

A RANDOMIZED CLOUD SEEDING EXPERIMENT AT CLIMAX, COLORADO, 1960-65

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1. Introduction

Investigations of snowfall and snowfall modification were initiated in the Central Colorado Rockies by Colorado State University during the latter part of the 1959-60 winter season. These studies have continued and expanded since that time.

The broad objectives are to obtain an increasingly complete understanding of mountain clouds, their precipitation processes, and changes in their behavior when artificial ice nuclei are supplied. The evaluation of the effects of seeding on precipitation, consequently, forms a basic but single phase of the program.

The specific objective of the program with respect to weather modification is to determine if changes in precipitation result from the ground releases of silver iodide on the upwind mountain slopes. If the observed results appear negative, an understanding of the reasons for this is essential; and, if results are positive, it is considered important to determine how this occurred and how even more precipitation might be obtained with operational changes.

This paper deals primarily with the experimental design and statistical analyses used in the detection of actual changes in precipitation. The analyses of physical factors intermittent between the actual seeding and resulting precipitation are also integral parts of this experimental design. These physical factors include the material transport mechanisms, ice nuclei concentrations, in-cloud processes, and so forth.

2. Design of experiment

Atmospheric variability severely complicates studies of precipitation processes and their modification. This variability extends to all phases of the process including the general atmospheric circulation in which the cloud system forms, the thermodynamics of the cloud itself, the physical characteristics of the cloud, and to the precipitation which is highly variable in intensity, form, and amount. Consequently, statistical evaluations based on a sound experimental design are essential to this project. The basic features of the experimental design are the following.

(a) Randomization is employed in obtaining the seeded and nonseeded samples.

(b) The randomization is unrestricted (see Neyman and Scott [4]).

(c) The experimental time unit is 24 hours. This is a compromise that minimizes variations in the physical parameters during an event and is still long enough to lower the "noise" level to reasonable values when establishing correlations with upwind precipitation controls.

(d) The observations of meteorological variables, in both seeded and nonseeded cases, are made as intensively as feasible during all stages of the precipitation process.

The following is a description of the operational procedures.

(a) Randomization is accomplished in a manner established by Dr. Donald Bentley, formerly of the CSU Mathematics and Statistics Department. This involves drawing 100 paired slips from a container at the start of each season. A chronological ordering of decisions is prepared.

(b) The suitability of each day is determined by the Denver Branch of the U. S. Weather Bureau. The criteria of a suitable day is that Leadville, Colorado, which transmits airway data every two hours, is expected to have at least 0.01 inches of precipitation in the 24 hour period. The forecast is made some six to eight hours prior to the start of each experimental period. The Weather Bureau forecasters have no access to the seeding decisions or specifically how they will be used.

(c) Two changes have been made in the start of an experimental period since the project started. The time unit, however, has remained constant at 24 hours. During the spring of 1960, the period extended from 1600 MST ($D - 1$) until 1600 MST the following day (D). This procedure, however, exposed snow which fell during the night, followed by daytime clearing, to day melting and evaporation. The interval was changed to 0800 MST ($D - 1$) to 0800 MST (D) for the 1960-61 winter season. This largely eliminated the daytime melting problem. It also coincides with the low point in a very pronounced cycle in diurnal variation in the intensity of precipitation. The experimental interval was changed slightly to the 0900-0900 interval for the 1961-62 and subsequent winter seasons to accommodate snow observers.

(d) The "yes" or "no" for suitable experimental conditions from the Weather Bureau is relayed daily by teletype to Colorado State University. The relay has been through the High Altitude Observatory in Boulder, the Climax Molybdenum Co., and directly to the CSU Weather Station at different intervals during the experiment.

(e) A phone relay operator at the Colorado State University Weather Station processes the forecast and takes appropriate action to initiate seeding operations if the next consecutive listing of a random decision is for an operational day.

(f) Generator operators at Minturn, Red Cliff, south of Tennessee Pass, and south of Leadville turn on silver iodide ground generators at 30 minutes prior to the start of the experimental period, run them continuously and terminate

operations 30 minutes prior to the end of the period. The procedure is the same for operators at Aspen and Reudi but a one hour lead time is used. Specific units used are changed during the interval as specified by the Weather Bureau wind forecast.

A CSU modified Skyfire, needle type ground generator is used for seeding at the rate of about 20 gm of AgI per hour. These generators have been extensively calibrated in the CSU cloud chamber to establish the temperature activation characteristics of the particles produced. Figure 1 shows the output of effective ice nuclei from these generators (CSU modified Skyfire) with respect to other highly efficient AgI generators and with respect to Fletcher's theoretical curve. These units produce about 10^{14} particles/gm AgI effective at -12°C and 4×10^{16} particles/gm AgI effective at -20°C .

(g) Snowboard observers hired locally—Leadville, Minturn, Frisco, and Breckenridge—read daily some 70 snowboards located at about one mile intervals over Fremont, Hoosier, and Vail Passes. Climax is located near the summit of Fremont Pass. The summit area of Fremont Pass is considered the primary target for the seeding. The Hoosier Pass network forms a backup for the Fremont Pass network further downwind from the seeding sites. Four observations are made at each site: (1) snow depth; (2) the weight of a core of snow taken at an average depth location as established from the depth measurements; (3) a collected water sample for future analysis; and (4) observer's description of drifting or melting conditions, if any. The "water depth" of new snow is calculated from the weight of the sample. The snowboards over each Pass are read in a systematic order each day. The observers have no information as to seeding decisions, and in general, know very little about the project. A number of changes in observers have been necessary due to the part time nature of the job, moves, sickness and so on. Mr. Robert Rinker, a local resident in the area and an employee, directly supervises the local observation program.

