A LONG TERM WINTER OROGRAPHIC CLOUD SEEDING PROGRAM CONDUCTED IN CENTRAL AND SOUTHERN UTAH

by

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ABSTRACT

North American Weather Consultants (NAWC), a subsidiary of the TRC Environmental Corporation, has conducted a wintertime cloud seeding program in Utah during most years since 1973-74. The goal of this program has been to augment the snowfall in the mountainous regions in central and southern Utah. Additional surface runoff that results from this program is utilized primarily for irrigation of farm lands during the summer months.

This program relies primarily upon a network of ground based silver iodide generators sited upwind of the mountain barriers. Seeding operations are directed from a central forecast facility in Salt Lake City.

An evaluation of this program has been based upon high elevation precipitation and snowpack measurements. A target/control regression prediction analysis based upon these measurements indicate approximately a 15 percent increase in precipitation over the target area for the 17 seeded seasons.

INTRODUCTION

North American Weather Consultants (NAWC) has conducted a winter snowpack augmentation program in most winters since 1974 in southern and central Utah. The intended target areas have included mountain ranges above approximately 2,130 m MSL typically covering an area of approximately 23,000 km^2. The goal of the program has been to augment snowfall from naturally occurring winter storms. Augmentation is accomplished through "cloud seeding" utilizing silver iodide as the seeding agent. Streamflow that results from the augmented snowfall is then utilized for irrigated agriculture or municipal water supplies. Figure 1 provides the location of the mountainous (orographic) target area and locations of generators utilized in the 1993-94 winter program.

PROJECT DESIGN

Sponsorship

The sponsorship of the program has been on a voluntary, county-by-county basis. Each county participates either through their county commission or water conservancy district(s). The program began in the winter of 1973-74. The State of Utah became a financial participant in the local program beginning in the 1975-76 winter season. State funds are allocated each year in the legislative process and administered by the Utah Division of Water Resources. State funds have been allocated on a percentage basis that has varied from

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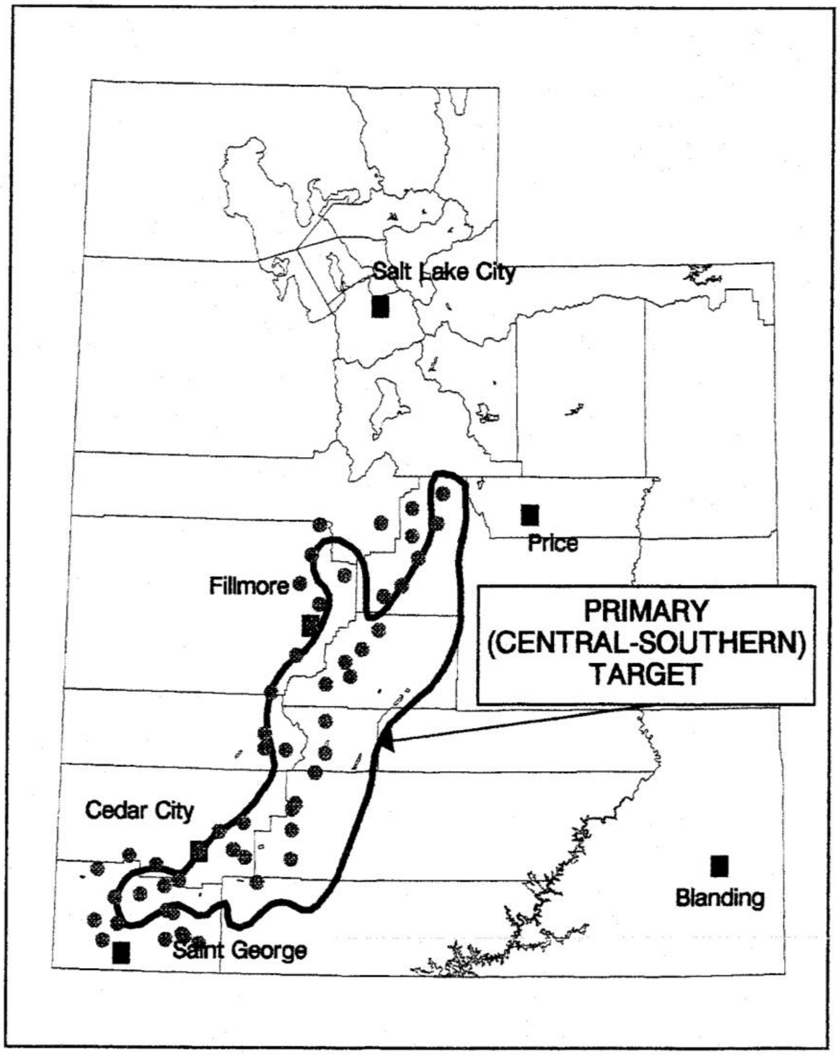

Figure 1. Target area and locations of the ground based silver iodide generators for the 1993-94 winter season.

