Cloud Seeding Opportunity Recognition

by
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between -13C and -23C, and cloud top wind speeds between 11 mps and 28 mps and from 33 mps through 41 mps.

Snowfall is doubled when seeded events have cloud top temperatures from -13C through -20C, and wind speeds between 11 mps and 28 mps. Natural snowfall may be reduced by nearly 25 per cent when seeded events have cloud top temperatures colder than -27C, wind speeds less than 11 mps, and limited supplies of moisture.

Evidence is found that seeding may both initiate or prohibit snowfall under certain conditions.

The results of the study offer a crude verification of the basic tenets of current orographic cloud seeding theory.

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CHAPTER I

INTRODUCTION

Introductory Remarks

Water resources of the western United States are presently severely taxed, and the need for additional water grows each passing year. This region depends heavily upon mountain snows to provide the water for their myriad of needs. Consequently, the possibility of increasing snowfall over the western mountains is being explored as an important part of this urgent quest for additional water.

Moisture is stored in the atmosphere in three forms. These include invisible water vapor, liquid water droplets and ice crystals. Less than 10 per cent of this storage is realized in precipitation during transit over Colorado. A greater tapping of this moisture storage may result when meteorological conditions that favor the artificial augmentation of natural snowfall are known.

The natural snowfall process depends upon the presence of moisture, upward motion, and condensation and sublimation nuclei active at existing cloud temperatures. Moist air cools when lifted. If the cooling proceeds temperatures are reached at which the vapor condenses into water droplets, and ice crystals may form from the vapor by sublimation, or by the freezing of water droplets. These processes depend upon the number, size and type of the cloud's nuclei. For snow to be realized at the earth's surface, the growth of ice crystals must continue until they attain a fall speed which exceeds the upward motion in the clouds. Ice crystal growth is very complex, and depends upon the interaction of ice crystals and cloud droplets, and between individual ice crystals to form aggregates or snowflakes.

This complex precipitation process may be inefficient if sufficient cloud nuclei are not available. In these cases a portion of the potential precipitation is retained in the atmosphere in the form of supercooled cloud droplets.

A study of the precipitation processes which accompany central Colorado mountain snowfall was begun in 1959 at Colorado State University. An important part of this investigation includes a study of the possibilities of beneficially modifying important phases of the natural precipitation process.

The Problem Under Consideration

Early attempts to increase mountain snowfall were frequently plagued by poor experimental design. Little attention was directed toward a determination of atmospheric conditions which are most favorable for augmenting natural snowfall. Thus, many of the early cloud seeding endeavors yielded little information pertaining to the physical processes accompanying the modification of snowfall.

Broadcast seeding experiments have usually resulted in quite modest increases in precipitation. These increases are generally quoted as being less than 15 per cent. The nature of these small increases in precipitation has not been explained. Do these small increases reflect consistent small individual gains, or are they a result of significant increases and decreases which nearly cancel one another over a long period of indiscriminate seeding?

Research oriented toward determining when conditions are favorable or unfavorable for seeding orographic storms has been limited. An investigation of this nature requires an experiment with a good statistical design, conducted over a sufficient time interval to assemble meaningful sample sizes. The Colorado State University weather modification experiment fulfills most of these requirements.

Purpose of This Study

The purpose and objectives of this study are to:

1. Investigate the relationship between seeding effects and meteorological conditions present over the Climax experimental area.
2. Determine atmospheric parameters which are associated with favorable and adverse seeding effects at Climax.
3. Determine if the variation in precipitation changes observed are consistent with certain aspects of current orographic cloud modification theory.

CHAPTER II

DESIGN OF EXPERIMENT

Importance of Experimental Design

The study of the snowfall process and its modification is complicated by the large variability within the atmosphere. This variability is found in all the atmospheric processes leading to the formation of precipitation. The planetary wave configuration with its embedded synoptic scale disturbances may vary widely over a period of a few days. Even yearly fluctuations are noted in these configurations. The thermodynamic and physical characteristics of the cloud system share this large variability. Important fluctuations occur in the form, intensity and quantity of snowfall. Variations in precipitation between wet and dry years in most areas exceed 400 per cent.

If the smaller fluctuations in snowfall due to seeding are to be isolated, the experimental design should reduce other variabilities to a minimum, and eliminate them when possible.

Design of the Climax, Colorado, Experiment

The basic features incorporated in the Climax experiment have been discussed by Grant and Mielke (1967). The important features are summarized as follows:

1. Randomization is employed in obtaining the seeded and non-seeded samples. The randomization is unrestricted (Neyman and Scott, 1965).
2. The experimental time unit is 24 hours. This compromise minimizes variation in the physical parameters during an event. It is still long enough to (1) lower the "noise" level to reasonable values when establishing correlations with upwind precipitation controls, and (2) minimize uncertainties of seeding in the area near the start and end of the experimental period.
3. The observations of meteorological variables, for both seeded and non-seeded cases, are made as extensively as feasible during all stages of the precipitation process.
4. Standard Weather Bureau stations southwest, west, and northwest of the experimental site were chosen for control stations. This procedure was initiated because the terrain upwind of the target is unsuitable for the establishment of special control stations. A separate statistical investigation was performed to select stations that correlated well with the target. The historical data from the Weather Bureau gage at Climax were used in this study. It was not employed in the primary experiment once station selection was completed.

Operational Procedures Employed

1. Randomization is accomplished by drawing 100 paired slips from a container at the start of each season. A chronological ordering of the decisions is then prepared.
2. The criteria of an experimental day is that Leadville, Colorado, is expected to receive at least .01 inches of precipitation within the 24-hour period. This forecast is prepared by the United States Weather Bureau in Denver, Colorado. The forecast is prepared from 6 to 8 hours prior to the start of each experimental day. The forecasters have no access to the seeding decision or specifically how they will be used.
3. Two changes have been made in the start of an experimental period since the Project began. The 24-hour time unit however, has been conserved. During the spring of 1960 the experimental day began at 1600 MST. This occasionally exposed nighttime snowfall to daytime melting and evaporation off observation snowboards. Beginning with the 1960-61 winter season the experimental period was altered to begin at 0800 MST. This time corresponds to the low point of a very pronounced diurnal variation in precipitation intensity. The experimental interval was changed slightly for the 1961-62 winter, and subsequently has begun at

0900 MST. This change was to accommodate snow observers.

4. Generators at Minturn, Redcliff, south of Tennessee Pass, and west of Leadville are turned on 30 minutes prior to the start of the experimental day. They are run continuously until operations are terminated 30 minutes prior to the end of the period. The procedure is identical for generators at Aspen and Reudi except a one-hour lead time is employed. Specific units used are changed during the interval as specified by the Weather Bureau wind forecast.

5. A Colorado State University modified Skyfire, needle-type ground generator is used for seeding. These generators have been extensively calibrated in the Colorado State University cloud chamber to establish the temperature activation characteristics of the particles produced. A seeding rate of about 20 grams of silver iodide per hour is used. Figure 1 shows the output of effective ice nuclei from these generators. The output is compared with Fletcher's (1962) theoretical curve and other efficient silver iodide generators. The modified Skyfire generator produces about 10^{14} particles per gm AgI effective at -12C and 4 X 10^{15} particles per gm AgI effective at -20C.

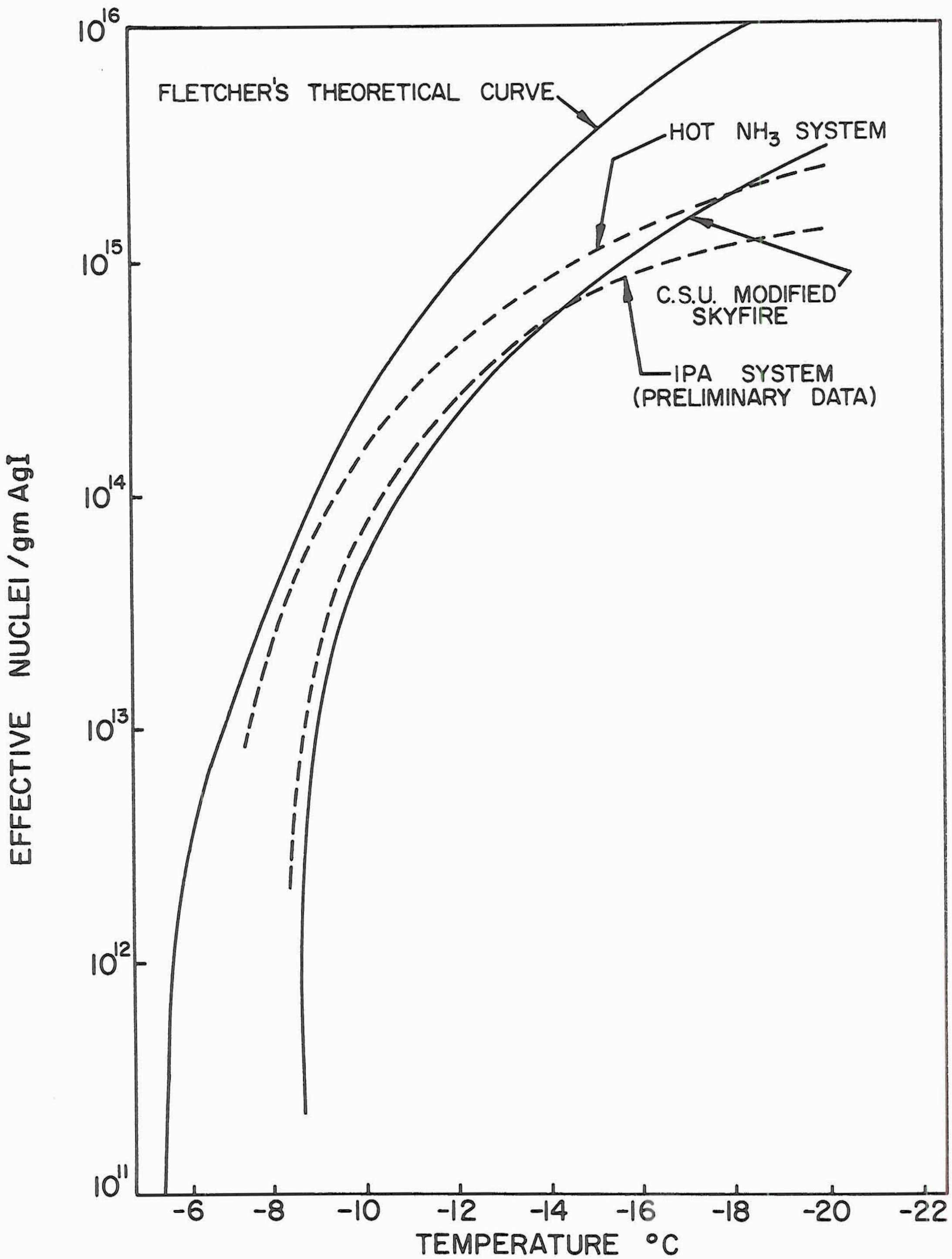

Fig. 1. Seeding output as a function of temperature for generator used in the Climax experiment (Effective Particles/gm AgI).

6. The precipitation observed at the High Altitude Observatory (HAO) of the University of Colorado is used in this study. Data from gages at different elevations on Fremont Pass and from nearby passes are the subject of other investigations, and are not included in this study. The summit of Fremont Pass is considered the primary target for the seeding. Climax, Colorado, is located near the summit of Fremont Pass, and the High Altitude Observatory is located about two miles northwest of Climax.
7. Many physical observations are taken which are indirectly related to this study. Ice nuclei observations have been made on most days. Intermittent observations are made of snow crystals reaching the ground on seeded and non-seeded days. Other physical observations include ice crystal replications, cloud photography, radar photography, and atmospheric electricity.

CHAPTER III

DESCRIPTION OF EXPERIMENTAL SITE

Topography of Experimental Area

The experimental area is located along the continental divide of central Colorado. Figure 2 shows the important topographical features of the region. The primary target (summit of Fremont Pass) lies along an expanse of the Continental Divide, which is oriented east-west for about 18 miles across the region.

Three passes, Tennessee (10,424 ft msl), Fremont (11,318 ft msl), and Hoosier (11,542 ft msl) traverse this east-west section of the Divide separated by distances of about 8 miles. These passes are kept open all winter despite snow accumulations of 6 feet to 8 feet by early spring. Thus, the area is accessible during the long winter, and daily observations can usually be taken. Elevations in the experimental area vary from 8,000 feet to 12,000 feet with a few peaks reaching over 14,000 feet. Timberline is at approximately 11,500 feet, and the area is covered extensively by coniferous forests.

The Sawatch Mountain Range lying 15 miles to 20 miles southwest through west northwest of Climax is a formidable

Fig. 2. Topography of experimental area with generator locations.

barrier. This range generally exceeds 12,000 feet with several peaks over 13,500 feet, and includes the combination of Mt. Elbert and Mt. Massive which rise over 14,400 feet just 20 miles southwest of the target.

