THE DESIGN, EXECUTION, AND EVALUATION OF A WEATHER MODIFICATION EXPERIMENT

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1. Introduction

There are various reasons for disagreement as to the effects of seeding supercooled clouds to produce rain. Clearly, the most basic reasons are our lack of understanding of the natural precipitation processes and their variations throughout the life cycle of the cloud, and an inadequate set of physical measurements to define the state of the system before and after seeding. Sometimes certain complex processes can be changed without understanding and usable results can be obtained. The evidence for the case of weather modification now makes it clear that changing natural events can only be interpreted intelligently against a background of understanding of the natural course of events.

Thus, the logical approach to cloud modification is first to obtain a sufficient physical understanding to enable prediction of the evolution of clouds and, then, to attempt to change the natural behavior of the clouds through properly designed experiments.

A casual glance at any precipitation map or any radarscope showing the distribution of rainfall intensity makes it quite apparent that natural variations are very large. Our present limited ability to observe the necessary physical parameters generally prohibits the designing of a very conclusive experiment. On the other hand, there are certain meteorological situations where a fairly good understanding can be obtained and where, through systematic studies, physical models can be derived and conditions well enough defined to establish physical controls.

It is of the utmost importance that consideration be given to all scales of motion in the design of any weather modification experiment no matter on what scale the experiment is to be carried out. There is no *one experiment* which can be designed to give conclusive answers concerning all the benefits (or liabilities) to be derived from weather control by cloud seeding. The complexity of the microphysical, meso- and macroscale interactions is too great. Conclusive answers will come only from a group of coherent experiments covering the various aspects of natural variations and artificial modifications.

2. Preseeding studies

In 1959, a program was begun to investigate the distribution of showers in central Pennsylvania and to determine their characteristics and the magnitude of their variations. The first approach was to use radar as a tool to gather data which could be used in order to look at the average characteristics or climatology of the area [1], [2]. Much of the analytical procedure paralleled investigations along these lines by others so that geographical comparisons could be made.

Characteristics such as the areas of formation and dissipation of showers were studied as well as the duration of the showers, their movement, frequency of occurrence in bands and lines, and the percentage of the area covered with showers. All these parameters were related to the synoptic circulation as well as to the mesoscale atmospheric structure. In addition, special raingage networks were established and detailed measurements of airflow over the area were obtained with balloons tracked by radars [1].

From the synthesis of this observational data, physical models were developed to describe the general results. These models set the guidelines for refining the physical concepts and dictated certain experiments necessary to develop a more quantitative understanding. While it was clear that the complexity of natural precipitation is no less than in other areas, it was found that distinct patterns could be recognized under conditions suitable for mountain waves to develop over the area. The unique spacing and alignment of the modest topography was found to be related to these precipitation patterns. Evidence gained from these studies suggested that this topographic influence was transmitted to the precipitation process by alteration in the airflow and stability over the alternate ridges and valleys which simultaneously influence the buoyancy and structure of the showers. Subsequent investigations were thus tailored to define more clearly the atmospheric conditions related to the development of wave patterns and the associated distributions of clouds and rainfall.

Congruent with the development of our physical knowledge of precipitation in this area has been the progressive development of observational tools necessary to handle more complex situations and to provide more quantitative data to supplement the earlier qualitative observations. A complex observational system which includes a combination of versatile radars, balloon techniques, instrumented aircraft, and ground networks is a necessary part of these studies.

Once a certain amount of quantitative information was available, crude calculations [2] were made to determine the magnitude of the natural variations in cumulus clouds and, in particular, how the topographically induced flow altered the buoyancy of the clouds. With some understanding of the magnitude and variations of natural events, it was then possible to estimate the extent to which cumulus clouds might be modified by altering the buoyancy through artificial release of the heat of fusion. From these test calculations and the evaluation of other studies of precipitation [2], it was clear that the amount of precipitation depends largely on the properties of the cloud environment as it regulates the dynamics and microphysics of clouds and cloud groups.

3. Mountain wave influence

One of the most familiar examples of terrain influences in Pennsylvania is the mountain wave phenomenon. The intensity and importance of these modifications are not only determined by the somewhat unique ground features, but also by the properties of the general air stream. For example, the amplitude of a mountain wave is controlled not only by the size and shape of the mountain, but also by the distribution with height of wind and temperature in the air stream. Consequently, the topographic disturbance can be variable and thus requires detailed observations to monitor its structure. From the series of observational studies, it has become clear that topographic disturbances do occur repeatedly in particular regions and large scale flow situations. Through observational [12] and theoretical [13] studies, the relations of air motion to cloud alteration processes have been derived in order that this influence can be recognized and be usefully incorporated into the analysis and understanding of precipitation processes.

The observed buoyancy in cumulus clouds is generally small due to mixing with environmental air. Consequently, small changes in buoyancy are important in the life cycle of clouds. The areas of lifting tend to be favorable for initiation of clouds and also tend to steepen the environmental lapse rate. However, in areas where the air is sinking, the descending motions tend to develop negative buoyancies (dry air descends dry adiabatically, cloud air moist adiabatically) and furthermore, the subsidence produces areas of increased static stability.

