AN ASSESSMENT OF EXTRA-AREA CLOUD SEEDING EFFECTS ON THE UINTA MOUNTAINS AND BASIN OF UTAH

FINAL REPORT

TO

UTAH DEPARTMENT OF NATURAL RESOURCES

BY

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EXECUTIVE SUMMARY

An analysis of the cloud seeding operations in northern Utah has been made to make an estimation of seeding effects on precipitation in targeted and downwind areas. Highly definitive results could not be expected from this analysis due to the small number of treated cases, the restrictions in available control areas caused by other seeding projects in Utah, and the overlapping project areas and seeding intervals of the various northern Utah cloud seeding target areas. Despite these complications, some consistent indications of the seeding impacts are indicated. Both for the intentional seeded target areas and for the downwind areas,the precipitation was consistently, though not always, greater than would be expected from statistical precipitation and snow course prediction equations. In general, the indicated excesses from expectancy are greater for the downwind regions than the excesses for the intentionally seeded target areas. The probability of all of these greater than expected precipitation and snowfall amounts are not statistically significant at generally accepted confidence levels. However, many of the probability levels look encouragingly low considering such the small data sample.

The precipitation station analyses consistently show greater than expected amounts of natural precipitation. This finding includes the analyses for precipitation stations in the Uinta Mountains and Uinta Basin areas. Most of the target area precipitation stations used are in or on the border of the Uinta Basin.

The snow course analyses show generally greater than expected amounts of snowpack for the Wasatch, Western Uinta, and Northern High Uinta snow courses during seeded and downwind periods. The snow pack at the Southern High Uintas snow courses has generally been near or slightly below natural expectancy despite the finding that precipitation data for esentially this same area shows greater precipitation than expected during seeded and downwind periods. These conflicting indications likely result from the small data base.

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AN ASSESSMENT OF EXTRA-AREA CLOUD SEEDING EFFECTS ON THE UINTA MOUNTAINS AND BASIN OF UTAH

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I. INTRODUCTION

The possibility of extra-area effects from intentional weather modification has been an issue since the inception of efforts to modify precipitation by cloud seeding treatments. These issues have been explored both through statistical analyses and studies of physical mechanisms that could lead to downwind precipitation changes (Brown et al.,1978; Mulvey 1977; and others). The primary finding has been a consistent indication that there may be a positive effect on precipitation in the downwind area for a distance of 50 to 100 miles or more, or that there is no observable effect. The authors of this report are not aware of any analyses of wintertime extra-area seeding effects that show a decrease in precipitation in a downwind area. The authors of this report are also not aware of previous analyses of this issue for cloud seeding programs that have been carried out in Utah.

This is a report on a study to evaluate the possibility that extended area effects may have occurred from the Utah seeding programs in the Wasatch Range that may have affected the downwind Uinta Mountains. This represents a special situation due to the unique east-west

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orientation of the Uinta Mountains downwind of the generally north-south oriented Wasatch Range. This presents a "mountain-weather" situation dissimilar from those in other areas which have been studied and reported in the literature.

II. OBJECTIVES OF THIS STUDY

The purpose of this study has been to specifically investigate the likelihood that cloud seeding programs in areas upwind of the Uinta Mountains (and specifically those in the Wasatch Range) are having an effect, either negative or positive, on the precipitation in the Uinta Mountains and Basin. This implicitly includes the objective of evaluating effects that the operational cloud seeding is having on either or both the Wasatch Range or the Uinta Mountains. The study utilizes statistical analyses to determine the likelihood that precipitation and snowpack have been different than would be expected from natural occurrences.

III. APPROACH

The evaluation of weather modification has proven to be very difficult. The basic difficulty derives from the fact that various studies have shown that the most likely effect of the intentional artificial seeding is a 10 to 15 percent increase, while the natural variability, even on an annual basis, is the order of 400 percent. Despite this problem, and the problem of non-normality of precipitation data, sensitive statistical evaluation tests have been developed. These tests are most reliable when applied to data for which both seeded and non-seeded cases are selected at random. This minimizes the possibility that statistical relationships developed from historical data are different than in those that occurred naturally during the seeded period.