(h) As many other physical observations as possible are made on seeded and nonseeded days. Ice nuclei observations, two groups of at least three readings, have been made on almost all days. A detailed weather observation is taken at the time of each ice nuclei observation. Various other physical observations have been possible on at least a portion of the experimental days. These include ice crystal replications, cloud photography, radar photography, and atmospheric electricity, and have been made with increasing intensity as the program progresses, but still on a minority of the experimental days. A second ice nuclei counter was installed at a similar but completely unseeded upwind site in the fall of 1962. Data from this site were intermittent during the first year but have been continuous since the fall of 1963. Ice nuclei counters at these two sites have been compared with each other and a similar unit at NCAR in Boulder. These units have also been interchanged.

(i) A program of systematic in-cloud sampling on seeded and nonseeded days is just getting underway.

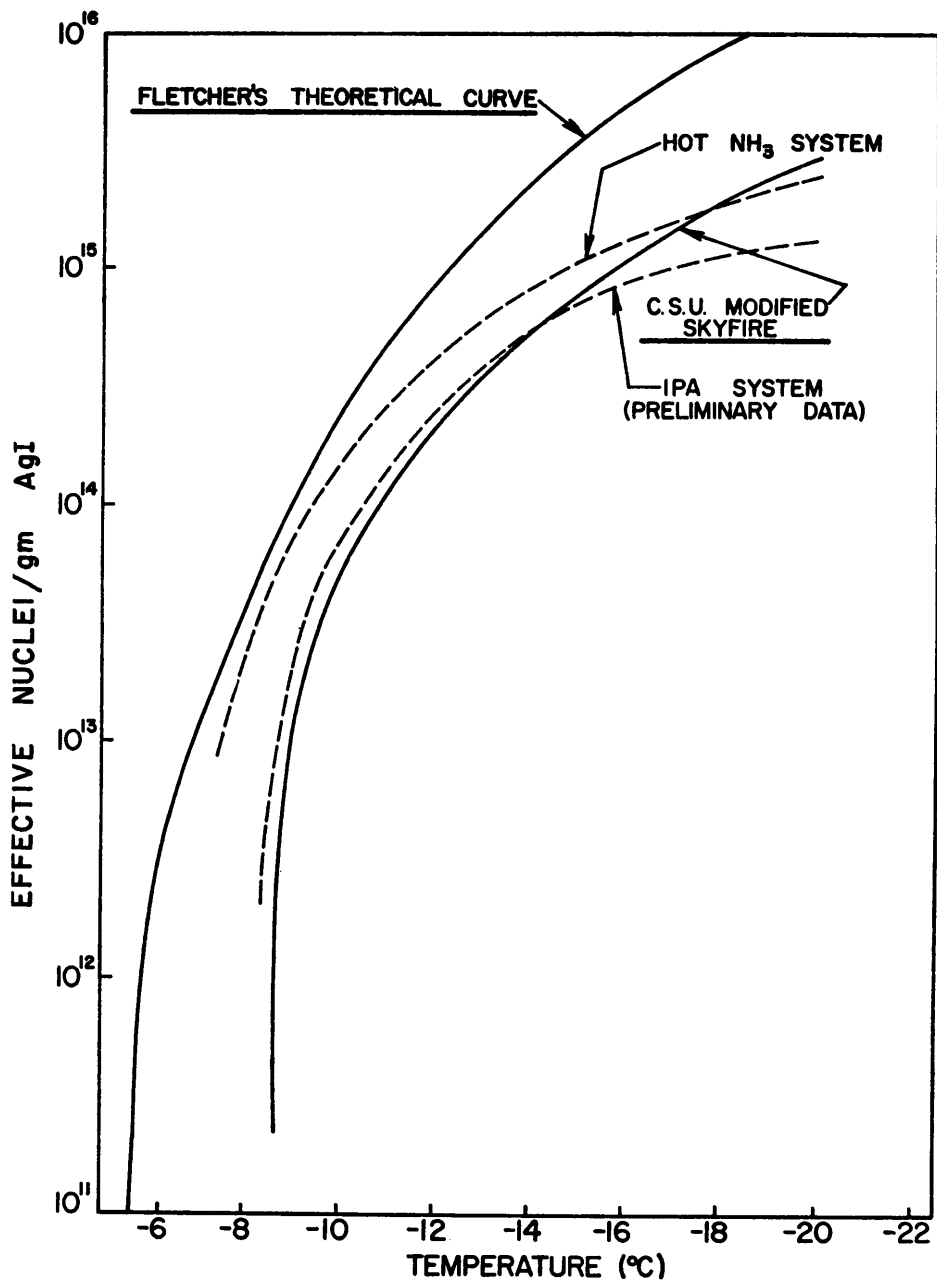


FIGURE 1

Seeding output, as a function of temperature, for generator used in the Climax experiment (effective nuclei/gm AgI).

3. Statistical evaluation

3.1. *General procedures.* The evaluation procedures were established at the outset of this project after numerous discussions with members of the statistics staff at Colorado State University. During the discussions, the following specific decisions were reached.

(a) The basic evaluation procedure would be the general procedure developed by Thom [6] utilizing normalized target and control relationship established for the control and for seeded cases.

(b) Terrain upwind of the target is unsuitable for the establishment of special control stations; therefore, standard Weather Bureau Stations southwest, west, and northwest of the target were chosen for control stations.

