Development and Application of a Predicator Control for the Evaluation of a Winter Orographic Cloud Seeding Project

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ABSTRACT

Evaluation of an operational-type winter cloud seeding project in Utah is made by developing meteorological predictors of target precipitation. Predictors (covariates) are developed by matching 1200 GMT rawinsonde data and 24 h precipitation amounts. These predictors and precipitations are summed over seven unseeded seasons to form a seasonal predictor-predictand relationship, for which the correlation is 0.975 when the average precipitation for all stations is used, and 0.879 when only the two highest altitude stations are used. Then, the predictor is found for each of the seeded seasons, and based upon the unseeded predictor-predictand relationship, the predicted precipitation is obtained. Differences between predicted and observed precipitation in seeded years are compared and tested for seeding effects. Application of the method to the first two years of the project indicates a substantial chance that little or no effect of seeding occurred. It is concluded that the method offers a promising approach to the evaluation of winter cloud seeding projects.

1. Purpose and scope of effort

The present paper is concerned with the development of a predictor technique for the evaluation of either randomized or nonrandomized cloud seeding projects. In particular, an evaluation is made of a nonrandomized cloud seeding project to increase winter precipitation in southern and central Utah. This project was carried out by North American Weather Consultants. The results presented here represent an independent evaluation of that project. Four seasons of operation have been completed; however, only the first two seasons are evaluated because the remaining data required were not available.

Several approaches to the problem of evaluation of both randomized and unrandomized cloud seeding projects are available. Because the project with which we are concerned is an unrandomized one, we need consider only the unrandomized evaluation methods. Within this category the target's control is based on either precipitation measurements outside the target area (Area Control) or other meteorological measurements made both in and out of the target area (Aerological Control).

In the Area Control method, precipitation is represented by direct sampling with gages, snowpack measurements or streamflow measurements. For example, the latter has been used by Henderson (1966). Data may be arranged according to a storm-by-storm period, by the month or by the season. The choice may depend upon how often the measurements are made. In the case of the Utah project, a short-period evaluation unit, such as a day or a storm period, is not likely to be fruitful because the correlation between precipitation in the target and area control would likely be low. On the other hand, over a full winter season the correlation is higher—around 0.8 at least.

In the Aerological Control method, precipitation in the control area is replaced by an estimated value of target precipitation based upon meteorological data. This approach has been followed, for example, by Simpson and Wiggert (1969) in the evaluation of a randomized cumulus seeding project.

In the present study the Aerological Control method was used, primarily because it is believed that higher seasonal correlations may be achieved, at least ultimately if not at present, than with the Area Control method; in such a case the technique would be a stronger one than an Area Control evaluation. Also there is the possibility of eliminating some periods when no seeding is done. To arrive at seasonal amounts of precipitation and the corresponding predictors, daily precipitation and meteorological predictors are summed over a whole season or portion of a season. In the Aerological Control method it is assumed that the relationship between the predictors and target precipitation remains stable in both the historical and operational periods. Also, it is assumed that the predictor variables are not affected by seeding.

To develop a suitable predictor, precipitation and meteorological data were assembled from a period prior to the project when no seeding was done. From

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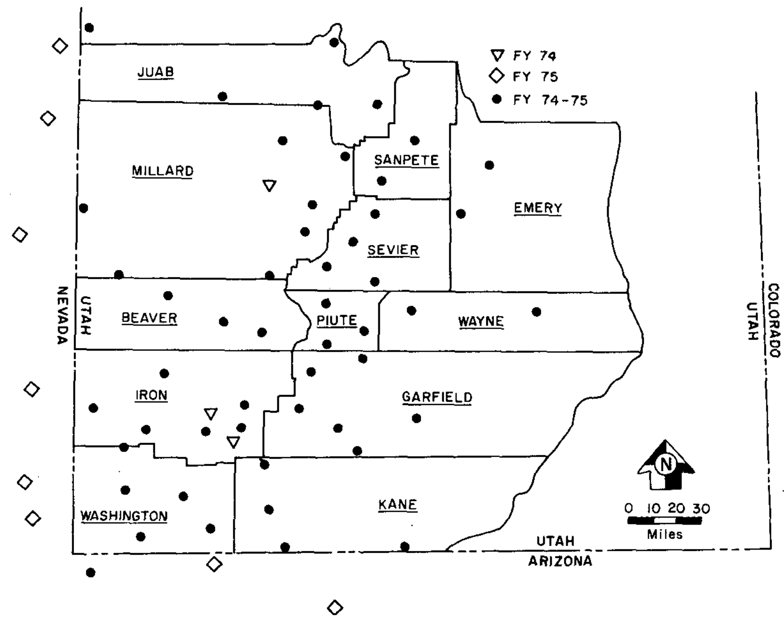

FIG. 1. Seeding generator locations.

these two large sets of data various predictors were formulated. Individual predictors were combined in several ways to improve their capability. Then the final predictor was applied to the two seeded winters in 24 h increments to find the predicted, or estimated, amounts of precipitation. The observed precipitation and the predicted values were summed over the period of operation in order to complete the evaluation.

