitation growth. [Chain reaction of raindrop growth to breakup size and subsequent growth of the fragments require updrafts exceeding 5 m sec^{-1}.]

Day-to-day measurements of condensation nuclei, particularly of the large and giant ones, would indicate how far seeding can modify their concentrations.

4.2.2 Madagascar

The experiment in Madagascar was conducted for one season (April - September 1953) only, using aircraft to disperse finely powdered salt particles in cloud (3). Results were deduced by visual observations from ground and aircraft. Sometimes the results were dispersal of the clouds and sometimes light rain fell from the seeded cloud an hour or so after seeding. It is not known if there were any special efforts taken to measure meteorological parameters other than the routine ones. Experiments aimed at individual clouds, such as this one, must have, as a minimum, radar or photographic equipment for observing precipitation growth.

4.2.3 Indian Subcontinent

Most of the experiments conducted over India and Pakistan assumed, as in the case of the East African experiments, that the major part of

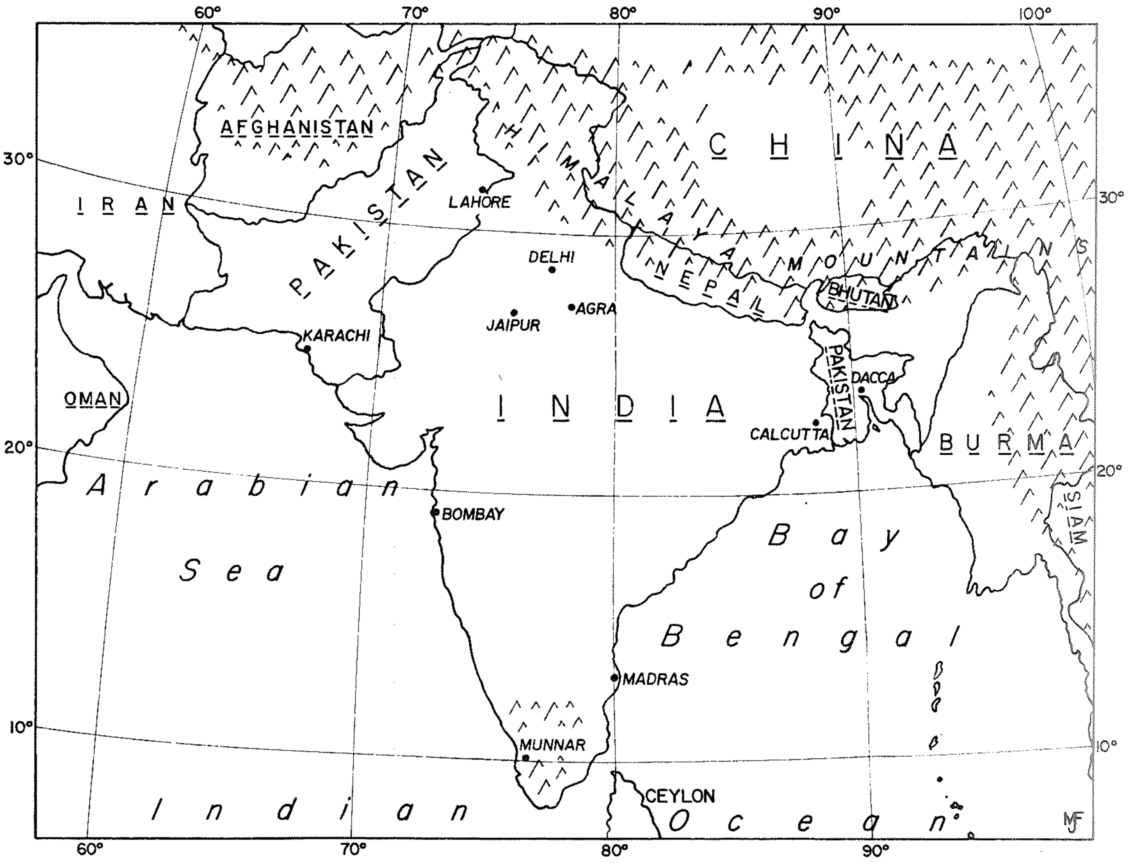


Fig. 4.1. The main experiment in India was conducted over the semi-arid region of Delhi, Agra and Jaipur. The other short term experiment was in the south in the orographic region of Westernghats, at Munnar, about 50 miles from the coast.

the rain-bearing clouds lies in the temperature region warmer than 0C. Accordingly, the technique adopted was that of dispersing hygroscopic nuclei usually from the ground and allowing upcurrents due to insolation to carry them to the cloud. At times, seeding by aircraft below cloud base was used. Isolated trials to seed supercooled clouds with silver iodide and dry ice were done as early as 1952 (3), with no definite results.

The rainy and cloudy days in the whole of the subcontinent are mainly influenced by deep moisture laden monsoon air currents in the rainy season and by the passage of low pressure troughs through the northwestern part of the land during winter. These troughs, known as western disturbances, bring moisture incursions from the Arabian sea.

The Himalayan barrier plays a great part in guiding the Bay of Bengal monsoon currents through the river valleys of northern India and monsoon rainfall slowly decreases downwind with depletion of moisture content. In the southern part of the country the summer monsoon current from the southwest strikes the coastal hilly tracts known as Western Ghats, inducing heavy rainfall which decreases considerably on the leeward side. The southern part of the country also gets some rain during the winter with the southeast monsoon. The northwestern part of the land has the lowest impact from the monsoon, making the region semiarid. The meteorological and microphysical condition of a locality in India thus varies considerably with the distance from coast and also due to topography.

The first systematic trial of seeding with a ground based salt particle generator was done in Punjab, Pakistan in 1954, with positive results (7). The short life of individual convective showers as observed in this region during the monsoon led to the method of nucleation of the atmosphere in general rather than trying to seed individual clouds. In an experiment of this type, the amount of convective cloud cover (in tenths of sky) is the basic need. The forecast based on local soundings should be capable of predicting the amount of convective cloud coverage. Low level winds will determine the area affected by seeding and the upcurrent measurements during the hot period of the day will indicate the possibilities of the ground generated particles reaching cloud base. In general the upcurrents should exceed 0.2 m $\sec^{-1}$ to fulfill this requirement. The concentrations of giant condensation nuclei in the surface layer and aloft are required to ascertain the effect seeding will have in increasing the concentration of these particles.

The later experiments conducted near Delhi, India (Fig. 4.1) were designed in a better way for the purpose of evaluation of results. The usual technique was dispersal of finely ground common salt powder from ground generators (1, 20), but seeding from aircraft was also done for a year (21). The concentration of hygroscopic particles of radius

1 μ or more, as estimated from the measurements in surface air layer in this region, runs as high as 50 per litre but falls in many instances to near zero in a hundred litre air sample, and similar fluctuations at cloud level may account for lack of rain from some clouds in this region. The low level ascending currents, of the order of 0.2 to 0.8 m sec^{-1}, as determined earlier from liftless balloon soundings, (Fig. 4.2), indicated that the fine salt particles dispersed had a fair chance to reach the clouds. Measurements throughout the seeding period would have been a better indication of the presence of low level upcurrent during the hot afternoon hours of the rainy season.

Since the natural distribution of rainfall varied with wind direction, it was necessary to stratify the rainfall data on the basis of wind direction. The mean wind up to the 3 km level was estimated from local wind observations. The forecast, based on morning soundings, indicated winds aloft to 3 km level and the base, height and amount of expected convective cloud, which was the basis for judging the suitability of the day for seeding. A constant watch with X-band radar supplemented or corrected the local forecasts. Analysis of areal coverage by precipitation echo and their vertical development and intensity before and after seeding served as a check on the analysis based on raingage observations. Since the primary object of the experiment was to increase the amount of seasonal rainfall, no attempt was made to study the effect on individual clouds, nor was this feasible with the ground-based generators (Table 4-2).

Direct measurements of aerosol concentrations by aircraft below the cloud would have removed the uncertainties as to whether the seeding particles reached the cloud or not. The seeding from aircraft was carried out mainly to remove this uncertainty and a year's experiment did show a positive trend. As the experiment was not continued further, no definite conclusion could be drawn on the basis of the aircraft experiment (Fig. 4.3).

It is interesting to note, from a separate study with radar observations (17), that quite a large proportion of precipitating clouds in Delhi (about 30 to 40 percent) have their growth limited to below the freezing level, but their actual contribution to total rain is not substantial although the contribution to rain by all convective clouds taken together is quite high (about 65 percent). This indicates that simultaneous seeding with freezing nuclei could also be effective in initiating precipitation in this region.

The situations were quite different with the short duration experiment conducted over hills of southern India (18), where orography has marked influence over the weather formation. Even during the relatively dry period (March to May) good amounts of cumuliform and stratus clouds develop in this coastal region of India. For most of the remaining period it gets copious rain from the monsoons.

