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EVALUATION OF SOUTHERN AND CENTRAL

UTAH CLOUD SEEDING PROGRAM

by

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for the

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ABSTRACT

An evaluation of a winter operational-type cloud seeding project in Utah is made by developing meteorological predictors of target precipitation. Twenty-four hour precipitation amounts in seven unseeded years are matched with 12:00 GMT rawinsonde data to form predictor-predictand relationships. Application of the predictors to the first two years of the project indicates that the observed seeded precipitation is about what would be found in the absence of seeding.

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1.0 INTRODUCTION

1.1 Purpose and Scope of Effort

The present report is concerned with the evaluation of a cloud seeding project to increase winter precipitation in Southern and Central Utah. The project has completed three seasons of operation; however, only the first two seasons are evaluated because the data required were not yet available until several months after the third winter season.

As described in a recent report,[1] the Utah Water Research Laboratory examined several approaches to the problem of evaluation of both randomized and unrandomized cloud seeding projects. Because the project with which we are concerned is an unrandomized one, we need consider only the unrandomized evaluation designs. Within this category the Target to Control or the Seed to Predicted designs are available.

The Target to Control design utilizes a seeded target such as Utah, and a control area, such as the surrounding states, or portions thereof. In this design the precipitation data can be arranged according to either a storm-time period, by the month, or by the season. In the case of the Utah project, a storm-by-storm approach is not likely to be fruitful because the correlation between precipitation in the target and the control would likely be low. On the other hand, over a full winter season the target-control correlation is higher, around 0.8 at least.

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[1] The Assessment of Cloud Seeding Programs and Evaluation Techniques in the State of Utah. Utah Division of Water Resources, Salt Lake City, Utah. June 1975.

In the Seed to Predicted design the control is replaced by an estimated value derived in some other way, such as by use of other meteorological observations. In this design the storm-by-storm design is appropriate because meteorological data are available in the target region. In addition, monthly, or winter-season values for predicted amounts can be obtained simply by summing the individual storm amounts.

In the present study the Seed to Predicted design was used, primarily because it is believed that higher seasonal correlations may be achieved, at least ultimately if not at present, than with the Target-Control method; in such a case the technique would be a stronger one than a Target-Control evaluation. Also there is the possibility of eliminating some periods when no seeding is done.

1.2 Summary of Evaluation Method

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

2.0 DATA PREPARATION

2.1 Analysis of Data Requirements

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

In the case of 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 incre-
ments 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. That is, rawinsonde

units are sent aloft by a helium filled balloon to make measurements of temperature, humidity, pressure and wind at various altitudes. From these measurements many of the National Weather Service charts are derived. In addition, with the use of theoretical models other useful charts are made. We can also construct such charts, but by using uniform methods throughout the period.

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. 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 U.S. (05:00 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 12:00 GMT soundings. The study will be based upon data from the five winter months, November through 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 through March, 1967 is the winter of FY 1967.

In summary, the meteorological data for the unseeded period will be derived from 12:00 GMT rawinsonde data collected between November, 1966 and March, 1973 (FY 67-73) or seven winters. Data for the seeded period will be from the two winters, FY 74-75. Likewise, precipitation data will be obtained from available stations during the same periods, and recomputed into units of tenth inch increments.

2.2 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 hour intervals for 21 stations. These stations and their respective altitudes are shown in Figure 1. 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, it is filled in by use of three surrounding stations. These surrounding data are modified both according to their mean values and a distance weighting factor. The distance weighting is in accordance with the inverse 1.6 power, which is a value used frequently in hydrologic studies.