The analysis approach used in the analysis herein presented utilizes efficient statistical techniques that have been developed during the past 30 years specifically for weather modification evaluations. Since the Utah seeding has not been conducted on a randomized basis, this study utilizes various techniques to test the likelihood that there were statistical differences between precipitation and snow course data between an historical unseeded period and the seeded periods. The analyses have been carried out for Wasatch and Uinta seeding targets and for the Uinta Mountains when they were not seeded and downwind from other areas employing cloud seeding.

The specific analysis techniques used are largely those explored and developed in a Master Thesis by Medina (1981). Medina's assessment employed correlation analysis, stepwise linear regression, principal component analysis, and the Wilcoxon two-sample rank test. The use of a nonparametric technique on residuals where the nontreated values are obtained by regression on an ample historical base allows greater flexibility in the analysis.

Medina considered precipitation, snow course, streamflow, and the output of seasonal volume precipitation from the Rhea orographic precipitation model as response variables. His results for 13 watersheds in Colorado with 10-18 years of historical data using the best covariate relationship gave r^2 values of .83 to .95 (explaining .83 to .95 percent of the variances). The estimated time required for a 50 percent probability of detecting a 10 percent increase in runoff at the 10 percent significance level for his watersheds was four to five seasons. The time required dropped to only two seasons with a 15 percent increase.

In most Colorado watersheds the stepwise program showed that the output of the Rhea model was the strongest single predictor. In addition to being a strong predictor covariate, the Rhea model, which is initialized by upwind radiosonde data, is not susceptible to contamination from other seeding projects as the precipitation, snowpack, and streamflow response variables might be. While the Rhea orographic model is running on an operational (to predict seasonal runoff) and a research basis at Colorado State University for Colorado, it would require incorporating the Utah mountain terrain in the model before it could be employed in Utah. It would also require an interpolation scheme for determining the best estimate of upper air atmospheric parameters from all directions for initializing the respective model runs. It was thus not feasible during the fall of 1990 to use this model as an evaluation tool. The evaluation reported here has been made, in response to a Utah request for a partial evaluation during the fall of 1990, to determine the likelihood that downwind seeding effects might have occurred in the High Uinta Mountains. The analysis has used available target and downwind precipitation and snowcourse data for seeded and non-seeded years. The limited seeded sample precluded using seasonal streamflow as a evaluation paramteter.

IV. PROCEDURES

The procedures for this analysis involved the following stages.

A. Familiarization with Utah cloud seeding operational reports.

B. Identification of the seeded areas in the state and in Nevada for all years since 1960.

C. Collection of precipitation and snowcourse data for target and potential control areas.

D. Selection of control stations for precipitation and snow course analyses.

E. Statistical analyses.

F. Preliminary investigation of the requirements for adapting Utah topography and upper air input data for use in the orographic model.

The following is a brief description of the procedures followed for these respective stages of the analysis.

A. Familiarization with Utah Cloud Seeding Operational Reports

Four reports of Utah cloud seeding operations were provided by North American Weather Consultants. These included:

1. A "Summary of Operations (1989 Water Year) and Evaluationtion of a Cloud Seeding Program in the North Utah (Western Uinta Mountains", NAWC Report WM 89-6.

2. A "Summary of Operations (1989 Water Year) and Evaluation of a Cloud Seeding Program in Northern Utah (Wasatch Mountains", NAWC Report WM 89-8.

3. A "Summary of Operations (1989 Water Year) and Evaluation of a Cloud Seeding Program in the High Uinta Mountains", NAWC Report WM 89-11.

4. A "Summary of Operations (1989 Water Year) and Evaluation of a Cloud Seeding Program in Central and Southern Utah", NAWC Report WM 89-12.