The Gore Range rises abruptly just east of Climax and reaches elevations over 14,000 feet within 3 miles of the target.

Large scale uplifting occurs over the experimental area as upper wind currents are forced over the high mountain ranges of the region. The extent that the local terrain influences and modifies this broad-scale orographic uplifting is not fully determined.

Relationship of Generator Sites to Primary Target

Six generators are employed in the project. The location of these generators with respect to the primary target is shown in Figure 2. The azimuth and distance of each generator from the primary target is shown in Table 1.

TABLE 1.--Location of seeding generators with respect to the primary target

Location	Azimuth and Distance from Target (degrees/nautical miles)
Minturn, Colorado	320/16
Redcliff, Colorado	316/11
South of Tennessee Pass	250/ 7
West of Leadville, Colorado	218/11
Aspen, Colorado	249/31
Reudi, Colorado	267/29

The generator sites at Aspen and Ruedi lie west southwest and west of the target about 30 nautical miles. Particles released by these units are forced to ascend the western slope of the Sawatch Range 15 miles to 20 miles west of the target.

Four generator sites are within 7 to 16 nautical miles of the target. These are located in the high valley which separates the Sawatch and Gore Ranges. They extend from southwest through north northwest of the target.

The Chicago Ridge separates the generator south of Tennessee Pass from the primary target. This short range reaches 12,000 feet only 3 miles to 5 miles west of the target. As a result the nuclei from this generator are subject to strong orographic lifting a few miles west southwest of the target.

The particles emanating from the generator west of Leadville are subject to gradual orographic lifting as they approach the target. The upwind fetch from this generator is severely limited by the Mt. Elbert-Mt. Massive combination.

The nuclei generated at Minturn and Redcliff are embedded in an orographic stream having a long, continuous fetch directed toward the target. This northwesterly flow appears to most closely approximate an idealized orographic current.

Climatology of the Target Site

During the winter months (November through April) the target area is affected by traveling cyclones which occasionally penetrate this long-wave ridge position. These occur more frequently during the late winter and early spring months. Through the winter period cloud temperatures remain below freezing. Consequently, cloud temperatures are within the range where ice nuclei can be expected to play an important part in the formation of precipitation.

Table 2 describes the important characteristics of the snow season precipitation at Climax, Clolorado.

The large number of days having measurable precipitation (almost one half of total possible) provides a great opportunity to assemble experimental events rapidly. The many days of light amounts results from the orographic origin of most precipitation. Table 2 shows that one half of all measurable precipitation days yield amounts of .11 inches or less, while 90 per cent of such days result in .36 inches or less.

Table 2 also indicates that the range of daily precipitation amounts for 80 per cent of all cases remains within one order of magnitude. This is a highly desirable feature for statistical analysis. It is also noted that the total range oi measurable snowfall has remained within two orders of magnitude during the eight-year period of record.

TABLE 2.--Climatological data for Climax, Colorado, for the period November through April

Based on records from November 1953 to April 1960 (Grant and Schleusener, 1961)

Mean temperature	18.6F
Mean precipitation	14.14 inches
Average number of days with precipitation	85
Median number of days with precipitation	88

Based on records from November 1956 to April 1964

Daily Precipitation (inches)	Relative Cumulative Frequency (percentage)
.06	35
.11	50
.15	60
.21	70
.26	80
.30	85
.36	90
.43	95
.57	98
.63	99
.72	99.5
.95	100.0

Based on records from November 1956 to April 1964

Daily Precipitation Range (inches)	Relative Frequency (percentage)
.04 to .40	80
.03 to .50	90
.02 to .65	99
.01 to .95	100

CHAPTER IV

DESCRIPTION OF STATISTICAL AND METEOROLOGICAL PROCEDURES

Data Employed in This Study

All experimental cases used in this analysis were accumulated during the period extending from the spring of 1960 through the spring of 1965. Cases are confined to days where the 500 mb wind direction remained between 210 and 360 degrees. This restriction assures that a portion of the seeding plume could reach the primary target.

Statistical Procedures

In an initial study of 194 cases each meteorological parameter was stratified. Then the percentage difference in snowfall between seeded and non-seeded cases was computed for each stratum by the equation

$$\text{Percentage Difference} = \frac{T_s - T_{ns}}{T_{ns}} - \frac{C_s - C_{ns}}{C_{ns}} \qquad (1)$$

where T refers to the target precipitation, C the control precipitation, and subscripts s indicate seed cases and ns non-seed cases. The categories were adjusted to yield the greatest differences in seeding effects, or to denote important trends in the seeding effect.

The final study of 252 cases maintained the initial stratification, and estimates of scale changes resulting from seeding were computed by parametric and nonparametric techniques. The computer program is presently limited to the calculation of scale changes between -50 per cent and +100 per cent. The program requires a minimum of 20 seeded and 20 non-seeded events in order to evaluate scale changes. This has resulted in a few scale changes being unavailable in the final study of 252 cases.

Three methods which evaluate differences in precipitation between seeded and non-seeded periods have been discussed by Grant and Mielke (1967). The first two methods apply nonparametric procedures. The third method is based on a parametric technique introduced by Thom (1957).

The two nonparametric techniques employ simple ranking procedures. These techniques utilize all pairs of target and control observations. The number of observations of the seeded and non-seeded periods must be approximately the same. The underlying assumption in both techniques is that if seeding has no effect on the amount of precipitation, then the difference between the control and target precipitation for seeded and non-seeded days represent observations from identical distributions.

The parametric approach assumes that precipitation data may be approximated by a gamma distribution. The raw data is transformed into normalized data which is suitable for the application of a single regression analysis. The basic information for both seeded and non-seeded periods consists of non-zero paired observations (target and control). The expectation of the resulting normalized test statistic is taken in terms of the assumed underlying gamma distributed variables. Then a point estimate of a scale change during the seeded period with repsect to the non-seeded period can be obtained.

The large variability in the experimental data combined with the relatively small sample sizes resulting from partitioning, make it impossible to derive tight confidence intervals of scale estimators. In order to supply some meaningful interpretation of the results, the probability of the scale change being exceeded in the same sense by chance is included in the final tabulated summaries.

Meteorological Procedures

The meteorological data assembled for this investigation was interpolated from standard 700 mb and 500 mb charts received over the National Facsimile Network. These charts are prepared from upper air observations taken twice daily.

Grand Junction and Denver, Colorado, are a part of this national network, and take radiosonde observations daily at 0500 MST and 1700 MST. The observing site at Denver lies 80 miles east northeast of the target. Grand Junction is located 130 miles west of the target. Values of wind direction, wind speed, temperature and dew point temperature were interpolated for the target from the 700 mb and 500 mb charts. These standard pressure surfaces are approximately 10,000 feet and 18,500 feet above sea level. The first height is near or just above the altitude of the generator sites. The latter height coincides closely with the top of wintertime cloud systems over the experimental area (Furman, 1967).

The diurnal distribution of precipitation for each experimental day was investigated. These results were used to select the time of meteorological data employed. The data at (or nearest) the time of precipitation occurrence was chosen. In a few cases when precipitation occurred continuously through the experimental period, the data was selected at the time of greatest precipitation. Unless otherwise noted, all results, tables, and graphs have been compiled using data chosen by the above criteria.

CHAPTER V

THEORETICAL ASPECTS OF SEEDING OROGRAPHIC CLOUDS

Introduction

Since Wegner (1911) first suggested the rapid growth of ice crystals within supercooled water-clouds, the artificial stimulation of precipitation was believed possible under certain conditions. If cloud systems existed where effective natural nuclei were not present in the required number, and an artificial means could be found to supplement this deficit, a more efficient precipitation process was envisioned. Schaefer (1946) showed that it was possible to create ice nuclei in the atmosphere by seeding with dry ice (solid carbon-dioxide). A method for nucleating ice formations in the atmosphere by the use of silver iodide was then pointed out by Vonnegut (1947).

The physical basis for the orographic cloud seeding experiment at Climax was presented by Bergeron (1949), and discussed in more detail by Ludlam (1955). The orographic induced clouds along and windward of the mountain ranges over the western United States are composed of supercooled liquid droplets. The temperature activation spectra of natural nuclei is such that the number of effective natural ice nuclei frequently do not meet cloud requirements at the warmer temperatures. In such cases snow may not develop, or the precipitation process may be quite inefficient. The inadequate supply of natural nuclei may be supplemented by the introduction of artificial ice nuclei from ground generators, far enough upwind of the mountain barrier to allow the resultant snow crystals to grow in saturated conditions within the orographic stream.

The Growth of Snow Crystals by Diffusion

If it is assumed that the concentration of vapor molecules near a growing crystal obeys Laplace's Equation, it follows there is a close analogy between the vapor field and the electric field near a charged conductor. Jeffreys (1918) using this analogy showed that the rate of growth of a crystal could be expressed by

$$dM/dt = 4\pi CDm(N_o - N_c) \tag{2}$$

where C is the electrostatic capacity which depends upon the shape of the crystal, D is the coefficient of diffusion of water vapor in air, m the mass of a vapor molecule, N_o the concentration of vapor molecules in the environment, and N_c the concentration at the surface of the growing crystal.

Ludlam (1955) has written the growth equation in terms of the difference between the vapor densities in the environment and at the crystal surface $\Delta\rho$, and has added a velocity-coefficient V which accounts for the increase of condensation due to the settling motion of the crystal. His form of the equation becomes

$$dM/dt = 4\pi CDV\Delta\rho \tag{3}$$

where C and D are defined as previously.

The coefficient of diffusion D is a function of both air pressure and temperature. The electrical capacity C, and the velocity-coefficient V are strongly dependent upon the shape of the ice crystal. The snow crystal habit may assume a variety of forms. Aufm Kampe et al. (1951), Nakaya (1954), Magono and Tazawa (1966), and Magono (1962) have shown the particular crystal habit (plates, columns, prisms, plane dendritic, and stellar) is mainly a function of the temperature. Marshall and Langleben (1954) suggest the type of snow crystal growth is determined principally by the excess of the ambient vapor density over that at equilibrium with the ice crystal at its own temperature.

Reynolds (1952) and Mason (1953) found crystal growth at a rate in excess of that given by Equation 3. Marshall and Langleben (1954) suggested the presence of cloud droplets acted as nearby sources of vapor not considered in the simple diffusion theory.

Ludlam (1955) made certain assumptions which enabled him to integrate Equation 3 to any desired crystal size from an initial radius of 200 microns. He assumed a correction to the vapor density excess to account for the warming of the crystal surface by the latent heat release. He removed the dependence of this correction upon the air temperature and pressure by assuming a mean value valid for pressures near 900 mb and a temperature range from -6C to -15C.

Ludlam (1955) assumed that the crystal growth occurred in three stages. In the first stage the crystal radius is assumed to reach 75 microns in a period of 90 seconds. This is consistent with the observations of Reynolds (1952) and Schaefer (1953). It was assumed in the second stage of growth that the thickness of the crystal increases uniformly to 40 microns as the radius increases to 200 microns. A value of 1.6 was used for the velocity-coefficient during this stage. During the third stage of growth the thickness is assumed to remain constant at 40 microns while a constant fall-speed of 40 cm/sec is maintained. The relation $V=1+5r^{\frac{1}{2}}$ is used for the velocity-coefficient during this last stage of growth, where r is the crystal radius. Table 3 shows the time required for crystal growth under these assumed conditions.

TABLE 3.--Crystal growth time and distance settled relative to the air as a function of crystal radius (Ludlam, 1955)

Radius of Crystal (microns)	Growth Time (seconds)	Distance Settled (meters)
200	630	180
400	1400	480
600	2000	740

The values in Table 3 are not seriously affected by assuming different shapes for the growing crystal. The likelihood of crystal collisions and aggregation, which would increase the fall speed considerably, are not considered. Smith (1949), Shellard and Grant (1951), Aufm Kampe _et al._ (1953), and Hall _et al._ (1953) have conducted experiments which are in general agreement with the theoretical computations of Ludlam.

The Growth of Crystals by Accretion

The growth of ice crystals within supercooled clouds may result from accretion as crystals collide with water droplets. The growth rate due to accretion depends upon the concentration of droplets lying in the path of a falling crystal, and its ability to collect them. This process is complicated by the air flow around the crystal, which allows some of the droplets to escape collection by the falling crystal.

Kumai (1951) found traces of condensation nuclei scattered over the surface of ice crystal replicas. He suggested that accretion of very small droplets might contribute importantly in the growth even of very small ice crystals in clouds. However, Kuroiwa (1955) found that a small water droplet moving uniformly relative to a larger ice crystal at a temperature below 0C tends to evaporate because of the diffusion gradient surrounding the crystal. He showed that only droplets larger than about a micron in diameter could reach a typical small ice crystal without evaporating. Aerodynamic effects which were not considered, make it highly unlikely that droplets smaller than several microns in radius can be collected. Ludlam (1955) suggests that the critical radius is about 8 microns.