35 to 50 percent. The costs assessed each of the participating counties has been based upon each counties assessed valuation (after the removal of special facilities such as mining activities and power plant installations).

Conceptual Model

Briefly, the cloud seeding conceptual model utilized in this cloud seeding program is as follows. Observations in winter storms in mountainous areas have frequently indicated the presence of supercooled (below freezing) water droplets in clouds associated with these winter storms. These droplets appear to be especially prevalent in the zone on the upwind side of mountain ranges at elevations up to and approximately 1 km above the crest height of the barrier (Super, 1990).

A relatively large percentage of these supercooled droplets exist because there are inadequate numbers of "freezing nuclei" in the atmosphere that are active at temperatures warmer than -12 to -15°C (Dennis, 1980). These freezing nuclei are typically submicron sized particles that have the ability to cause these supercooled water droplets to freeze upon contact. Soil particles are the most common natural freezing nuclei.

Research conducted in the late 1940's demonstrated that submicron sized particles of silver iodide were very effective freezing nuclei at temperatures colder than -5 or -6°C (Vonnegut, 1947). Means of generating silver iodide particles were developed consisting of either airborne or ground based, dispersing methods. The object of a winter orographic cloud seeding program is to dispense silver iodide freezing nuclei into the region of the accumulation of supercooled water droplets on the upwind side of the mountain barrier. These nuclei need to be dispersed enough to cover significant volumes of this supercooled water droplet zone and yet remain in concentrations high enough to create significant numbers of ice crystals. These ice crystals, once formed, have the opportunity to grow into snowflake sized particles. If these artificially nucleated ice crystals are produced in the right locations, the resulting snowflakes will fall onto the targeted mountain barrier. Conditions change (height of the freezing level, wind direction, wind speed, atmospheric stability) from one storm to the next which necessitates the consideration of the "targeting" of the artificially created snowfall from storm to storm.

Control Center

A weather forecast laboratory is maintained at NAWC's Salt Lake City office. This office is equipped to receive National Weather Service weather observations, analyses and prognostic charts and forecasts. Weather satellite information is also received in this office. Cloud seeding meteorologists monitor the weather from this location and determine whether each storm or portion of a storm is "seedable" then request different ground based seeding generators be activated or deactivated.

The seeding criteria utilized to determine if a portion of a winter storm is "seedable" are provided in Table 1.

Table 1

NAWC WINTER CLOUD SEEDING CRITERIA

1) Cloud bases are below the mountain barrier crest.

2) Low-level wind directions and speeds that would favor the movement of the silver iodide particles from their points of release into the intended target area.

3) No low-level atmospheric inversions or stable layers that would restrict the vertical movement of the silver iodide particles from the surface to at least the -5°C (23°F) level.

4) Temperature at mountain barrier crest height expected to be -5°C (23°F) or colder.

5) Temperature at the 700 mb level (approximately 10,000 feet) expected to be warmer than -15°C (5°F).

Ground Generators

A network of ground based silver iodide generators (so called because they generate silver iodide crystals) is installed each fall at selected locations sited upwind of the intended target barriers. Each generator is located at a local residence at which the resident is trained in the operation of the generator. The generator is activated upon request via telephone from the meteorologists located in Salt Lake City.

Each generator consists of a stainless steel tank of 30 l capacity. This tank is filled with a solution of acetone and 2% by weight, silver iodide. A small amount of ammonium iodide is used to assist in dissolving the silver iodide in acetone. A propane tank is located next to the generator. Propane is used to pressurize the solution tank and to act as a burning medium in which the acetone-silver iodide solution is injected. The solution is vaporized then silver iodide particles crystalize as the vapor cools. Literally trillions of tiny silver iodide nuclei (approximately .1 μm in diameter) are formed from each gram of silver iodide burned in one of these generators. Figure 2 provides a test of the effectiveness of one of the generators as conducted at the Cloud Simulation Laboratory located at Colorado State University (Demott, 1994). From this figure, approximately 1.8 x 10^{14} ice crystals are produced from the combustion of one gram of silver iodide at a temperature of -8°C. Each generator is regulated through a flow valve to release approximately 8 g of silver iodide per hour. Figure 1 shows the locations of generators utilized in the 1993-94 winter program.