North American Weather Consultants also provided a disc of ground generator seeding operations conducted in Utah from 1978-79 until the 1989-90 season. They did not have the earlier data in a format that could be readily merged with the 78-79 to 89-90 file. They did enclose a list of counties participating in cloud seeding beginning in 1972. This information was very useful but had some serious limitations. First, the description of counties participating in cloud seeding is not very definitive for defining the specific areas in those counties that were the actual targets. Reasonable estimates of the target areas were made by considering the locations of snowpack accumulation areas and the generator locations when pertinent. Another limitation of these data is that some parts of certain counties in certain years were seeded although they were not listed as seeded counties, apparently since the county as such was not officially participating in the Utah program. A specific example of this relates to Wasatch county which shows no seeding in years during which parts of the targets described in the above listed seeding reports are within the Wasatch county.

North American Weather Consultants also provided an evaluation paper on seeding in the area northeast of Bear Lake, Utah. This paper is entitled "Winter Orographic Cloud Seeding Northeast of Bear Lake, Utah" by D. A. Griffith, J. R. Thompson, and R. W. Shaffer, all of North American Weather Consultants. This paper describes the various areas defined as targets and the seeded and not seeded years in that area back to the 1947-48 water years.

North American Weather Consultants also provided portions of NAWC Report WM 89-4 (the title is not listed since the portion provided did not include the cover page) that describes the 1988-89 cloud seeding in southeastern Idaho.

Based on information provided by Clark Ogden, contact was made with the University of Nevada at Reno regarding cloud seeding in eastern Nevada that could effect possible evaluation control areas in western Utah. Mr. Dick Smith of the Desert Research Institute provided the basic information by telephone.

B. Identification of Cloud Seeding Areas Since 1960

Based on the information described in Item A above, areas of cloud seeding of specific interest for this evaluation were defined. This included seeding which has taken place for the Wasatch Range, for the Western Uintas, and for the High Uintas. Areas of Utah were identified which could realistically be considered as unaffected by cloud seeding for any of the other seeded areas in Utah, Nevada, or Idaho. The identification of areas unaffected by cloud seeding use as control areas is very difficult due to the extensive cloud seeding that has been carried out in Utah in a number of areas and for differing years.

It has not seemed appropriate to use the control area used by North American Weather Consultants even though the correlation of precipitation and snowpack in that area with the precipitation and snowpack in the Wasatch and Uintas is higher than in the areas selected for controls in this study. The North American control area has, in a number of years, been itself downwind of seeding for other areas of Utah. Since a major objective of this analyses is to look at downwind effects from seeding in the Wasatch and western Uintas, it does not appear reasonable to use another area with significant similar downwind characteristics as a control area.

An area of northwestern Utah was used in the search for control stations for this study. While this area appears to be the best available for use in locating control stations, it is not completely free from having had seeding carried out even further upwind in Nevada. The potential for having been contaminated, however, seems less since all of that seeding has been at least 100 miles upwind of the sites selected for this analysis and appears to have been less directed than that for the Utah targets. The Nevada seeding has been carried out for the Ruby Mountains. The seeding generator furthest north and east has been located near Halleg, Nevada. Other generators were located south and west of this site. Seeding in this area was reported to have been carried out during the period from the 1981-82 water year until the 1984-85 water year except for the 1983-84 water year. There are no other obvious choices for the selection of unseeded control stations except for the use of the orographic model output as discussed in the "approach" section above. Since the model is initiated by upper air sounding data, it is not subject to direct contamination from other seeded areas.

C. Collection of Precipitation and Snow Course Data

Three sources of precipitation data were used.

1. NOAA precipitation data was available through 1988 at the CSU Atmospheric Science Library on "CDROM Climate Data - Summary of the Day".

2. Data for 1987 through May 1990 was available in published form, "Climatological Data for Utah" at the Colorado State Library.

3. John Thompson of North American Weather Consultants provided monthly precipitation data from October 1989 through April 1990.

Snow course water equivalent values for the period 1961-1990 were obtained for 47 Utah sites from the Soil Conservation Service Data Analysis Center located in Portland, Oregon.