The droplet spectra of orographic clouds over the Central Colorado rockies would be expected to exhibit strong continental characteristics. These include smaller droplet sizes, a narrow distribution spectrum, and higher overall droplet concentrations with the largest number occurring around 10 microns or less. Consequently, few droplets would be collected by a typical ice crystal, and the initial accretion rate would be quite small. Under these conditions significant rates of accretion are not possible until previous mass deposits generate a large relative velocity between the falling crystal and the supercooled water droplets. The relatively small vertical extent of orographic clouds therefore precludes significant crystal growth by accretion, since crystals would leave the cloud system before the process reached its final significant stage. The infrequent appearance of snow graupel, and only occasional riming on snow crystals, strongly suggest that accretion does not contribute significantly to crystal growth at Climax.

Inside large cumuliform clouds, which contain many large size droplets, the accretion process may assume the dominant role in crystal growth. Evidence of this is seen in the frequent appearance of graupel or small hail under these conditions.

The presence of cloud droplets is important in seeding orographic clouds of limited vertical extent. Although the droplets may not contribute to crystal growth by accretion, they provide a source for crystals and contribute to their rate of growth by diffusion. The liquid droplets act as reservoirs which help maintain saturation with respect to water even in the absence of updrafts.

Activation Temperatures and Nucleating Particles

Schaefer (1946) found that the temperature threshold for the first appearance of ice crystals in the supercooled cloud depends upon the kind of particles available in the air for nucleating. Measurements in a cloud chamber within an artificial supercooled cloud at water-saturation indicated natural ice nuclei begin to form ice crystals at an average threshold activation temperature of about -12C (Schaefer, 1951). The number of nuclei activating increases approximately exponentially as the temperature lowers. At about -24C the concentration of effective natural nuclei is normally enough to satisfy wintertime orographic cloud requirements. Complete activation of natural nuclei is approached when temperatures reach about -36C (Smith and Hefferman, 1954).

The silver iodide (AgI) ice nuclei threshold activation temperature at water-saturation is about -8C for the CSU modified Skyfire generators used in the Climax project (Grant and Mielke, 1967). The introduction of AgI ice nuclei by these generators into clouds with tops warmer than -24C can be expected to increase the number of active nuclei up to a level that satisfies cloud requirements.

Optimum Seeding and Overseeding a Specific Target

For effective seeding there is initially the requirement that effective natural nuclei are insufficient to initiate precipitation, or to provide an efficient precipitation process. If this initial requirement is fulfilled, then physical processes which control the transport of nuclei, the growth rate of ice crystals, and the final settling rate of snow crystals determine the design conditions favorable for seeding a specific target.

The optimum wind speed for a given generator is the speed which results when the generator-target spacing is divided by the time required for completion of the following processes; the time for the artificial nuclei to be transported into the cloud system and activated (t_1), the time for the snow crystal to grow to its ultimate size (t_2), and the time for the snow crystal to complete its settling and be deposited at the target surface (t_3).

This definition may be written in a simple generalized formula as

$$\text{Optimum Wind Speed} = \frac{\text{Generator-target Spacing}}{t_1 + t_2 + t_3}$$

where $t_1 + t_2 + t_3$ is the total time required for completion of the direct seeded snowfall process.

Similarly, the optimum generator-target spacing is that distance which when divided by the mean wind speed over the mountain barrier yields the time required for the direct seeded snowfall process.

When distances are larger than this optimum spacing, the physical processes are completed upwind of the target and the snow crystal falls short of the primary target. If the distance is less than the optimum spacing, the crystal is carried past the target. The crystal may then continue its growth and fall to earth beyond the target, or may be carried out of the orographic stream. If the latter occurs the crystal growth will be interrupted, and the crystal subject to evaporation.

Fluctuations in the time required for the three physical processes can be expected as meteorological conditions vary over the experimental area. For example, the time required for the artificial nuclei to be transported into the cloud system may vary with wind speed, vertical wind shear, stability, and local orography. The final settling time of the crystal may vary according to its ultimate size and habit, wind speed and local orography. Possible fluctuations in crystal growth times have been discussed previously.

The variability in time for completion of the physical processes results in a dispersal of the seeding effects about the target. Clearly, seeding from a fixed generator over a wide spectrum of wind speeds results in optimum spacing for only a limited range of speeds. The optimum separation between a fixed generator and target must usually be designed for an average or median wind speed and crystal size.

The function of the orographic updraft is to maintain a state of saturation with respect to liquid water for the environment in which the snow crystals grow (Ludlam, 1955). If the crystals settling through the updraft are to grow at the maximum rate, they must not be so numerous that the updraft is unable to maintain this state of water saturation.

An estimate of the number of crystals required to produce a precipitation process of peak efficiency may be estimated for the Climax region. If saturated air ascends at 700 mb with a temperature of -5C about .5 gm/m^3 of water vapor for condensation will be provided in a rise of 500 meters. Assuming this rate of vapor supply is removed by the rate of crystal growth, and estimate of the number of crystals can be obtained (Ludlam, 1955). For crystal radii between 200 and 500 microns (most commonly observed at Climax), the optimum concentration of crystals needed to insure an efficient precipitation process at Climax is found to be 10 to 20 crystals per liter. If the concentration of crystals in the cloud should be less than this optimum amount, then not all of the vapor provided by the orographic updraft can be readily condensed upon the snow crystals.

The process of overseeding is quite important but complex. If concentrations of crystals above the optimum number are introduced into the clouds, several effects may occur. As the crystals remove more water vapor from the environment than is being supplied by the updraft, the growth rate must eventually fall to a new steady state value. For crystals more than 200 microns a reduction of growth rate usually has little effect on the fall speed. However, since the vapor pressure excess would be reduced there may be changes in the crystalline structure. Greater concentrations of crystals may also affect changes in the formation of aggregates. The total effect is difficult to assess. It is difficult to derive crystal concentrations associated with the threshold of overseeding. Previously discussed theory indicates overseeding would be more easily attained (at smaller crystal numbers) with cold cloud temperatures, and when the rate of moisture supplied by condensation is small. The latter is also strongly dependent upon cloud temperature. During the special situation when overseeding occurs, the resultant precipitation may be less than would have occurred naturally.

Successful seeding depends upon the introduction of sufficient artificial nuclei into the clouds to obtain optimum crystal concentrations. Ground based generators are usually employed since aircraft seeding is frequently hazardous. They have the additional advantage of a continuous seeding capability, and are usually less expensive to operate. The dispersal of nuclei into clouds from ground generators depends mostly upon diffusion created by the turbulent stirring of winds over rough terrain. The wind shear and stability within the cloud layer may therefore influence the upward diffusion of the seeding material.

CHAPTER VI

RESULTS

Ice Nuclei Observations at the Target

Measurements of ice nuclei at Climax indicate that large concentrations of seeding material are arriving in the target area on most days (Grant and Mielke, 1967). Occasionally, peak values during seeded days have been one hundred times greater than on previous or following non-seeded days. A substantial percentage of the observations of ice nuclei concentrations at -20C have exceeded the optimum value of 10 per liter on seeded days. Concentrations greater than 10 per liter have not been observed in control periods at Climax. The mean value for concentrations at -20C on the seeded days is 13 per liter compared to about 2 per liter on non-seeded days. The probability of this difference occurring by chance is less than one in a hundred (Grant and Mielke, 1967).

Table 4 shows the concentration of effective natural nuclei observed at Climax as a function of temperature.

The optimum concentration of ice nuclei for orographic snowfall of the character observed at Climax was computed to be about 10 per liter. Values listed in Table 4 indicate that concentrations of effective natural nuclei are usually less than this

TABLE 4.--Concentrations of effective natural nuclei generally observed at Climax, Colorado, within different temperature categories

Temperature Category Temperature Category	Concentration of Effective Natural Nuclei
-20C or warmer	2 per liter or less
-21C thru -23C	2 to 10 per liter
-24C or colder	10 per liter or more

optimum number at cloud temperatures of -20C or warmer. Observed concentrations are also occasionally below the optimum value when cloud temperatures are between -21C and -23C. Cloud temperatures of -24C or colder are normally associated with a plentiful supply of natural ice nuclei.

<u>Seeding Effects Related to Cloud Top Temperatures</u>

The 500 mb level is usually near cloud top during winter precipitation in the Climax area (Furman, 1967). The temperature at this level was used to investigate the influence of cloud top temperatures upon seeding effects.

Table 5 shows estimated scale changes computed for the total of 252 cases. In this table (and subsequent tables) S refers to the seeded events, NS the non-seeded events, NP the first nonparametric method, and P the parametric method described by Grant and Mielke (1967).

The nonparametric technique yields a scale change in excess of 100 per cent at HAO for cloud top temperatures -20C or warmer.

The parametric method indicates a scale change of 101 per cent for this same stratum. Both methods give near zero scale changes for temperatures between -21C and -27C. Small negative scale changes are noted for the coldest cloud temperatures.

Grant and Mielke (1967) using a preliminary analysis equivalent to Equation 1 found a 55 per cent increase in snowfall for cloud temperatures of -20C and warmer. They used all 283 cases, as required by the original design, although in 31 cases wind flow precluded a seeding effect at the target.

TABLE 5.--Estimate of scale changes at HAO during seeded periods with respect to non-seeded periods as computed by two statistical methods. Scale changes are shown as a function of the 500 mb temperature

Temperature Category (degrees C)	Number of Events	Test	Scale Change (percentage)
-13 thru -20	34 S	NP	over 100
	43 NS	P	101
-21 thru -23	31 S	NP	3
	32 NS	P	-6
-24 thru -27	33 S	NP	0
	30 NS	P	-7
-28 thru -35	21 S	NP	-13
	28 NS	P	-16

Another method of viewing the relationship between cloud top temperatures and seeding effects is to consider only cases where the temperature remains within a certain range during the entire experimental period. This eliminates events having large temperature changes, and reduces the error in approximating temperatures over the precipitation period by a single observation.

Table 6 shows the scale changes computed for events where cloud top temperatures remained -20C or warmer for the experimental period. The nonparametric technique continues to indicate a scale change in excess of 100 per cent, while the parametric method reaches a value of 106 per cent.

TABLE 6. --Estimate of sclae changes at HAO during seeded periods with respect to non-seeded periods as computed by two statistical methods. Scale changes are shown for 500 mb temperatures which remained within category for the entire experimental period

Temperature Category (degrees C)	Number of Events	Test	Scale Change (percentage)
-20 or warmer	26 S	NP	over 100
	32 NS	P	106

Seeding Effects Related to Stability Within Cloud Layer

Seeding effects were related to the stability within the cloud layer by two different methods.

One measure of stability within the cloud layer was obtained by defining a lapse rate parameter. Values of this parameter for an event were obtained by subtracting the 700 mb temperature from the 500 mb temperature.

Table 7 shows the scale changes computed for three lapse rate stability categories using the total of 252 cases.

TABLE 7.--Estimate of scale changes at HAO during seeded periods with respect to non-seeded periods as computed by two statistical methods. Scale changes are shown as a function of a lapse rate stability parameter

Stability Category (degrees C)	Number of Events	Test	Scale Change (percentage)
-8 thru -16	49 S	NP	23
	41 NS	P	4
-17 thru -19	50 S	NP	10
	56 NS	P	10
-20 thru -25	20 S	NP	2
	36 NS	P	7

Scale changes computed for the various lapse rate stability strata have small positive values. The nonparametric method suggests that scale changes may increase slightly with the lapse rate stability.