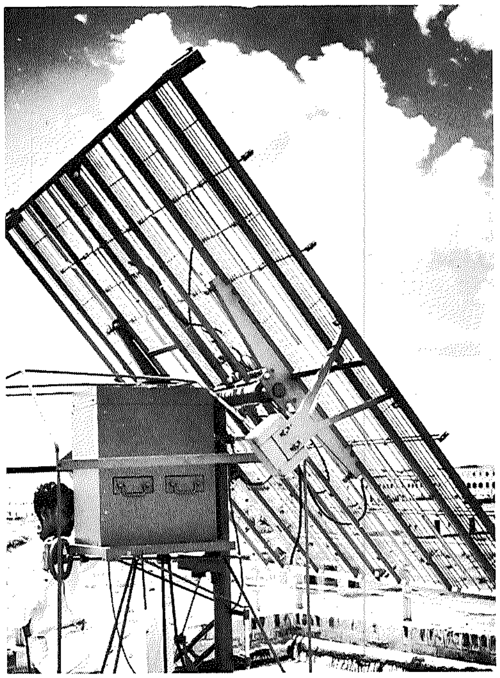


Fig. 4.2. In the early period of the experiment in India, the mean magnitude of low level upcurrent around Delhi was determined by tracking liftless balloon with rawinsonde (20).

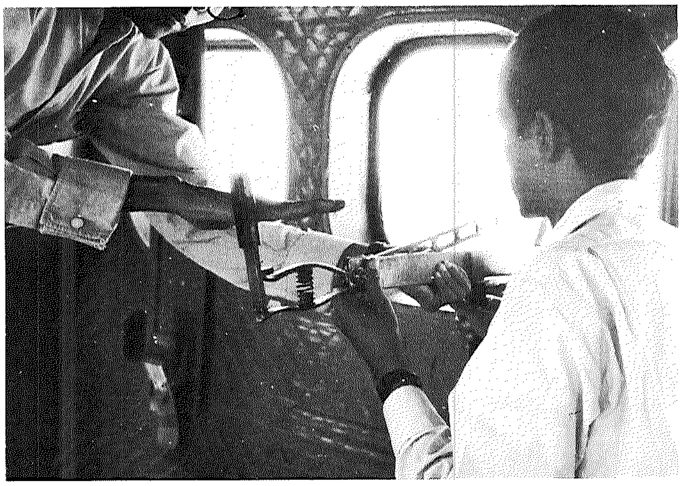


Fig. 4.3. During a year's experiment with aircraft magnesium oxide coated slides were exposed in cloud from aircraft with simple mechanical device to make an estimate of liquid water content from the dropsize impressions (21).

[Rainfall (mm) per station in target (T) and control (C) sectors with respect to cloud type at Delta]

Year	Seeded			Not Seeded			
	T	C	T/C	T	C	T/C	Result
			(Convective Clouds)				
1960	13.7	13.0	1.05	29.7	36.8	0.81	positive
1961	80.5	59.7	1.35	95.5	91.9	1.04	positive
1963	226.3	104.4	2.16	38.9	55.6	0.70	positive
1964	34.0	8.4	4.05	187.7	121.9	1.54	positive
1965	61.7	68.6	0.90	7.1	41.7	0.17	positive
			(Layer Clouds)				
1960	31.0	17.6	1.76	73.4	81.0	0.91	positive
1961	43.4	13.0	3.34	42.4	13.2	3.21	positive
1963	47.0	39.1	1.20	20.8	43.9	0.47	positive
1964	16.3	11.2	1.46	8.4	3.6	2.33	negative
1965	3.0	6.6	0.45	50.0	44.7	1.12	negative

TABLE 4-2

Results of seeding experiment around Delhi, when stratified according to predominant cloud type of the day, indicated significant positive trend for days with convective clouds, but not so for days with predominant stratiform type clouds (1).

The forced upcurrents due to southwest wind are expected to aid the salt particles to go up from the ground-based generators. This should be confirmed by low level upcurrent measurements for certainty of the effect. The day's suitability, as in the case of Delhi, was judged from the expected convective cloud amount and winds at different levels as obtained from the nearest local forecast and also by local cloud and wind observations. In a place like this, which is only about 50 miles from the sea, measurements on variations in concentration of giant size hygroscopic nuclei are essential to ascertain the effectiveness of salt particles as seeding agents. It is desirable, too, that measurements be made on the drop-size spectrum of cloud particles to ascertain the cloud's colloidal stability state, as indicated by Squires (29), which would further show how far the salt particles will be effective. The winds in this hilly region, both near the ground and aloft, are complex due to topography, and close observation is required to best locate generators to effect a desired region. Soundings during periods of maximum insolation heating and close to the region of the experiment would be essential to estimate the temperature, humidity and stability conditions of the atmosphere.

The experience with the limited experiments conducted over India has indicated considerable variation of climatological and local weather conditions from region to region. The seeding technique adopted and the measurements required for one region may not be suitable for another region, but for most experiments, observations of cloud amount (in tenths of sky) with base, height and depth, and closely spaced soundings (within 25 km of station) to indicate temperature and humidity profiles, appear essential. Updraft measurements below cloud base would also be required when modifying precipitation growth by a coalescence process. In addition, when the cloud is not purely maritime in nature, it is desirable to get its drop-size spectra to determine its colloidal stability.

4.2.4 Pacific Experiments

Attempts were made to modify tropical clouds in Hawaii with dry ice seeding as early as 1948-49 (11, 12). With trials made on cumulus clouds whose tops extended just beyond the freezing level, it was observed that the largest rains were associated with relatively thick clouds where cloud-top temperatures were slightly colder than 0C. Thus the necessity of making measurements of some basic meteorological and cloud parameters was realized from the beginning. The cloud-top temperature and thickness were both important but their relative importance could not be evaluated as the coldest cloud-top temperature observed during the experiments was only -5C. Importance of measurement of temperature profile was also evidenced by the fact that, when cumulus clouds were capped by a temperature inversion with decreasing moisture above, seeding produced partial dissipation of the clouds or no effect whatsoever. In the absence of an inversion moisture occurred through a deep layer that promoted growth of sea breeze clouds. This obviously requires measurements of cloud-base and top heights, humidity, wind at different levels and the synoptic situations apart from the temperature profile and inversion strength mentioned earlier. It was also felt that a day-to-day measurement of concentration of condensation nuclei, including giant salt nuclei, would indicate the effectiveness of these particles in rain initiation when a major portion of the cloud lay below the OC level.

4.2.5 Central American Experiments

During the years 1947-1957 a number of experiments were conducted in the American tropics using silver iodide as a seeding agent. A good summary of them has been given by Howell (8). Most of the experiments were motivated from a commercial viewpoint and were short-lived. However, they showed apparent positive results, some at a statistically significant level (Table 4-3).

Over these regions cumulus development has two distinct categories. One is that of nearly continuous and rapid growth from humble beginning through congestus stage to the formation of cumulonimbus, the entire development taking place in perhaps half an hour to an hour. This occurs typically when conditional instability of a deep moist layer is released by a definite impulse, such as arrival of a sea breeze. The second category is characterized by much more gradual development of a given cloud even though the convective activity remains high. Clouds display great growth activity in their lower parts and dissipation in their upper part, the average size of the cloud gradually increasing and the total number of clouds decreasing. This state may continue for hours until it is ended by a decrease in diurnal activity or development of precipitation in one or another cloud. Marked increase of rate of growth of a cloud is often connected with the onset of precipitation in it, accompanied by degeneration of other clouds in the vicinity. The ensuing rainfall, while sometimes heavy, is spotty.

The general indication was that the seeding had been more effective on the second-category days and there had been more natural rain initiations and little seeding effect on first-category days. Thus for these regions the effect of seeding will be variable, often ineffective but sometimes extremely effective, depending upon the habitual sequence of cloud development over the seeded region. The effect of seeding would be more apparent if it were possible to isolate the situations characterized by the second group.

The meteorological observations should be closely spaced and extended over the entire region that is expected to be influenced by seeding. Soundings of temperature and humidity profiles along the vertical will be required at close intervals of perhaps 10 to 20 km. Cloud amounts and base and top heights with temperatures at those levels are the requirements for determination of a suitable seeding level. Low