2.3 Meteorological Data (Predictors)

Rawinsonde data were obtained from NCC for 17 stations covering the period of study. 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 humidity at 500, 650,
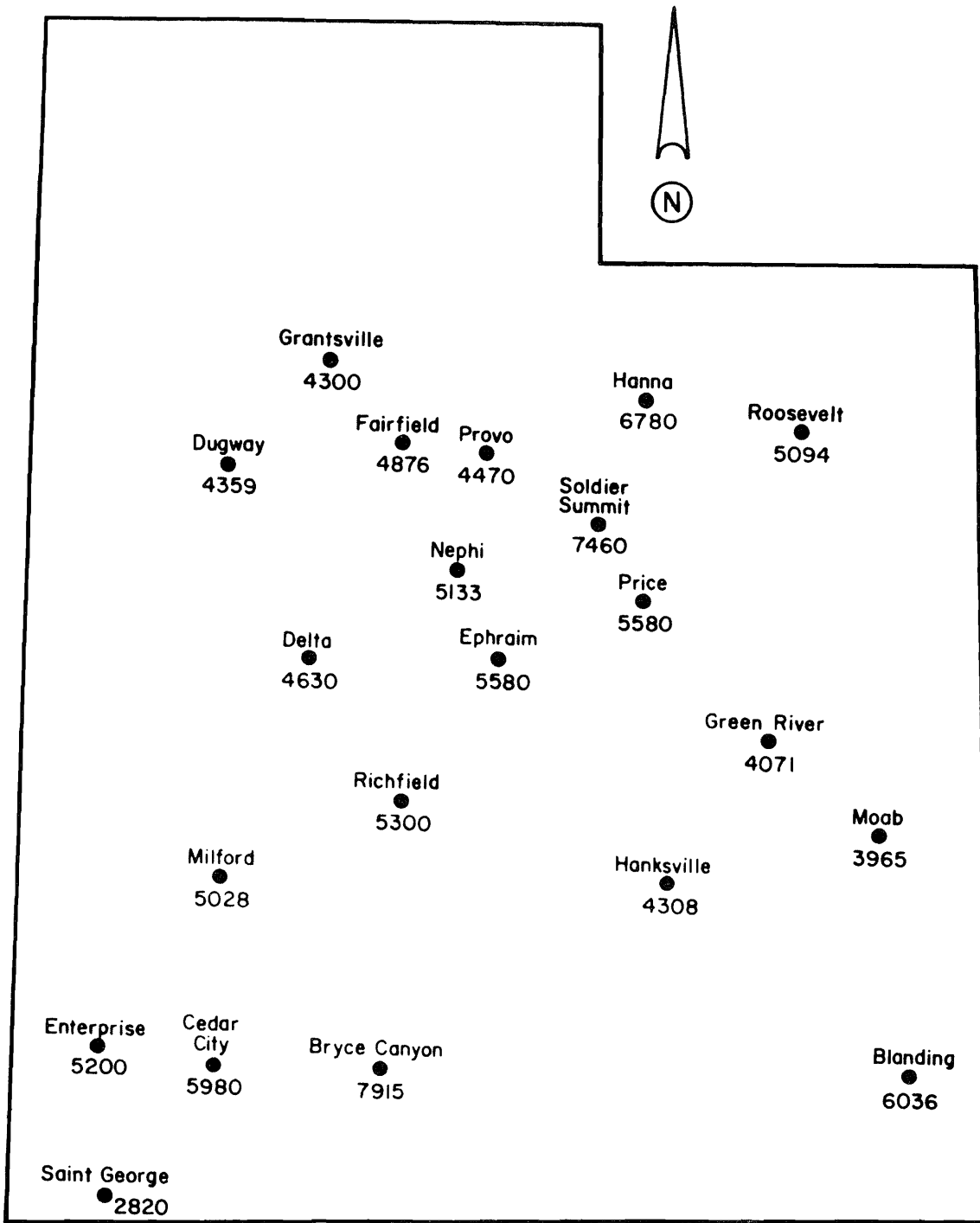
Figure 1. Precipitation stations and their altitudes.