Figure 1 demonstrates the wave influence schematically. In part A a typical temperature distribution (log P with skew T) is indicated as well as the change of stability across the wave crest. This modification of the environmental sounding will regulate the cloud structure which is shown here as a decrease in the tops of the clouds. The waves have been indicated to be prominent at only one level for simplicity.

4. Design of cloud seeding experiment

Several investigators have described distinct changes of cloud growth after seeding. Evidence shows that these sudden alterations are due to the release of latent heat as the cloud glaciates [4], [5], [6]. The importance of the release of latent heat on the buoyancy of clouds is shown schematically in part B of figure 1. Previous calculations [2] have shown that for typical clouds the temperature increase due to heat released on the conversion of liquid water and excess vapor to ice is just about sufficient to offset the effects of environmental decreases of cloud buoyancy.

The physical understanding of the natural sequence of cloud events and how these events are altered by natural disturbances gives a measure of the magnitude of effects to be expected from artificial modification of clouds. We believe that the key to the design of successful experimental studies of artificial alteration of clouds lies in taking advantage of certain meteorological situations which

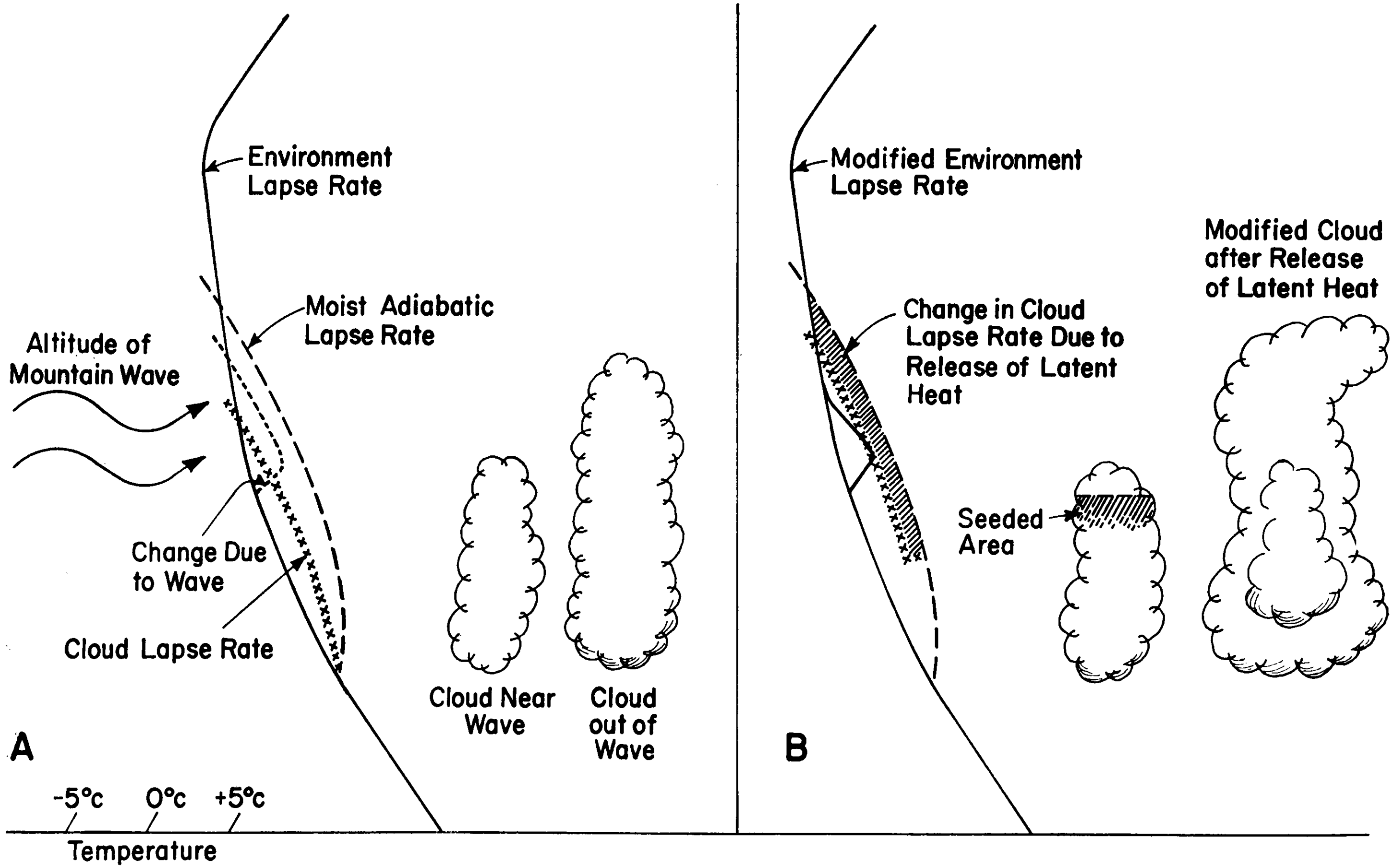

FIGURE 1

Schematic of skew T diagram indicating changes in buoyancy of cumulus clouds.

permit detailed observations and for which we do have a good physical understanding. It is important that detailed observations be made prior to and after each part of the seeding experiment. Very small differences in parameters such as cloud duration, thickness, and the time required to achieve colloidal instability determine, in nature, which clouds precipitate. All this points to the necessity of precise observational and diagnostic operations in order to prescribe time and type of treatment for producing desirable and predictable modification.