After editing data files from the original format from the data tapes provided, values were spot checked for accuracy. No evaluation of the NOAA or Soil Conservation data quality itself was attempted.

D. Selection of the Control Areas

The selection of control precipitation and snowcourse stations involved several iterations. The search for control stations was carried out only in areas upwind of the areas being studied and in areas most unlikely to be significantly contaminated by other cloud seeding programs. This restricted the search area to the northwest portion of Utah.

As a first stage in the iterative process, target area precipitation and snowcourse averages were established for each of the study areas.

These included:

1. The Utah Wasatch target
2. The Utah "Western Uinta" target
3. The Utah "High Uintas" target
4. An area downwind of the Wasatch target located northeast of this target.

These study areas are shown in Figure 1.

Precipitation and snow courses within the respective target areas were used in determining the "target" average. The following is a listing of the stations used.

1. The Utah Wasatch Target
    a. Precip Stations:

       Alta, Cottonwood Weir, Mountain Dell, Redden Mine, Silver Lake Brighton

    b. Snow Courses:

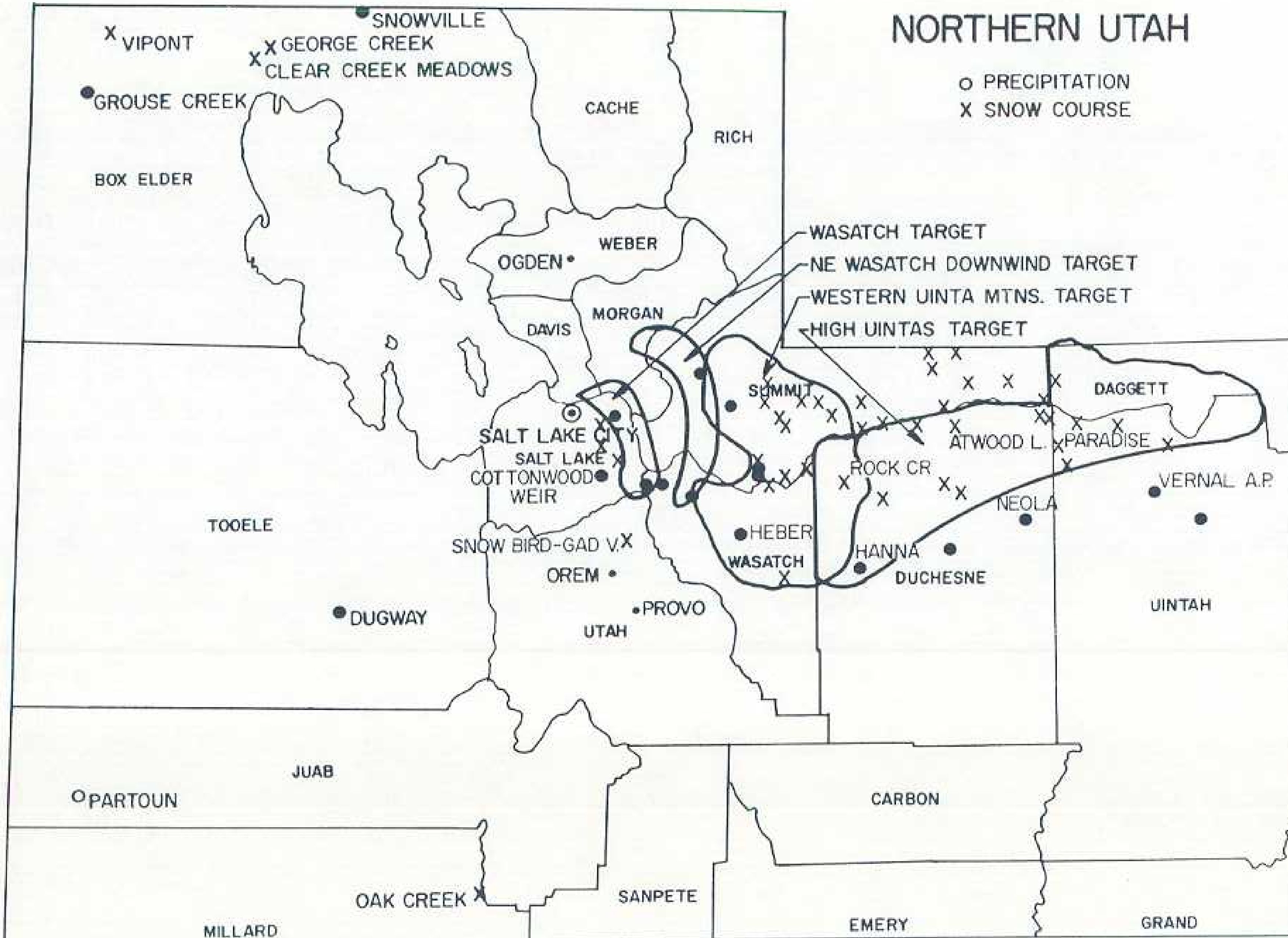
       Lambs Canyon, Mill Creek, Mill D-South Fork, Parley's Canyon Summit, Silver Lake-Brighton, Snow Bird-Gad Valley