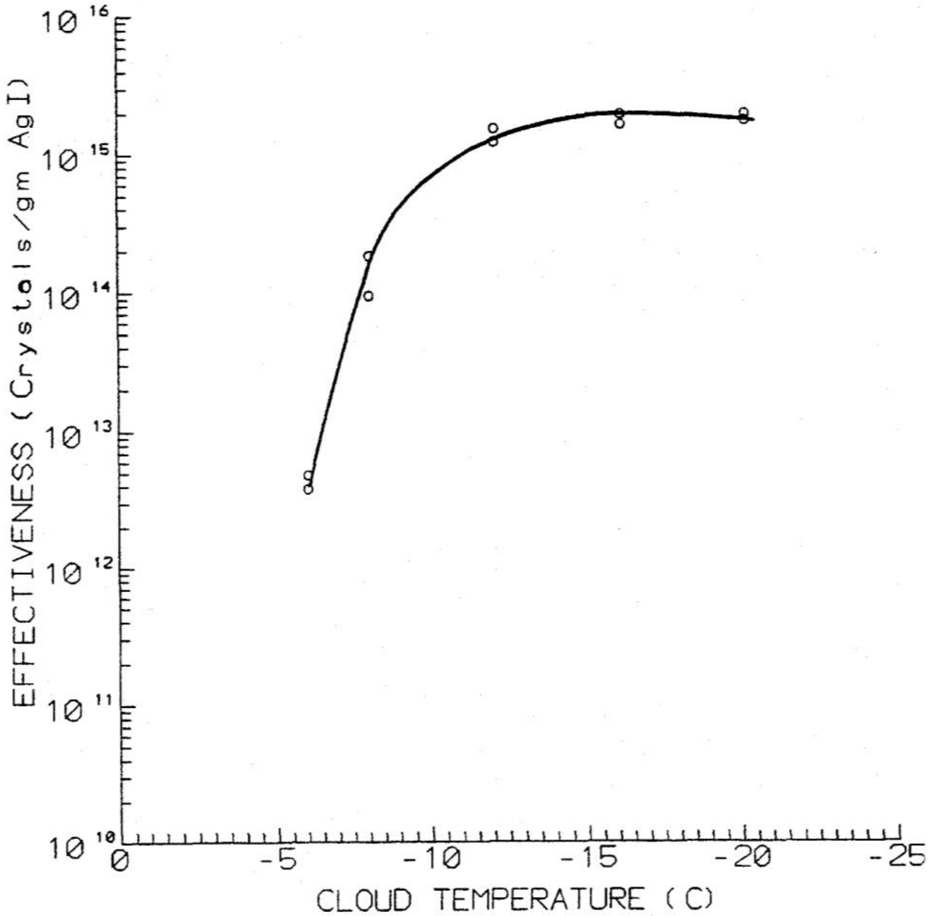

Figure 2. Effectiveness of the NAWC manual silver iodide generator as determined at the Colorado State University Cloud Simulation Laboratory.

Aircraft (up to four in one winter) were used in addition to the ground generators during the early years of the program. Analyses of the amount of time aircraft could be upwind of a given point in the target area indicated seeding was only occurring approximately 10 percent of the time that precipitation was falling at a specific location. This finding led to the conclusion that aircraft seeding was not economically viable for a target area the size of that in central and southern Utah, considering the relatively low value of agricultural irrigation water in Utah. Remotely controlled higher elevation silver iodide ground based generators were also utilized for a few winter seasons. The increased cost of operation of this type of generator led to a similar conclusion reached in the use of aircraft; the central and southern Utah target area is too large to establish a cost effective network using this type of generator. Smaller, high yield portions of the target area might offer some consideration of the use of remotely controlled generators. The main advantage of such generators is that they may be effective in some storm situations where valley based generators are ineffective (i.e., low-level trapping atmospheric inversions).

OPERATIONS

Periods of Operations

The cloud seeding program has typically been operated from November 15 through April 15 each winter season. This period spans a large majority of the winter snowpack accumulation period in Utah's mountains. Cloud seeding operations were conducted each winter beginning in the 1973-74 winter season through the 1982-83 season. Operations were terminated in February 1983 due to high snowfall accumulations in mountainous target areas. For example, portions of the target area had operations suspended due to heavy snowpack during the latter half of the winter of 1993-94. There have been other periods when cloud seeding operations have been suspended or terminated due to heavy snowpack conditions. Heavy precipitation in the 1983 through 1987 period curtailed operations. Drier conditions that began in the 1986-87 winter led to reinstatement of the program which has continued to the present.