(c) Other evaluation procedures would also be used to provide maximum understanding of the processes involved. The following criteria were considered to be important in formulating specific analyses: storm type; upper air temperature and lapse rate; direction and velocity of air flow; concentrations of ice nuclei; variation among experimental years; variation among various calendar months; time of day; use of various generator combinations; variation of non-seeded cases with historical data.

Statistical investigation to establish the control stations was started in the first year of the project and completed during the third year. The historical data from the Weather Bureau gage at Climax were used in determining control stations. These investigations were for the sole purpose of establishing stations that correlated well with the target region.

3.2. *Statistical procedures.* In this study, two different approaches are used to evaluate possible differences in precipitation amounts during seeded and nonseeded periods. The first approach is based on a parametric technique introduced by Thom [6]. The second approach involves an application of distribution free procedures. If differences in precipitation amounts are assumed to be scale changes, then either approach will yield point estimates of these scale changes. Both of these approaches will be outlined in this section.

3.2.1. *Parametric approach.* Since a complete description of the technique devised by Thom [6] is available in the literature, only a few highlights of this procedure will be given here.

Under the assumption that precipitation data may be approximated by a gamma distribution, this technique begins by transforming the raw data into normalized data which is suitable for the application of a simple regression analysis. Since the basic information for both seeded and nonseeded periods consists of paired observations (that is, target and control), the only acceptable information is the set of all paired observations in which neither the target observation nor the control observation is zero. With this in mind, the remainder of the technique is quite straightforward. If 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 respect to the nonseeded period is easily obtained.

3.2.2. Distribution free approach. The two techniques discussed in this section employ simple ranking procedures. It is the desire of the authors that modifications within the framework of these distribution free techniques will provide satisfactory analyses for a variety of investigations. Both techniques utilize the same basic information for seeded and nonseeded periods. This information consists of all pairs of target and control observations. Also, these techniques avoid elimination of data resulting from transformations used in certain parametric techniques when either target or control observation of a pair is zero. Let $[(T_1, C_1), \dots, (T_n, C_n)]$ represent n pairs of target (T) and control (C) observations for the nonseeded period. Similarly, let $[(T'_1, C'_1), \dots, (T'_m, C'_m)]$ represent m pairs of target and control observations for the seeded period. Also, let $N = m + n$ be the total number of pairs of target and control observations in the pooled seeded and nonseeded periods. The design of this study requires that the number of observations of the seeded and nonseeded periods are approximately the same. A description of each technique (that is, Technique A and Technique B) follows.

Technique A. The underlying assumption in employing this technique, which is associated with the Wilcoxon method, is that if seeding has no effect on the amount of precipitation, then $T_i - C_i$ and $T'_j - C'_j$ represent observations from identical distributions. The first step is to rank the N pooled values

$$(1) \quad T_1 - C_1, \dots, T_n - C_n, \quad T'_1 - C'_1, \dots, T'_m - C'_m$$

from smallest to largest according to their values on the real line. When dealing with the type of meteorological data under consideration here, many tied observations will occur if the total number of observations is reasonably large. This leads to a partitioning of the ranked N pooled values into r disjoint classes of tied observations. These r classes are, in turn, ranked in the same order as their respective tied observations were ordered relative to the initial ranking of the N pooled observations. Let t_k be the number of tied observations in the k th smallest class according to its rank, that is,

$$(2) \quad \sum_{k=1}^r t_k = N.$$

Also, let S_h denote the partial sums of the number of tied observations,

$$(3) \quad S_h = \sum_{k=1}^h t_k, \quad h = 1, 2, \dots, r,$$

and $S_0 = 0$, $S_r = N$. Then define the mean rank of the k th class of tied observations by

$$(4) \quad R_k = \frac{1}{t_k} [(S_{k-1} + 1) + (S_{k-1} + 2) + \dots + S_k].$$

If j is used as an index over the observations in each class of ties, then the

expression W , corresponding to the Wilcoxon statistic in the case of ties, is defined by

$$(5) \quad W = \sum_{k=1}^r \sum_{j=1}^{t_k} R_k \delta_{jk}$$

where $\delta_{jk} = 1$ if the j th observation in the k th class of ties was a seeded observation, 0 otherwise. The mean of W is given by

$$(6) \quad \mu_W = \frac{1}{2} m(N + 1).$$

The variance of W (Hemelrijk [1]) is given by

$$(7) \quad \sigma_W^2 = \frac{mn}{12N(N-1)} \left(N^3 - \sum_{k=1}^r t_k^3 \right).$$

If $t_k = 1$ for $k = 1, \dots, r = N$ (that is, there are no ties), then the variance of W reduces simply to

$$(8) \quad \sigma_W^2 = \frac{1}{12} mn(N + 1).$$

For a reasonably large number of observations, as in the present study, in the case seeding has no effect on precipitation, the statistic

$$(9) \quad U = \frac{W - \mu_W}{\sigma_W}$$

is distributed approximately as the normal distribution with mean zero and variance one.