From our observations and studies on the specific patterns produced by mountain wave conditions, we found that the loss of buoyancy in a typical wave case was about 1° C. We concluded that the release of latent heat by artificially glaciating the supercooled portion of the clouds would produce enough buoyancy to offset the loss of buoyancy in the areas of subsiding motion [2]. A series of field projects was devised to test this hypothesis.

5. Execution of cloud seeding experiment

The primary features of the field operations are shown in figure 2. A "test" cloud is chosen from a field of several clouds growing within the wave crest. The tops of the extending turrets are generally at an altitude in the vicinity of 5 km and temperature of −4° C to −12° C, but they are not cold enough for substantial amounts of ice to form naturally and thus there exists several kilometers of supercooled cloud. No objective criteria were derived to select the test cloud (randomized selection was not used). The actual choice was usually dictated by operational timing. Control clouds were chosen such as to be in the vicinity of the test cloud, about the same stage of development, and located such that the aircraft could be controlled by the radar.

The general plan was to make penetrations through the test cloud with the research plane in order to obtain measurements of the cloud diameter and internal parameters. The seeding plane then made passes over the top of the cloud, dispensing seeding materials which fell through the center of the cloud creating a large curtain of ice. The research plane continued to make penetrations at various levels to measure the effects of the ice conversion. The research plane measures changes in temperature, liquid water content, turbulence, vertical drafts and takes samples of cloud particles. Meanwhile the seeding plane circles the test cloud at a distance taking photographs of the test and the control clouds at regular intervals.

In coordination with the aircraft operations, one M33 radar system is making continuous 3 cm profiles through the test cloud to determine the changes in radar reflectivity, vertical and horizontal extent of cloud echo, and changes in maximum reflectivity. The 10 cm search radar is used to coordinate the aircraft maneuvering and to monitor other traffic in the working area.

The second M33 radar system is responsible for obtaining radar data on control clouds and measures the air flow patterns by tracking balloons.

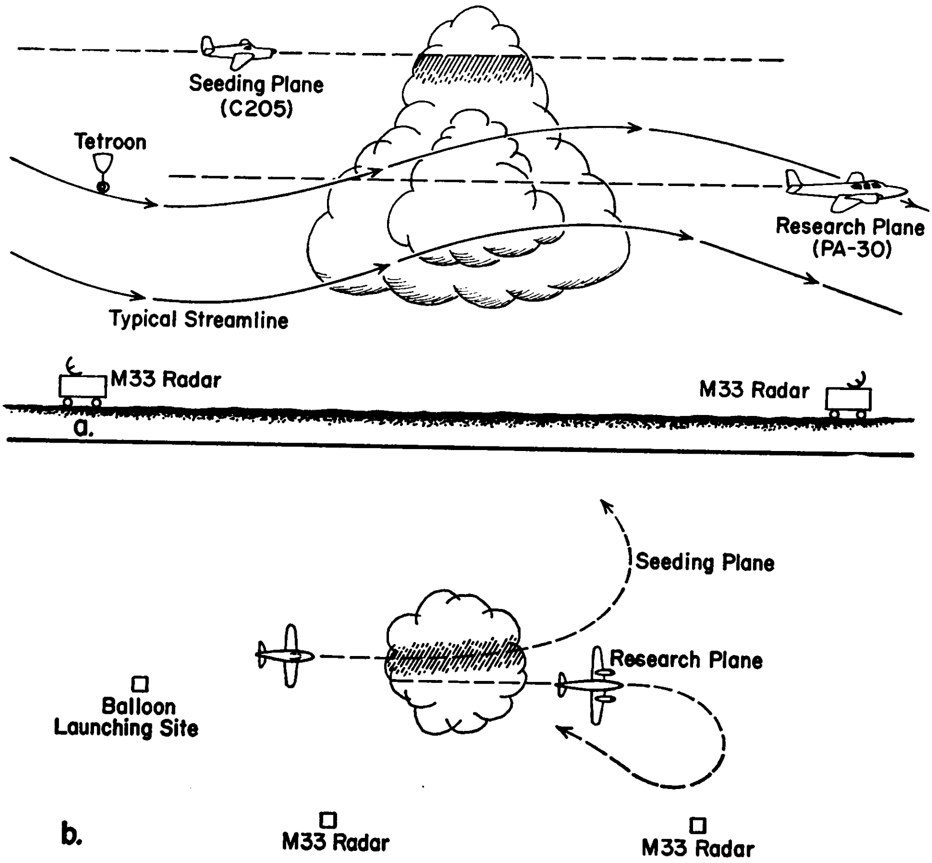

FIGURE 2

Schematic showing observational system.

6. Evaluation of seeding experiment

The evaluation of the experiment is based upon observation of physical parameters related to the dynamics and microphysics of the clouds. The test of the hypothesis is evaluated in terms of the following comparisons:

(1) comparison of physical parameters in the subject cloud with predicted parameters based on model calculations;

(2) comparison of the subsequent events in the subject cloud with similar events of control clouds;

(3) comparison with background data on "climatological" values of parameters determined for this area.