Typical Operational Sequence

Table 2 provides the normal sequence followed in the conduct of the cloud seeding program.

Maintenance

Maintenance and refilling of the generators is scheduled to occur during non-storm periods based upon weather forecasts made by the project meteorologists.

EVALUATION OF SEEDING EFFECTIVENESS

Difficulties in Evaluating Operational Cloud Seeding Programs

Evaluating the results of an operational cloud seeding program are unfortunately rather difficult. The seemingly simple problem of determining the effects of cloud seeding has received considerable attention over the years. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. Since cloud seeding is only feasible when there are clouds and usually only when there are clouds that are near to or are already producing precipitation naturally, the question then becomes, "Did the seeding increase the precipitation that was observed, and if so, by how much"? The ability to detect a seeding effect becomes a function of the size of the seeding increase compared to the natural variability in the precipitation pattern. Larger seeding effects can be detected easier and with a smaller number of seeded cases than are required to detect small increases.

Historically, the most significant seeding results have been observed in wintertime seeding programs in mountainous areas. The apparent differences due to seeding are relatively small, however, being on the order of a 5-15 percent seasonal increase. The relatively small percent increase, in part, accounts for the significant number of years required to establish these results (often five years or more).

Table 2

Typical Operational Sequence

- Weather conditions are monitored from Salt Lake City.
- A forecast is made of the progress of a winter storm through the Utah target area.
- National Weather Service rawinsonde data, constant height analyses, weather satellite photographs, and forecasts are examined to determine if the approaching storm or portion of a storm meet the "seedability criteria" (Table 1).
- If the storm, or portion of the storm is deemed seedable, then the meteorologists call selected generator operators to request that the generator at their location be turned on at a specified time.
- The progress of the storm through the target area is monitored. As wind directions change, some generators are turned off and others activated in order to "target" the seeding effects in the intended area. The normal sequence is for the lower level winds associated with storms to blow from the southwest as the front approaches. The winds then shift to winds out of the west with frontal passage then out of the northwest following frontal passage. Activation of generators follow a similar sequence. Those located southwest of the target area are activated first then turned off as winds become westerly. Generators west of the target area are then activated then turned off as winds become northwesterly at which time generators to the northwest are activated.
- Weather conditions are monitored and operations terminated either when the seeding criteria are no longer met or the storm leaves the target area.

In spite of the difficulties involved, there are techniques available to evaluate the effects of operational seeding programs. The techniques are not as rigorous or scientifically acceptable as is the randomization technique used in research, where roughly one half the sample of storm periods is randomly not seeded. They do, however, offer the potential of at least establishing an indication of the effects of seeding on operational programs.

Probably the most commonly employed evaluation technique, and the one that NAWC has utilized, is the "target" and "control" comparison. This technique is based on the selection of a variable that would be affected by seeding (such as liquid precipitation or snow). Records of the variable to be tested are acquired for an historical period of several years duration (20 or more if possible). These records are divided into those that lie within the designated target area of the project and those in a nearby control area. Ideally the control area should be selected in an area which would be unaffected by the seeding. All the historical data, e.g., precipitation, in both the target and control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the two areas. These two sets of data are analyzed mathematically to develop a regression equation which predicts the amount of target area precipitation, based on observed precipitation in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been based on that observed in the control area. A comparison can then be made between the predicted target area precipitation and that which actually occurred. Any resulting difference can be tested for its significance through statistical tests. This target and control technique works well where a good correlation can be found between target and control area precipitation. Generally, the closer the two areas are together, the higher will be the correlation. Areas selected too close together, however, can be subject to contamination of the control area by the seeding activities. This can result in an underestimate of the seeding effects. For precipitation and snowpack assessments, correlations of 0.90 or better would be considered excellent and correlations around 0.85 would be very good. A correlation of 0.90 would indicate that over 80 percent of the variance (random variability) in the historical data set would be explained by the regression equation used to predict the expected precipitation or snowpack in the seeded years. Correlations less than about 0.80 are still acceptable, but it would likely take much longer to attach any statistical significance to the apparent seeding results.

Additional mathematical tests can be made to determine how <u>significant</u> the excess is, but unless the difference is very large it usually requires several episodes (in this case, seasons) to achieve a meaningful level of significance. In the evaluations which follow two independent statistical tests were employed. One was the student's t-test (one tailed) as developed by Thom (1957) for multiple events and the other was the non-parametric Wilcoxon, Mann-Whitney ranking U-test (one tailed) as described in Seigal (1956). The application of statistical tests is actually intended to be applied to randomly collected data sets. This approach is used in weather modification research programs where the seed, no-seed decision is determined randomly. This randomization approach is typically not used on operational programs in an attempt to maximize the cloud seeding results. Dennis (1980) describes some of the difficulties of applying statistics to non-randomized operational programs. Consequently, statistical test results reported here can only be considered as an indicator of validity of the result and not absolute proof.