Trials of cloud seeding in the American tropics

Location	Year	Area	Operations			Results	
			Category	Agent	Duration	Increase	Probability
		sq.mi				pct	
Atlantic off Florida	1947	...	Uninvolved	Dry ice	1 day	Conversion of stratiform supercooled clouds observed in hurricane	
Honduras	1948	...	Uninvolved	Water	1 day	Extraordinary rainfall in dry season	
Hawaii	1948–49	...	Uninvolved	Dry ice	15 days	Some showers thought to be triggered	
Mexico, Necaxa	1949–59[a]	800	Practical	AgI	54 mo.	+9	0.0001
Bolivia	1951	50	Practical	AgI	...	Uncertainty as to smoke trajectory	
Peru, Rio Chicama	1951–59	3500	Practical[b]	AgI	80 mo.	+25	0.0001[c]
Rio Mantaro	1951–56	2500	Commercial	AgI	30 mo.	+20	0.07
Cuba, Francisco	1951	300	Commercial	AgI	4 mo.	+26	...
Cespedes	1952	100	Commercial	AgI	3 mo.	+25	0.04
Ermita	1952	50	Commercial	AgI	7 mo.	+46	0.005
Francisco	1952	300	Commercial	AgI	11 mo.	+28	0.08
Macareno	1952	150	Commercial	AgI	5 mo.	+35	
Najasa	1952	50	Commercial	AgI	6 mo.	+33	
Hawaii	1952–53	...	Uninvolved	Water	...	...	...
Cuba, Los Canos	1953	100	Commercial	AgI	3 mo.	+20	...
Macareno	1953	150	Commercial	AgI	6 mo.	+20	...
Cuba, Baltony	1953	30	Commercial	AgI	3 mo.	+15	...
Preston, Boston	1953	500	Commercial	AgI	3 mo.	+19	0.002
Francisco	1953	400	Commercial	AgI	5 mo.	+15	...
Puerto Rico, Fajardo	1953	250	Commercial	AgI	2 mo.	+14	...
Nearby waters	1953–54	...	Uninvolved	Water	5 mo.	...	0.02[d]
Cuba, Macareno	1954	300	Commercial	AgI, water	2 mo.	+61	0.02
Puerto Rico, Fajardo	1954	250	Commercial	AgI	2 mo.	+13	...
Cuba, Baltony	1955	30	Commercial	AgI	3 mo.	+12	0.03
Puerto Rico, Fajardo	1955	250	Commercial	AgI, water	2 mo.	+27	0.07
Cuba, Francisco	1956	550	Commercial	AgI	7 mo.	+25	0.005
Colombia, Santa Marta	1956–57	350	Commercial	AgI	12 mo.	39 decrease in wind damage per stormy day	
Cuba, Havana-Mantanzas	1956	4000	Commercial	AgI	3 mo.	+27	0.03
Manati	1956	400	Commercial	AgI	3 mo.	+9	0.40
Manati	1957	400	Commercial	AgI	8 mo.	+15	0.21
Puerto Rico, south coast	1957	400	Commercial	AgI	2 mo.	+42	0.05
Cuba, Baltony	1957	30	Commercial	AgI	2 mo.	+20	0.06
Hispaniola, Romana	1957	600	Commercial	AgI	4 mo.	+31	0.10
Cuba, Esperanza	1957	120	Commercial	AgI	2 mo.	+27	0.06
Los Canos	1957	100	Commercial	AgI	2 mo.	+21	0.02
Florida, Boca Raton	1957	...	Uninvolved	AgI	...	No effect of seeding observed	
Average of all AgI seedings			(24 cases)			+22	
Average of all AgI and water seedings			(3 cases)			+43	

[a] Excepting 1952.

[b] On commercial basis prior to 1955.

[c] Separate evaluations of runoff showed increase of 35%.

[d] Water seeding with coarse spray in tops of trade Cumulus. Probability figure refers to likelihood that seeding caused precipitation in a cloud that would not otherwise have precipitation

TABLE 4-3

In the decade following Schaefer's trial, a great number of experiments were conducted in the tropics of America also. A good summary has been prepared by Howell (8).

level stability conditions can be determined from the heat and moisture flux from ground or sea. Measurement of freezing nuclei and giant condensation nuclei concentration and their vertical variation over the region will indicate the effect the seeding will have in modifying cloud drop-size distribution. Measurement of updraft rate below cloud and in the core will indicate the operation of collision-coalescence mechanism in precipitation growth.

4.2.6 Mexico

The experiment in Necaxa (Mexico) has lasted over 15 years (24, 25). The first few years' experiments were done from aircraft. Since 1955 seeding has been done with ground-based silver iodide generators on a randomized basis.

Seeding was found to have no significant effect for those days when there were more than 20 mm of rainfall, but days with daily rainfall amounts below 20 mm show considerable increase in precipitation with respect to unseeded days within the same limit (Fig. 4.4). This requires one to stratify rainfall data for the purpose of evaluation of results, and one should be able to predict those days with chances of rainfall of less than 20 mm to control the seeding operation.

With disturbances of the trade wind, the control area was sometimes affected by the seeding intended for the target; the orography of the region requires wind observations at close intervals both surface and aloft. Radar observations of precipitation growth in target and control would perhaps indicate the results of seeding in a better way in this type of experiment than depending upon raingage data alone.

4.2.7 Peru

An experiment in the Andes of northern Peru was conducted for 12 years beginning in 1951 with ground-based silver iodide generators (9). This region is under the influence of prevailing easterlies that bring tropical air across the Andes from the Amazon Basin. Weather changes are primarily associated with movements of the intertropical convergence zone, easterly waves and an occasional polar trough. The seasonal influence and orography also play a part on the Pacific side. An inversion is maintained throughout the year over the adjacent ocean by the cold water of Humboldt Current, which in combination with the down slope motion of the prevailing easterlies maintains desert conditions over the entire coast line. A diurnal tide under the influence of strong daytime heating carries the moist marine air inland from the Pacific beneath the inversion. Except during winter, this tide produces cloudiness over the high slopes west of the divide and, flowing across the divide and into the valley to the east, influences convective cloudiness in the overlying equatorial air. The complex interactions between equatorial air from the Amazon Basin and the Pacific marine layer control the rainfall over this region.

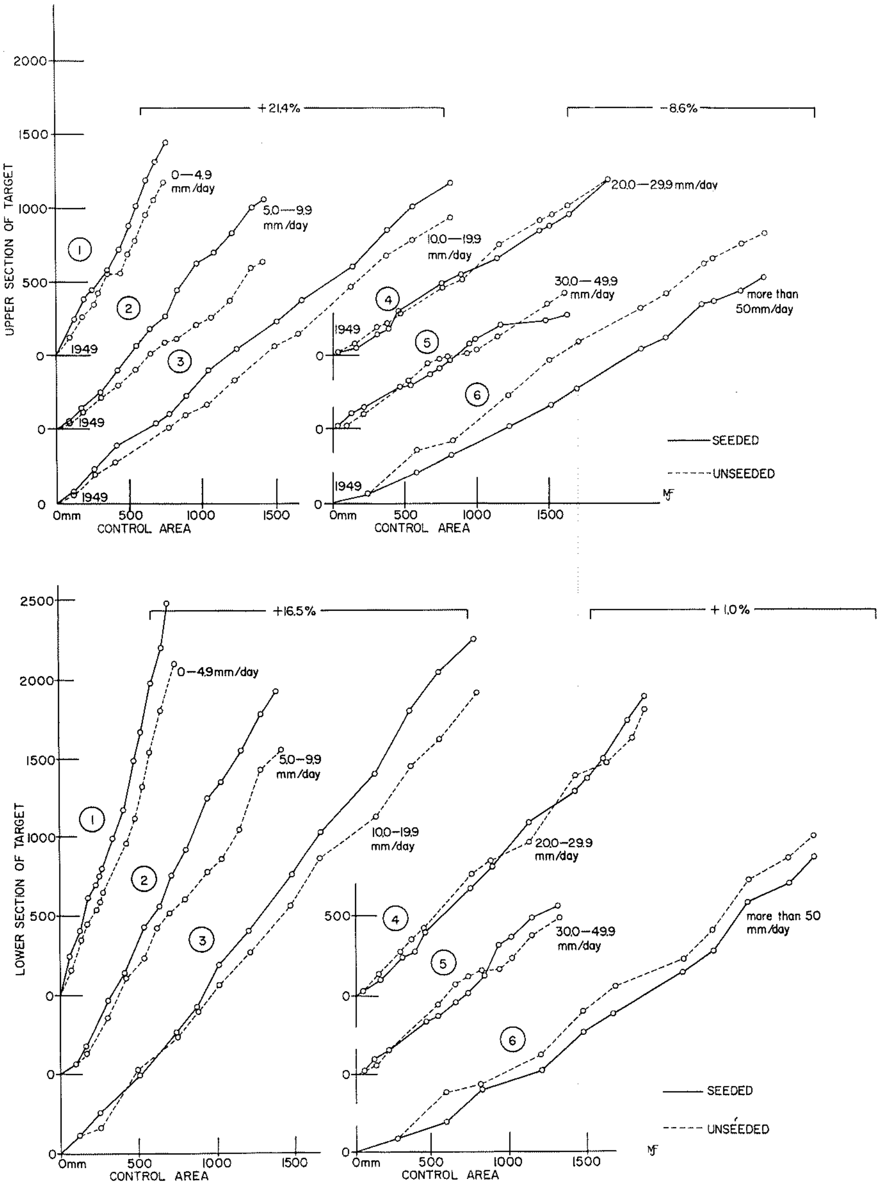


Fig. 4.4. Analysis by classes of rainfall amounts for the two target sections in Necaxa. Stratification of rainfall data according to the daily amount may sometimes be indicative of effectiveness of seeding or otherwise as in the case of Mexican experiment. Seeding indicated positive results for days with rain amount less than 20 mm per day, whereas for days with higher rainfall amount, there was no significant effect.

Total percentage increase or decrease for the groups (less than 20 mm per day and more than 20 mm per day) are shown on the top of each diagram (24).

The complexity of meteorological conditions indicates that the site was not ideal for conducting controlled experiments on weather modification. The situation could perhaps be improved by a number of soundings at close intervals of 15 km or so with extensive observations on cloud development and wind profiles. This should be supplemented by radar observations to facilitate evaluation of the results.

4.2.8 Medellin, Colombia

Experiments at Medellin, Colombia were initiated because of a great demand for hydroelectric power and potable water (13). Silver iodide seeding was chosen because a preliminary study showed that dry season precipitation on the city's watershed comes principally from daytime convective clouds that showered only after surpassing the freezing level. General results indicated rain increases of 20 to 40 percent.

4.2.9 Santa Marta, Colombia

Cloud seeding was undertaken in the Santa Marta banana plantation of Colombia to reduce damages due to windstorms (14). The hypothesis was that stimulation of showers early in the diurnal build-up of instability would dissipate some of the instability and reduce insolation at the ground, thus diminishing the intensity of convective overturning later in the day. Comparison of damages during the seeded seasons with those of preceding and subsequent seasons indicated marked reduction in the ratio of severe windstorm to mild ones during the campaign.