2. The Utah "Western Uintas" Target
    a. Precip Stations:

       Coalville, Hanna, Heber, Kamas, Wanship Dam

    b. Snow Courses:

       Beaver Divide, Chalk Creek #1, Chalk Creek #2, Chalk Creek #3, Current Creek, East Shingle Lake, Hayden Fork, Lightening Lake, Redden Mine-Lower, Smith and Morehouse, Trial Lake


NORTHERN UTAH
O PRECIPITATION
X SNOW COURSE
WASATCH TARGET
NE WASATCH DOWNWIND TARGET
WESTERN UINTA MTNS. TARGET
HIGH UINTAS TARGET
SNOWVILLE
VIPONT
GEORGE CREEK
CLEAR CREEK MEADOWS
GROUSE CREEK
BOX ELDER
CACHE
RICH
WEBER
OGDEN
DAVIS
MORGAN
SUMMIT
DAGGETT
SALT LAKE CITY
SALT LAKE
COTTONWOOD WEIR
ATWOOD L.
PARADISE
ROCK CR
VERNAL A.P.
NEOLA
HEBER
WASATCH
HANNA
DUCHESNE
UINTAH
TOOELE
SNOW BIRD-GAD V.
OREM
PROVO
UTAH
DUGWAY
JUAB
PARTOUN
CARBON
OAK CREEK
SANPETE
MILLARD
EMERY
GRAND

3. <u>The Utah "High Uintas" Target</u>

a. Precip Stations:

Altamont, Dinosaur Quarry Area , Hanna, Neola, Vernal

b. Snow Courses (North Slope):

Black Flat-U.M. Creek, Black's Fork, Black's Fork Junction, Brown Duck, Buck Pasture, Henry's Fork, Hewinta G.S., Hickerson Park, Hole-in-Rock, Spirit Lake, Steel Creek Park, Stillwater Camp

c. Snow Courses (South Slope):

Atwood Lake, Brown Duck, Chepeta, Chepeta-Whiterocks, Five Points Lake, Hayden Fork, King's Cabin-Upper, Lakefork Basin, Lakefork Mountain #3, Lakefork #1, Lightening Lake, Mosby Mountain, Paradise Park, Reynolds Park, Rock Creek, Trout Creek

4. <u>The Area Downwind of the Wasatch Targets to the Northeast</u>

a. Precip Stations:

Coalville, Heber, Kamas, Snake Creek, Warship Dam

In the first iteration for identifying control stations all precip and/or snowcourse in the potential control area were considered individually by correlating them with the target average values. The stations with the best correlations were joined together in various combinations to attempt to provide both improved and more stable relationships between the control groups and the respective target areas.

To the extent possible, individual stations in the control area were combined in a manner to provide control area sensing for airflows from southwest, westerly, and northwesterly directions. A third iteration was used after studying these results to define the control stations to be used for each of the respective target areas for the actual analyses. Only not seeded years were used in the control station selections. The following are the control stations used.