A second measure of stability within the cloud layer was obtained by defining a parcel stability parameter. This stability

Category (°C)	Seeded Cases	Non-seeded Cases
-2 to 1	18	23
2 to 3	23	32
4 to 5	22	26
6 to 14	29	21

Stability Index: 500 mb temperature of the environment minus the 500 mb temperature of a parcel lifted adiabatically from the 700 mb level

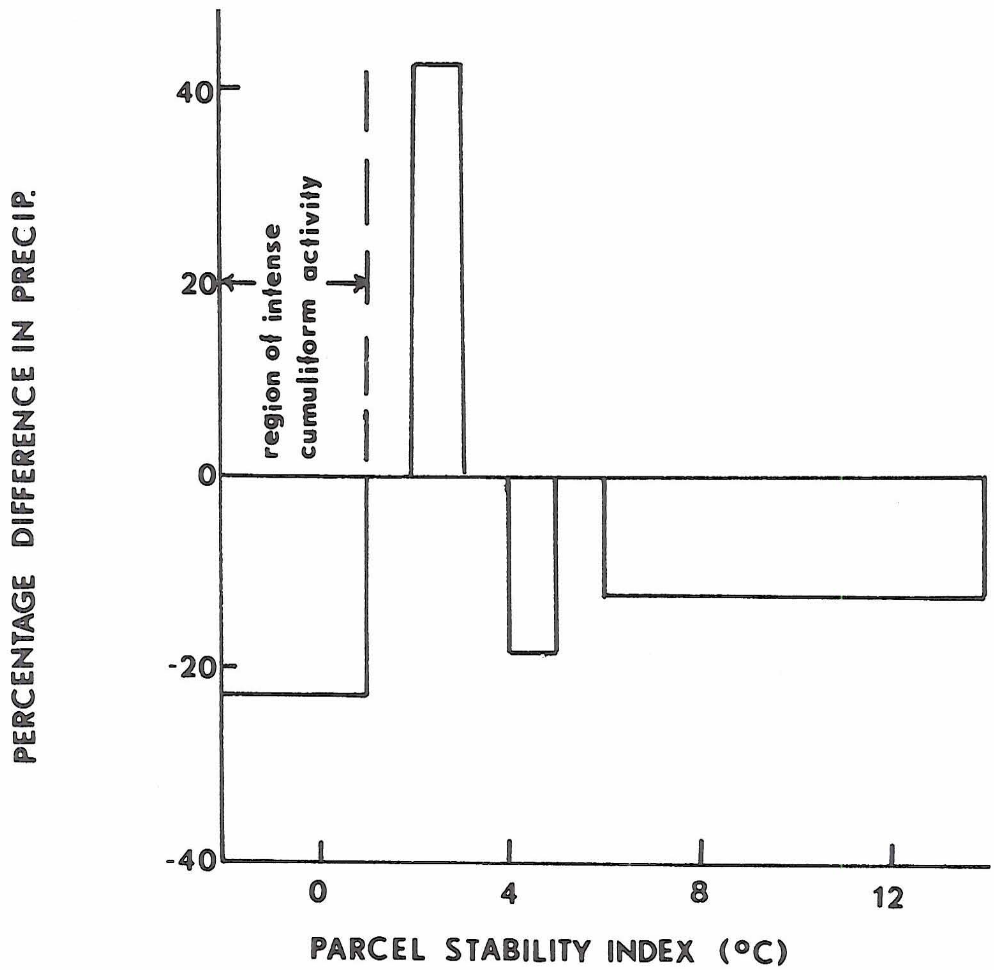

Fig. 3. Percentage difference in precipitation between seeded and non-seeded cases (adjusted for control) at HAO as a function of a parcel stability index within the cloud layer.

Category (gm/kgm)	Seeded Cases	Non-seeded Cases
1.60 to 3.72	32	28
1.00 to 1.59	31	43
.19 to .99	28	32

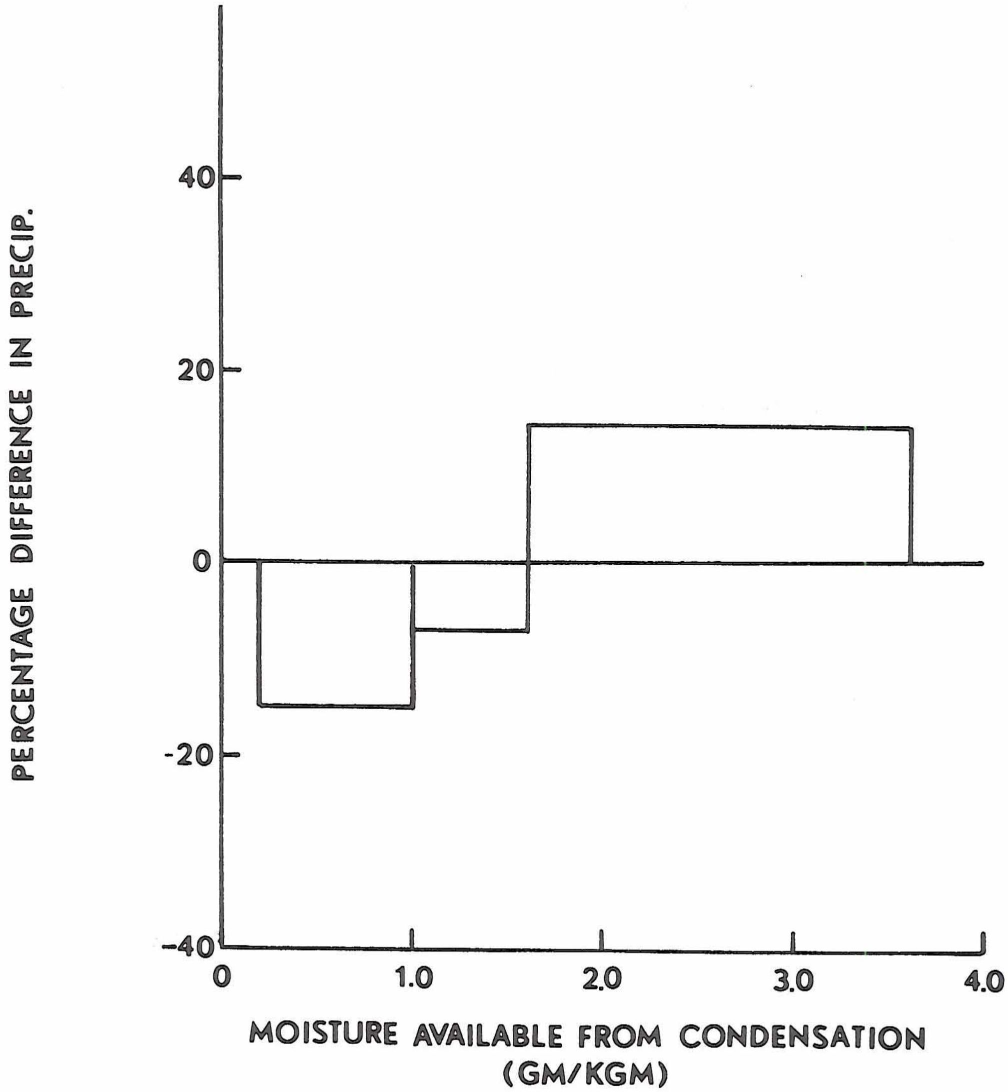

Fig. 4. Percentage difference in precipitation between seeded and non-seeded cases (adjusted for control) at HAO target as a function of the moisture resulting from adiabatic ascent from 700 mb to the 500 mb level.

parameter is obtained by comparing the 500 mb temperature with that of a parcel lifted adiabatically from the 700 mb level.

Figure 3 indicates that values of the parameter between -2C and 1C, and in excess of 4C are associated with near zero or small negative seeding effects. When values of the parameter are 2C or 3C, snow increases of 43 per cent are observed at the target. These values are determined for the initial study of 194 cases.

Seeding Effects Related to Moisture Supply

The moisture which is condensed in the orographic updraft determines the amount of water available for conversion to snowfall. An estimate of this moisture quantity was derived by lifting adiabatically a parcel from 700 mbs up to the 500 mb level. The percentage differences in precipitation between seeded and non-seeded cases as a function of this moisture supply is shown in Figure 4 for the initial study of 194 cases.

A trend is exhibited by the seeding effects although precipitation changes are small. A slight negative seeding effect exists for the drier cases, which changes to a small positive value for more moist events.

The 700 mb level is very near the elevation at which the seeding material is introduced into the orographic stream. The relationship between scale changes and the relative humidity at 700 mb was investigated, and the results are shown in Table 8.

TABLE 8.--Estimate of scale changes at HAO during seeded periods with respect to non-seeded periods as computed by two statistical methods. Scale changes are shown as a function of the 700 mb relative humidity

Humidity Category (percentage)	Number of Events	Test	Scale Change (percentage)
70 thru 93	31 S	NP	11
	33 NS	P	13
50 thru 69	48 S	NP	22
	40 NS	P	6
19 thru 49	40 S	NP	under -50
	60 NS	P	-13

Scale changes computed for the various humidity categories yield small increases in snowfall for relative humidities above 50 per cent. A negative seeding effect in excess of 50 per cent is indicated by the nonparametric method for humidities below 50 per cent. The parametric method gives a lesser value for this decrease in snowfall.

Seeding Effects Related to 500 mb Wind Structure

The 500 mb wind is representative of the flow near cloud top over the experimental region. Seeding effects were determined for ten degree increments of wind direction and the results stratified as shown in Table 9.

Variations in scale changes with wind direction are small. Near zero precipitation changes are indicated for southwesterly and westerly wind directions. A small positive scale change is observed for northwesterly flow.

TABLE 9.--Estimate of scale changes at HAO during seeded periods with respect to non-seeded periods as computed by two statistical methods. Scale changes are shown as a function of the 500 mb wind direction

Wind Category (degrees)	Number of Events	Test	Scale Change (percentage)
210 thru 240	23 S	NP	5
	24 NS	P	-16
250 thru 280	47 S	NP	1
	40 NS	P	6
290 thru 360	49 S	NP	15
	68 NS	P	14

The relationship between the 500 mb wind speed and seeding effects was also studied. These results are depicted in Figure 5 for the initial study of 194 cases.

At light wind speeds (10 mps or less) a negative seeding effect is observed. Snow increases of 19 per cent appear at wind speeds of 11 mps thru 21 mps, which increase to 58 per cent at speeds of 22 mps thru 28 mps. The positive seeding effect disappears for wind speeds between 29 mps and 32 mps. Snow increases of 29 per cent are observed again for winds from 33 mps thru 41 mps. The two highest wind speed strata have relatively few events and could have been combined to yield a near zero

Category (mps)	Seeded Cases	Non-seeded Cases
10 or less	12	18
11 to 21	48	44
22 to 28	23	23
29 to 32	4	8
33 to 41	6	8

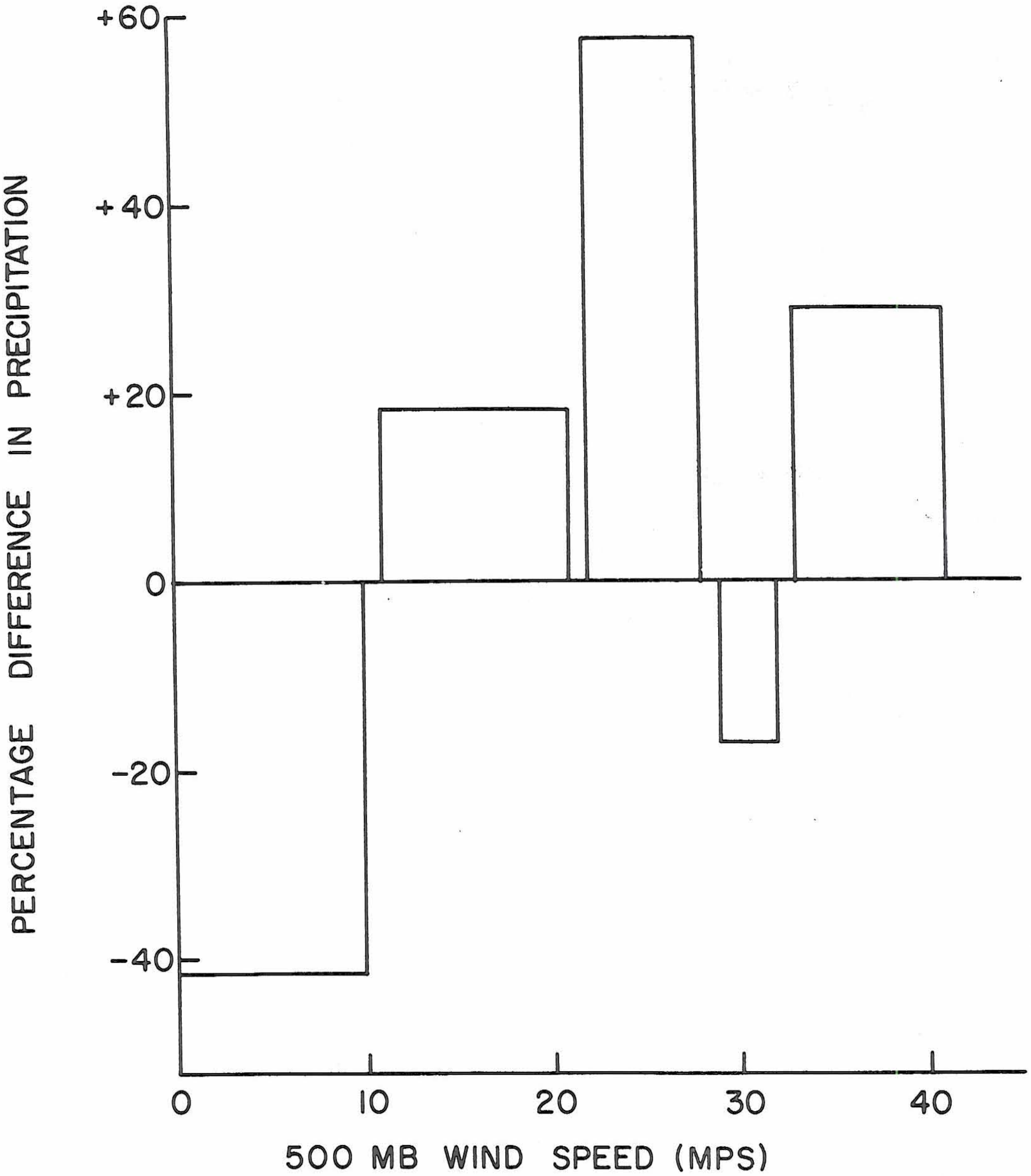

Fig. 5. Percentage difference in precipitation between seeded and non-seeded cases (adjusted for control) at HAO target as a function of the 500 mb wind speed.