7. Model for buoyancy in clouds

A set of four equations is used to describe the vertical development of cumulus clouds. The first equation used is the equation of motion in the vertical with the buoyancy term modified by the negative accelerations due to the weight of the liquid water carried by the cloud and the drag due to turbulent mixing [7].

The second and third equations were developed by Austin and Fleisher [8] to evaluate changes of cloud temperature due to mixing, resaturating the mixed air, and the temperature change from condensation. The fourth equation is the continuity equation for water substance which includes loss of water in turbulent mixing. In the model used, the overall rate of dilution of the cloud decreases as the size increases, and the heights attained by the clouds consequently depend on their diameters. The model requires as inputs environmental temperature and humidity, cloud base, and cloud size. The entrainment parameter is obtained by knowing the radius of the updraft (taken as one fourth the cloud diameter in the growing stage) and using the relation given by

$$\mu = \frac{1}{M}\frac{dM}{dt} = \frac{0.2}{R}. \tag{1}$$

The equations were integrated numerically in time steps of two seconds and grid increments of 150 meters. The initial conditions were such that the virtual temperature of the cloud, at base height, was the same as the environment and the cloud had a perturbation velocity of 0.1 m/sec.

Seeding is simulated in the model by allowing all or a certain part of the liquid water to freeze, releasing the heat isobarically, and then resaturating the cloud parcel. After all the water is frozen, the excess water vapor is sublimed and the equations are subsequently used with respect to ice saturation.

8. Example of evaluation of test

As an example of the analysis and evaluation procedures, a specific case will be given which points out the diverse reactions which can be obtained. On October 27, 1963, three clouds were seeded with CO_2 pellets. Figure 3 shows the local sounding taken by an aircraft just prior to the seeding test. The bases of the clouds were 2.2 km and the general tops were about 4.5 km. Figure 4 shows the model computations, for the sounding given in figure 3, giving the variations of vertical velocity versus height for clouds of various entrainment rates (equivalent to various sizes).

The first seeding tests were conducted with CO_2 pellets on two small clouds, 1.6 and 2.8 km in diameter. Curves A and B of figure 4 give vertical velocities and tops for these cloud sizes. Nonseeded clouds were observed to have tops at 4.4 km, whereas the seeded clouds subsequently grew 0.3 to 0.5 km higher and then dissipated within 20 to 35 minutes. This agrees well with the predictions based on the model calculations. The additional buoyancy given to these clouds through conversion of the supercooled water was not adequate to allow them to penetrate beyond the stable layer.

At 1615 EST a relatively large cloud (7 km diameter) was seeded with CO_2 on three repetitive passes. The seeded cloud subsequently grew into a well developed thunderstorm. Curves C and D in figure 4 predict the development of clouds in this category. Note that there is relatively little difference in the ultimate altitude to which the cloud reaches for the case of freezing all the liquid water at −6° C or linear freezing of the water content between −6° C and −20° C. Other cases have shown differences. In this case, once the heating is sufficient to pass the stable layer, the slight instability aloft permits extensive development. This case illustrates that "explosive" growth after seeding occurs only with special lapse rate conditions and cloud sizes. The conditions require a stable layer imbedded in a conditionally unstable environment with the stable region having temperatures from −5° C to −15° C. Due to mixing and drag, the nonglaciated clouds will be stopped by the layer. These layers may be the result of a topographic influence, such as mountain waves, or associated with the large scale circulation. Since extensive natural glaciation is not observed at high temperatures, artificial glaciation can give spectacular results. It further illustrates the wide variations in results to be expected from a given field of clouds.

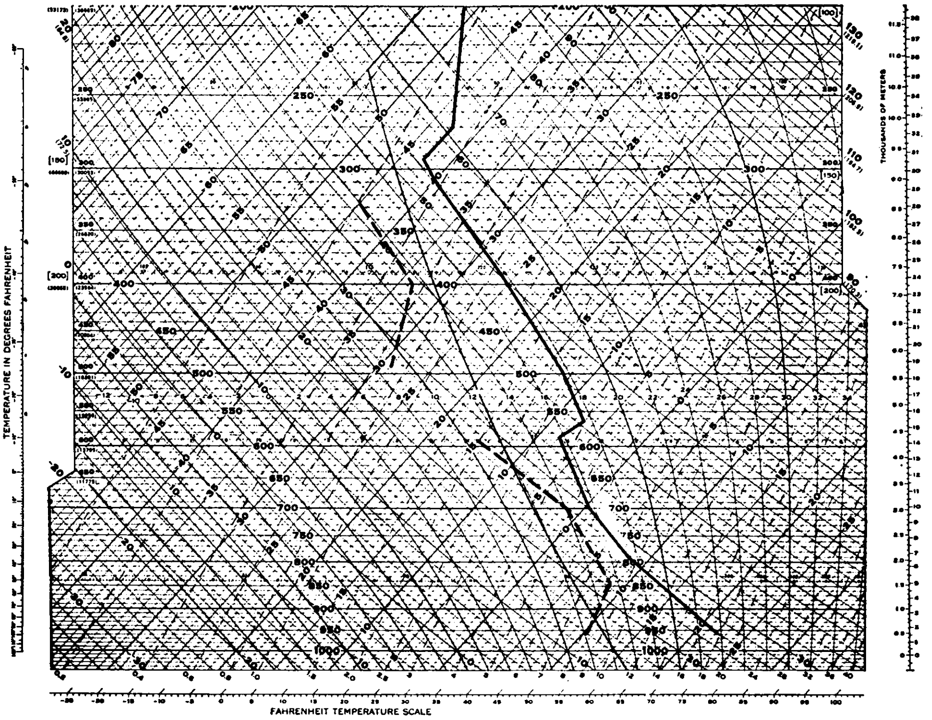

FIGURE 3

Environmental sounding for October 27, 1963.