A point estimate of the scale change using the present technique is obtained in the following simple manner. Essentially, this estimation procedure is accomplished by replacing the seeded observations $(T'_1 - C'_1, \dots, T'_m - C'_m)$ in the N pooled values by specifically adjusted nonseeded observations $(\Delta T_1 - C_1, \dots, \Delta T_m - C_m)$. This adjustment of the nonseeded observations consists of two steps. The first step, if necessary, is either to add or subtract observations from the n nonseeded observations in order to match the sample size m of the seeded observations. This is done in such a manner that alteration of the empirical nonseeded distribution will be minimized. To accomplish this, consider the n nonseeded observations $(T_1 - C_1, \dots, T_n - C_n)$ ranked from smallest to largest according to their values on the real line. If $n = m$, this first step is unnecessary. If $n > m$, the $n - m$ ranked nonseeded observations which most closely correspond to the $n - m$ cumulative distribution values $i/(n - m + 1)$ for $i = 1, \dots, n - m$, of the empirical nonseeded distribution are eliminated (for example, if $n - m = 1$, then the median value of the empirical nonseeded distribution is eliminated). If, however, $n < m$, then the $m - n$ ranked nonseeded observations which most closely correspond to the $m - n$ cumulative distribution values $i/(m - n + 1)$ for $i = 1, \dots, m - n$, of the empirical nonseeded distribution are added to the n existing nonseeded obser-

vations (for example, if $m - n = 1$, then the median value of the empirical nonseeded distribution is added to the existing n nonseeded observations). The second step is to modify the size adjusted nonseeded observations with appropriate target scale changes (that is, different values of Δ) yielding adjusted nonseeded observations of the form $(\Delta T_1 - C_1, \dots, \Delta T_m - C_m)$. Next, for each replacement of $(T'_1 - C'_1, \dots, T'_m - C'_m)$ by $(\Delta T_1 - C_1, \dots, \Delta T_m - C_m)$, the associated values of W_Δ and U_Δ are determined for selected values of Δ (for example, $\Delta = 0.80, 0.85, \dots, 1.95, 2.00$). Then by using interpolation, the value of U_Δ which corresponds to the observed value of U obtained from the m seeded observations yields the estimate of the scale change Δ . It should be noted that this scale change estimate is based strictly on the empirical nonseeded data. Also, for a reasonably large sample, approximate Δ alternative power curves may be obtained for an arbitrary set of significance levels.

Technique B. Again, the underlying assumption when applying this technique, which follows Mood, is that if seeding has no effect on the amount of precipitation, then $T_i - C_i$ and $T'_j - C'_j$ represent observations from identical distributions. However, the first step now is to rank the N pooled values $T_1 - C_1, \dots, T_n - C_n, T'_1 - C'_1, \dots, T'_m - C'_m$ from smallest to largest according to their absolute values. Again, the encounter with ties results in the partitioning of the ranked N pooled values into r disjoint classes of tied observations. Also these r classes are again ranked in the same order as their respective tied observations were ordered relative to the N pooled observations. Again, let t_k be the number of tied observations in the k th smallest class according to its rank, $S_k = \sum_{i=1}^k t_i$, $S_r = N$ and $S_0 = 0$. This time, define the mean value assigned to the k th class of tied observations to be

$$(10) \quad Q_k = \frac{1}{t_k} [(S_{k-1} + 1)^2 + (S_{k-1} + 2)^2 + \dots + S_k^2].$$

If j is used once again as an index over the observations in each class of ties, then the expression X , which is motivated by a distribution free test given by Mood [3], is defined by

$$(11) \quad X = \sum_{k=1}^r \sum_{j=1}^{t_k} Q_k \delta_{jk}$$

where δ_{jk} was previously defined in Technique A above. The mean and variance of X are given respectively by

$$(12) \quad \mu_X = \frac{1}{6} m(N + 1)(2N + 1)$$

and

$$(13) \quad \sigma_X^2 = \frac{mn}{36N(N-1)} \left\{ \frac{16}{5} \left(N^5 - \sum_{k=1}^r t_k^2 \right) + 6 \left(N^4 - \sum_{k=1}^r t_k^4 \right) \right. \\ \left. + 3 \left(N^3 - \sum_{k=1}^r t_k^3 \right) - 12 \left[\sum_{k=1}^r t_k^3 S_{k-1}^2 + \sum_{k=1}^r t_k^3 (t_k + 1) S_{k-1} \right] \right\}.$$

If $t_k = 1$ for $k = 1, \dots, r = N$ (that is, there are no ties), then the variance of X simplifies to

$$(14) \quad \sigma_x^2 = \frac{1}{180} mn(N + 1)(2N + 1)(8N + 11).$$

Again, in the case where seeding has no effect on the precipitation and the number of observations is quite large, the statistic

$$(15) \quad V = \frac{X - \mu_x}{\sigma_x}$$

is distributed approximately as the normal distribution with mean zero and variance one.

Finally, a point estimator of the scale change based strictly on the empirical nonseeded distribution is obtained in a manner analogous to that described in Technique A above. Also, for a reasonably large sample, approximate alternative power curves may be determined for an arbitrary set of significance levels.

Preliminary numerical results of empirical precipitation data show that a power comparison of these techniques depends specifically on the relationship between target and control.

4. Summary of preliminary analysis of data

4.1. *Ice nuclei observations.* Large concentrations of seeding material are arriving in the target area on seeded days. Figure 2 shows the type of increases that are being observed consistently in seeding sequences. This sample was selected since ice nuclei observations were made intermittently throughout the 24 hour period. April 14th and 15th show background concentrations observed prior to the start of the seeded sequence. April 16th through 24th are omitted since they involve a mixing of seeded and nonseeded cases with only the two ice nuclei observations sequences each day. As can be seen, concentrations were low on the 25th but increased by a factor of ten shortly after seeding started. It can be noted that peak values observed during the day were nearly one hundred times greater than on previous or following days. Considerable variations occurred during the period but the values were consistently higher than during adjacent unseeded periods. It can also be noted that values lowered during the night. Seeding operations terminated at 0830 on the 27th. Concentrations were considerably lower on the 27th and at least near original background levels.