1. The Utah "Wasatch" Targets

   a. Precip:

   Average Grouse and Snowville

   b. Snow Courses:

      March and April - Average Vipont, George Creek, Clear Creek Meadows and Oak Creek

      May - Clear Creek Meadows

2. The Utah "Western Uinta Mountains" Target

   a. Precip:

      Average Dugway, Grouse and Snowville

   b. Snow Courses:

      Average Vipont, George Creek, Clear Creek and Oak Creek

3. The "High Uintas" Target

   a. Precip:

      Average Delta, Dugway and Partoun

   b. Snow Courses:

      South Facing Slopes - Average George Creek and Vipont

North Facing Slopes - March and April - Average George Creek, Oak Creek and Vipont

North Facing Slopes - May - Oak Creek

4. NE Wasatch Downwind Area

   a. Precip:

      Average Grouse and Snowville

E. Statistical Analysis

As pointed out earlier, the analysis is complicated by the many different areas in the state that have been seeded. This causes serious problems in defining clean, unseeded areas that can serve as control areas for estimating the precipitation that should be expected without seeding.

A second factor seriously complicates the analyses. This is a time factor: seeding started in the respective seeded years at different times during the water year. In some targets it started as early as November. The other targets and/or year's seeding started as late as March. The following is a description of the seeded periods and seeded times considered for the respective study areas. The months shown are the ones considered for monthly analysis purposes. If seeding started early in a month, the month was considered seeded. If it ended early in a month, the month was considered not seeded.

1. The Utah "Wasatch" Target

   1977 January through March (actually early January to early April)

1988 March and April

1989 November through April (actually early November to mid-April)

1990 November through March (actually early November to early April)

2. <u>The Utah "Western Uinta Mountains" Target</u>

1977 January through May (actually early January through May)

1978 November through April

1989 December through April (actually December through mid-April)

1990 January through April (actually early January through early May)

3. <u>The Utah "High Uintas" Target</u>

1977 March through May

1978 November through April

1989 March through May

Based on all other information available to us, all other water seasons from 1961 through 1990 were considered to have not been seeded.

For the precipitation analyses an effort was made to look at the actual seeded months. This could not be done, however, by lumping them all together since the correlations with the control areas are different for different months. Consequently, the analysis was made for each month and then the results in terms of the precipitation change and the probability values were combined to provide a best estimate from the total number of months.

The combined P-value is based on Fisher's statistic $T = -2 \sum_{i=1}^{K} \ln[P(i)]$ where P(i) is the ith P-value among K monthly P-values and the weighted double ratio is $WDR = [\sum_{i=1}^{K} WF(i)DR(i)]/[\sum_{i=1}^{K} WF(i)]$ where WF(i) is the ith control total weighting factor for the ith of K months and DR(i) is the ith double ratio for the ith of K months.

For the snow course analysis, it was only feasible to look at snow course readings near the end of each month. Years and months were considered for which a significant amount of seeding had been done prior to that monthly snow course reading. In many cases, only a portion of the winter season had been seeded by, say, March 1 or April, but if at least two months had been seeded, the season was considered seeded.

A small (large) P-value represents an increase (decrease) in the target area relative to the control area. If W denotes the two-sample Wilcoxon-Mann-Whitney test statistic, then the standardized test statistic given by

$$Z = [W - \mu(W)]/\sigma(W)$$

is approximated by a standard normal distribution under the null hypothesis that there is no effect attributed to seeding. Also $\mu(W)$ and $\sigma(W)$ denote the mean and standard deviation of W under the null hypothesis. If Cn, Cs, Tn and Ts respectively denote the non-seeded target mean and the seeded target mean for the non-seeded and seeded time periods, then the double ratio is given by

$$DR = (Ts/Tn)/(Cs/Cn)$$

and a large (small) value of DR implies an increase (decrease) in precipitation due to the seeding treatment.

In order to evaluate how the target and control values are related to one another, Pearson's product-movement correlation coefficient has been obtained for the various comparisons in question.