Figure 5 shows the PPI radar plots for the third seeded cloud and for various control showers during the same time period. The seeded cloud grew to about 9.4 km, the maximum diameter was 20 km, and the echo lasted 2.1 hours. On the other hand, the selected control cloud (similar to this seeded class) grew to 5.5 km and had a maximum diameter of 10 km and an echo duration of 45 minutes.

Figure 6 shows a plot of the climatologically expected distribution of durations for the test area in central Pennsylvania. The group of control echoes have durations about double the climatological average, whereas the third seeded shower had a duration much greater than any previously observed for this particular area.

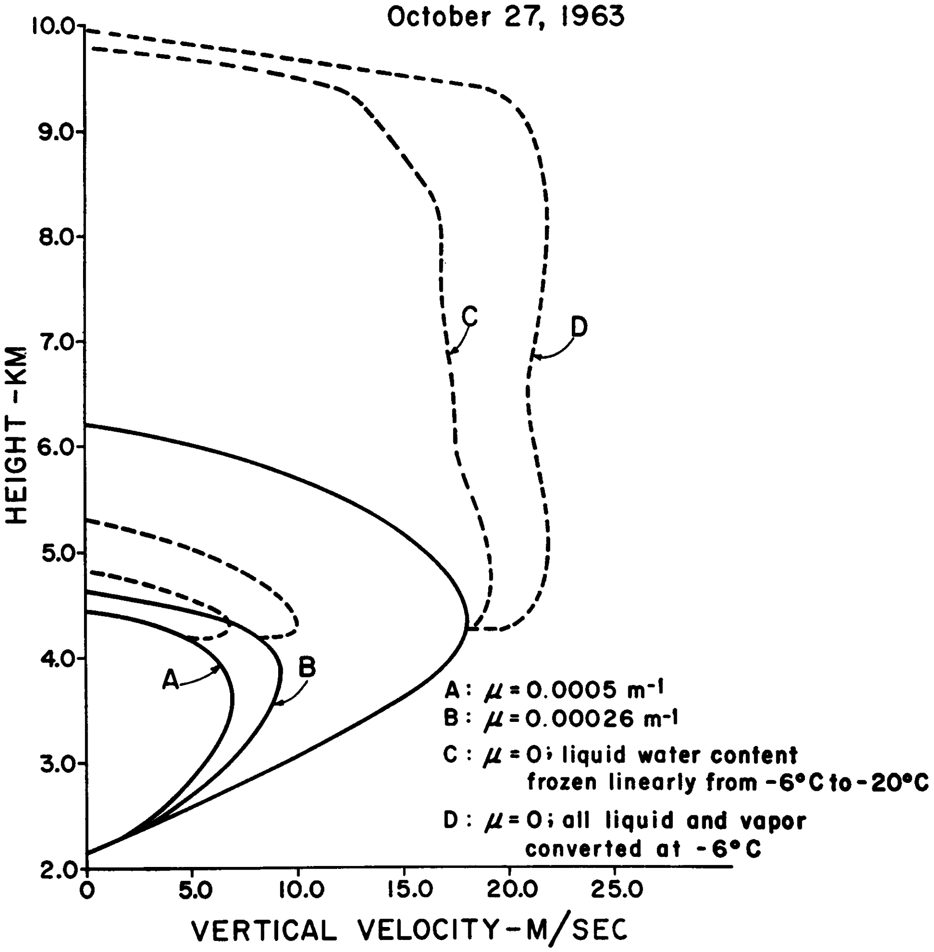

FIGURE 4

Vertical velocity profiles computed from model for clouds formed on October 27, 1963.

From these studies it has become clear that significant alterations to individual