2. Operational project

North American Weather Consultants contracted with the Southern Utah Water Development Corporation to conduct cloud seeding operations during suitable storms. During the first two years of the project, the target area was composed of 12 counties in southern Utah as shown in Fig. 1. All seeding was accomplished using ground generators. Fifty-three generators were operated in the first season and 58 in the second; generator locations are also shown in Fig. 1. Silver iodide at 6 g h^{-1} was released from each activated generator when a storm was believed suitable for seeding. During the first two years, the operators seeded in accordance with the 500 mb temperature as an estimate of the cloud top temperature. These estimates were replaced by more-direct means, such as deduced from timely rawinsondes or aircraft reports. (Currently, aircraft measurements of cloud tops are made regularly.) The present paper, however, is not concerned with the details of how the project was carried out, but rather, the question of whether any net gain in precipitation was achieved by the seeding.

3. Data

a. Analysis of data requirements

In the development of a precipitation predictor a set of both precipitation and meteorological data are needed. The length of the data records is made as long as possible subject to the restriction that each measurement used in the analysis, such as relative humidity, precipitation or any other quantity, is made in the same way throughout the period consisting of both the unseeded and seeded seasons. Although the predictor is based solely upon unseeded precipitation, the use of that predictor to test for seeding effects requires that the uniformity of data measurements include seeded periods as well. Any deviation from uniformity of data may well impose an unwanted bias on the evaluation.

For precipitation measurements, the length of record varies from station to station, but a large fraction of the stations have existed for 30 years or more. The main problem with precipitation data is that some stations report each hundredth inch accumulated, while others report only each tenth inch. However, this difference in data format can be eliminated simply by reaccumulating the hundredth inch data into increments of tenths.

In the case of meteorological data, it would be desirable to use National Weather Service (NWS) charts available from the National Climatic Center (NCC). However, these charts have been prepared over the years with varying analysis techniques. Thus it is necessary to use original data from which many of these charts are derived. The bulk of these data consists of rawinsonde sounding data, from which temperature, humidity, pressure and wind at various altitudes may be obtained.

Rawinsonde data itself must be examined for uniformity. During the latter part of 1965 and early 1966 the rawinsonde humidity devices used in the western United States were changed from a lithium chloride to a carbon element. Therefore, our use of rawinsonde data is restricted to data acquired starting in the fall of 1966.

In addition, a change in the ventilation duct for the humidity sensor was made during late 1971 (Brousaides and Morrissey, 1971). The effect of the modification was significant; daytime readings of relative humidity were found, correctly, to be much higher than previously. Because this change affects the readings only when sunlight illuminates the rawinsonde unit, it is possible to use the early morning soundings in the western United States (0500 LT), but not the late afternoon soundings. If the afternoon soundings were used, the relative humidity would be higher in the modified units and the predicted values of precipitation would be higher than comparable situations in earlier years. The result would lead to an apparent deficiency in observed precipitation during the later years, including the seeded ones. Therefore, we are further restricted to use only the 1200 GMT soundings. The study is based upon data from the five winter months (November–March), the months of the seeding operation. To simplify reference to dates we shall make use of the fiscal year designation, e.g., November 1966–March 1967 is the winter of FY 67.

In summary, the meteorological data for the unseeded period are derived from 1200 GMT rawinsonde data collected between November 1966 and March 1973 (FY 67–73) or seven winters. Data for the seeded period are from the two winters, FY 74–75. Likewise, precipitafion data are obtained from available stations during the same periods, and recomputed into units of tenth inch increments.

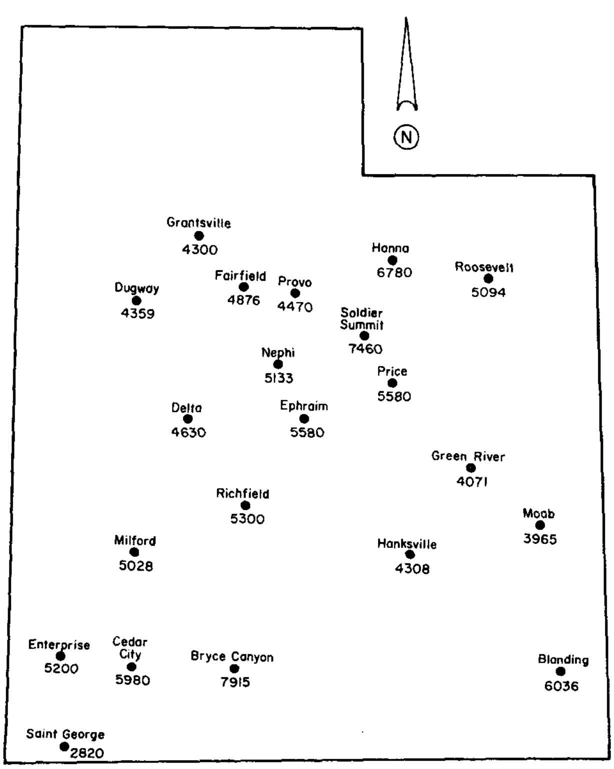

Fig. 2. Precipitation stations and their altitudes.