F. Orographic Model Adaptation for Utah

Preliminary investigation of stations and procedures for initializing upper air data for Uinta have been considered and a procedure for inputing Utah topography into the model has been explored. It appears that available computerized topography such as that used by Jensen et al.(1990) can be adopted for use in the model. Medina (1981) found for Colorado that the use of the 10 km grid as used by Rhea was adequate for use in generating precipitation data suitable for use in evaluating weather modification. We suspect that this would also be the case for Utah. Preliminary considerations have also been given to establishing upper air input data at all azimuths around Utah for initializing the model. The use of only the Salt Lake City sounding for initialization would certainly not be satisfactory. The use of just this one station by Jensen et al. (1990) demonstrated the model capabilities but produces nonspecific results for many if not most real world situations. The air being lifted into various mountain areas for initializing the model can be very different for different areas and wind directions. For example, the airmass characteristics of southerly airflow being lifted over the Uintas even a relatively short distance east of Salt Lake City can be grossly different for any of the model generated 12-hour increments than airmass characteristics over Salt Lake City.

IV. RESULTS

This analysis has attempted to make a reasonable estimate of the cloud seeding effects in intentionally seeded target areas in the Wasatch Range, the Western Uintas, and in the High Uintas of northern Utah. It has also placed emphasis on making a reasonable estimate of how the precipitation might have been affected in the areas downwind of the Wasatch and Western Uinta targets when these downwind areas were not intentially seeded. The first part of this discussion of the results will consider the seeding effects when targets were intentionally seeded. The second part considers downwind effects when the downwind areas were not intentionally seeded.

A. Seeded Target Analyses

1. Wasatch Target

In the Wasatch seeded target there is a consistent indication of greater precipitation than would be expected from chance during seeded periods. This is apparent in both precipitation and snow course analyses as can be seen in Table 1. The indicated advantage for the precipitation analysis is 27 percent and for snow course the indicated advantage varies from 11.3 percent to 52.4 percent for the different months. The number of seeded cases, however, is very small and none of these values are statistically significant. The positive amounts of precipitation and the relatively low P-values might be considered encouraging with the small sample available for this analysis.

Table 1

Seeding: Wasatch Seeding Target

	Weighted Double Ratio	Combined P-Value (16 Seeded Months)
Precip Analysis	1.27	.1105

	Seeded Cases	Not Seeded Cases	Correlation	Double Ratio	P-Value
Snow Course Analysis					
March 1	3	27	.751	1.327	.052
April 1	4	27	.830	1.113	.136
May 1	3	15	.748	1.524	.384

2. <u>Western Uinta Target</u>

In the western Uinta seeded target there is again a consistent indication of greater precipitation than would be expected by chance during seed periods. These occur in both the precipitation and snow course analyses as can be seen in Table 2. The indicated advantage is 4.3 percent from the precipitation analysis and for the snow course data the advantage varies from 7.9 percent to 24.7 percent for the respective months. The number of seeded cases is small and none of these values are statistically significant. Again the positive precipitation values and the relatively low P-values for the snow course analyses could be considered encouraging.

Table 2

Seeding: Western Uintas Target

	Weighted Double Ratio	Combined P-Value (20 Seeded Months)
Precip Analysis	1.043	.4079

	Seeded Cases	Not Seeded Cases	Correlation	Double Ratio	P-Value
Snow Course Analysis					
March 1	4	26	.752	1.247	.080
April 1	4	25	.765	1.079	.171

3. <u>High Uinta Target</u>

The evidence of a seeding effect when the high Uintas have been specifically designated a seeding target area is not consistent between the precipitation and snow course analyses. There is an indicated advantage for precipitation of 18.8 percent. The snow course analyses shows very large positive differences March and May for the north facing slope of the High Uintas when in each of these months only one seeded case was available, while just the amount of snowpack expected by chance occurred for April when three seeded cases were available for analysis. On the south facing slopes on the High Uintas, the snowpack was almost exactly the amount expected by chance. The number of cases is small and none of these values are statistically significant.