The very complex nature of climatology and local weather of these two regions of Colombia, and the topography of the places demand a dense sounding network and visual and photographic observations on cloud development over the region for any weather modification program.

4.2.10 Puerto Armuelles, Panama

A cloud seeding program was also undertaken in Panama (16) in 1959 to reduce the damages caused by high winds.

It was observed that the basic factor for high winds in this region was the rapid growth that occurs in both vertical and horizontal of cumulus type cloud. The principle involved to suppress the high windstorms is based on the fact that vertical growth is retarded whenever the tops of growing cumulus clouds spread or flare out. This flaring action is caused by the formation of ice crystals in the upper region. Cloud seeding can assist in the formation of these ice crystals at warmer temperatures, i. e., at lower altitudes.

No definite conclusion has been drawn from one year's experiment although some interesting trends have been shown.

The weather of this region is determined primarily by the position of the intertropical convergence zone. Dry season (December to May) begins when ITC moves south of the area. Winds aloft are then northeasterly or northerly flowing down slope off the mountains with their warmer, drier air. The strong trade inversion aloft prohibits most cloud development above it. With the northward movement of the sun in early March more intense heating for convection occurs and, if the trade wind inversion is weak, clouds build through it. If the northwesterlies have decreased speed and there are lighter winds aloft, the clouds develop to a height in one spot without being blown away. The convection is the major process involved in severe storm development during dry seasons although orographic lifting does start the cumulus development in this area.

Rainy season starts with northward movement of the sun when ITCZ moves northward. This zone, about 100 miles wide, is the cause of most of the rainfall in Panama during the rainy season - May to December. The intensity of the sun's heat is at its peak during the wet season, but daily occurrence of clouds cuts down the amount of heating the earth's surface receives. In addition, vegetation cover and a cooler earth caused by frequent rain reduces the atmospheric instability. However, these effects are offset by convergence in the ITCZ, the greater moisture supply in the lower layer, and a shift to a sea breeze making orographic lifting play a major role in early cumulus growth. The wet season generally produces milder storms but, when a severe storm does occur, it is more widespread and the destruction potential covers a larger area.

The additional measurements other than general meteorological observations that were carried out during the experiments involved photographic and radar observations together with balloon and surface measurements on winds and the electrical field strength measurements at various points. Wind measurements are perhaps of more importance in an experiment of this type with soundings at closer spacing.

4.2.11 Puerto Rico

More recently experiments have been conducted in southern Puerto Rico. Seeding has been done simultaneously from the ground by silver iodide generators and pyrotechnic flares and also from aircraft flying below cloud base dispersing finely powdered salt. The rationale of both seeding methods has been explained by Howell (10). Except for local weather effects due to topography, conditions and requirements are much the same as in any other tropical island experiment.

4.2.12 Stormfury

The most comprehensive observations to date of seeding of individual supercooled tropical cumulus clouds were made by Project Stormfury over the Caribbean in 1963 and 1965. Experiments of 1963, (Fig. 4.5), suggested that seeding stimulated cloud growth by increased buoyancy release through the freezing of supercooled water (15). In the 1965 experiment the approach was to find out what silver iodide seeding does to cumulus under various conditions, to develop a model to predict with fair skill the amount of growth and the conditions required for it, and to run the numerical model with adequate technology in real time so that seedability could be predicted in advance of undertaking a seeding operation (26, 27, 28). From the beginning, arrangements were made to conduct studies before and after seeding by radar, photography and multiaircraft penetrations through the seeded cloud and environment. Improved liquid-water content measurements, soundings of the cloud environment in close proximity to the treated cloud, extensive measurements of cloud base, still and motion pictures, and photographs of many radar scopes were some of the basic improvements in 1965 experiments. The radar and photographic studies were the main tools for observing developments in seeded and control clouds. The photographic studies were essential in understanding the sequence of events and in interpreting the radar observations.

In the analysis it was found that silver iodide seeding does increase the vertical growth of tropical cumuli under specifiable meteorological conditions. The analysis of data compiled on cloud liquid-water content, volume median drop-size, temperature profiles in cloud and the dynamic life history of seeded and unseeded clouds also suggested that natural glaciation does not proceed rapidly enough in the critical cloud updraft areas to spoil the effectiveness of silver iodide in modifying tropical maritime cumuli (23).

The water content of cloud groups, compared to mean tropical values, indicated more moisture in the lower and middle portions of the clouds that had large subsequent growth. Therefore, the moisture contents of the lower and middle cloud layers were suggested as easily measured environmental criteria that may enable prediction in advance of seeding effects upon a given field of clouds.

One of the important outcomes of Project Stormfury is the model for tropical maritime cumuli that has been developed. It predicts (Fig. 4.6) with fair skill the amount of growth possible through seeding and the conditions required for it. It could be run in real time. It suffers from the drawback that seedability cannot be expressed as a function of ambient conditions only, but requires the horizontal dimension of the cloud tower in order to prescribe the entrainment rate of environmental air.

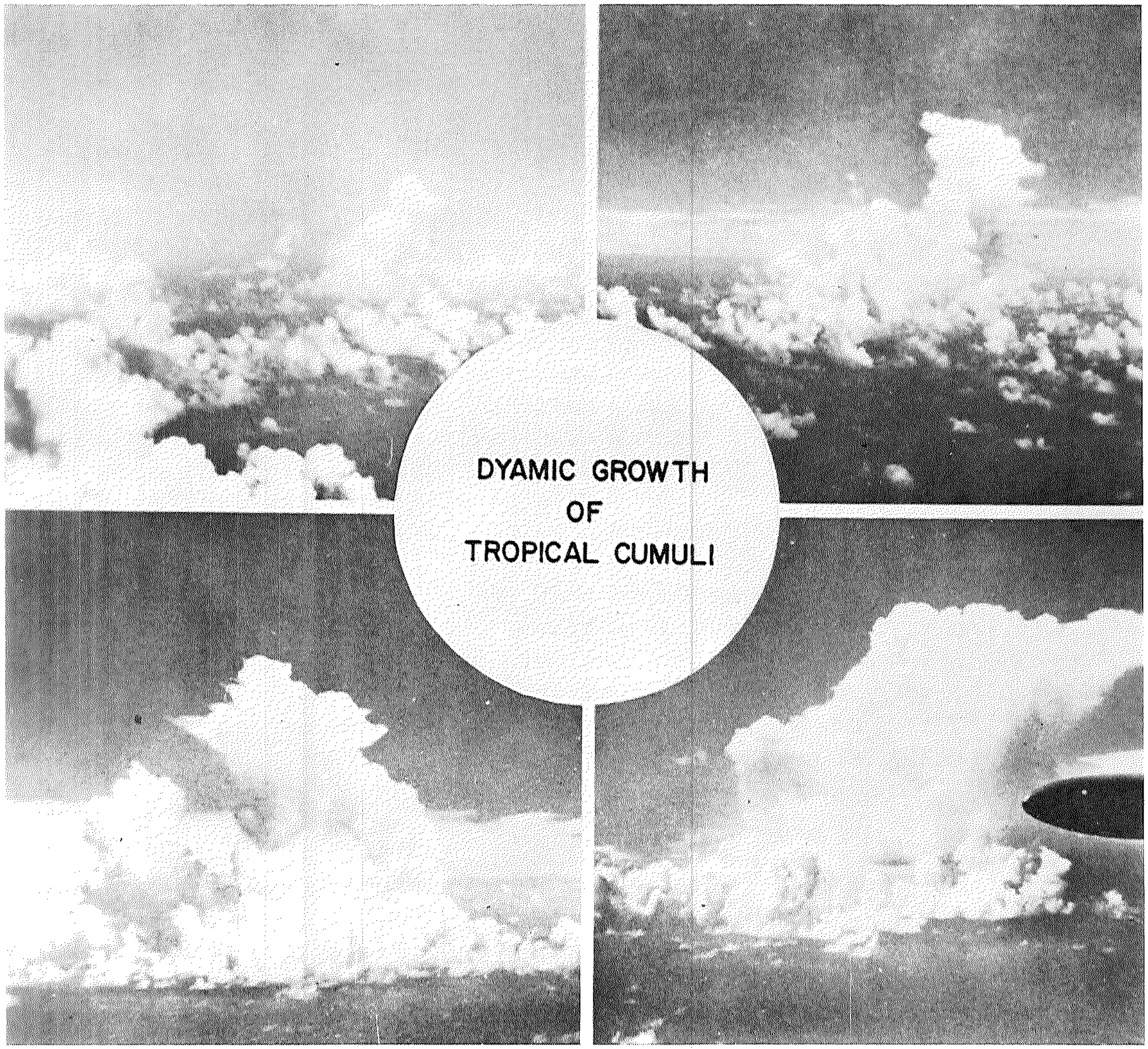
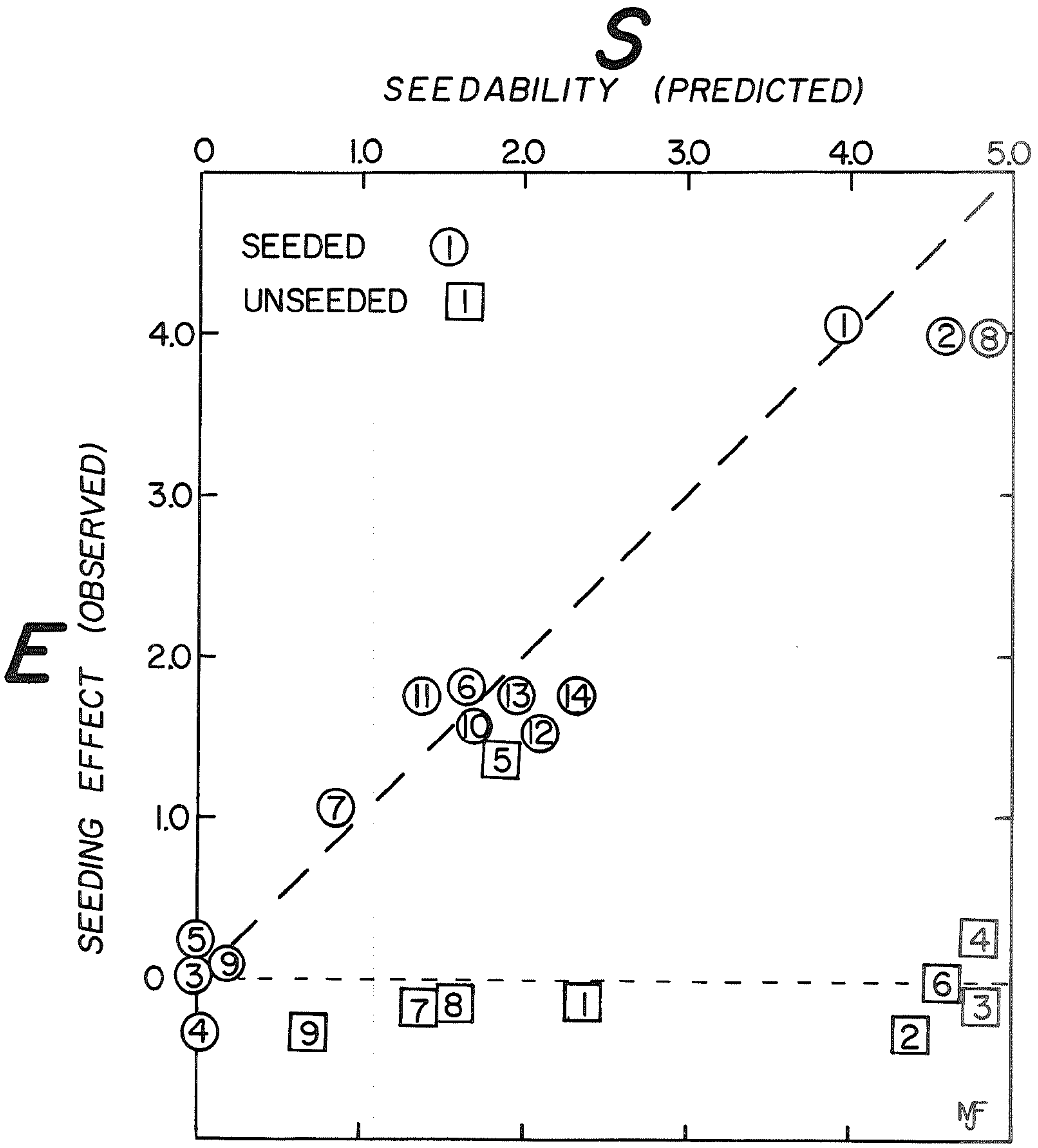