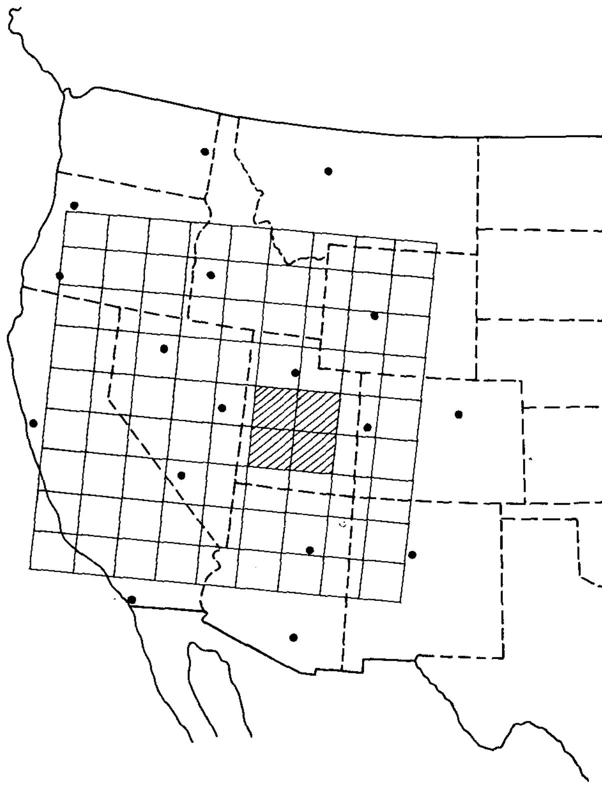

Fig. 3. Rawinsonde stations and data grid.

b. *Precipitation data* (*predictand*)

Precipitation data were obtained from NCC and were processed onto data cards and then magnetic tape. Hourly precipitation data in increments of 0.1 inch were summed over 24 h intervals for 21 stations. These stations and their respective altitudes are shown in Fig. 2. For this study two categories of precipitation data are made, one consisting of the average precipitation of all stations, the other consisting of the average precipitation of the two highest stations, Soldier Summit and Bryce Canyon.

When data are missing, they are filled in by use of six surrounding stations. These surrounding data are modified both according to their mean values and a distance weighting factor. The distance weighting is inversely proportional to the distance to the 1.6 power; however, it was found that over a broad range the results are very insensitive to the choice of this power.

c. *Meteorological data* (*predictors*)

Rawinsonde data were obtained from NCC for 17 stations all of which are outside the target area. These data were first processed onto data cards and then magnetic tape. The data used consist of the following: temperature at 500 mb, height of 500 mb level, relative