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 grid spacing is 150 km as shown in Figure 2. Values of these data and other derived quantities were then found from the gridded data. Gridded data at intermediate times were obtained by simple interpolation.
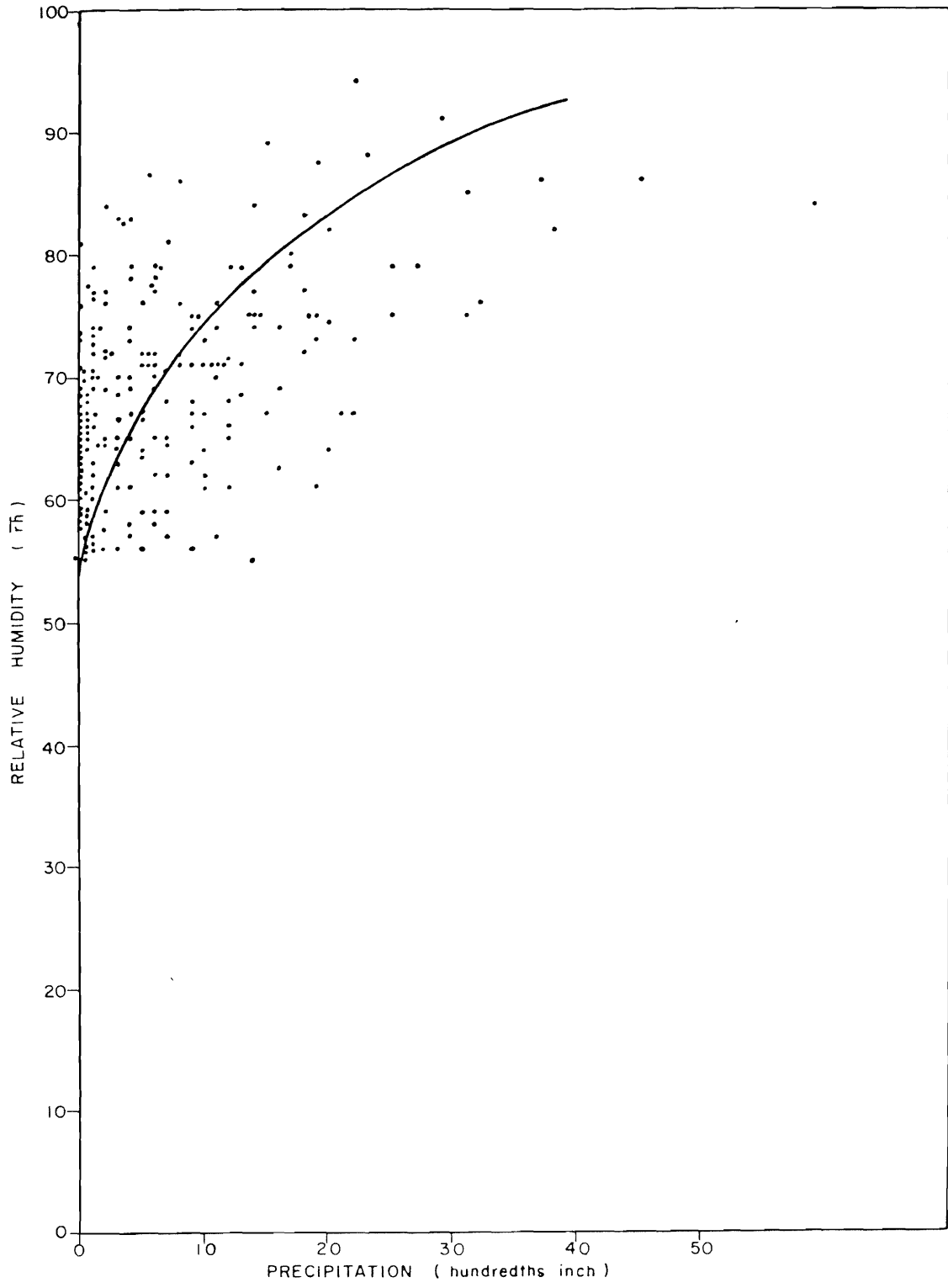
Figure 3. Precipitation versus relative humidity.