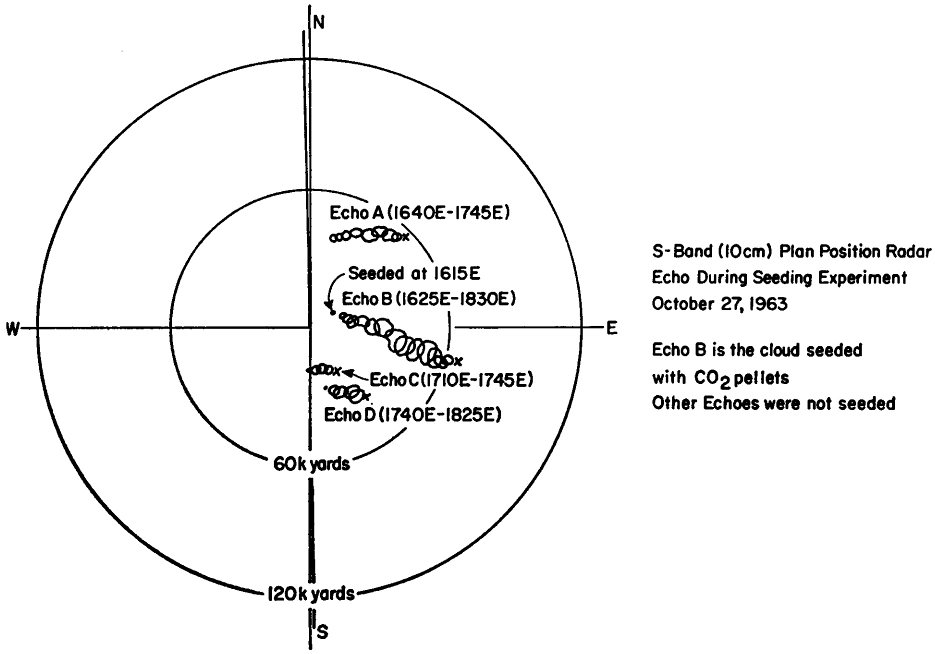

FIGURE 5

PPI radar echoes during test period on October 27, 1963.

cumulus clouds are possible under certain conditions. The conditions can generally be specified and appear to vary climatologically, as well as spatially within given large scale systems. It is evident, furthermore, that it would be difficult

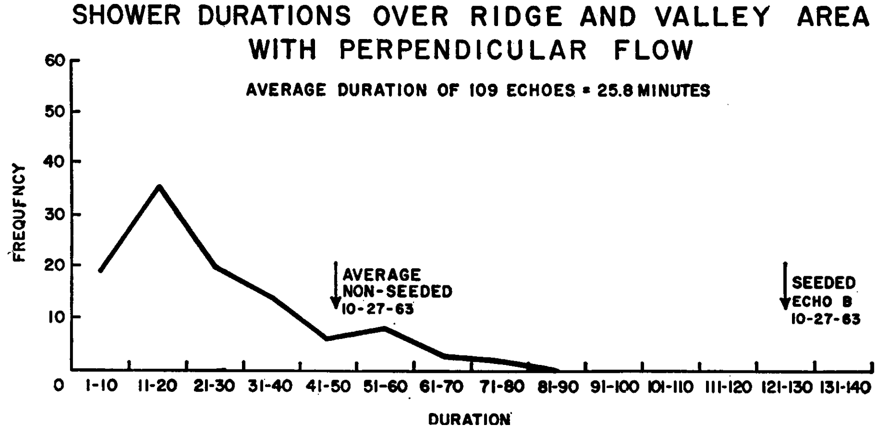

FIGURE 6

Comparison of seeded cloud performance with similar echoes with the same flow in the same area.

to carry out meaningful experiments without the prior observations and studies performed in this area. Most important of all, it would be nearly impossible to evaluate the worth of these modifications without some information on the frequency of occurrence of "seedable" periods. These data are only available if background studies are accomplished.

9. Extension of evaluation

On the basis of observations, background data, and predictions from models, it is possible to group several experimental tests in such a manner to give an estimate of the significance of the basic hypotheses. Some of these tests have been proposed previously by Brier as part of Project Stormfury [9]. By obtaining correlation coefficients for various parameters, such as observed height and growth versus predicted height and growth, the significance of the models and seeding effect can be evaluated. Since similar tests are being conducted in the tropics, geographical comparisons also can be made. Figure 7 presents the results of tests on nine clouds showing the observed height change versus the predicted height change due to the artificial liberation of the heat of fusion. Of the nine clouds seeded, five grew less than 1 km, two between 1 and 2 km, and two about 4 km. The percentage increase in maximum vertical extent ranged from 7 to 77 per cent with an average for the nine clouds of 33 per cent.

10. Generalizations on weather modification experiments

In the typical seeding experiment where the main goal is to achieve colloidal instability, nuclei are generally released from generators and allowed to diffuse into the clouds. The concentrations of active nuclei suitable for initiating colloidal instability are not usually the proper concentrations to have a direct influence on the buoyancy and dynamics. Secondary influences may occur, such as decreased water drag and eventual natural seeding of new turrets, but the glaciation will proceed slowly, in patches, and will not provide significant heating over a critical volume needed to derive buoyancy effects. It is important to realize that different seeding techniques may cause different effects on clouds depending on when, where, and how much glaciation occurs. Furthermore, experiments, such as described here, bring out the fact that of a given field of clouds, with the *same* seeding technique, drastically different results can be expected depending on the size of the clouds and the existence of stable layers in the environment.

Whereas some initial weather modification experiments lacked any design whatsoever, either physical or statistical, it seems that the second generation of experiments have been primarily controlled by statistical considerations and based on a much oversimplified physical model. This oversimplified physical model has failed to take into consideration that the seeding can have a variety of consequences in a variety of situations; these consequences can be either positive or negative, or have no bearing at all on precipitation, which is the principal