Fig. 4.5. Explosive growth of a tropical cumulus following silver iodide seeding. Project Stormfury observations on 20 August 1963. First picture at time of seeding; second, 9 minutes later; third, 19 minutes later; and the last, 30 minutes after seeding (15).



Seeding Effect and Predicted Seedability

Fig. 4.6. The seeding effects on some of the cloud parameters can be well predicted by numerical models, at least for clouds of smaller dimension; as seen in the above illustration from Stormfury experiment, 1965, on the dynamics of cloud. Seeding effect is the difference between observed cloud top of seeded cloud minus predicted top of the same cloud if unseeded, while seedability is the difference between predicted seeded and unseeded top of the same cloud. The numbers refer to the cases of seeded and unseeded cloud. Heavy dashed line represents perfect predictability for seeded clouds, i.e., zero seeding effect independent of seedability (28).

Dynamic models require more realistic treatment of hydrometeor growth. They will likely require improved measurement facilities, including frequent whole tropospheric soundings close to the clouds and accurate measurement of water content, hydrometeor character and size spectra, and vertical motions within clouds. A calibrated weather radar is required for giving echo size and height along with precipitation structure within clouds and that reaching ground, so that hydrometeor growth and fall out can be introduced in the dynamic model.

4.3 Conclusions

Considerable knowledge has been gained from tropical weather modification experiments, which have ranged from stray attempts at rainmaking to the comprehensive approach to understand the effects expected from cloud seeding under specifiable conditions. It has been apparent from the experiments conducted in the tropics that the climatology, local weather, and topography, together with the need of a particular region, vary widely. The most suitable seeding material, the technique of seeding and the required measurements of meteorological and microphysical parameters differ also from region to region.

Although large scale weather systems cannot be ignored, the mesoscale systems apparently play the major role in the development of convective clouds and precipitation in the tropics. Although the clouds sometimes occur at random, the mesoscale systems are present and it is desirable that we monitor them.

In the above light, the following measurements will likely be of primary importance in the tropics generally:

A. Soundings of the whole troposphere in close spacing of 15 km or so and at short time intervals (say once every 3 hr) covering the whole period of experiment. The sounding is expected to give (1) temperature along the vertical with a resolution of 100 m and accuracy of ±0.5C, (2) humidity in different layers; and (3) winds aloft.

B. Observations on Clouds: This includes (1) cloud type and amount, (2) height of cloud base and top along with horizontal dimensions, (3) temperature of cloud base and tops with lapse rate inside the cloud and, (4) growth rate in horizontal and vertical dimension. The present techniques for observing these include visual observations, radar observations, satellite pictures, still and moving photographs, sounding through the clouds, and instrumented aircraft observations.

C. Measurements of giant salt nuclei and freezing nuclei at concentrations as low as 0.01 per litre.

A number of ground and airborne techniques are available at present for these measurements.

In addition to these, the following measurements will also be required depending upon the region and the technique of the experiments.

1. Flux of heat and moisture from ground or sea, measurable in 0.1 cal cm^{-2} min^{-1}.
2. Thermal updrafts near the ground with accuracy of ±0.2 m sec^{-1}, and updraft below the cloud base and at different levels inside the cloud with accuracy of ±1 m/sec.
3. Cloud particle size spectrum depending upon the region and the type of cloud concerned.
4. Precipitation rate (or its equivalent radar reflectivity) with total amount and form of precipitation and cloud liquid water content.
5. Electrical activity such as field strength, space charge and the sferics observations.

The principal measurements required are shown further in simplified and grouped form in the table following.

TABLE 4-4

Principal Measurements for Modification of Tropical Cloud Systems

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Temperature	± 0.5C	3	100	15	In some cases the spacing required is 10 km and repetition time every 1 hr. Numerical models may require observations at intervals of 0.2 hr similar to cloud updraft or total water content.
2	Humidity lapse rate	± 0.5C	3	100	15	
	or					
	Precipitable water	± 1 mm	3	1000	15	
3	Wind aloft:					
	speed	±0.2 m sec^{-1}	1	500	15	May be required every 10 min.
	direction	± 10°	1	500	15	
4	Type and amount of cloud	± 0.05 of sky	1	100	10	
5	Height of top and base of cloud	± 50 m	0.2	--	1	Could be selective. Yields base and top temp. Top measurements could be done with temperature sensors.
6	Cloud updraft	± 1 m sec^{-1}	0.2	100	--	Region and dimension required.

Priority	Measurements or observations	Accuracy	Repetition time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
7	Cloud particle size (modal diameter and spread)	± 1 micron	1	100	15	
8	Precipitation					
	(i) Type	--	0.2	--	1	Sometimes continuous record preferred.
	(ii) Rate	25%	0.2	--	1	
9	Cloud phase	± 0.1	0.05	100	0.1	In selected clouds.
10	Total water content	± 0.1 gm m^{-3}	0.2	100	0.1	
11	Aerosol measurements					
	(a) Giant-condensation nuclei	± 0.01 $liter^{-1}$	6	1000	30	
	(b) Freezing nuclei	± 1 $liter^{-1}$	6	1000	30	
	(c) Cloud nuclei	*10%	6	1000	30	
12	Low level upcurrents	± 0.1 m sec^{-1}	1	100	15	
13	Flux of heat and moisture from ground or sea	0.1 cal cm^{-2} min^{-1}	3	--	50	
14	Electrical activities	10%	continuous	--	15	

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5. MODIFICATION OF TROPICAL HURRICANES

5.1 Introduction

Few investigators have proposed means of reducing the severity of hurricanes.* The tropical hurricane, which is an extremely complex meteorological phenomenon with gigantic scale and destruction power, is one of man's dangerous natural enemies (Fig. 5.1). Until recently, attempts at mitigating the vast destructiveness of these storms were based on conjecture, but research on hurricanes has been intensified and as a result many of their principal features are now partially understood.