Correlation coefficients relating precipitation and meteorological quantities are listed in Table 1 in order of strength, without regard to sign. The 1000 mb height (nearly equivalent to surface pressure) 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 (+.29) and the vorticity at 500 mb (+.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 is 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.

Table 1. Predictor variables and correlation coefficients.

Pressure Height (A)[a]	- .47
Relative Humidity (55% cutoff)	+ .43
N-S Wind (B)[b]	+ .29
Vorticity (B)	+ .20
Pressure Height (B)	- .18
Vorticity (A)	+ .16
Vorticity Advection (B)	- .15
Temperature (A)	+ .13
Stability $(T_{1000} - T_{500})$	+ .13

[a] A refers to 1000 mb level (about sea level equivalent).

[b] B refers to 500 mb level (about 18,000 ft msl).

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Some of these predictors are combined into a single predictor by use of a multi-regression equation. In the present work a three variable equation is used. It is of the form

$$p = \bar{p} + a_1 (X_1 - \bar{X}_1) + a_2 (X_2 - \bar{X}_2) + a_3 (X_3 - \bar{X}_3) \quad . \quad . \quad . \quad (2)$$

where p is precipitation, X_1 is a meteorological variable, the a's are coefficients derived by standard methods, and the overbar denotes a summation of a variable over all cases, divided by the number of cases, N. Corresponding to the multi-regression, or predictor equation, there is a multi-correlation coefficient, which gives a combined measure of relationship to the predictand. With the three selected variables being 1000 mb height, 700 mb relative humidity, and 500 mb vorticity, the multi-correlation coefficient is 0.51. Based upon our requirements as stated in our previous report a correlation of 0.5 would be adequate for an improved evaluation over a target control design. However, we believe some improvement can be made in the level of correlation using the existing data set. These improvements will be discussed in the next section.

3.2 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 mb and 500 mb heights. The cutoffs used are 200 and 5700 meters, respectively. The new variables are the departures from these cutoffs in the negative direction. Cases with higher heights are eliminated from the data.

In the case of a change of variable, it may be noted, for example, that in Figure 3, 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 two 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 upon combining simple variables into a more complex variable. One useful way of combining variables is to take their product. In some instances, this way of combining them leads to improvement. To see how this comes about, consider two variables, each bearing some relationship to a third variable, in our case, precipitation. In Figure 4, a schematic graph is shown for two variables both related to precipitation. These curves obey the relationship $p = kxy$, where k is a constant and x and y are the individual predictors. This relationship means that, for example, a doubling of either predictor will double the precipitation.