Figure 3 shows the percentage of low concentrations of ice nuclei observed at Climax during the respective operation seasons through 1964. The following are considered to be interesting aspects of these data.

(a) Concentrations of ice nuclei were, in general, less than 1/liter at -20°C at Climax before the experiment started and also at the upwind station near Steamboat Springs during 1963–64. The pre-experiment and the upwind Steam-

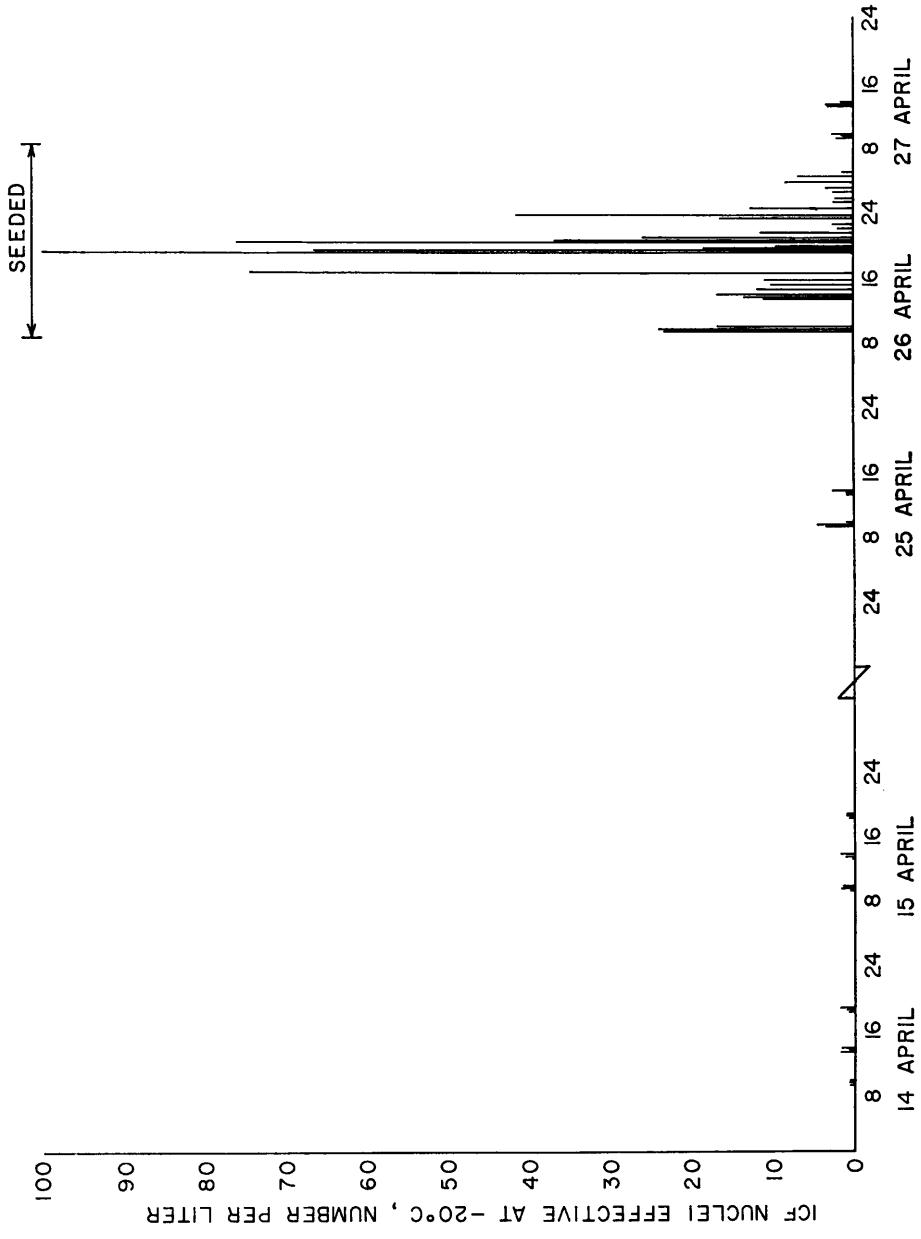


FIGURE 2
 Concentration of ice nuclei effective at -20°C ,
 Climax, Colorado. April 14, 15, 25, 26, 27, 1964.