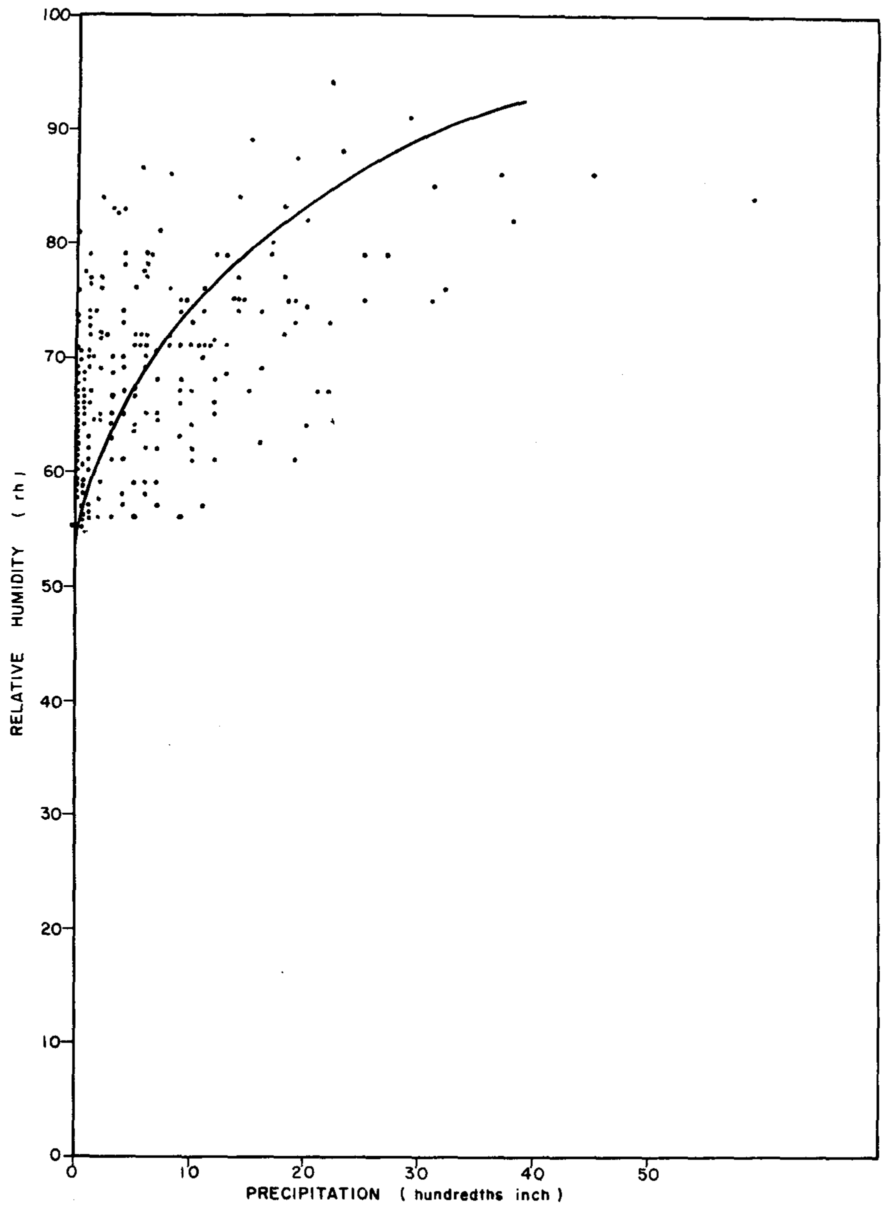

FIG. 4. Twenty-four hour precipitation versus relative humidity parameter for average of all stations of Fig. 2.

humidity at 500, 650, 700 and 750 mb, surface station pressure and temperature. The date time and station identification are also listed.

Extensive checking of data was carried out to ensure data accuracy. In addition to proof reading, various computer checks were made to find inconsistencies. Hydrostatic calculations were made to check the consistency of temperatures and pressure-heights. Date and time scans were made to validate key punching. The final nine seasons of checked data consisted of over a quarter million pieces of information.

Data from the 17 stations were then placed on a grid by interpolating from their surrounding stations with inverse 1.6 power distance weighting. The use of gridded data facilitates both the calculation of various gradients of the original data, and replacement of data when observations are missing as in the case of an auxiliary analysis to be discussed later. The grid spacing is 150 km as shown in Fig. 3. Values of these data and other finite difference quantities were then found from the gridded data. The hatched area is an approximate representation of the target area shown in Fig. 1. Thus, the grid point at the center of this area is located at the center of the target area.

4. Development of predictor

a. Analysis of basic predictors

Meteorological variables which might reasonably be related to precipitation were correlated with precipitation data for the unseeded seasons. To do this several derived meteorological quantities were calculated such as wind (geostrophic), temperature lapse rate, vorticity, and vorticity advection. Precipitation data for 24 h intervals were paired with 1200 GMT values of meteorological data for comparison.

Probably one of the most important meteorological parameters related to precipitation is relative humidity (e.g., Glahn and Lowry 1972),. Because this is likely to be the case, it is useful to examine this relationship in some detail. To see how relative humidity and precipitation are related, 24 h amounts of unseeded precipitation (prior to seeding project) averaged for the 21 stations versus the relative humidity at the central grid point within the target area are shown in Fig. 4. Days with relative humidity less than 55% were omitted. The relative humidity used in this comparison is the average for the 500 mb level and a 700 mb value derived from three humidities. That is,

$$\overline{\mathrm{rh}}=\tfrac{1}{2}[\mathrm{rh}_{500}+(\mathrm{rh}_{650}+\mathrm{rh}_{700}+\mathrm{rh}_{750})/3]. \qquad (1)$$

For the whole 35 months of unseeded precipitation, the correlation coefficient between daily amounts of precipitation and the relative humidity parameter $\overline{\mathrm{rh}}$ with a cutoff value of 55% is 0.43. Without the cutoff the coefficient is only 0.26. Further discussion on cutoffs will be made later.

Corrlation coefficients relating precipitation and meteorological quantities are listed in Table 1 in order of strength, without regard to sign. The 1000 mb height correlates the best at −0.47. Next is the relative humidity at +0.43. The next two correlations, the N-S wind at 500 mb (+0.29) and the vorticity at 500 mb (+0.20), are physically similar. The former is a measure of the vorticity further to the west, while the latter is measured at the center of the target area. The probable reason for the higher correlation of the N-S wind compared to the vorticity is that storminess may be better related to upper level vorticity to the west than to the vorticity overhead. The remaining correlations in Table 1, while physically meaningful, are rather small.