Target/Control Evaluation

Higher elevation precipitation measurement sites, maintained by the Natural Resources Conservation Service (previously the Soil Conservation Service), or the National Weather Service, have been utilized in evaluations of the effectiveness of the central and southern Utah cloud seeding programs. Thirteen sites were selected to be "control" sites from higher elevation areas in eastern Nevada and northern Arizona. Thirty-six sites were available from the central and southern Utah "target" area. Figure 3 provides the locations of these sites. An 18 year historical period of record was selected from which a linear regression relationship was established. This period included the years from 1957-1973 and 1983-84. This period was selected since it represented a time period when cloud seeding programs were not conducted in central or southern Utah. A four month period, December through March, was selected for analysis since cloud seeding has typically been conducted for the entirety of these months in the conduct of the cloud seeding program. An average for each four month period was calculated for all of the control sites and for all the target sites. These average values for the target and control areas were used to develop the following linear regression equation:

$$y = 1.39\, b \; -2.60$$

Where: y = Calculated average target area precipitation
b = Observed average control area precipitation

The correlation coefficient (r) was a very high .967 or an r^2 value of .935.

This equation was then utilized to predict the average target area precipitation for each seeded season. This prediction can then be compared to the average observed target area precipitation in the form of a ratio (observed divided by predicted). Table 3 contains the results of this analysis.

The average ratio for the 17 season period was 1.15 suggesting 15 percent more precipitation in the target area than expected. One-tailed student's t and Mann-Whitney u tests indicate these results are highly significant ($>$.001). Figure 4 provides a plot of the predicted versus observed average target area precipitation values.