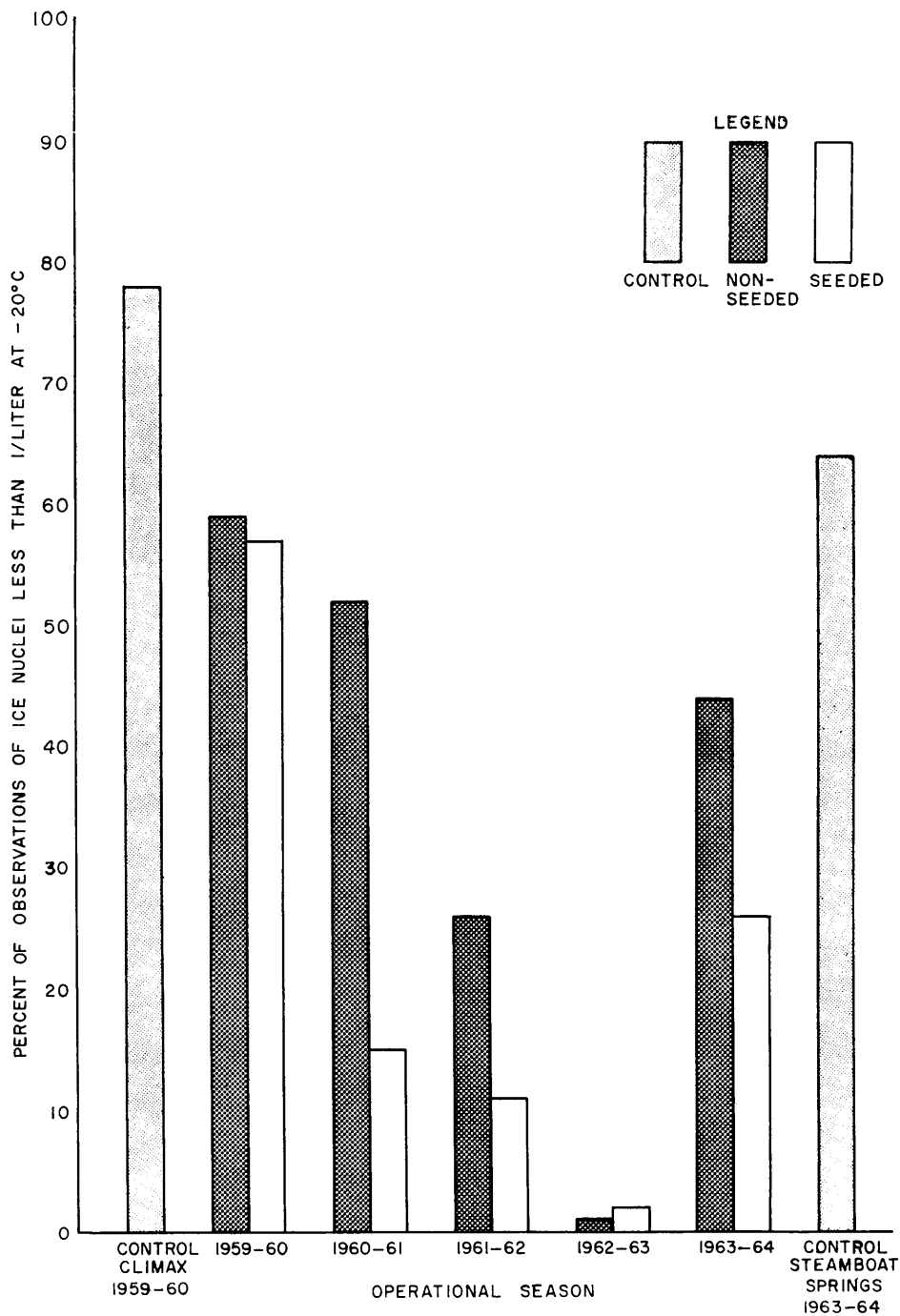


FIGURE 3

Frequency of ice nuclei concentrations less than 1/liter at -20°C on seeded and nonseeded days at Climax and Steamboat Springs, Colorado, 1959-64.