Some of these predictors are combined into a single predictor by use of a multi-regression equation. To find out whether a significant improvement over the single variable relationship could be achieved, a three-variable equation ($n=3$) is used of the form

$$p=\bar{p}+\sum_{i=1}^{n}[a_i(X_i-\bar{X}_i)], \qquad (2)$$

where p is precipitation, X_i are meteorological variables, a_i are coefficients derived by standard methods, and the overbar denotes a summation over all days with available data, divided by the number of days, N. With the three selected variables being 1000 mb height. the relative humidity parameter and 500 mb vorticity, the multi-correlation coefficient is 0.51. This value represents only a small improvement over a single-variable relationship. However, we believe additional improvement can be made in the level of correlation using the existing data set. This subject will be discussed in the next section.

b. Synthesis and development of improved predictors

There are at least three kinds of improvements over simple linear regression analysis, which can be made. The first is the use of cutoff values such as already made with relative humidity. The second is a change of variable such as raising the original variable to some power. The third is the combining of different variables to form a new one.

The use of a cutoff value could be extended to other meteorological variables when the predictand is precipitation. Usually wintertime precipitation occurs when a variety of conditions prevail simultaneously. When any one condition is far from being satisfied it becomes much more unlikely that substantial precipitation will occur. For example, if the surface pressure is very high it is unlikely that precipitation will occur. Therefore, we have applied the use of cutoffs for both 1000 and 500 mb heights. The cutoffs used are 200 and 5700 m, respectively. The new variables are the departures from these cutoffs in the negative direction. Days with higher heights are eliminated from the data.

In the case of a change of variable, it may be noted, for example, that in Fig. 4, the relationship is better described by a curve than a straight line. If the square of the excess of relative humidity above the cutoff value is used, the correlation coefficient increases from 0.43 to 0.52. It appears that a power of 2 is probably close to the optimum in describing the humidity-precipitation data. Use of logarithmic regression is precluded because there are many zero values of precipitation which must be retained.

The third method suggested for improved relationships is based on combining simple variables into a product variable. For some combinations of predictors, straight line relationships are rather unrealistic. One product factor is the relative humidity predictor, i.e., $(r\overline{H}-55)^2$ for humidities greater than 55%. Any of the other predictors could be used along with the humidity

TABLE 1. Predictor variables and correlation coefficients.

Pressure height (A)*	−0.47
Relative humidity (55% cutoff)	+0.43
N-S wind (B)**	+0.29
Vorticity (B)	+0.20
Pressure height (B)	−0.18
Vorticity (A)	+0.16
Vorticity advection (B)	−0.15
Temperature (A)	+0.13
Stability (T_{1000}—T_{500})	+0.13

* (A) refers to the 1000 mb level (about sea level equivalent).
** (B) refers to the 500 mb level (about 18 000 ft MSL).

TABLE 2. Improved predictor variables and correlation coefficients.

Pressure height (A)*	−0.61
Relative humidity parameter	+0.52
N-S wind (B)	+0.48
Vorticity (B)	+0.56
Pressure height (B)	−0.52
Vorticity (A)	+0.50
Vorticity advection (B)	−0.24
Temperature (A)	+0.52
Stability ($T_{1000}-T_{500}$)	+0.52

* This and other following variables are multiplied by the relative humidity parameter.
** (A) refers to the 1000 mb level, (B) to the 500 mb level.

predictor to form a product result. For this reason, all the predictors were multiplied by the humidity predictor. However, some quantities such as temperature lapse rate between 1000 and 500 mb remain nearly constant, so a multiplication by the humidity predictor produces a new variable nearly the same as humidity predictor except for a multiplier constant. For other variables the new predictor shares the effects of both of the original predictors.

The results of modifying the original predictors are shown in Table 2. It is clearly evident that the individual correlations have increased considerably over the previous values. The pressure-humidity predictor has a correlation of −0.61. Thus, this predictor was selected as the predictor to be used.

The use of cutoffs and other procedures needs to be examined with respect to statistical bias. That is, if the predictor has systematic error over its range and the seeded seasons have systematically different values of the predictor from unseeded seasons, then an unwanted bias may be present. Concerning the first of these conditions for bias, we may use relative humidity as an example predictor to clarify the effect of our modifications. If a least-squares fit which included values of humidities *lower* than the cutoff were drawn on Fig. 4, the line would overpredict precipitation at low humidities and underpredict precipitation at high humidities. When a humidity cutoff is used this systematic error is greatly reduced, and as shown in the figure, a quadratic form reduces the systemaric error as well. While there is no clear-cut guarantee that all such bias potential has been removed, the use of a cutoff for humidity clearly reduces the potential for bias in the predictor range accounting for nearly all of the precipitation, and the use of a quadratic form of humidity reduces it even further.

Several attempts were made to improve upon this correlation coefficient (0.61 magnitude) by forming a multi-correlation coefficient. It is believed from a physical standpoint that the best additional predictors are vorticity and vorticity advection at 500 mb and low-level wind speed. The first is a measure of upper level storm strength, the second of storm intensification and the third of orographically forced precipitation. However, there was practically no change in the multi-correlation coefficient. It remained 0.61. Therefore, the single combined predictor of 1000 mb height times the humidity parameter was used as the predictor.