On the other hand, a simple linear regression would force straight lines through the data field. For some combinations of predictors, such
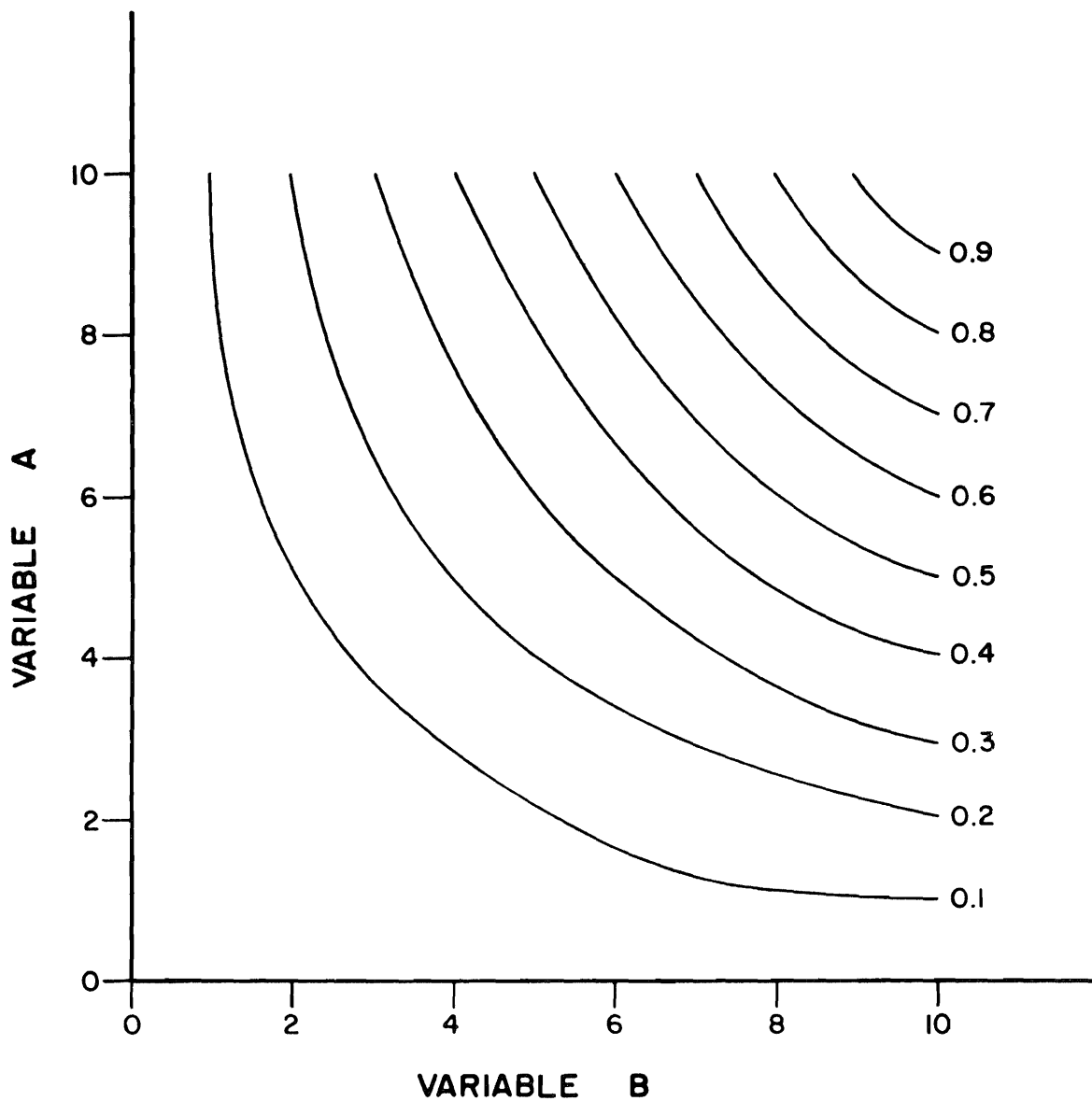
Figure 4. Two arbitrary variables related to precipitation.

straight line relationships are rather unrealistic. Therefore, use is
made of products to form new combined predictors.

One such combination utilizes the relative humidity predictor, i.e.,
$(\overline{rh} - 55)^2$ for humidities greater than 55 percent. Any of the other pre-
dictors could be used along with the humidity predictor to form a result
as depicted in Figure 4. For this reason, all the predictors were multi-
plied by the humidity predictor. Caution must be exercised at this point.
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. In other cases such as depicted in Figure 4, 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.

Several attempts were made to improve the predictor coefficient (0.61
magnitude) by forming a multi-correlation coefficient. It is believed
from a physical standpoint that the best additional predictors are vor-
ticity 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 coef-
ficient. It remained 0.61. Therefore, the single combined predictor of
1000 mb height times the humidity parameter is used as the predictor.

They reported also that seeding effects were <u>diluted</u> because seed-
ing was not done in all months each winter. The overall assessment is
that seeding has increased precipitation 15 percent and that locally,
much higher increases are evident. Because this assessment is somewhat
different from our findings, we have re-examined their analysis in the
following section.

<u>4.3.2 Review of Target-Control evaluation</u>. There are several
aspects of the NAWC evaluation that should be subjected to critical re-
view. One aspect concerns the belief that by including precipitation
from November and December 1973 of the first winter and November 1974 of
the second winter, the seeding effects are diluted, because those months
were not actually seeded. Yet in their analysis the month of February
1976 is omitted because of an exceptional storm that affected primarily
the control area. The three months that indeed should be left out of
the analysis are included. We have re-analyzed the data leaving those
months out. The results are summarized in Table 4. Only the first

Table 4. Seeding ratios for NAWC and UWRL evaluations.