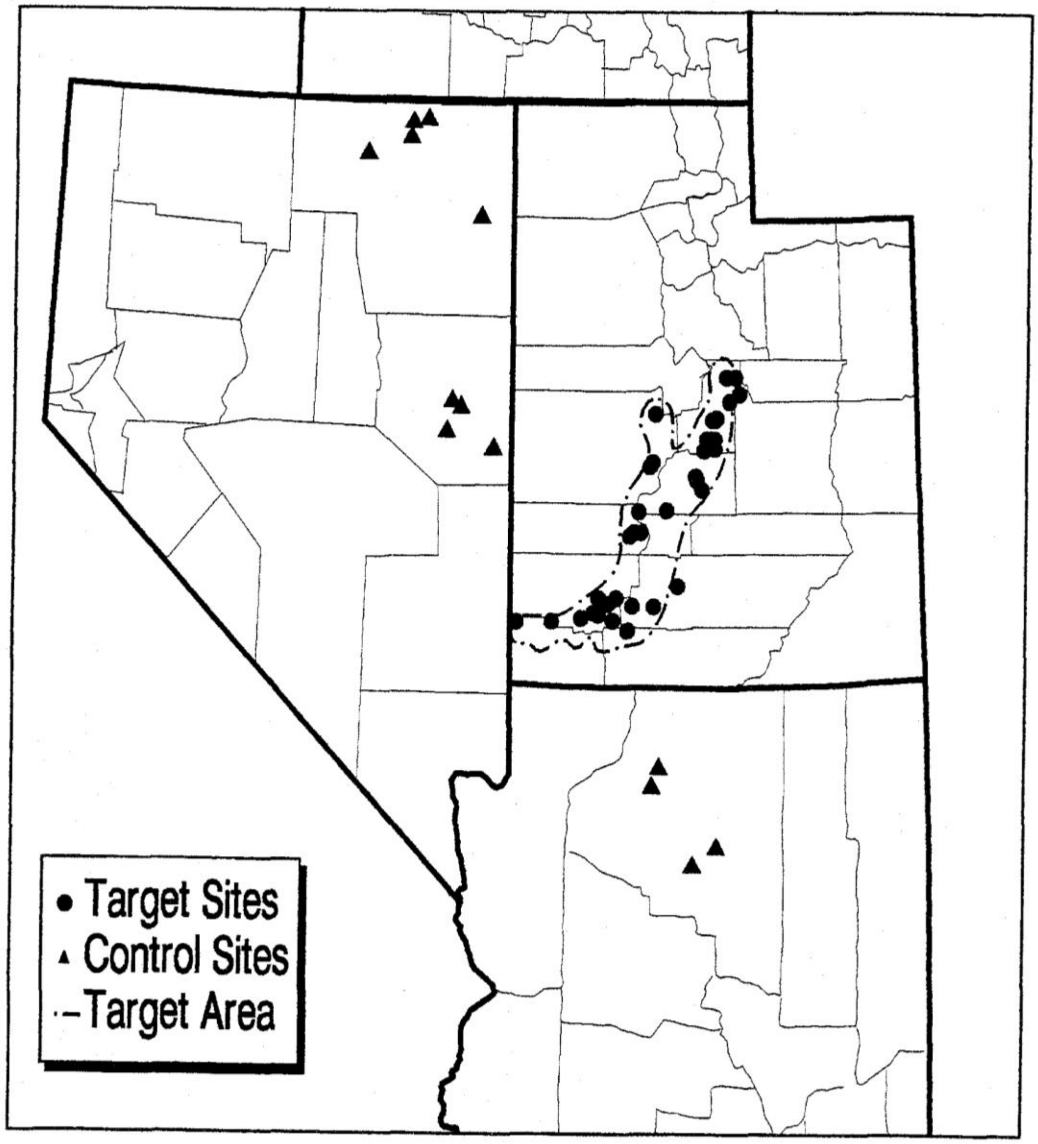

Figure 3. Location of precipitation stations used in the target/control evaluation.

Double Mass Analysis

A double-mass curve is a term used to signify a plot of the accumulated values of one variable versus the accumulated values of another. If the first variable is proportional to the second, these accumulated values plot as a straight line. If the factor of proportionality has one value for the first part of the series of data and then has another value for the second part, the plot will appear as a pair of intersecting straight lines. The point where these straight lines intersect is called a "break".