21 mps, and reaches a maximum over 100 per cent at speeds between 22 mps and 28 mps. The parametric method gives similar results except for the smaller scale change in the 22 mps thru 28 mps stratum. Scale changes for winds above 28 mps are not available due to the limited number of events.

Cloud Top Winds Related to Cloud Top Temperatures

Mean cloud top temperatures were computed for the four wind speed categories depicted in Figure 5 using the meteorological data from the initial study of 194 events. These are shown in Figure 6.

The lower wind speeds are associated with colder cloud temperatures. Wind speeds of 10 mps or less have a mean cloud top temperature of -25.6C. Mean temperatures warm to -23.4C for wind speeds between 11 mps and 21 mps, and reach -22.1C for speeds between 22 mps and 28 mps. At high wind speeds (29 mps or greater) cloud top temperatures average -23.0C.

Figure 6 also shows the percentage of events within each wind speed stratum where cloud top temperatures were warmer than -24C. It is noted that only 25 per cent of the events are warmer than -24C at wind speeds of 10 mps or less. The percentage of these warm events increases with wind speed reaching a maximum of 65 per cent at speeds between 29 mps and 41 mps.

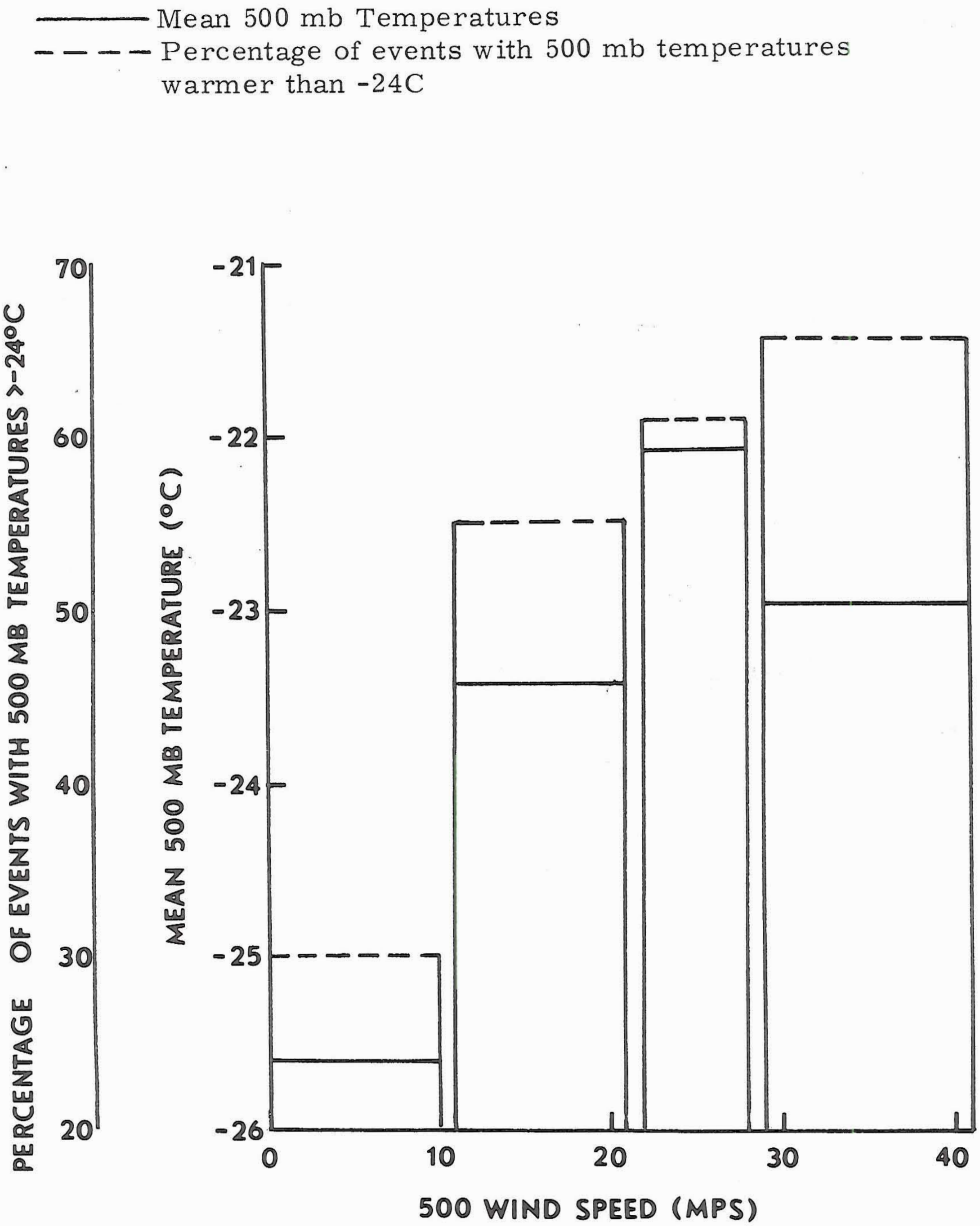

Fig. 6. Mean cloud top (500 mb) temperatures related to cloud top (500 mb) wind speed. Solid lines: mean 500 mb temperatures for four wind speed categories. Dashed lines: percentage of events within each category having 500 mb temperatures warmer than -24C.

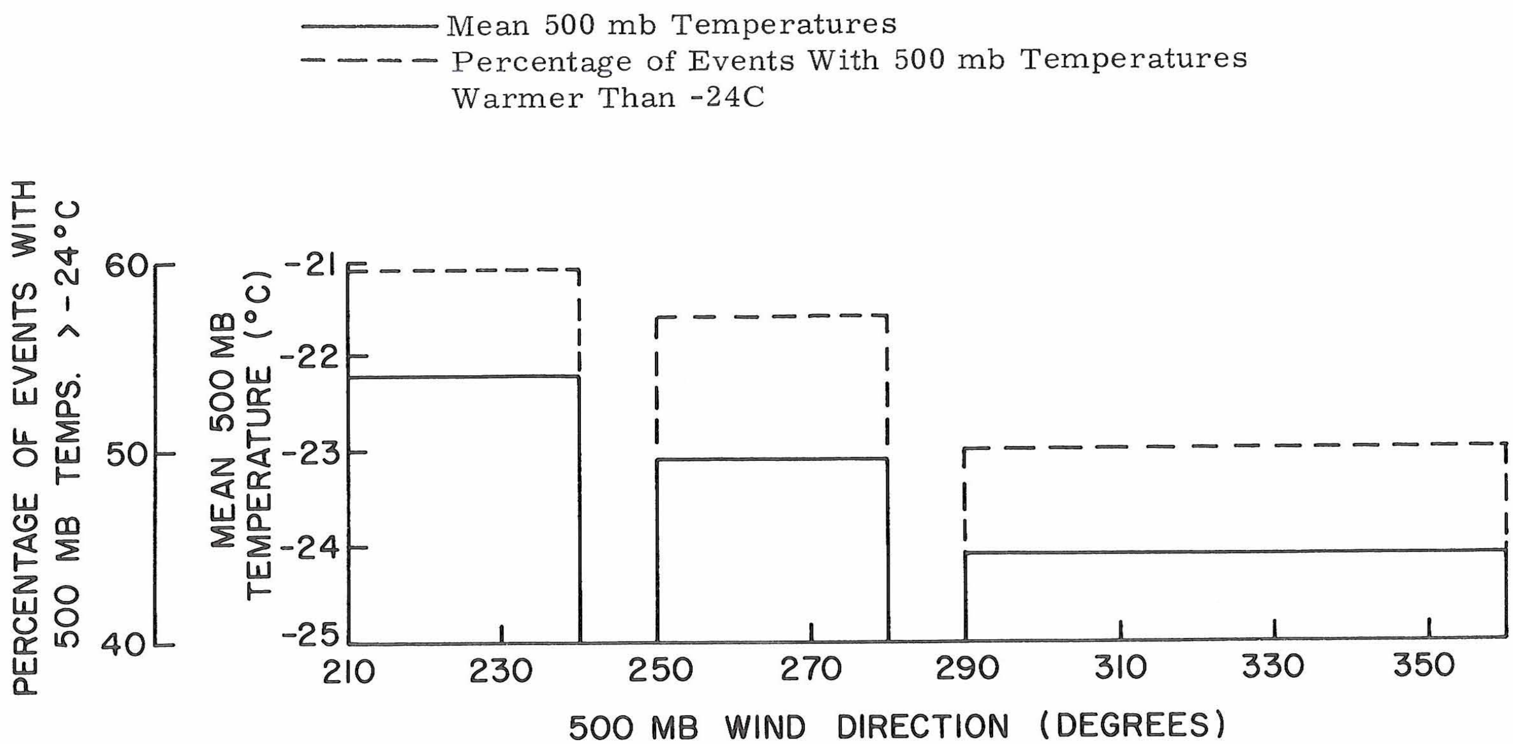

Fig. 7. Mean cloud top (500 mb) temperatures related to cloud top (500 mb) wind direction. Solid lines: mean 500 mb temperatures for three wind direction categories. Dashed lines: percentage of events within each category having 500 mb temperatures warmer than -24C.

Mean cloud top temperatures were also computed for the three 500 mb wind direction strata depicted in Table 9. It is seen from Figure 7 that warmer cloud temperatures are associated with 500 mb winds from the southwest. Colder cloud temperatures accompany northwesterly winds. The percentage of warm events (warmer than -24C) within each stratum is greatest with south-westerly winds, and decreases as winds become west and northwesterly.

<u>Cloud Top Winds Related to Lapse Rate Stability</u>

Mean lapse rate stabilities (500 mb temperature minus 700 mb temperature) were computed for each of the four wind speed categories designated in Figure 5. These mean stabilities are shown in Figure 8.

It is seen that larger stabilities are associated with higher wind speeds. The stability lessens as wind speeds decrease reaching a minimum for 500 mb wind speeds of 10 mps or less.

The percentage of events within each wind speed category where the stability was between -17C and -19C (wet adiabatic lapse conditions for 700 mb temperatures between 0C and -10C) is a maximum of 50 per cent for the lowest wind speeds. This percentage decreases smoothly as wind speeds increase reaching a minimum of 25 per cent for 500 mb wind speeds of 29 mps or higher.