It is important to check the amount of precipitation excluded from the data by any cutoff procedures. Presumably, if the basis for employing cutoffs is correct, then the amount of precipitation "lost" will be small. For the data shown in Table 2, there were 224 valid days, whereas a total of 561 days were excluded. However, all these excluded days together account for only 16% of the precipitation. In any operational project, much of this precipitation would be left unseeded anyway because of the limited area or time likely involved. It is highly doubtful that the small percentage of seeded precipitation excluded could have a significant impact on an evaluation. Furthermore, if desired, a separate analysis could be made of these days.

5. Evaluation of southern and central Utah winter cloud seeding project

a. Unseeded seasons (FY 66–73)

To find the expected values of precipitation we have used the combined predictor, defined as the product of 1000 mb height departure and the relative humidity parameter. The correlation coefficient for this parameter is −0.61.

To find a relationship between the predictor and the precipitation, values of each are summed over each of the winter seasons for the days not excluded because

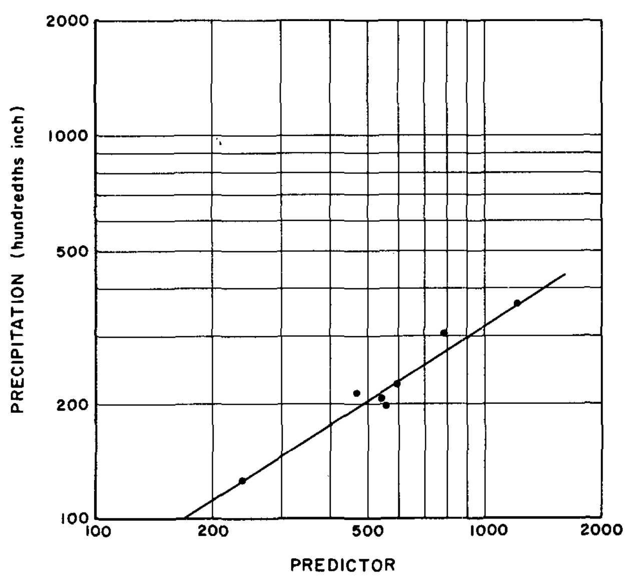

FIG. 5. Logarithmic relationship of observed and predicted unseeded precipitation on seasonal basis for network average. The units of the predictor are obtained from the surface pressure-height departure in meters times the square of the relative humidity parameter in percent. The plotted values of the predictor have been multiplied by 10^{-3}.

of missing meteorological data. Separate relationships are found for the average network precipitation and for the average of the two high-altitude stations. The general form of the relationships is assumed to be logarithmic. The regression lines for both seasonal data sets (network average and two high stations) with precipitation departures minimized are shown in Figs. 5 and 6, respectively, along with the individual data points.

The regression relationships for both seasonal data sets are

$$p_{\mathrm{AVE}} = 3.4493\epsilon_{\mathrm{AVE}}^{0.65942}, \tag{3}$$

$$p_{\mathrm{HI}} = 9.5537\epsilon_{\mathrm{HI}}^{0.59864}, \tag{4}$$

where p and ϵ are the precipitation and predicted values and subscripts AVE and HI refer to the average for the 21 stations and the average of the two high-altitude stations, respectively. The correlation coefficient relating seasonal values of unseeded precipitation to the predictor is 0.975 for the network average precipitation and 0.879 for the average of the two high-altitude stations.

b. Seeded seasons (FY 74–75)

We are now in a position to examine the two seeded seasons. Meteorological data from the seeded seasons are used in the same way as in unseeded years. Values of precipitation are found from observations, in the same way as in unseeded years. Then seasonal values are derived by summing the daily values over the seeded seasons for the days not excluded because of missing rawinsonde data.

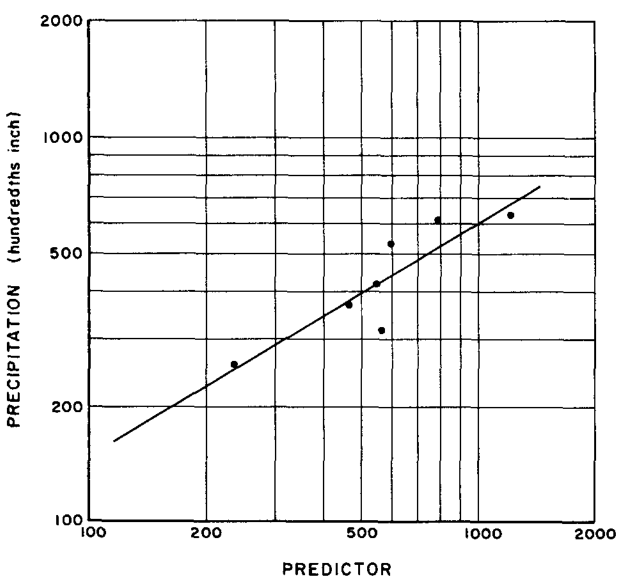

Fig. 6. Logarithmic relationship of observed and predicted unseeded precipitation on seasonal basis for average of two high-altitude stations. Predictor units same as in Fig. 5.