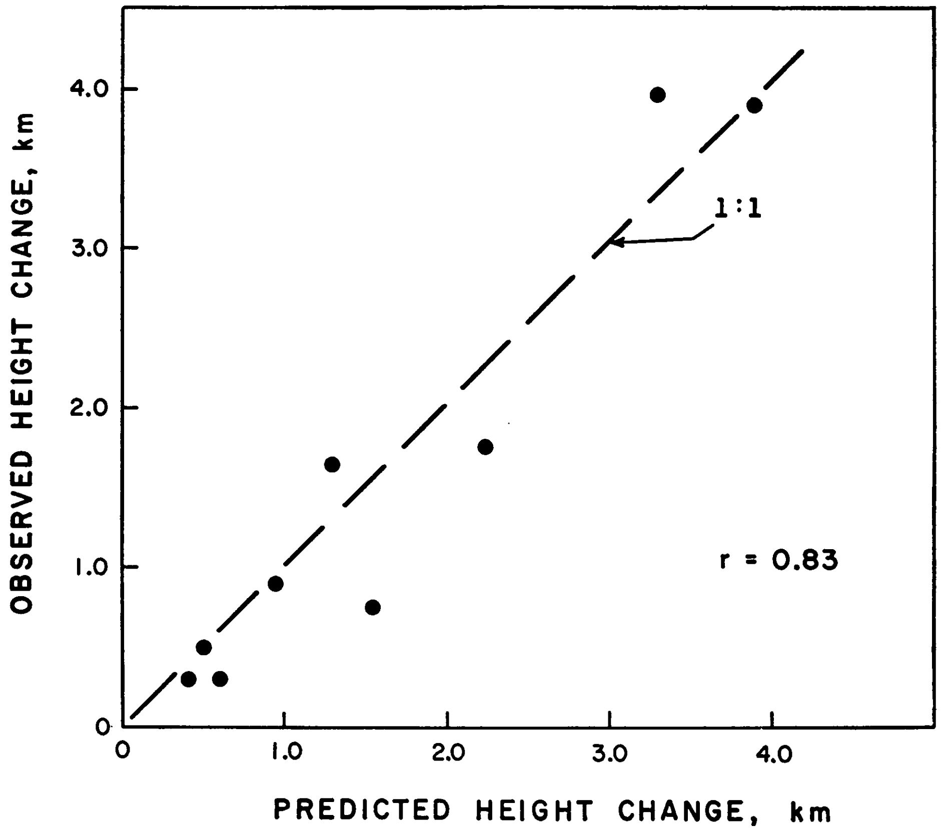

FIGURE 7

Scatter diagram for observed height change versus predicted height change of seeded clouds.

parameter that the statistics have been applied to. Experiments based purely on a randomized design to seed a given field of clouds appear to be not only sterile from the scientific viewpoint, but doomed to inconclusiveness from a practical viewpoint. Yes and no, black and white, or spectacular results are not to be expected at this stage.

Again, the importance of observations, models, and the understanding of natural events as prerequisites for meaningful modifications are pointed out. In particular we want to emphasize the philosophy that the experimental design of seeding tests must be based on physical understanding. We feel this is in contrast to certain experiments where the design has been dictated by statistical requirements rather than applying the statistics as a tool to help evaluate the results. This has come about because the meteorological profession, not having sufficient understanding of natural processes, stated the problem wrongly to the statistician who then applied his tools to a poorly designed experiment full of unknown traps. One very upsetting aspect of the evaluation of precipitation modification experiments conducted thus far has been the failure to take into consideration the changing role that the cloud seeding may take with time, presuming the cloud seeding has some effect when initially begun. Certainly if cloud seeding has any effect, it will lead to propagation or alteration of the mesoscale structure.

For example, if the seeding leads to profound development of a group of cumulus clouds, and formation of a traveling circulation system, this may suppress other cloud development in the immediate environment and successive seeding in the same area, or even upwind from the already growing cloud system, may produce only minor effects. Such moving and changing circulations within target and control areas over a flat region will continuously change the seeding opportunities or susceptibility. In regions where there is heating or cooling by the surface or topographic irregularities which influence cloud processes, it will be even more complex.

11. Extension of present experiments to speculations on weather control

Obviously the successful alteration of individual cumulus clouds is limited to proper environmental conditions and is only a small portion of the group of coherent studies required to derive some inference about the potentials of weather control. For example, in the studies of precipitation characteristics in central Pennsylvania it was found that very seldom does significant rain come from scattered or isolated showers. In fact the data indicate that 90 to 95 per cent of the summer rainfall comes from organized bands, groups, or lines of showers [1]. Calculations of entrainment effects on individual showers amplify this observation in that even small amounts of entrainment lead to significant reduction in the available kinetic energy and the liquid water content in clouds. One is led to believe that nature's way of beating these severe environmental influences on clouds is through organization of the convection to reduce the mixing effects.

One thing that must be admitted is that, in any modification attempts, one strives to alter natural processes merely by *imitating* what nature does at other times and places. Thus, if nature only produces significant rain by organization of convective cells, then it is also very likely that artificial attempts to alter cumulus will only produce significant rain when the cumulus are altered into organized patterns of certain sizes and spacing.

Based upon this premise, it is possible to formulate concepts which offer a reasonable potential for significant weather control. These concepts further dictate the background material needed and the observational capability required in order to establish a meaningful experiment.