Hurricane damage increases roughly as the square of the highest sustained winds. A 10% reduction in wind speed should perhaps reduce the destruction by roughly 20 percent. Considering that a billion dollars' damage can be caused by one large hurricane, it is worthwhile to spend on hurricane experiments although it is costly in terms of trained manpower and equipment.

5.2 Review of Experiments

The first known attempt at weather modification in a hurricane occurred in 1947 with the experiments conducted in a small hurricane using dry ice by Project Cirrus (5), (7). It was difficult to evaluate the results as no facilities were available to monitor changes in circulation or cloud structure. (Shortly after seeding the storm abruptly reversed its course and 54 hours later moved into Georgia where it caused considerable damage. This implies that precautions must be taken to experiment only with storms that cannot conceivably strike land within a reasonable time.)

At present, experiments are being conducted on hurricanes by an inter-agency program of the U. S. Government called Project Stormfury. The two main participants are the U. S. Navy and the Environmental Science Service Administration (ESSA). So far seeding experiments have been carried out on three hurricanes, Esther in 1961 (9), (3); Beulah in 1963 (10), (11), (3); and Debbie in 1969 (4). The results are encouraging but inconclusive; the observed changes following seeding being small. The main reason for the inconclusive results in hurricane experimentation is the very large natural fluctuations that these storms undergo. Since hurricanes can develop, weaken, or entirely reverse course in six hours, the consequences of man-made alterations are very difficult to isolate.

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*In this chapter, the term "hurricane" is used to describe tropical cyclones in general.

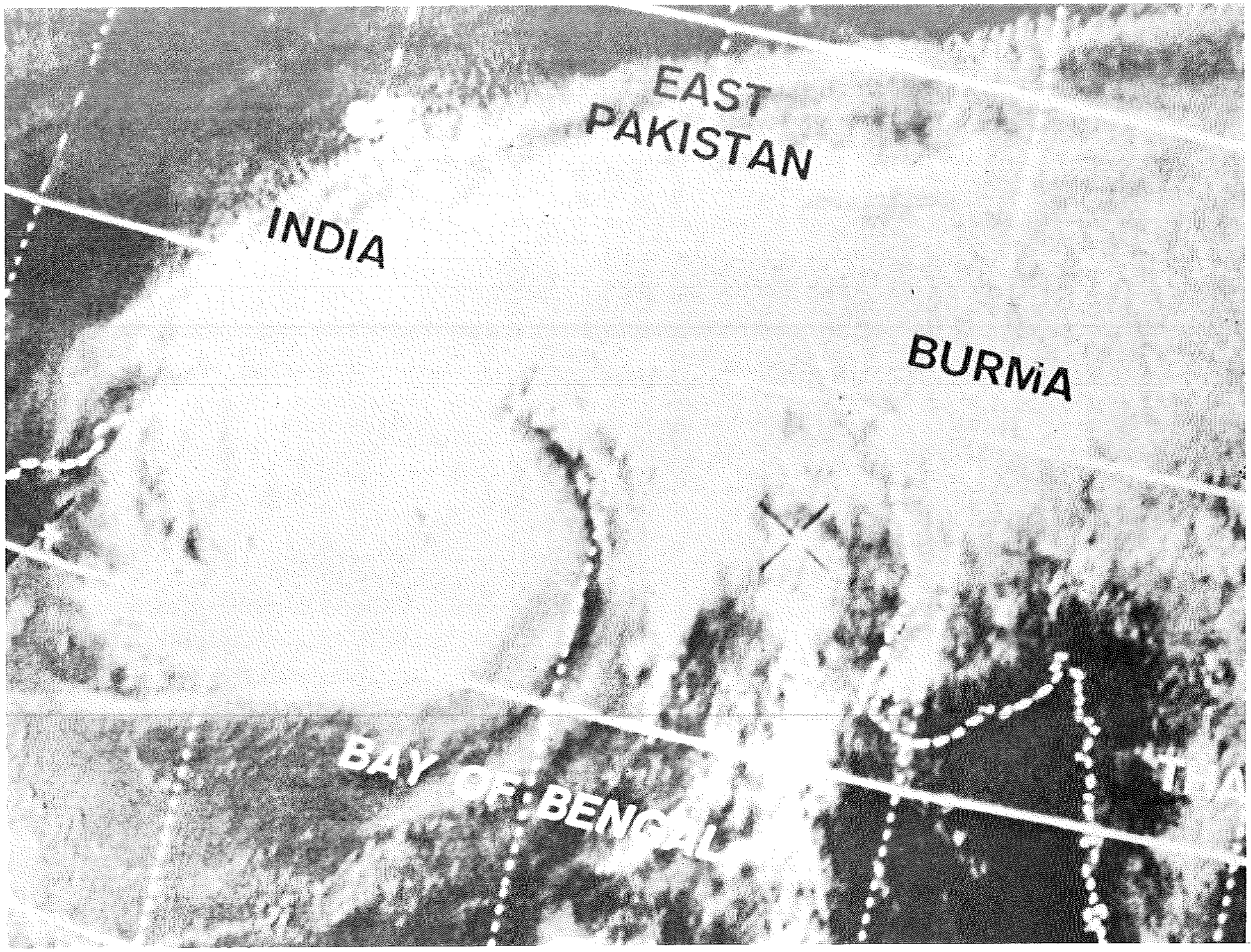

Fig. 5.1. The satellite picture of the cyclone Hurricane of Indian Ocean that hit East Pakistan on November 13, 1970. Observed impersonally it had classic feathery beauty driving northward into East Pakistan over the low islands of the Ganges Delta. Beneath lay natural disaster on a scale quite unprecedented in this century. Wind speed went up to 150 miles an hour followed by 20 foot tidal waves. All traces of villages were erased and entire islands submerged for days. Estimated death range 300,000 and beyond (6).

So far attempts to reduce the severity of hurricanes involved seeding selectively in the wall cloud surrounding the eye (Fig. 5.2), allowing the strong winds to carry a dense sheet of silver iodide crystals introduced just upwind of the most intense convection around the center of the storm. The principal assumptions for the silver iodide to work are - that large amounts of supercooled liquid water exists in the hurricane cloud which does not naturally become converted into ice. (Measurements are required to confirm this.) Once the supercooled drops are frozen as a consequence of seeding the ice crystals are exported by the storm outflow. At the upper boundary of the storm near the tropopause the pressure surfaces are approximately level, i.e., inward pressure gradients in the storm are produced by relative warming in the troposphere. The wind speed decreases outward from the center rapidly enough so that if a ring of air is given an initial push outward, it may be expected to continue accelerating outward despite higher pressure towards which it moves. If these conditions are met, then the latent heat release by seeding may correspond to a pressure fall (of about 6 mb) in the eye wall region, thus reducing the slope of the surface pressure profile closer to the center (Fig. 5.3). If the gradient is weakened as described, the previous eye wall would dissipate and reform further out. Consequently the main ascent of air would occur at a greater radius and winds may not penetrate the storm core any more than they do in weaker tropical storms. Thus, perhaps, the winds will not attain such high speed as before the modification occurred. It has not yet been possible to predict the distance the eye wall clouds would move outward, nor the consequent amount of wind speed reduction and also whether or how soon a hurricane might regain its equilibrium after seeding effects.

In some new programs of hurricane modification emphasis has turned to seeding hurricane rainbands away from eye wall. The idea has emerged from recent studies with mesoscale numerical models (8), (1). These have indicated that proper seeding of clouds in large convection cells in the hurricane rainbands may alter the circulation in the eye wall. The increased convection due to seeding would divert a portion of the inflowing air upward before it reached the eye wall, which would produce a reduction of surface wind speed from angular momentum principle. The additional vapor needed to feed this convection would be obtained at the expense of the eye wall clouds, which might further reduce the intensity of eye wall circulation. A simulated rainband seeding experiment has indicated further that, if the source of water vapor is the middle troposphere, there is very little effect on eye wall circulation but, if the vapor source is the boundary layer, seeding can reduce the eye wall circulation by 40%. Maximum effect is expected when the rainband clouds could be stimulated to grow to the main hurricane outflow region (13 to 15 km) and the cloud circulation extends down to surface boundary, as that would divert inflow and also deplete vapor available to the eye wall.