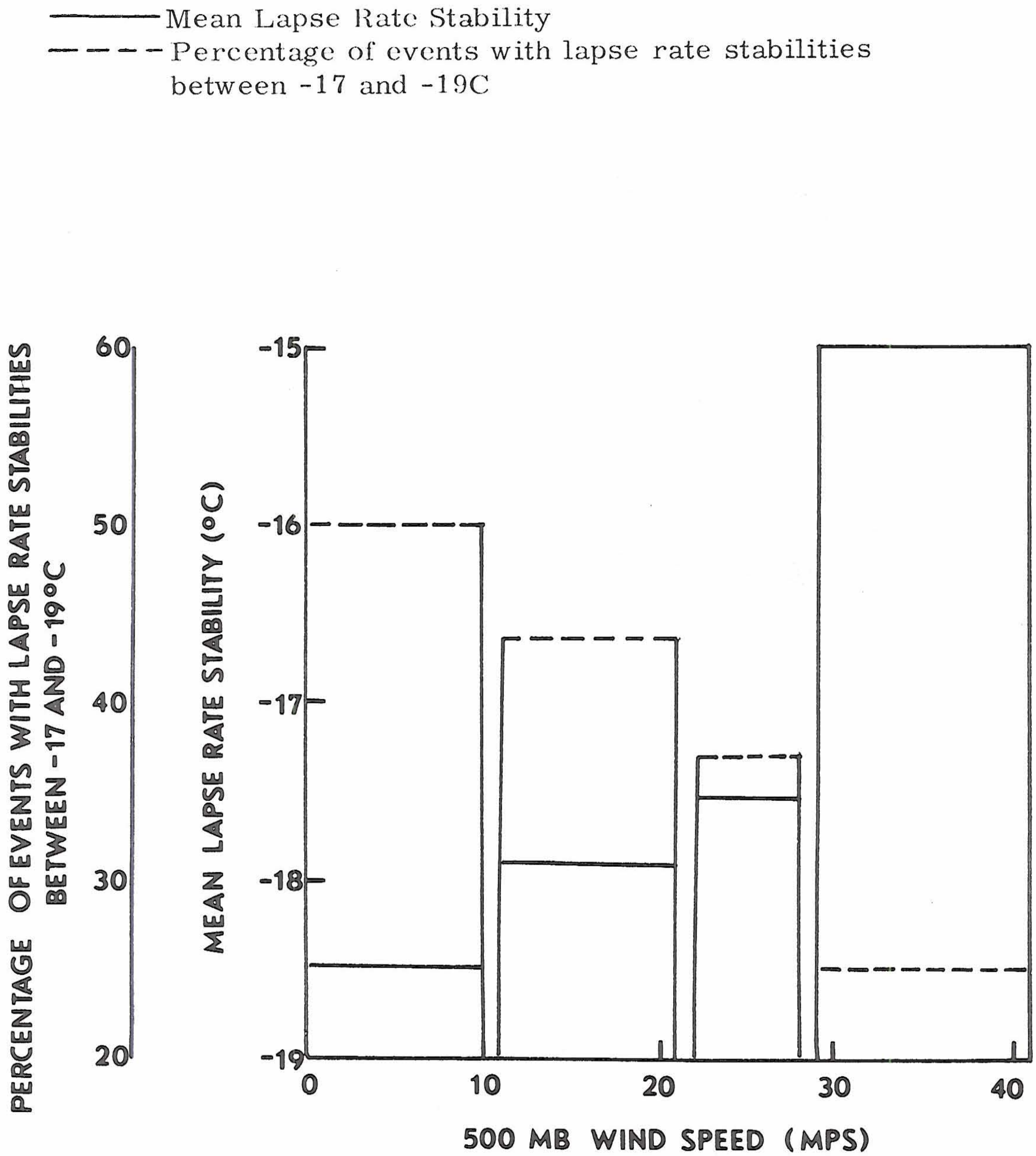

Fig. 8. Mean lapse rate stabilities related to cloud top (500 mb) wind speed. Solid lines: mean lapse rate stabilities for four wind speed categories. Dashed lines: percentage of events within each category having lapse rate stabilities between -17 and -19C.

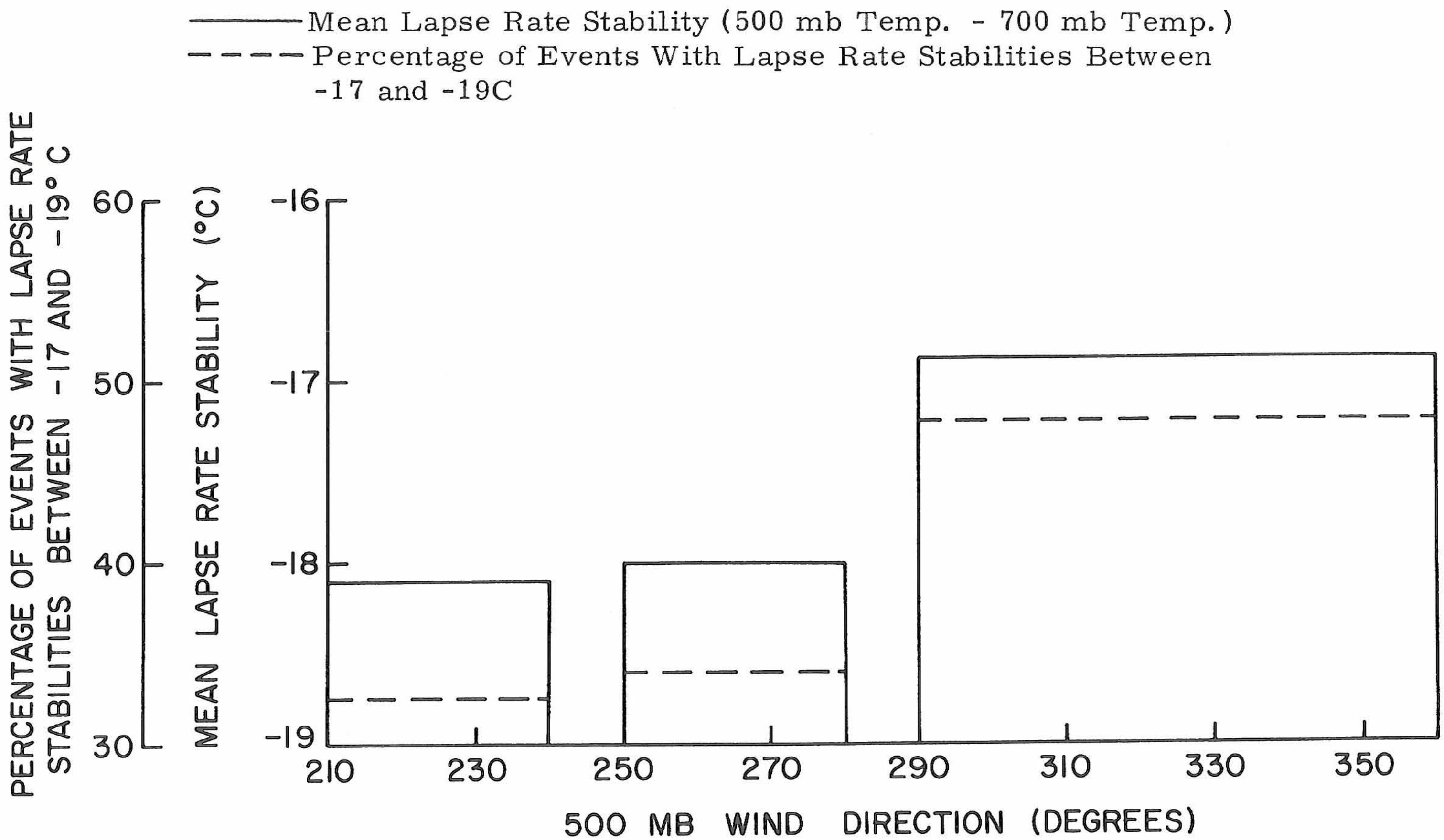

Fig. 9. Mean lapse rate stabilities related to cloud top (500 mb) wind direction. Solid lines: mean lapse rate stabilities for three wind direction categories. Dashed lines: percentage of events within each category having lapse rate stabilities between -17 and -19C.

Mean stabilities were also computed for the three 500 mb wind direction categories in Table 9. Figure 9 shows the greater stabilities are associated with northwest winds. Mean stabilities accompanying winds from the west and southwest are approximately equal, and less than those from the northwest.

The percentage of events with wet adiabatic lapse conditions has a maximum value of 48 per cent for northwest wind flow, but decreases to 32 per cent and 34 per cent for southwest and westerly wind directions respectively.

CHAPTER VII

ANALYSIS

Seeding Effects and Cloud Temperatures

The relationship between cloud temperatures, snow crystal growth, and cloud seeding opportunity were demonstrated in Chapter V. Several important quantities that were noted to be temperature dependent are summarized below.

1. In a supercooled cloud the vapor density can be considered a function only of the temperature.
2. The coefficient of diffusion of water vapor in air increases slightly with temperature.
3. Crystal habit fluctuates with cloud temperatures.
4. The quantity of water available for snow crystal growth resulting from condensation during adiabatic ascent increases with cloud temperatures.
5. The number of activated natural nuclei increases as cloud temperatures decrease. The threshold temperature is about -12C with most activating at -36C.
6. The number of activated AgI nuclei increases as cloud temperatures decrease. The threshold temperature is about -8C

with most activating by about -23C. The increase in activated AgI as temperatures decrease is approximately exponential.

7. Concentrations of effective natural nuclei at Climax are less than optimum at -20C and warmer, occasionally less than optimum between -21C and -23C, and normally plentiful at -24C and colder.

Cloud seeding opportunity lies mainly in the temperature range from -8C thru -20C. The reason is that concentrations of effective natural nuclei at Climax may be less than the optimum number required for peak precipitating efficiency in this temperature range (Table 4). Contributing to the lack of effective natural nuclei at these temperatures is the observation that only a small fraction of the nuclei present at these temperatures are activated. Thus, the introduction of artificial AgI nuclei within this temperature range should supplement the usual inadequate supply of natural nuclei.

It follows that the opportunity to increase snowfall by seeding rapidly disappears as cloud temperatures approach -24C. This is attributed to the number of activated natural nuclei that increase to help meet cloud requirements. Measurements at Climax indicate effective natural nuclei are normally plentiful at -24C and colder.

The precipitation changes due to seeding observed at HAO are in good agreement with the results deduced from physical considerations. When cloud top temperatures are -20C or warmer, seeding appears to double the natural snowfall. The effects of seeding are near zero in the range of temperatures from -21C thru -27C. There is evidence that seeding may be reducing snowfall a little below natural levels at the coldest cloud temperatures (-28C and colder).

While the slight negative seeding effect at the colder cloud temperatures is small, it is not physically unreasonable. At the colder temperatures there are not only higher natural concentrations of ice nuclei, but the rate of seeding is some 10 to 100 times greater due to the increase in number of the artificial nuclei activating at these temperatures. This could lead to excessive ice nuclei concentrations, which might produce many individual ice crystals having insufficient mass for deposition at the target site. This possibility was suggested by Grant and Mielke (1967). The smaller rate of moisture supplied by the condensation process at these colder temperatures would further contribute toward this possibility.

When cloud top temperatures remain -20C or warmer through the entire experimental period the parametric method reaches a scale change of 106 per cent (Table 6). This indicates a further augmentation of snowfall is realized when the warmer cloud temperatures continue uninterrupted.

An effect that appears inconsistent with physical considerations is the lack of a small increase in snowfall at temperatures between -21C and -23C. This might have been expected due to the occasional lack of effective natural nuclei at these temperatures. A possible explanation for this result is deferred to a later chapter.

Seeding Effects and the 500 mb Wind Structure

The distribution of seeding effects with wind speed (Figure 5 and Table 10) indicate that snowfall increases are grouped into three ranges of wind speed. A modest increase in snowfall appears to be centered near 16 mps. A second positive seeding effect is larger, and is centered about 25 mps. Another modest increase in snowfall is observed to be centered about 37 mps. It is tempting (and consistent with the physical basis of the experiment) to anticipate that these wind speeds may represent optimum conditions for some of the generators employed in the experiment. This possibility is pursued.

It is assumed that the mean orographic stream is represented by the wind flow at 12,000 ft over the experimental area. These winds are computed in appendix A. The wind speeds at 12,000 ft which correspond to the observed snowfall increases are 8.5 mps, 12.5 mps, and 15.8 mps respectively. It is now assumed that snow increases observed at these wind speeds result from the generator-target separations of 7, 11, and 16 nautical miles. These are distances from the target to the four nearest generators with two generators located at 11 nautical miles separation. The total time for the completion of the direct seeded snowfall process can now be estimated by dividing these separation distances by their corresponding wind speeds at 12,000 ft.

It is found that the direct seeded snowfall process generated at 7 nautical miles from the target transpires in 1520 seconds. For the 11 and 16 nautical mile separation the seeded snowfall process is completed in 1630 seconds and 1875 seconds respectively.

Ludlan (1955) gives the growth time for a crystal of 300 micron radius as about 1000 seconds (table 3). The observed snowfall at the primary target is generally of a single crystal nature and averages about this size. This crystal growth time is subtracted from the total time computed for the seeded snowfall process. The result is an estimate of the time required for transport of the seeded material into the cloud system, plus the time for the crystal to settle from cloud base to the target. The observations of Furman (1967) are used to establish the usual cloud base as about 150 meters above Chalk Mountain (about 12,500 ft) during wintertime precipitation in the Climax area. If a final fall speed of 0.5 mps is used, then the time for the crystal to settle from cloud base to the target is approximately 300 seconds.

The time for crystal growth and final settling (1300 seconds) can now be subtracted from the total time for the seeded snowfall process to arrive at an estimate for the time of transport of artificial nuclei from generator to cloud base. The resulting times are about 220 seconds, 330 seconds, and 575 seconds respectively, for the generators at 7, 11, and 16 nautical miles separation.

The difference in transport times may be explained by the difference in altitude of the generators. The generator at 16 nautical miles separation is at an altitude of about 7,900 ft. The two generators at 11 nautical miles are at an average altitude of about 9200 ft, and the generator at 7 nautical miles is about 10,200 ft in elevation. If the difference in elevation of the generators are divided by the difference in transport times, estimates of the average vertical rate of dispersion can be obtained. The values range from 5.3 ft/sec to 9.1 ft/sec. The average rate of 7.3 ft/sec is now multiplied by the transport times to obtain an estimate of the average cloud height above each generator site. These are found to be 1,610 ft, 2,410 ft, and 4,100 ft respectively, for the generators at 10,200 ft, 9,200 ft, and 7,900 ft. Summing the elevation of the generator sites with the appropriate height of the cloud base above the site gives an estimate of the usual height of cloud base above sea level. These are found to be 11,810 ft, 11,610 ft, and 12,000 ft. All values are close to those observed by Furman (1967), allowing for some downward sloping of the cloud base upwind of the target.