In large scale circulation systems there occur variations in stability, air motion, and microphysical processes that produce unlikely conditions for precipitation in one area, marginal in another, and highly efficient processes elsewhere. It is in the areas of marginal conditions (generally ahead of and behind natural precipitation zones) where the opportunity lies to imitate nature and produce effects in a predictable manner. Again, from radar studies it is apparent that even in the large, uniform cloud layers, considerable structure exists in the precipitation patterns. The evidence shows that "natural seeding" causes imbedded convection that leads to larger vertical motions and more intense precipitation. There exists some evidence that the convective motions thus induced have considerable influence on the energy distribution and consequently cause adjustments in the larger scale circulation.

There are several critical points which apply in widespread cloud layers. First, it is clear that if glaciation is activated heterogeneously throughout the cloud, the influence of the release of latent heat is relatively minor. On the other hand, if the glaciation is rapid and uniform over a specific volume of cloud, the released heat is available as kinetic energy and is released in the local air motion. Since the larger cloud layer offers a less hostile environment for buoyant motions (entrainment effects should be negligible), vigorous mesoscale circulations can develop and produce conditions in which normal microphysical processes can operate to generate heavier precipitation in that area.

It should be clear that the success of any experiment like this would, of course, depend on the adequacy of the data gathered during the conduct of the experiment. One would have to be able to determine the times and places where the stability of the atmosphere would be marginal and where inducement of such mesoscale circulations, within the large scale cloud system, would be of significant help in concentrating precipitation in one area or another. It is further recognized that the formation of a mesoscale circulation, which would tend to promote upward vertical motion and precipitation in one area, would have balancing effects in the surrounding area by presumably inducing downward motions, suppressing cloud development, increasing stability, and as a consequence decreasing precipitation. It is also quite apparent that one could work either to organize such bands, and to increase precipitation or to promote competing smaller circulations to decrease it.

If one can promote the development of individual clouds or groups of clouds and concentrate convection in a given region, under certain conditions, one may also strive, under other conditions, to promote the development of many *small* disorganized centers of convection. Utilization of the potential energy available, in these many small centers, may eliminate the development of intense disturbances. The necessity for some organization in order for a severe thunderstorm or tornado to develop suggests the possibility that the latter technique, that of promoting many centers of convection rather than permitting large centers to develop, might be used to decrease the possibility of the formation of such severe storms. There is some indication from the work of Danielsen [10] and others that the organization necessary for the development of severe storms is not infrequently due to the extrusion of layers of stratospheric air down through the troposphere, or advected adiabatic layers which serve as a cap or lid on convection. Only when these layers are lifted is convection permitted to penetrate into rather confined regions leading to organization of the available energy for convection in the lower layers into lines or zones. Should the data gathering and analytical abilities proceed to the point where monitoring the structure of the atmosphere permits rapid identification of these areas, it seems reasonable to assume that alteration of the convection in advance of the natural breakthrough of the convective lines could cause smaller cumuli to grow over a wider region, thus suppressing the development of severe storms.

Whenever consideration is given to either the promotion or the discouragement of major convective development in large scale cloud systems, it must be fully realized that we are dealing with the momentum exchange between the lower and upper parts of the troposphere and are crossing the boundary between mesoscale systems and synoptic scale systems. We are entering the region where we are affecting the energy distribution within the synoptic scale system and may contribute to the development or lack of development of large scale circulations.

12. National programs (economics, social, and legal aspects)

If this country is to embark on a full scale program of investigating the potential of weather modification and actually applying developed technology to realizing this potential, it seems that thorough investigations of the economic, social, and legal implications of expected results of weather modification are necessary. It does not take much imagination to realize that a given increase or decrease in precipitation in an area has much more far reaching effect than its consequences to agriculture, electrical power generation, or the attendance at the local amusement park. From the very beginning of the exploratory tests to the present era of weather modification, the legal problems attendant to even the discussion of the possibility of weather modification have become rather obvious on frequent occasions. It seems obvious that one cannot even consider *designing* an experiment that would attempt to modify synoptic scale circulation without becoming involved with tremendous economic, social, and legal problems.

At the very least, some federal legislation is now necessary that will protect those responsible individuals or groups who are carrying on the experimental and operational phases of our weather modification efforts from being sued for damages by people who feel they are adversely affected. However, means must also be available to reimburse those with legitimate claims. Certain individual states now have laws concerning regulation of cloud seeding but these are inadequate and unrealistic for handling the future experiments in weather control.

13. Conclusion

It seems important to repeat that in weather modification experiments attempts are made merely to imitate nature. Until it is feasible to observe the natural sequence of events, derive proper analytical procedures and attain at least a partial understanding of the physical processes, the ability to imitate will be meager. Natural processes do not seem to be beyond understanding, but are primarily beyond current capabilities in observations and analyses. In order to improve these capabilities, we need to bring to bear on the problem some of the talent and techniques of the engineering profession which has so successfully pushed other large scale projects in our country. With all due modesty, it must be stated that the problem is a little bit bigger than the usual engineering project and it can hardly be expected that this job be handled on the basis of small individual projects. In the past, exploratory studies have been handled by small individual projects, by individual investigators working in the laboratory, and they have been adequately financed through the National Science Foundation and other federal agencies along with individual contributions of time and effort. In addition, it has been possible to handle some of the recent experimental aspects in this way. Future experimental avenues will have to be pursued on a much larger scale, involving a much larger scale of support. The operational techniques that will be required to bring anything of economic value from weather modification are completely beyond the capabilities of any presently existing meteorologically oriented organization.

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