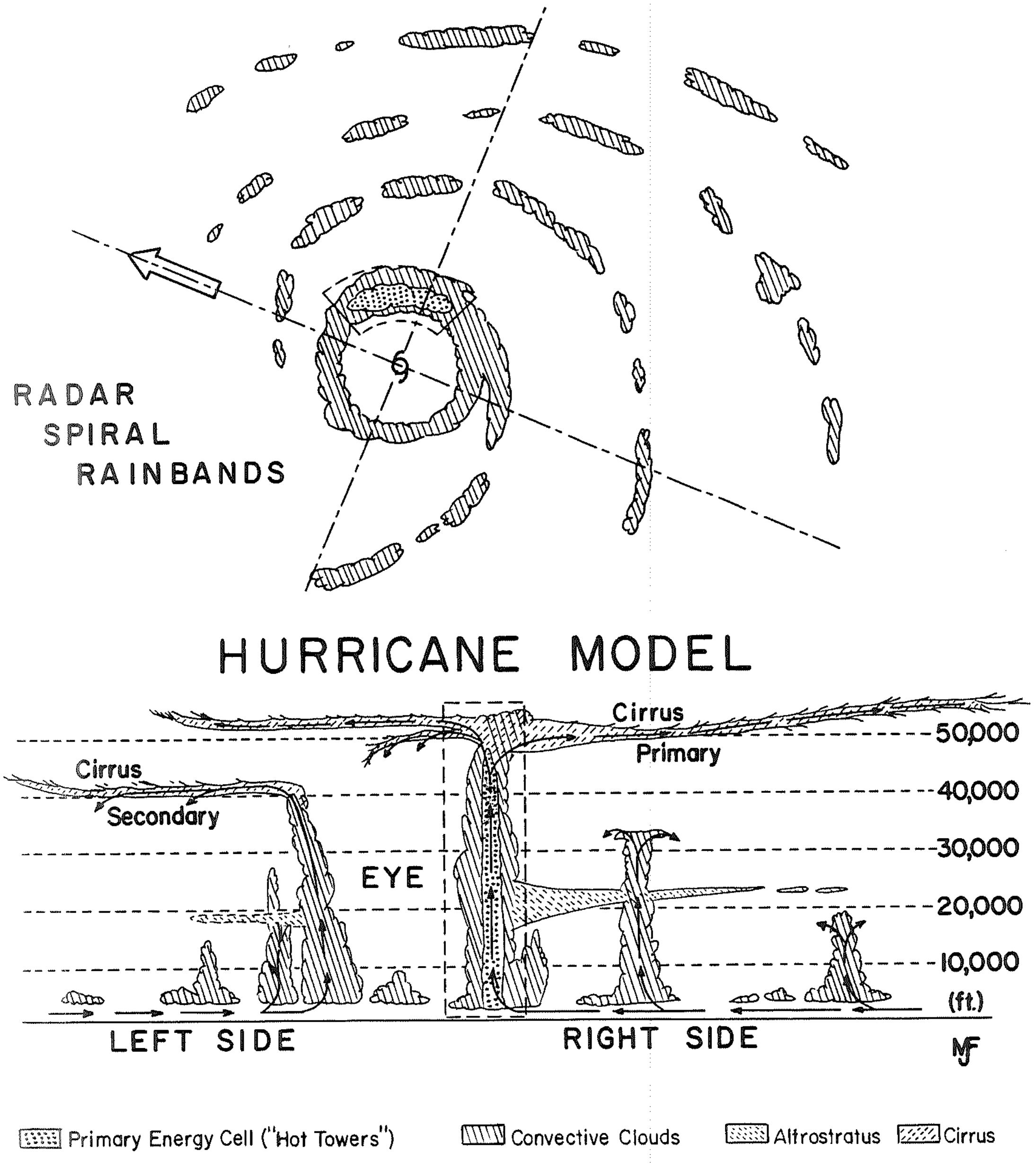

Fig. 5.2. The hurricane model. The primary energy cell convective chimney is located in the area enclosed by the broken line (4).

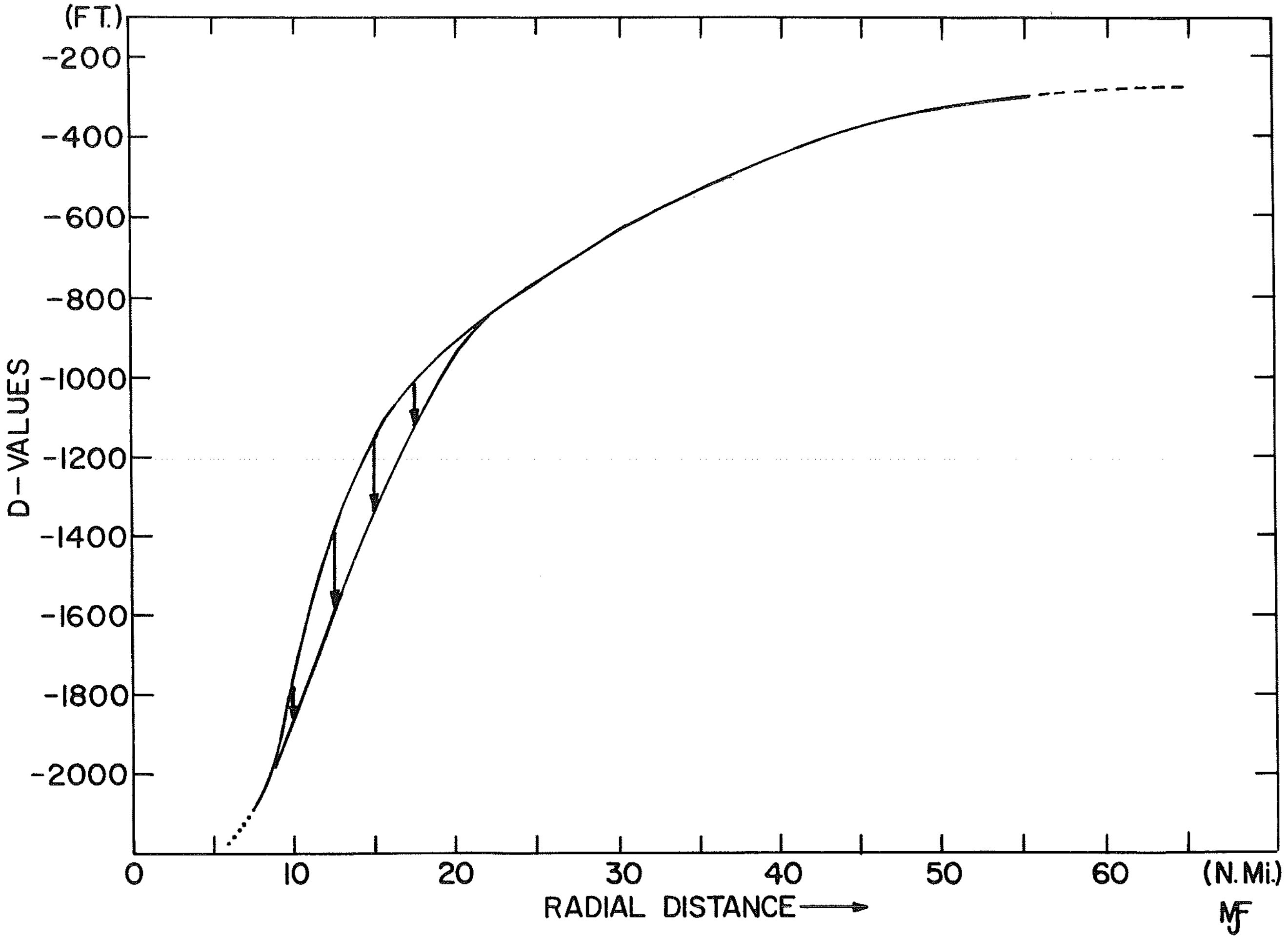

Fig. 5.3. Anticipated change in shape of pressure surface due to seeding. D is altimeter correction or radar altitude minus pressure altitude. Radial distance is from center of eye of the hurricane (11).

These numerical experiments have brought to light the interaction of the large convection cells embedded in the rainbands to the total hurricane circulation and their reaction to seeding by silver iodide. More and more attention is being given to numerically simulating the rainband clouds and performing seeding experiments on the numerical models in order to understand crucial effects of seeding on the hurricane rainbands.

Proper identification of rainbands from satellite and radar observation and measurements of moisture influx at low levels may be the primary observational needs if this type of experiment moves from the theoretical phase to actual experiments in the atmosphere.

5.3 Other Suggested Techniques

Recently another hypothesis has been put forward (2), whereby the production of ice phase precipitation by proper cloud seeding provides a way of reducing thermal energy in the influx air of a hurricane.

The principle is that when precipitation elements develop (by condensation-coalescence or freezing) in cloud and descend, they may be thought of as carrying negative heat in a latent form. The phase change of the elements during the descent allows the latent form of heat to come out as net negative heat and the consequent cooling lowers the heat energy content in the environment. As a result, the influx air to hurricane is forced to carry lower thermal energy which later reduce the heating when clouds form near eye wall with consequent reduction in wind speed (Fig. 5.4).

The seeding (that properly develops ice phase precipitation elements that falls out) can be applied to clouds or rainband or wherever suitable supercooled clouds exist outside the eye wall. Since the purpose is to develop precipitation elements, seeding material required will be much less than that required for excessive heating of clouds.

A number of other ideas have been proposed for reducing the severity of hurricanes. One that has come from early Tiros satellite findings with infrared radiation sensors, that the fluxes of long wave radiation emitted in outward space from hurricane and typhoon cloud systems were much larger than had been anticipated. The idea is to trap this radiation in the high troposphere. The tropopause would become warmer and lower, which would reduce the severity of the storm. This is proposed to be done with large number of small plastic bubbles of several micron diameter impregnated with material having selective absorption of radiation in the infrared range corresponding to the mean radiating temperature of the hurricane cloud system. These, when introduced at the top of the storm strategically to maintain their position relative to the moving center, will contribute to a progressive warming of the layer thereby lowering the tropopause height.