	NAWC Target-Control		UWRL Target-Control		UWRL Seed to Predicted[a]
	5 winter mos.	5 winter mos.	unseeded period	seeded period	seeded period
1973-74	1.16	1.06	1.22	0.94	0.94
74-75	1.10	1.01	1.24	0.97	1.04
75-76	0.85[b]	---	--	--	

[a]Missing 500 mb data not replaced.

[b]With February 1976 included.

two years are re-evaluated by UWRL to find the effect of the three un-
seeded months. Ratios computed for the entire five month periods should
be the same for the two evaluations if the same data were used. However,
in our review we deleted some of the control stations because they are
clearly in the path of seeding material much of the time. The stations
omitted are those in the C-4 region of NAWC and Copper Mine and Lees
Ferry of C-3. Other stations omitted were Contact, Park Valley, Pequop,
and Wendover, because long term means were not available. All other
stations of the control were retained. For Utah data we utilized the
data set prepared for our original analysis. Thus some differences
exist in the overall analysis by NAWC and UWRL as shown by the two left
hand columns in Table 4. Next we consider the effect of removing the
three months in which no seeding was done. In the pre-seeded period the
seeding ratios are 1.22 and 1.24 for 1973-74 and 1974-75, respectively.
Thus a substantial apparent effect of seeding occurred prior to any seed-
ing for those winters. The actually seeded periods yielded ratios of
0.94 and 0.97, respectively. For comparison, the UWRL Seed to Predicted
ratios are shown in the last column.

When the first and last columns are compared the results are some-
what different with one method showing increases, the other, little
change in precipitation. However, when the re-evaluated data and the
UWRL Seed to Predicted analysis are compared (the last two columns) the
results are rather similar. The two year Target-Control overall ratio
is 0.955 and the Seed-Predicted is 0.995. These results, although based
upon limited data, suggest that a positive effect from seeding on this
particular project has not been demonstrated, but that the seeding effects
if present are yet undetected.

A comment is in order concerning the omission of February 1976. If it is believed that this month was an extraordinary one and that it is desirable to leave it out, then it is imperative that similar data be removed from the unseeded data set. Otherwise, the natural statistical variations, which sometimes contribute in favor of an apparent seeding effect and sometimes against, are biased toward a positive effect. Therefore, seven or eight (1/12th of the data) of the unseeded monthly data points, which lie the furthest to the right of the regression line for the unseeded months, should also be omitted. Then whatever seeding effect is shown is much more realistic than what is found by outright omission of the month.

Other comments are in order concerning the snow course data, which are used by NAWC for another Target-Control evaluation. Their results for the 'Central' region, where by far the largest number of snowpack stations are found, yield ratios of 1.30, 1.03, and 0.83 for the three winters, respectively. These values are similar to those found for precipitation.

For two reasons the high ratio of the first year has little to do with seeding. First, the same effects of leaving out the months of un-seeded precipitation apply to snow course data. Second, the snow course water content is affected by the temperature at high elevations in late winter, especially March.

Concerning the second reason, in the NAWC evaluation long term stations with elevations of approximately 7500 feet and higher were selected for the basis of subsequent evaluations, because a preliminary survey of the April readings for stations in Arizona and Nevada, below

7500 feet, indicated that substantial snowmelt had often already occurred
by April 1. It is evident that NAWC justifiably attempted to remove
the effect of temperature on the snow course evaluation. Yet, we have
found that the average March 1974 temperatures at representative stations
in Nevada and Arizona were exceeded by one degree or more only once in
the last 25 years. The temperature anomaly occurred also in Utah, but
the temperature itself was substantially lower than in Arizona and
Nevada, by about 5 to 10 F. Therefore, it is likely that prior to
April 1 there was substantial snowmelt in Nevada and Arizona but not in
Utah. The effect of this is to make it appear that there was more pre-
cipitation in Utah than what would be expected based upon Nevada and
Arizona.