These internally consistent rough computations lend credence to the possibility that snowfall increases observed as a function of wind speed are reflecting optimum wind speeds for the four generators nearest the target. It is evident that the number of events which determined the positive seeding effect in the wind speed range from 33 mps through 41 mps is quite small. However, with the limited data available it appears this positive seeding effect may be a result of seeding from the generator at Minturn. This possibility is increased by the fact that about 80 per cent of the events at these high wind speeds occur with northwest flow.

It is difficult to evaluate the seeding effects of the two more distant generators (Aspen and Ruedi) because of the limited data available at high wind speeds. However, snowfall increases observed during the experiment have been reasonably attributed as emanating from the four nearest generators. It is therefore unlikely that the two distant generators are contributing <u>directly</u> to a favorable seeding effect at the target. It seems more likely from previous discussion in this section, that any snow increases produced <u>directly</u> by these generators, is realized along and windward of the Sawatch Range several miles upwind from the primary target. Indirect seeding effects from these distant generators are difficult to assess and have not been considered.

Snowfall decreases of -25 per cent and -19 per cent are indicated by the nonparametric and parametric methods respectively, for wind speeds of 10 mps or less. Several effects may contribute to this decrease in snowfall. Since 10 mps is considerably below the optimum wind speed associated with the smallest generator-target separation, positive seeding effects are not likely at the target. Other processes operating under these wind conditions indicate overseeding may be occurring. With such light wind speeds the volume of air seeded in a given time period is smaller, resulting in larger numbers of AgI nuclei per unit volume in the output plume. This large concentration of AgI nuclei is further enhanced by the greater generator efficiency realized at the cold temperatures which accompany these events (Figure 6). These colder temperatures are also associated with more abundant effective natural nculei.

The largest snow increases are observed when wind speeds are between 22 mps and 28 mps. In this range the parametric and nonparametric methods give scale changes of 29 per cent and over 100 per cent respectively. Four factors favor these large scale changes in this range of wind speeds. Two generators are likely to be quite effective in this wind speed range (Redcliff and west of Leadville). These generators are located southwest and northwest of the target, so that snow increases for this wind speed stratum are not being diluted by a number of noneffective events. These generators are also in the most favorable orographic position (Figure 2). Finally, this wind speed category also contains the warmest cloud temperatures (Figure 6).

The large difference between the nonparametric and parametric tests in this wind speed range deserves attention. The parametric method considers only non-zero data while the nonparametric technique uses all paired data. The difference in the two methods suggests that seeding may be occasionally initiating precipitation at the target when otherwise none would have occurred. The chi-square test was employed to determine the probability of this occurrence. The null hypothesis is that seeding has no effect on the number of individuals in the zero category. The alternate hypothesis is that seeding reduces the number of zero precipitation events. The value of chi-square for this test is computed in appendix B and is found to be 3.97. The null hypothesis may be rejected at the 5 per cent level, and there is a good chance some positive observations of target seed days would be zero without seeding.

The influence of the wind direction upon precipitation changes observed at HAO is small. This appears to be partly a result of unfavorable combinations of orographic features and cloud temperatures over the experimental region.

The maximum increase in snowfall occurs with northwest flow. This is probably due mainly to the more advantageous orographic features. These include a gradual and continuous upslope toward the target, and a relatively unobstructed upwind fetch. This positive scale change exists in spite of colder cloud temperatures which accompany these northwest flow events (Figure 7). This suggests the meso-scale orography is one of the dominant influences in providing a favorable seeding environment. This was strongly suggested by the physical treatment of the subject.

There is a lack of substantial seeding effects with southwesterly and westerly winds. This is observed in spite of relatively warm cloud temperatures which accompany these types of flow (Figure 7). The reason for the near zero scale changes is not clear, but the poorer orographic features and less favorable stability (Figure 9) probably contribute to this result.

The upwind fetch from the generators west of Leadville, and south of Tennessee Pass are severely limited by the Sawatch Range. The forced ascent and resultant precipitation over this barrier during southwest and westerly flow may dry and decrease the seeding potential of the airmass immediately east of the range. This condition may be aggravated occasionally by seeding from the

Aspen and Ruedi generators, which may increase snowfall along the Sawatch Range at the expense of precipitation that might otherwise have fallen further east over the target area. Further investigation of this possibility is hindered by the small number of events at the higher wind speeds.

Figure 9 indicates that westerly and southwesterly flows are associated with lesser stabilities than northwest flow. They also have substantially fewer events with lapse rates near the wet adiabatic value. Since lapse rates near the wet adiabatic value frequently reflect natural precipitation processes, it appears that southwesterly and westerly flow events are inherently less favorable for precipitation.

Seeding Effects Related to Moisture and Parcel Stability

The moisture available from the condensation process was computed by lifting a parcel adiabatically from the 700 mb level to the 500 mb level. This process determines a water supply that may or may not be used during a particular event. This moisture source is mainly dependent upon the temperature and height of the cloud base. The larger supplies are associated with warmer cloud base temperatures and/or lower condensation levels. The smaller moisture supplies are then related to colder cloud base temperatures and/or the higher condensation levels.

Small increases in snowfall are observed when seeded events have available larger moisture supplies, while the smaller moisture supplies have slight negative scale changes (Figure 4). The observed increases are smaller than might have been expected, considering the dependency of the available moisture upon cloud temperatures. It appears that the larger moisture supplies may also contain certain unfavorable features that occasionally reduce the positive seeding effect.

One such unfavorable feature may be the development of parcel instability, which is also enhanced by the existence of warm cloud base temperatures and/or low condensation levels. Figure 3 shows that precipitation increases observed at small parcel stabilities disappeared as the stability decreased into the range associated with the development of widespread cumuliform activity. This may result from the penetration to greater heights of the cumuliform cloud systems, where colder temperatures may generate sufficient effective natural nuclei to meet cloud requirements.

Small negative scale changes are observed for the events having smaller moisture supplies (Figure 4). This limited moisture category is composed of events having colder cloud temperatures and/or higher condensation levels, and also includes the majority of "bum" forecasts (no snow was measured at the target during 55 per cent of the events in this category).

This small decrease in snowfall is physically conceivable. The possibility of negative seeding effects at colder cloud temperatures has already been discussed. Seeding these drier events may result in dividing the limited moisture supply among more crystals, each having less mass than would have occurred naturally. These crystals may remain too small for deposition. It is also likely that the usual orographic cloud was not present during several of these events.

There is further evidence that the seeding of drier cases is having a detrimental effect at the target. This possibility arises again from the difference in results between the nonparametric and parametric methods for the driest category of 700 mb relative humidity (Table 9).

The nonparametric method considers all events, and indicates a negative scale change in excess of 50 per cent for these dry cases. The parametric method considers only non-zero paired data, and yields a negative scale change of 13 per cent.

This suggests the possibility that seeding prohibits precipitation at the target when otherwise small amounts would have occurred. The chi-square test was employed to determine the probability of this happening. The null hypothesis is that seeding has no effect on the number of individuals in the zero category. The alternate hypothesis is that seeding increases the number of zero events. The value of chi-square for these dry cases is computed in appendix B and is found to be 2.41. The null hypothesis may be rejected at the 12 per cent level, and there is a fairly good chance some zero observations of target seed days would be positive without seeding.

Seeding Effects Related to Lapse Rate Stability

The insertion of nuclei into clouds from ground generators depends mainly upon diffusion generated by the turbulent mixing of winds over rough terrain, and the production of eddies by the vertical wind shear. The stability within the cloud layer may influence the dispersal of the seeding material by exerting damping forces upon the eddies. Whether this influence has an important effect on seeding results probably depends upon the strength of the mountain top wind (initial intensity of the turbulent eddies), and the degree of damping provided by the lapse rate stability.

It is noted in Figure 8 that increases in the 500 mb wind speed are generally associated with larger stabilities in the layer from 700 mb to 500 mb. This suggests that when the stronger wind shears give rise to more intense turbulent eddies, the damping forces are also stronger, and it is difficult to deduce the general effect of the stability.

Table 7 indicates the lapse rate stability has little effect on the results of seeding. The parametric method shows no trend while the nonparametric technique suggests the greater stabilities favor slightly the augmentation of the snowfall by seeding. The small precipitation changes observed probably indicate that the stability generally is not a critical factor in the dispersal of the seeding material.

Initial Classification of Meteorological Parameters

The various stratifications of synoptic parameters have been evaluated as being very favorable, favorable, or neutral and unfavorable for the production of artificial snowfall at HAO. A preliminary classification of all strata with their estimated precipitation changes are displayed in Table 11, along with the number of seeded and non-seeded events. The probability of the scale change being exceeded in the same sense by chance is also included.

TABLE 11.--Estimate of precipitation changes at HAO during seeded periods with respect to non-seeded periods. Synoptic parameters are classified according to their relationship to seeding results. NP refers to the first nonparametric method, and P the parametric method described by Grant and Mielke (1967). F refers to Equation 1.

Stratification	Number of Events	Method	Precip. Change (Percentage)	Prob. Exceeding
VERY FAVORABLE CONDITIONS				
500 mb Temperature				
(-13C thru -20C)	34 S	NP	over 100	.0485
	43 NS	P	101	.0005
500 mb Wind Speed				
(11 mps thru 21 mps)	56 S	NP	24	.147
	51 NS	P	29	.068
(22 mps thru 28 mps)	28 S	NP	over 100	.0146
	32 NS	P	29	.0465
(33 mps thru 41 mps)	6 S	F	29	
	8 NS			
Parcel Stability				
(+2C thru +3C)	23 S	F	43	
	32 NS			
FAVORABLE CONDITIONS				
Moisture Supply				
(1.6 gm/kgm or more)	32 S	F	14	
	28 NS			
500 mb Wind Direction				
(northwest)	49 S	NP	15	.245
	68 NS	P	14	.218
700 mb Relative Humidity				
(70% thru 93%)	31 S	NP	11	.261
	33 NS	P	13	.271
(50% thru 69%)	48 S	NP	22	.154
	40 NS	P	6	.378
Lapse Rate Stability				
(-8C to -16C)	49 S	NP	23	.206
	41 NS	P	4	.409

TABLE 11.--Continued

Stratification	Number of Events	Method	Precip. Change (Percentage)	Prob. Exceeding
Lapse Rate Stability				
(-17C to -19C)	50 S	NP	10	.330
	56 NS	P	10	.315
NEUTRAL AND UNFAVORABLE CONDITIONS				
500 mb Temperature				
(-21C thru -23C)	31 S	NP	3	.432
	32 NS	P	-6	.405
(-24C thru -27C)	33 S	NP	0	.500
	30 NS	P	-7	.341
(-28C thru -35C)	21 S	NP	-13	.203
	28 NS	P	-16	.200
500 mb Wind Speed				
(10 mps or less)	20 S	NP	-19	.187
	26 NS	P	-25	.230
(29 mps thru 32 mps)	4 S	F	-17	
	8 NS			
500 mb Wind Direction				
(west)	47 S	NP	1	.492
	40 NS	P	6	.356
(southwest)	23 S	NP	5	.452
	24 NS	P	-16	.295
Moisture Supply				
(1.0 to 1.59 gm/kgm)	31 S	F	-7	
	43 NS			
(less than 1.0 gm/kgm)	28 S	F	-15	
	32 NS			
700 mb Relative Humidity				
(19% thru 49%)	40 S	NP	more than -50	.0107
	60 NS	P	-13	.316
Lapse Rate Stability				
(-20C to -25C)	20 S	NP	2	.440
	36 NS	P	7	.386
Parcel Stability				
(-2C thru +1C)	18 S	F	-22	
	23 NS			
(+4C thru +5C)	22 S	F	-18	
	26 NS			
(+6C thru +14C)	29 S	F	-12	
	21 NS			

Second Classification of Meteorological Parameters

The analysis of wind speed effects upon the observed snowfall increases indicated that artificial snow crystals originating from the three nearest generators are carried beyond the target at wind speeds in excess of 28 mps. It was also pointed out that the two distant generators were not likely to directly affect the primary target in a favorable manner. Although there were indications that the Minturn generator was effective for a few events between 33 mps and 41 mps, the predominant effect of including the higher wind speeds (greater than 28 mps) in the analysis would seem to be a dilution of the seeding effects that stem from the three closest generators. The emphasis in this study is to detect those meteorological conditions that favor a a successful seeding of orographic clouds. Elimination of the higher wind speeds should reduce the dilution, bring into sharper focus trends in the seeding effect, and further emphasize the conditions that favor the artificial augmentation of snowfall at HAO.

Following this premise, the higher wind speeds were eliminated from the original sample, and scale changes were recomputed for the various strata. The new estimated precipitation changes are reclassified and summarized in Table 12.