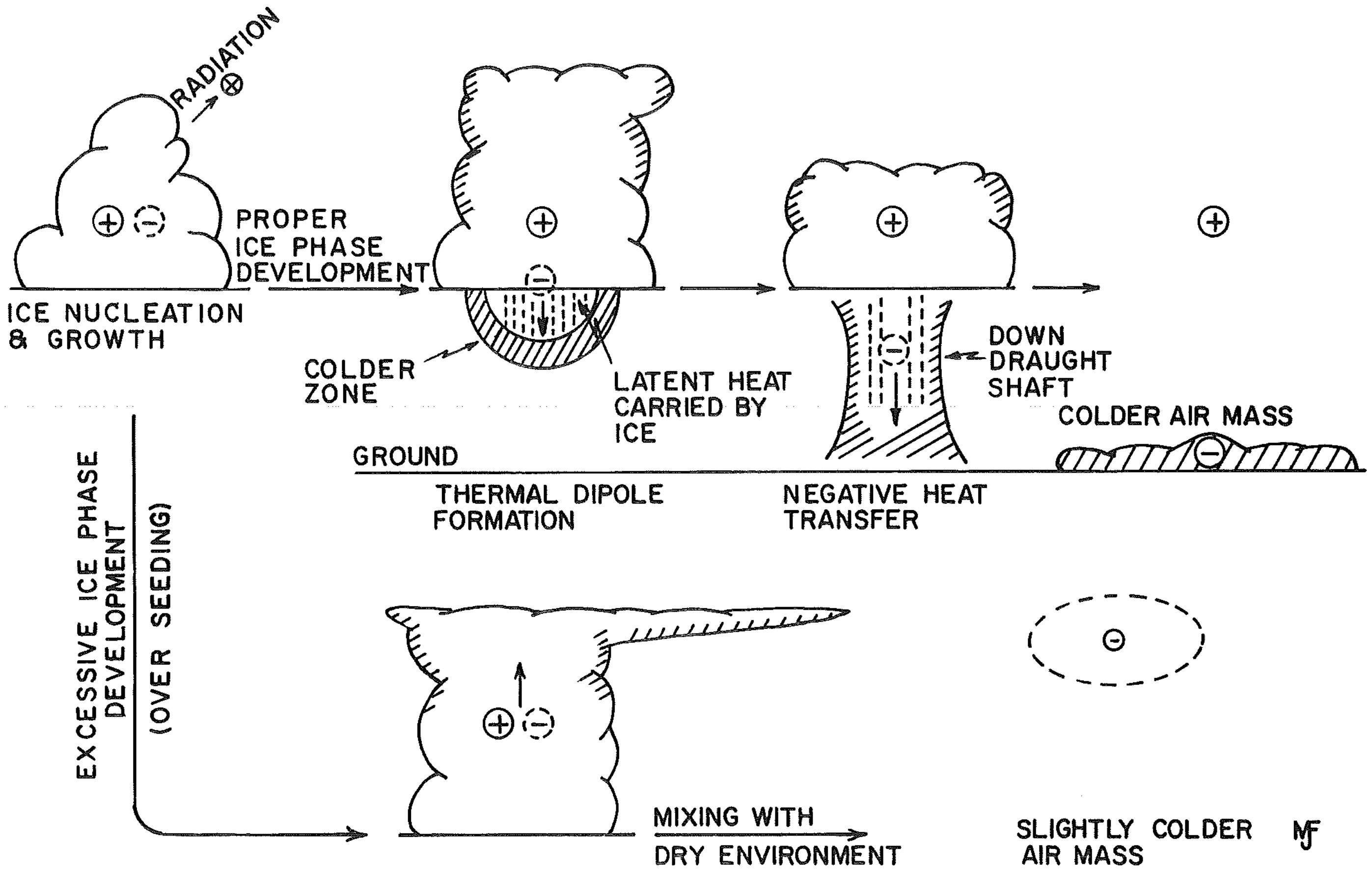

Fig. 5.4. Heat energy budget in ice phase cloud processes. The principle of increasing precipitation element by seeding in hurricane rainbands for reduction of thermal energy influx. Excessive seeding may be detrimental to this purpose (2).

Another approach is reduction of abnormally large fluxes of latent heat from the sea to the inward spiralling air current of the tropical storm, which is the main source of energy for the development of pressure gradient necessary to sustain hurricane force winds. It is suggested that this could be done by widespread application of immiscible fluids to the surface water near the coastline which, when applied to a water surface spread out in monomolecular layer and strongly inhibit evaporation. In both of these approaches, radiometric measurements of heat and moisture flux from surface would be the primary requirement.

5.4 Conclusion

The observational and monitoring requirements in a hurricane experiment are enormous. The precision maneuvering of numerous specially equipped aircraft calls for coordination by radar. The task is accomplished by a flight controller on board one of the radar-equipped planes from which the other aircraft are guided along prescribed flight paths with respect to the moving eye of the storm. The detailed measurements of the core structure are made by aircraft from several hours before seeding to several hours after seeding at different altitudes. The basic measurements made are wind speed, air pressure, temperature, humidity, liquid water content, number of freezing nuclei and cloud structure at levels up to 60,000 ft in the core and periphery. Special low-level cloud and rainband observations are done with lower altitude flights. Air pressures near the eye of the storm are obtained by dropping instruments from another aircraft circling the eye wall. The changing cloud patterns are photographed from above and also observed through satellite pictures.

Attempts to modify hurricanes are just beginning. Present day theory and models can predict only the artificial percentage change in the pressure gradient of the hurricane eye. The dynamic and thermodynamic relationships in hurricanes are not yet so well understood, nor are numerical or laboratory models able to simulate such experiments. Thus it has been felt necessary first to conduct careful measurements in full-scale hurricane experiments and then to test step by step the link that will lend itself to evaluation by available techniques.

The experiment conducted so far has revealed some of the basic primary meteorological measurements required for hurricane experiments and these are shown in simplified and grouped form in the table with anticipated required accuracy, resolution, frequency and spacing of observations.

TABLE 5-1

Basic Measurements for Hurricane Modification Experiments

Priority	Measurements or observations	Accuracy	Repetition Time (hr)	Vertical Resolution (meters)	Spacing (km)	Remarks
1	Wind speed	±1 km hr^{-1}	1	1000	25	
2	Air pressure	±0.5 mb	3	1000	25	(Required also are pressure altitude and radar altitude) D-values in different directions and at different levels.
3	Cloud observations Type and amount and detailed structure	±0.05 of sky	1	100 km^2 (Hor. Resolution)	Continuous	Detailed observations of core structure (by radar and satellite) at every hour is required which should cover all the area of major influence at high levels and also observations on low level clouds in rainbands.
4	Heat and moisture flux from sea	±0.1 cal cm^{-2} min^{-1}	3	--	100	
5	Temperature lapse rate	±05C	6	100	25	
6	Humidity	±2%	6	100	25	
7	Cloud liquid water content	±0.01 g/m^3	3		100 meter	
8	Aerosol measurements freezing nuclei	±1/liter	1	500	25	

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6. CONCLUSIONS AND SUMMARY

In the above chapters we have considered the meteorological observations required to conduct and evaluate weather modification projects in such diverse areas as fog dissipation, rainfall increasing, hail suppression, and modification of hurricanes. Three facts have emerged from our considerations:

1. Meteorological observations of certain parameters such as temperature are required for all types of weather modification projects and the spacial resolution requirements do not vary greatly with the objective of the project.

2. The observations required for conduct and evaluation of weather modification programs are in general those which are required for accurate forecasting of the meteorological phenomena being treated.

3. While most of the requirements are for observations of familiar variables, they go far beyond what can be achieved with existing networks in terms of spacing and frequency of observations.

One area in which the requirements for weather modification programs differ from those for conventional forecasting is in the increased emphasis upon condensation and ice nuclei and the composition of clouds. At present attention to aerosols is increasing rapidly because of their role as air pollutants so that devices to monitor them on a routine basis are being developed independently of weather modification activities. However, such factors as the relative ice-water composition of clouds will not likely be monitored by air pollution specialists and the instrumentation will have to be developed by weather modification groups.

It is beyond the scope of this report to specify the exact manner in which the various required observations will be acquired. The reader may have noted that weather modification pioneers have visualized their needs being met by "more of the same", e.g., by additional radiosonde stations. It appears to us that the frequent observations at close spacings required for experiments on convective clouds in particular must be met by new approaches, if costs are to be kept within reason. In fact, some of the requirements pose almost insuperable physical problems if solutions are sought by conventional means; for example, how many sampling aircraft can fly through a cloud without altering its characteristics? However, calls for radiosonde stations at spacings of 20 to 50 km will vanish if lidar probes provide continuous monitoring of the temperature, humidity, and wind fields in three dimensions, and remote sensing may also permit experimenters to keep their test clouds intact.

There will be a requirement for recording data, say on magnetic tape, in formats suitable for direct examination by computers. This will be especially important when computers are brought into the decision loop (observations → treatment → observation) and real-time readouts are required.

With the rapid development of weather satellite technology and the increased sophistication of such devices as weather reporting buoys and the tying together of the various systems with land lines and central computers, the requirements for weather modification observations may be met without any particular effort from the weather modification groups. It is more likely, however, that the weather modifiers with their special requirements will lead the way in the development of such systems. The U. S. Bureau of Reclamation is already tying together its various field projects in the western United States by land lines connected to a computer at Denver, Colorado. The introduction of weather satellites and communication satellites into such a system would provide an extremely powerful means of collecting and disseminating weather information. It is difficult to envision what the system of 1980 will look like; it is only possible at this point to state that a definite need exists and it is almost certain that large expenditures will be made over the next decade to develop the required hardware systems.

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