Thus, in the case of snowpack data the high ratio of 1.30 for the
first winter is suspect on two accounts, one the temperature effect, and
two, the effects of removing the unseeded months of November and December
previously discussed. Again, we conclude, a positive seeding effect
based upon snow course data has not yet been detected.

5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

We have evaluated the Southern and Central Utah cloud seeding project independently by means of a so-called Seed to Predicted evaluation design. That is, predicted values of precipitation are derived from upper air meteorological data. The relationship between precipitation and other meteorological parameters is derived from 12:00 GMT data over a period of seven unseeded winters. Results from this analysis yield ratios of 0.94 and 1.04 for 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.

So far, the Seed to Predicted analysis shows little effect from seeding. and that a probable upper limit is a 10 percent increase for the whole area and a 20 percent increase for the high altitude stations. However, any increase in precipitation from seeding, if any, has not yet been detected.

A review of the NAWC's evaluation shows that the increase found in the first year of operation was not substantiated. When precipitation data from two months not seeded were removed, the increases disappeared. A similar, but smaller effect, was found for the second year when the unseeded month of November was removed.

In the NAWC evaluation for the third year, it was argued that the month of February 1976 should be removed from the data. In this month anomalous precipitation apparently occurred. However, an equal proportion of unseeded months with similar precipitation anomalies would have to be removed in order to prevent a strong bias toward a positive seeding effect. Thus, a positive effect in the third year is not well based.

The first two years of the snow course target-control evaluation suffer from the same deficiencies as with precipitation. Another difficulty in the snowpack evaluation is that substantial snowmelt had already occurred in Nevada and Arizona prior to April 1 and made the Utah snowpack appear deeper than expected.

In summary, the analysis so far has not detected an increase in precipitation from cloud seeding in the Southern and Central Utah Cloud Seeding Project. It is stressed here that all of these results have to be viewed in a statistical sense. That is, it is unlikely that substantial large-scale increases due to seeding have occurred in the Southern and Central Utah Cloud Seeding Project. There is a substantial chance that little or no effect is present, although it is possible that a modest increase in precipitation could have occurred during the first two seasons.

A final conclusion 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 to increase precipitation. Several specific recommendations follow from this and other considerations.

5.2 Recommendations

Evaluation of the ongoing cloud seeding project should be continued. Emphasis should be placed upon further development of the predictor method, in which meteorological data, within or near the target area, other than precipitation are used to assess seeding effectiveness. Additional emphasis should be placed upon developing the method in such a way as to improve the evaluation of seeding effects at high elevations. The current method should be modified so that a longer period of unseeded precipitation can be used to develop predictors.

These recommendations require rather significant departures from the present set of predictors. The method itself remains essentially the same, but the type of data used for both the predictor and the predictand are different than at present. The use of surface pressure and various derivatives of it constitute the prime predictor variables. In addition, limited upper level data, but not humidity--for the reasons cited herein, can also be used.

Precipitation data, in the recommended approach, are used in two ways. First, daily values of precipitation can be used in combination with meteorological data to develop predictors. Then, to obtain new predictors and predictands, the daily values are summed over individual months or seasons. This procedure is the method used in this report. However, to evaluate high elevation seeding effects, use of monthly data is required because of a lack of available daily data at high elevations.

Because the monthly storage-gage data is not significantly modified by factors such as melting, evaporation, etc., as is snowpack, the former is preferred. Use of streamflow data is not recommended because of the

complex relationship between it and precipitation. The only sizable problem with the storage data is that readings are often made on different days near the end or beginning of the month. This difficulty can be overcome by forming separate relationships for each station and then calculating over the appropriate period for each month at each station. Departures from the predicted value in seeded periods for each station in a given month or season can be summed for the geographical region of interest.

Finally, the method developed should be applied to as many seeded years as available data permit.