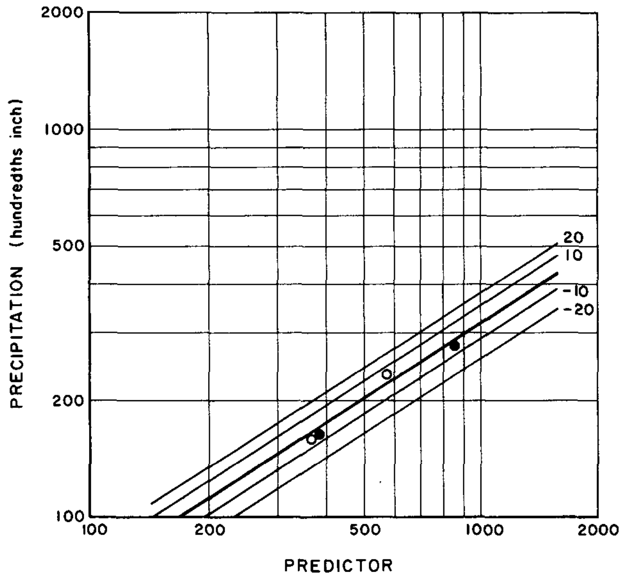

Fig. 7. Logarithmic relationship of observed and predicted seeded and unseeded precipitation on seasonal basis for network average. Open circles indicate days with missing upper level data are not included; large solid circles indicate missing data are estimated and those days included. Predictor units same as in Fig. 5.

We note that all days other than those with missing data are included in the analysis, regardless of whether meteorological conditions were actually favorable for seeding or whether they were seeded at all. The reasons are, respectively, that 1) we are concerned here only with an evaluation of the *overall* effectiveness of the seeding program rather than assessment of whether some selected periods yielded increases, and that 2) a strong bias in favor of seeding effects would result if only seeded days were included in the analysis. Concerning the second reason, the operators choose storms to seed which are believed suitable for modification. It happens that these storms yield far more precipitation, both in the target area and upwind of the target area, than what is given by the predictors. For example, at Ely, Nev., the two-year double ratio of observed to expected precipitation for seeded and unseeded periods is 3.34. In other words, the operators tend to seed the "wettest" storms. In the absence of explicit seeding criteria, this fact can only be taken into account by including all days during the season of seeding.

An auxiliary analysis was made to account for days within the seeded seasons with missing rawinsonde data. Precipitation on such days amounted to about 1% in FY 74 and about 16% in FY 75. Although these added days are included in the auxiliary analysis, it is recognized that any replaced rawinsonde data may introduce some bias, because all days with missing rawinsonde data in the unseeded seasons were excluded.

The observed and predicted values for the average of all stations over each of the two seeded seasons are

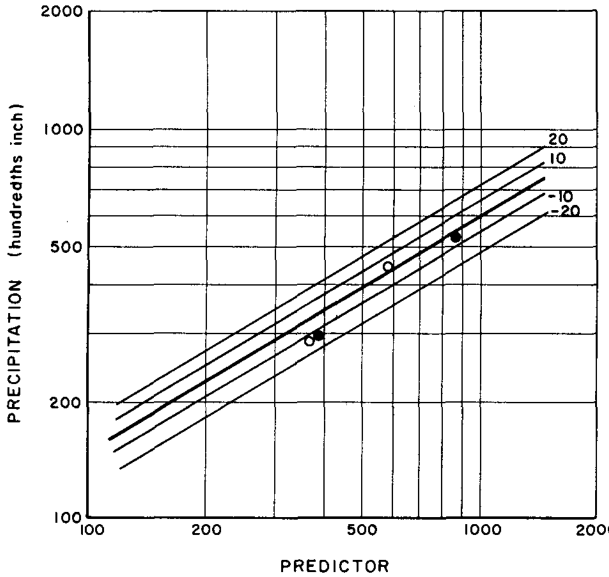

FIG. 8. As in Fig. 7 except for average of two high-altidude stations.

shown in Fig. 7. For the primary analysis, wherein missing upper level data are not replaced, the seasonal values are shown by open circles. When missing upper level data are estimated, the seasonal values are shown by solid circles. Similarly, the high-altitude seasonal values for the two seeded seasons are shown in Fig. 8. The regression lines on these figures are those derived for the unseeded seasons. Also, included on the figures are the lines for both a 10 and 20% increase or decrease in precipitation over what would be predicted from the meteorological data.

The usual approach to a statistical analysis of this data is by an analysis of covariance. However, what seems more appropriate is a method which is sensitive to both an intercept shift and a change in slope as well. In fact, the slope of the predictor-predictand regression line, as well as its intercept, is based solely upon unseeded seasons. Consequently, another statistic (A), defined below, is used for this problem.

Let

$$A=\sum_{i=1}^{n_s}(\ln r_{si}-\ln p_{si})/n_s-\sum_{j=1}^{n_u}(\ln r_{uj}-\ln p_{uj})/n_u, \quad (5)$$

where:

- r_{si} observed precipitation, ith seeded season
- r_{uj} observed precipitation, jth unseeded season
- p_{si} predicted precipitation, ith seeded season
- p_{uj} predicted precipitation, jth unseeded season
- n_s number of seeded seasons
- n_u number of unseeded seasons.