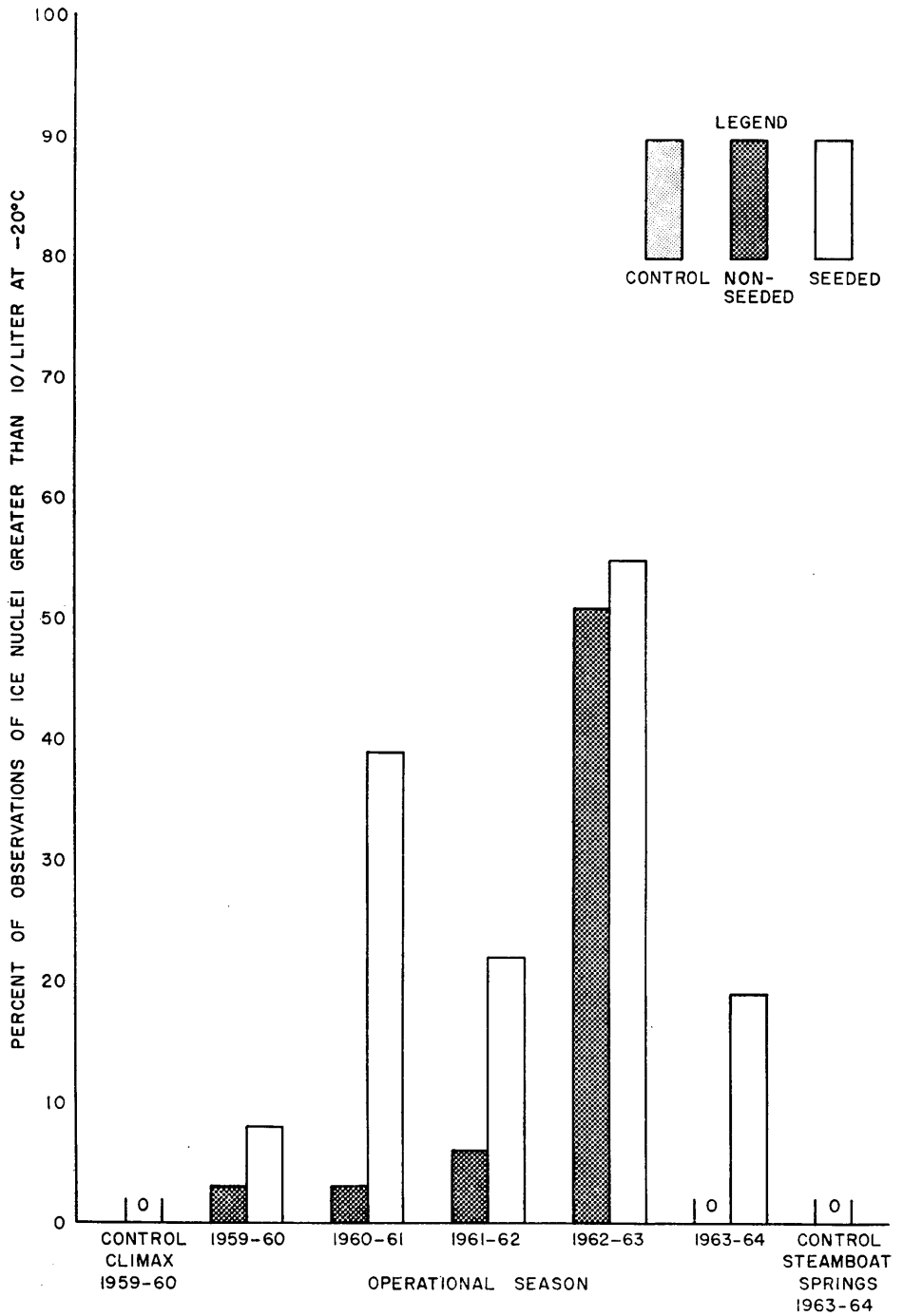


FIGURE 4

Frequency of ice nuclei concentrations greater than 10/liter at -20°C on seeded and nonseeded days at Climax and Steamboat Springs, Colorado, 1959-64.

boat Springs concentrations are quite similar with some 60 to 70 per cent of all observations in each of these categories less than 1/liter at -20°C .

(b) A much smaller per cent of low observations have occurred on seeded days during all but the first seeded year. The lack of a substantial decrease in low concentrations during the first year is related to the poor efficiency of the early generator models and the few cases of operation during the first year.

(c) It can be noted also that a progressively smaller concentration of low observations occurred on nonseeded days as the experiment progressed except in 1964. Concentrations during 1964 were still smaller than the control observations.

Seeding operations have been extensive during the 1961–62 season and the 1964–65 season. Numbers of experimental cases have been considerably more limited in all other seasons due to either inadequate project funding or operations resulting from commercial seeding interference.

Figure 4 shows the per cent of ice nuclei observations at high concentrations ($>10^4/\text{m}^3$). The following characteristics can be noted: (1) concentrations greater than $10^4/\text{m}^3$ have not been observed in control periods at either Climax or Steamboat Springs; (2) substantial percentages of the observations on seeded days have shown concentrations greater than $10^4/\text{m}^3$; (3) a substantial per cent of the observations on the nonseeded days during the experimental period have shown concentrations greater than $10^4/\text{m}^3$ following long periods of seeding. This is particularly true for the 1962–63 season. This was also true for the latter part of the 1961–62 season following the very extensive seeding operations during that year. A contamination of the control days is suggested. Despite the suggestion of a residual of the seeding effects on the nonseeded days, the mean value for the concentrations on the seeded days is $1.3 \times 10^4/\text{m}^3$ as compared to $2.7 \times 10^3/\text{m}^3$ on the nonseeded days. This difference is significant at the one per cent confidence level.

4.2. Precipitation.

4.2.1. *Difference in precipitation between seeded and nonseeded cases during the accumulation of experimental cases.* Figure 5 shows the percentage difference in the precipitation between seeded and nonseeded cases as the experiment has progressed for the average of two representative target area stations (the snowboard at the High Altitude Observatory and the Weather Bureau recording gage at Climax) and for the mean of the control stations. It can be noted that during the early part of the experiment, the seeded cases in the target area received considerably greater precipitation than the nonseeded cases. This continued for a large number of experimental units and is still very apparent after 120 cases. This difference between seeded and nonseeded events did not occur in the control area.

The difference between seeded and nonseeded events dropped rapidly starting with about 100 cases and then generally leveled off with a slight advantage for the seeded cases. This advantage is quite similar to that occurring in the control area for the accumulation of correspondingly larger number of cases.