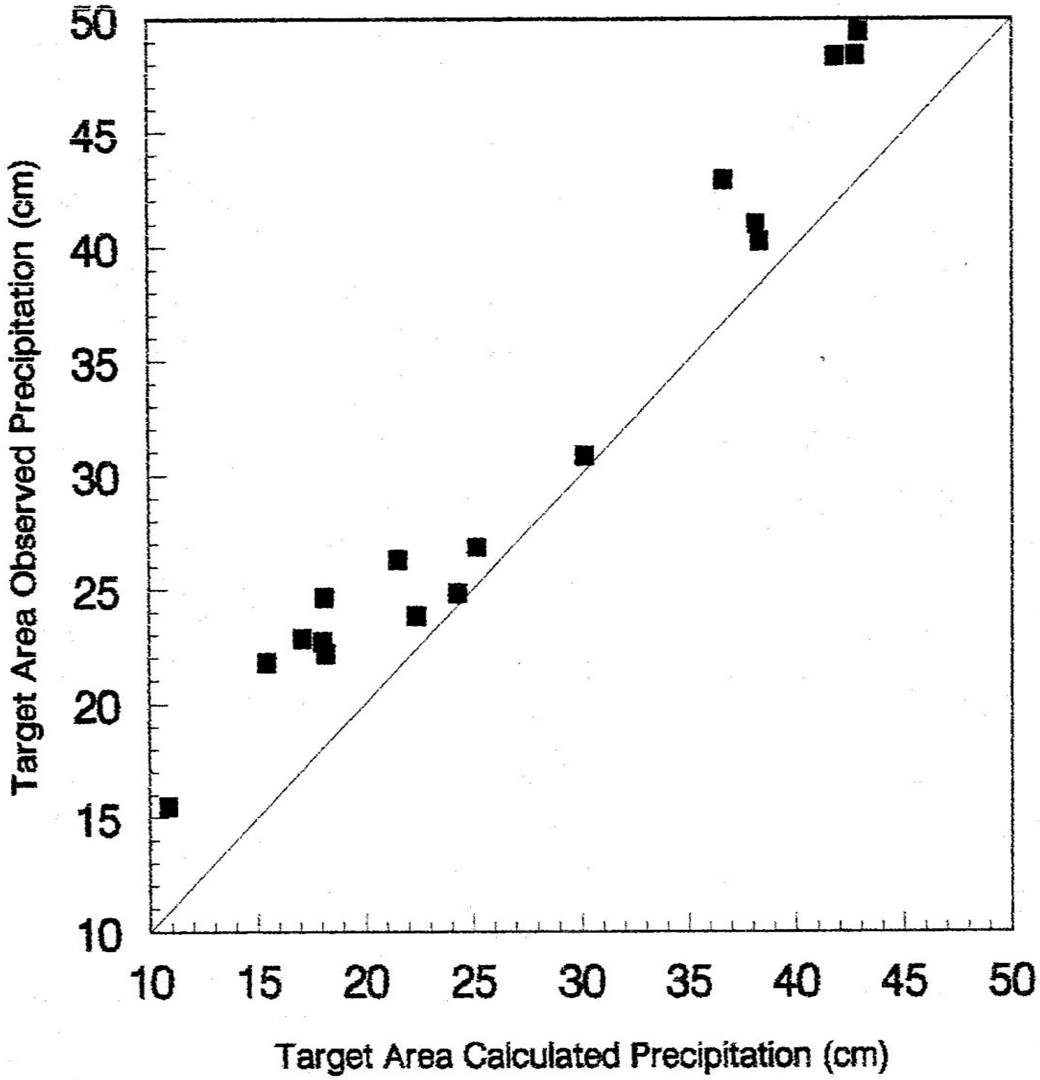

Figure 4. Plot of the predicted versus observed average December through March precipitation for the seventeen seeded seasons.

Table 3

Calculated and Observed Average Target Area Precipitation (December through March)

WATER YEAR	CONTROL AREA OBSERVED PRECIPITATION (cm)	TARGET AREA OBSERVED PRECIPITATION (cm)	TARGET AREA CALCULATED PRECIPITATION (cm)	DIFFERENCE BETWEEN TARGET OBSERVED CALCULATED (cm)	RATIO
1974	22.96	26.85	25.22	1.63	1.06
1975	26.57	30.86	30.20	0.66	1.02
1976	20.96	23.83	22.43	1.40	1.06
1977	12.60	15.49	10.87	4.62	1.43
1978	35.66	48.41	42.80	5.61	1.13
1979	32.31	41.02	38.18	2.89	1.07
1980	35.74	49.45	42.93	6.52	1.15
1981	17.91	22.20	18.21	3.99	1.22
1982	32.44	40.26	38.35	1.91	1.05
1983	31.24	42.93	36.68	6.25	1.17
1988	17.12	22.86	17.12	5.74	1.33
1989	22.33	24.84	24.33	0.51	1.02
1990	17.80	22.71	18.06	4.65	1.26
1991	20.35	26.29	21.56	4.73	1.22
1992	17.88	24.64	18.16	6.48	1.36
1993	34.98	48.34	41.86	6.48	1.15
1994	15.90	21.82	15.44	6.38	1.41

Double-mass curves are often used by hydrologists to adjust or correct precipitation (or snowpack water content) records for changes in gauge location, gauge environment or observation procedure when these changes introduce a new factor of proportionality. Changes in the slope of a double-mass curve or a break (offset) in the plot are indicated when an appreciable change in trend for a test station occurs without a simultaneous corresponding change in trend for the associated reference station.

The double-mass curve can also be used to indicate a change due to the effects of cloud seeding provided there has not been any change in gauge location, environment or observational procedure.

For the most part, there has been little or no change in precipitation gauge locations or gauge environment over the period of record. However, there has been a change in the observational procedure since many of the sites have undergone a change from a storage gauge (or snowcourse) to a SNOTEL site which incorporates state of the art electronic data gathering methods. Most of these changes were introduced in the time period of the late 1970's into the early 1980's and since these changes introduced a new factor of proportionality (such as a different monthly precipitation average) these changes in the earlier period of record have been adjusted to reflect the new average(s). Therefore, in effect, there has not been a change in the observational procedure since it has been compensated for by utilizing the relationship between the older site data and the newer site data to develop the 30 year averages.

This technique was utilized to compare the average target and control area precipitation data for the historical period and the seeded period. The plot of the December through March average accumulated precipitation double-mass curve is presented in Figure 5.