TABLE 12.--Estimate of precipitation changes at HAO during seeded period with respect to non-seeded periods. Synoptic parameters are classified according to their relationship to seeding results. Events having wind speeds above 28 mps are eliminated. NP refers to the first nonparametric method, and P the parametric method described by Grant and Mielke (1967). F refers to Equation 1.

Stratification	Number of Events	Method	Precip. Change (Percentage)	Prob. Exceeding
VERY FAVORABLE CONDITIONS				
500 mb Temperature				
(-13C thru -20C)	29 S	NP	over 100	.0485
	35 NS	P	120	.0027
(-21C thru -23C)	26 S	NP	15	.284
	23 NS	P	45	.068
500 mb Wind Speed				
(11 mps thru 21 mps)	56 S	NP	24	.147
	51 NS	P	29	.068
(22 mps thru 28 mps)	28 S	NP	over 100	.0146
	32 NS	P	29	.0465
Parcel Stability				
(+2C thru +3C)	22 S	F	39	
	31 NS			
Lapse Rate Stability				
(-8C thru -16C)	37 S	NP	56	.121
	25 NS	P	56	.0314
Moisture Supply				
(1.6 gm/kgm or more)	30 S	F	67	
	21 NS			
700 mb Relative Humidity				
(50% thru 69%)	41 S	NP	60	.0465
	31 NS	P	30	.062
500 mb Wind Direction				
(northwest)	39 S	NP	25	.154
	53 NS	P	29	.068
FAVORABLE CONDITIONS				
Lapse Rate Stability				
(-17C thru -19C)	47 S	NP	23	.206
	50 NS	P	17	.209

TABLE 12.--Continued

Stratification	Number of Events	Method	Precip. Change (Percentage)	Prob. Exceeding
700 mb Relative Humidity				
(70% thru 93%)	28 S	NP	5	.330
	27 NS	P	18	.169
NEUTRAL AND UNFAVORABLE CONDITIONS				
500 mb Temperature				
(-24C thru -27C)	28 S	NP	4	.405
	26 NS	P	1	.476
(-28C thru -35C)	21 S	NP	-12	.242
	25 NS	P	-16	.230
500 mb Wind Speed				
(10 mps or less)	20 S	NP	-19	.187
	26 NS	P	-25	.230
500 mb Wind Direction				
(west)	44 S	NP	5	.397
	34 NS	P	8	.341
(southwest)	21 S	NP	28	.348
	21 NS	P	-8	.397
Moisture Supply				
(1.0 to 1.59 gm/kgm)	29 S	F	-20	
	36 NS			
(less than 1.0 gm/kgm)	23 S	F	-12	
	29 NS			
700 mb Relative Humidity				
(19% thru 49%)	34 S	NP	-33	.164
	51 NS	P	-10	.371
Lapse Rate Stability				
(-20C thru -25C)	20 S	NP	-5	.390
	34 NS	P	8	.382
Parcel Stability				
(-2C thru +1C)	18 S	F	-9	
	19 NS			
(+4C thru +14C)	43 S	F	-6	
	35 NS			

From Table 12 it is noted that the parametric method now yields snow increases of 120 per cent when 500 mb temperatures are between -13C and -20C. An interesting feature is that the trend of the seeding effect is much smoother in the temperature range from -21C thru -27C, and modest snow increases now appear between -21C and -23C. This is in better agreement with observed effective ice nuclei counts at Climax, which are occasionally deficient (below optimum concentration) in this temperature range. The small negative seeding effect at the coldest cloud temperatures continues unchanged.

The slight increase in scale change with lapse rate stability indicated by the nonparametric method using 252 cases is much more pronounced with high winds eliminated. The parametric method also now indicates this trend, and snow increases of 56 per cent are estimated for the most stable category by both methods. Scale changes of the various parcel stability strata remain unchanged.

Scale changes as a function of wind direction continue relatively unchanged with snow increases favored by northwest flow.

A substantial increase occurs in the positive seeding effect for larger moisture supplies when high winds are removed. The drier categories however, continue relatively unchanged with small negative scale changes.

The 700 mb relative humidity categories show little change except for the stratification from 50 per cent thru 69 per cent, which now indicates a substantial snow increase. A small maximum in the scale change for this stratum was indicated initially by the nonparametric method.

General Discussion of Errors

The introduction of error into this investigation stems mainly from two sources. The first error is introduced by the interpolation of meteorological conditions over the experimental area from synoptic scale data. The second error arises from the modification of the synoptic scale data fields by the micro and mesoscale terrain and features of the area. There are of course, the usual radiosonde errors in the original synoptic data. Other errors arise in the analysis from the variation of cloud tops about the 500 mb level. The use of a mean wind shear, and the assumption that it is distributed linearly gives rise to errors in determining winds at 12, 000 ft.

Errors of interpolation arise since gradients of meteorological variables may vary considerably over a distance of 250 nautical miles. The interpolative problem is further intensified when the data field includes a climatic and weather divide (continental divide). Since synoptic gradients, and the effect of of the divide upon synoptic gradients usually decrease with height through the middle troposphere, more error is likely in the 700 mb data than at the 500 mb level. Only small interpolations are generally required to determine the 500 mb parameters. This was also frequently true when determining the 700 mb data.

The 700 mb moisture field may occasionally be altered by the divide. The reason is that the divide occasionally creates a discontinuity in the vertical motion field at this level, especially during wintertime orographic storms. This can produce humidities near saturation west of the divide and quite low immediately east of the divide. A distance weighted interpolation would result in humidities below those existing along the divide at the experimental site. The computations of moisture supply, parcel stability, and the 700 mb relative humidity are therefore subject to more interpolative error than other quantities.

The 700 mb data is near the surface over much of the experimental area. It is therefore subject to large modification effects due to the local terrain. These would include local winds such as drainage winds, mountain-valley currents, etc. Effects of surface heating and radiational cooling would be felt over the experimental site which would not be reflected in the free air temperatures at Grand Junction and Denver at this altitude.

The error introduced by the fluctuations of cloud tops above and below the 500 mb level are not considered to be serious, since the 500 mb temperature is a relative indicator of cloud temperatures in either event, and the final stratifications are determined relative to one another. This error is probably small except when vigorous cumuliform clouds are present.

CHAPTER VIII

CONCLUSIONS

Orographic Cloud Seeding Theory

The following observations are consistent with current orographic cloud seeding theory.

1. The largest snow increases are observed when the wind flow and topographic features combine to produce the most favorable and continuous orographic stream.
2. Snow increases are observed at wind speeds which probably represent optimum values for the four nearest generators. Assuming this to be true, then Ludlam's (1955) crystal growth times are employed to compute transport times, vertical dispersion rates, and mean cloud bases that appear to be quite reasonable. This suggests that Ludlam's crystal growth times are approximately correct for the size crystals most frequently observed at Climax (200 to 400 microns).
3. The largest snow increases are realized at cloud temperatures where the greatest deficiency of effective ice nuclei is observed, and only a fraction of the natural nuclei are activated. No snow increases are realized at cloud

This crude verification of orographic cloud seeding theory should lend impetus to a numerical modelling approach wherein many of the physical processes may be simulated and relevant parameters varied.

Recommendations

More detailed and frequent meteorological data is needed in the Climax Project. The limitations of the present meteorological data has already been discussed. It is important that radiosonde data be made regularly available at the experimental site. Work should also proceed on the remote sensing and automation of the meteorological data. The determination of reasonable transport times, vertical dispersion rates, and optimum wind speeds will provide an aid in redesigning the experiment should investigative goals and emphasis require a change.

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APPENDICES

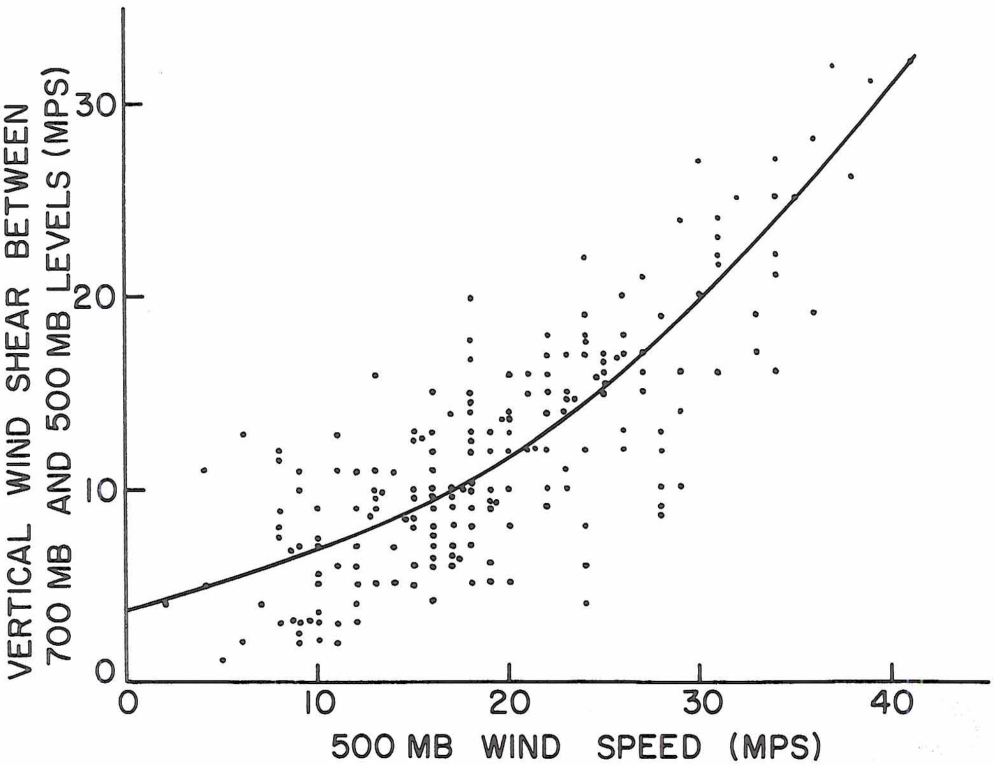

Fig. 10. Vertical wind shear between 700 mb and 500 mb as a function of the 500 mb wind speed. Solid curve is least square cubic fit.

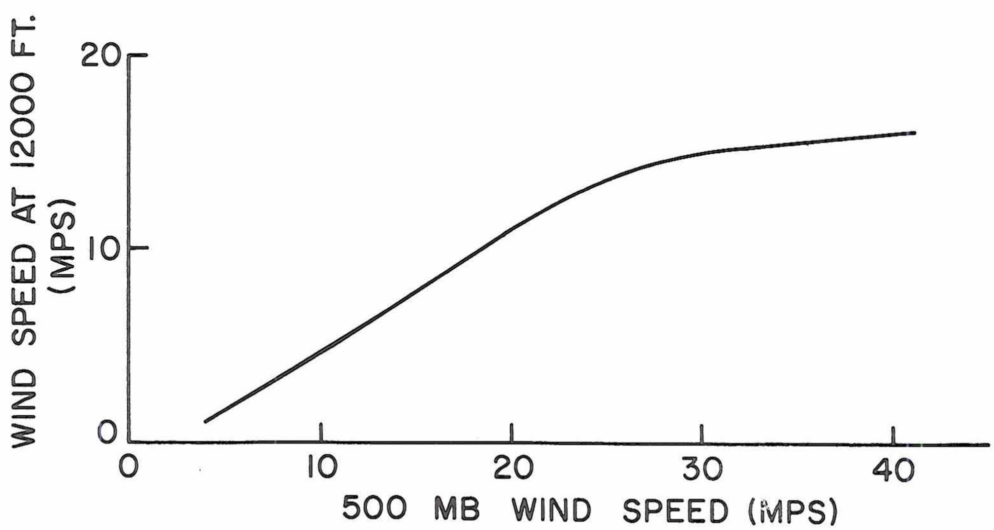

Fig. 11. Derived wind speed at 12,000 ft as a function of the 500 mb wind speed.

APPENDIX B

TABLE B-1

CONTINGENCY TABLE FOR ZERO AND POSITIVE EVENTS OBSERVED AT 500 MB WIND SPEEDS FROM 22 TO 28 MPS

	Seed	Non-seed	
Positive Events	a 25	b 21	46
Zero Events	c 3	d 10	13
	28	31	n 59

$$\chi^2_{1\text{ d.f.}} = \frac{n(ad - bc)^2}{(a + b)(c + d)(a + c)(b + d)} = 3.97$$

$$P(\chi^2 \geqslant 3.97) < .05$$

TABLE B-2

CONTINGENCY TABLE FOR ZERO AND POSITIVE EVENTS OBSERVED AT 700 MB RELATIVE HUMIDITIES 19% TO 49%

	Seed	Non-seed	
Positive Events	16	34	50
Zero Events	22	24	46
	38	58	96

$$\chi^2_{1\text{ d.f.}} = 2.41$$

$$P(\chi^2 \geqslant 2.41) \approx .12$$