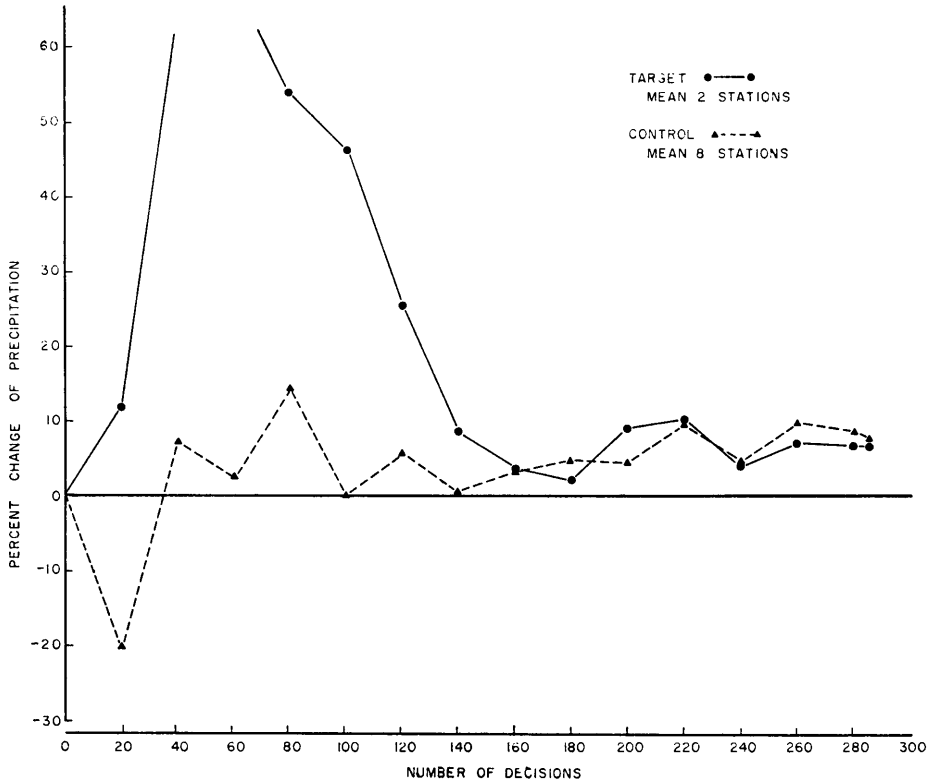


FIGURE 5

Difference in precipitation between seeded and nonseeded cases during the accumulation of experimental cases.

The rapid drop in the positive difference between seeded and nonseeded cases occurred during the interval when control day concentrations of ice nuclei were high, as noted in figures 3 and 4.

4.2.2. *Differences in precipitation between seeded and nonseeded cases with various temperature regimes.* It appears that the optimum concentrations of ice nuclei for orographic clouds is of the order of 10^4 effective particles per cubic meter (Ludlam [2]). Concentrations at Climax have, in general, been an order of magnitude or more less than this at a temperature of -20°C . On the other hand, they have, in general, been of this order of magnitude or greater at -24°C and colder. Considerable variability in concentrations in the range $10^3/\text{m}^3$ to $10^4/\text{m}^3$ has been noted in the temperature range -21° to -23°C . These data suggest that an artificial supply of ice nuclei might be required when cloud temperatures are -20°C or warmer but that little need for additional nuclei would exist when temperatures are -24°C or colder.

The Climax experimental samples have, consequently, been divided into the following three categories: (1) days when coldest 500 mb temperatures were -24°C or less; (2) days when 500 mb temperatures were 20°C or warmer; and (3) days when 500 mb temperatures were -21°C to -23°C . During winter storms in the area, 500 mb is consistently near cloud top level and the 500 mb temperature is considered as representative of the cloud top temperature.

Table I shows the difference in precipitation between seeded and nonseeded

TABLE I

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

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

() * number of cases

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

days for these temperature categories. The difference between seeded and nonseeded cases is

$$(16) \quad \frac{T_s - T_{ns}}{T_{ns}} - \frac{C_s - C_{ns}}{C_{ns}},$$

where T designates the target precipitation, C the control precipitation, and subscripts s indicate seeded cases and ns nonseeded cases. Target and control precipitation are for the same stations used in figure 5.

It can be seen from table I that less precipitation (14.8 per cent) has occurred in the seeded cases than in the nonseeded cases when the 500 mb temperature has been colder than -24° C. On the other hand, considerably more precipitation (54.5 per cent) has resulted on the seeded days when the 500 mb temperature has been -20° C or warmer. An intermediate value of 12.3 per cent more precipitation is noted on the seeded days when the temperatures were in the intermediate range of -21° to -23° C. While the analysis is not to the stage to be able to give probability levels for these differences, it should be noted that the sample size is substantial in each category, 74 for seeded and 80 for nonseeded in the cold category, 30 for seeded and 33 for nonseeded in the warm category, and 31 each in the intermediate class. A sizeable positive difference in precipitation between the seeded and nonseeded precipitation would be obtained even if the warmer and intermediate range were combined to increase the sample size to over 60 for both seeded and nonseeded.

The differences between seeded and nonseeded day precipitation for the cold temperature is negative. While it is not yet determined whether this value is statistically significant, it is not physically unreasonable that this result might occur. If excessive ice nuclei concentrations existed in these colder clouds, many individual ice crystals may not have had sufficient mass for disposition at the observation site or possibly even before evaporation started to the east of the Rockies. The areal network of snowfall observing sites, for which data are available, and for which analysis is not yet completed, appears adequate to explore this possibility in detail. It is interesting to note that in addition to the higher natural concentrations of ice nuclei at colder temperatures, the rate of seeding is some 10 to 100 times greater due to the increased efficiency of the artificial nuclei at these colder temperatures.

4.3.3. *Summary of precipitation analysis.* The necessity of detailed analyses at all stages of the physical process is critical to an understanding of weather modification. As is suggested by these preliminary analyses, both increases and decreases in precipitation may be occurring that, when considered together, give no change in the overall precipitation. However, consistently positive results might have been obtained if seeding had been carried out only when meteorological conditions were suitable.

The matter of residual effects of seeding, or at least the effect of high background ice nuclei levels, must also receive more attention before these results can be interpreted fully. The rapid decrease in positive differences between seeded and nonseeded precipitation that occurred during the middle portions of this experiment may have resulted from chance. The lack of a corresponding change in the control area, however, suggests that negative effects may have been more persistent during this period offsetting more persistent positive effects earlier in the experiment.



ADDENDUM

Dr. James E. McDonald has pointed out in personal discussions the desirability of presenting percentage precipitation differences given in table I in the same form as used in previous literature by Smith *et al.* [5]. The percentage differences for -12°C to -20°C , -21°C to -23°C , and -24°C to -39°C at 500 mb turn out to be -13.6 per cent, $+14.1$ per cent and $+39.5$ per cent, respectively, while figures in table I above are -14.8 per cent, $+12.5$ per cent, and $+54.5$ per cent for the corresponding temperature intervals.

More detailed analyses will be presented using the techniques described in section 3 above when all data have been processed.

REFERENCES

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