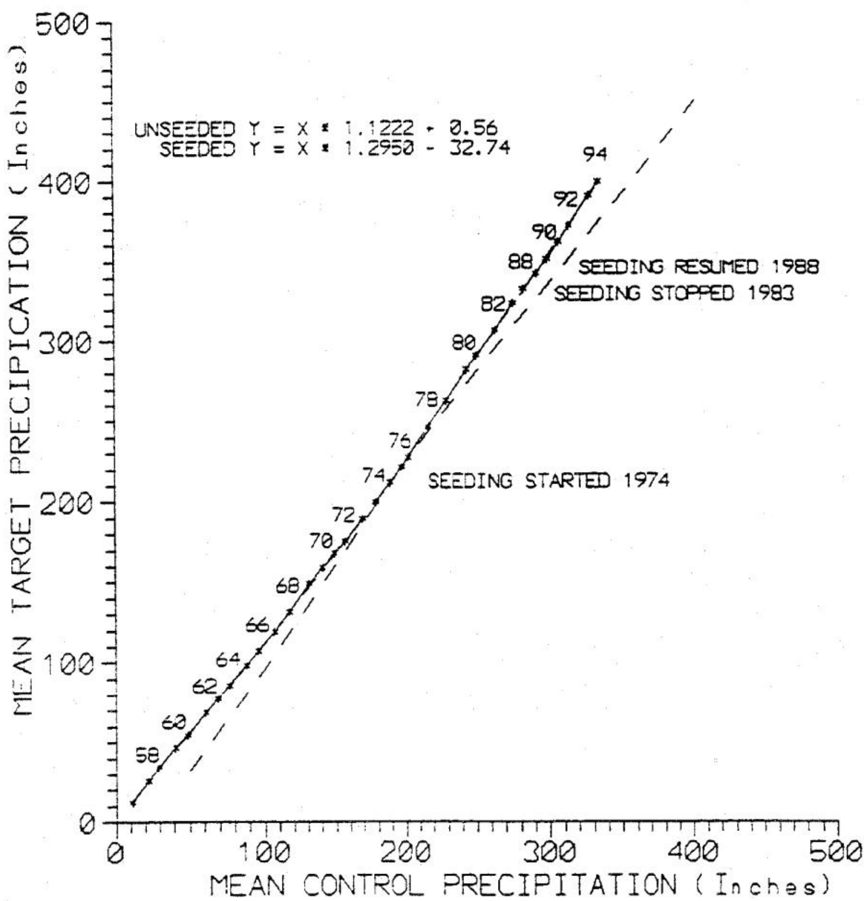

Figure 5. Double Mass Curve, Average Control Vs. Primary Target Area Precipitation (Dec. - Mar.).

The plot (Figure 5) begins in the 1957 water year and terminates with the 1994 water year. All the years between these two are included except the period between 1984 and 1987. These four years were not included since they represent a short duration (four seasons) when cloud seeding was not conducted in the middle of a longer period (17 seasons) when it was. The non-seeded historical period (1957-73) is also of 17 years duration.

Beginning in 1957 the plot of the accumulated precipitation is a straight line from the origin to the 1975 water year. The slope of this line is 1.12. At this point the slope of the line changes. The point where this change occurs nearly coincides with the start of the cloud seeding program, which began in January 1974. The second portion of the line, from 1975 through 1994, is also a straight line but it has a slope of 1.29. This is a difference in slope of .17, which clearly indicates that a different factor of proportionality has been introduced. Since the change in observational procedure has been accounted for and since there has not been any appreciable change in gauge locations or environment, this change in slope, which does occur in a positive manner, suggests that cloud seeding (the only unaccounted for large scale change) could have had a significant effect on the precipitation within the mountain watersheds within the seeded target area.

DISCUSSION

A target/control evaluation of the central and southern Utah cloud seeding program indicates an average 15 percent increase in precipitation in the intended target area. Each of the 17 seeded seasons has more precipitation observed in the target areas than predicted from an historical target/control regression equation. This result is highly statistically significant. The data are derived from a non-randomized data set, however, which restricts the usefulness of such statistical tests.

A double mass analysis of the target and control precipitation indicates an upward shift in precipitation in the target area coincident with the beginning of the cloud seeding program.

The target/control evaluation indicates an average increase in the target area of 4.14 cm per season. This result can be used to provide an estimate of the average volume of additional water over the target area that might result from the cloud seeding program. The following assumptions apply:

- Size of the target area is approximately 23,000 km^2
- Average increase in precipitation over the target area 4.1 cm.

Using these assumptions the calculated volume of additional precipitation is 9.43×10^8 m^3 (764,800 acre feet). Obviously, not all of this calculated volume would result in surface runoff due to ground water recharge and evapotranspiration considerations. If 10 percent of this estimated value was realized as surface runoff, the cost of this additional water would be approximately \$0.002 per m^3 (\$2.00 per acre foot).

The indicated increases in precipitation from the target/control evaluation are similar to those obtained in an earlier analysis (Griffith, **et al.**, 1991). This analysis suggests a 15 percent increase while the earlier analysis suggested 11 percent. Quoting from a 1994 policy statement by the World Meteorological Organization (WMO), "In our present state of knowledge, it is considered that the glaciogenic seeding of clouds or cloud systems either formed, or stimulated in development, by air flowing over mountains offers the best prospects for increasing precipitation in an economically viable manner." From the same policy statement, "statistical analyses suggest seasonal increases (usually over the winter/spring period) on the order of 10 to 15% in certain project areas." The results from the Utah program are definitely in line with this policy statement.

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