It is assumed in (5) that p_{si} and p_{uj} are derived from the same population.

TABLE 3. Confidence limits for $E(A)$ with $\alpha=0.10$.

Category	Lower limit	Upper limit
AVE 1	−0.0493	+0.0429
AVE 2	−0.0665	+0.0219
HI 1	−0.1239	+0.0749
HI 2	−0.1074	+0.0986

AVE, analysis with average precipitation of all 21 stations.
HI, analysis with average precipitation of 2 highest stations.
1, missing data left out (primary analysis).
2, missing data replaced in seeded years (auxiliary analysis).

Thus, we test

$$E(A)=E\left(\ln\frac{r_{si}}{p_{si}}\cdot\frac{p_{uj}}{r_{uj}}\right). \quad (6)$$

This statistic measures or compares the ratios (r_{si}/p_{si}) and (r_{uj}/p_{uj}). A value of $E(A)$ equal to zero indicates that seeded and unseeded years are not different in their expectation.

Assuming that r_{si}, r_{uj}, p_{si} and p_{ui} are lognormally distributed, an approximate α-level confidence interval on $E(A)$ is given by

$$A-t_{\alpha/2}S_A<E(A)<A+t_{\alpha/2}S_A, \quad (7)$$

where $t_{\alpha/2}$ is the upper $\alpha/2$ critical value from the Student's t distribution with appropriate degrees of freedom and S_A is the sample standard deviation of A. The confidence interval (7) is approximate because the p_{si}'s and p_{uj}'s are treated as nonrandom variables, which depend only upon the value of the ith or jth predictor as appropriate.

Calculations of confidence limits, based on (7), yield the results shown in Table 3. The statistic $E(A)$ is clearly bracketed by the lower and upper confidence limits for all four situations considered. Therefore, we may conclude that the precipitation in seeded and unseeded seasons are not significantly different from what would be predicted by a predictor based upon aerological variables alone. It should be remembered that these results are based on data from a nonrandomized seeding project.

For the network average (Fig. 7), all of the unseeded as well as the seeded seasons fall within about a 10% variation from the predicted values. While some increase may well have occurred in the two seeded years,

TABLE 4. Ratios of seeded to predicted precipitation by seasons.

	All stations		Two high stations	
	1	2	1	2
FY 74	0.94	0.94	0.90	0.90
FY 75	1.04	0.98	1.01	0.95

1, Missing data left out; 2, missing data replaced.

the effect is probably less than 10%, if any. A similar result is found for the two high-altitude stations, but because there is much more variability in these data, the result is considerably less certain. Any increase is probably less than 20%, if any. (The increased variability of the high-altitude data compared to the network average is not due to altitude, but to the greatly reduced number of stations used.)

A summary of ratios by seasons for both categories of stations, i.e., the average and the high stations, is given in Table 4. It should be stressed that these values are uncertain to within about 10% for the network average and about 20% for the high-altitude stations, based on the variability of the seven unseeded seasons.

To conclude, at this stage of the analysis there is little evidence to support or reject modest effects from seeding. We can place probable upper limits to seeding effects. That is, effects of seeding over the whole area probably did not exceed 10%, and at high elevation probably did not exceed 20%. Further analysis, by refinement of the method, and by extending the number of seeded years, would lead to more definitive conclusions.

6. Summary and conclusions

We have evaluated the southern and central Utah cloud seeding project independently by means of a so-called Aerological Control evaluation design. In this method it is assumed that predictor-predictand relationships remain stable and that the predictors are not affected by seeding. Predicted values of precipitation are derived from upper air meteorological data. Relationships between precipitation and other meteorological parameters are derived from 1200 GMT data over a period of seven unseeded winters. Results from this analysis yield ratios of seeded to unseeded precipitation of 0.94 and 1.04, for network averages during the first two winters, respectively. If missing data in the seeded years are estimated from surrounding data, these ratios become 0.94 and 0.98, respectively. When the two highest stations are used as a measure of seeding effects in high terrain, the ratios are 0.90 and 1.01 for the first two years, respectively. With the missing data replaced by estimations, the ratios are 0.90 and 0.95, respectively.

The analysis presented herein shows little effect from seeding, and that a probable upper limit is a 10% increase for the whole area and a 20% increase for the high-altitude stations. However, any increase in precipitation from seeding, if any, has not yet been detected. It is unlikely that substantial large-scale increases due to seeding have occurred. There is a substantial chance that little or no effect is present, although it is possible that a modest artificial modification of precipitation could have occurred during the first two seasons.

The primary conclusion of this paper is that some form of a predictor-type evaluation scheme such as presented herein appears to be a very promising approach to assessing the effectiveness of the Utah cloud seeding program or other winter programs to increase precipitation.

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