Table 3

Seeding: High Uintas
(High Uintas the Designated Target)

	Weighted Double Ratio	Combined P-Value (12 Seeded Months)
Precip Analysis	1.107	.5587

	Seeded Cases	Not Seeded Cases	Correlation	Double Ratio	P-Value
Snow Course Analysis					
South Facing Slopes					
April 1	3	23	.758	.996	.516
North Facing Slopes					
March 1	1	26	.629	9.482	.048
April 1	3	24	.832	.997	.531
May 1	1	17	.779	41.273	.051

4. <u>High Uintas and/or Western Uinta Target Seeded</u>

An additional seeded case analysis has been made for cases for the High Uinta when they were intentionally seeded and/or seeding was carried out for the Western Uintas. The indicated advantage for precipitation is

18.8% and varies for the respective months from 4.7 to over 200 percent for the snow course analysis for the north facing slopes of the High Uintas. The snow course data indicates 8.4 percent less precipitation than chance expectancy for the south facing slopes. Again the number of cases is small and the values, as would be expected with such a small sample, are not statistically significant. The relatively low P-values for the precipitation analysis and for the north slope snow course analyses could be considered encouraging for the small sample. The expected snowpack on the south facing slopes is slightly less than natural expectancy and should receive attention in future analyses more for its contrast with other indications of seeding effects than for its specific variance from natural expectancy.

Table 4

Seeding: High Uintas and/or Western Uinta Target
(High Uinta Considered Seeded when the High Uintas
or Western Unitas Seeded)

	Weighted Double Ratio	Combined P-Value (21 Seeded Months)
Precip Analysis	1.188	.1591

	Seeded Cases	Not Seeded Cases	Correlation	Double Ratio	P-Value
Snow Course Analysis					
South Facing Slopes					
April 1	4	22	.758	.916	.739
North Facing Slopes					
March 1	4	23	.629	1.475	.27
April 1	4	23	.832	1.047	.293
May 1	2	16	.779	3.463	.046

B. Downwind Effect Analysis

Downwind effects from seeding have been addressed in four separate analyses. These analyses are complex since there is a serious question as to whether the High Uintas should be considered as downwind of seeding or part of the seeded area when the Western Uintas are seeded. In their report on seeding for the Western Uintas, North American Weather Consultants show a significant number of hours of seeding extending into the High Uintas. The authors of this analysis would expect an even further extension to the east of the expected effect before considering it a downwind effect. Two downwind analyses consequently have been made for the High Uintas. In the first (Table 5), the High Uintas have been considered a downwind area, when they were not intentionally seeded but either or both the Western Uintas and Wasatch targets were seeded. In the second analysis (Table 6), the High Uintas have been considered downwind when neither the High Uintas or Western Uintas were seeded but the Wasatch target was seeded. The third and fourth downwind analyses have considered an arbitrary area northeast of the Wasatch target and generally northwest of the Western Uintas target. Table 7 addresses the case when this area was downwind of seeding in either or both of the Wasatch and Western Uintas Targets. Table 8 addresses the case when the area is downwind of seeding only the Wasatch target.

1. High Uintas Downwind of Wasatch and/or Western Uintas Seeding Targets

When the High Uintas have not been seeded and are downwind of seeding in either or both the Wasatch and Western Uintas targets the precipitation has been 36 percent greater than chance expectancy and, while not significant statistically, has a fairly low probability of being a chance occurrence. This picture is consistent with the indicated greater snowpack than expectancy, from 18.4 percent to 49.2 percent, for the north facing slopes. As with the intentional seeding for the High Uintas, the indicated difference from chance expectancy for the south facing slopes is less than chance expectancy by -16 percent. Again these results are not statistically significant and could not be expected to be so with such a small sample of events. The small sample applies even more directly to the snow course results than to the precipitation, although sample sizes are very small for both the snow course and precipitation analyses.

Table 5

Downwind: High Uintas
(High Uintas Not Seeded, Either or Both Wasatch
and Western Uintas Seeded)

	Weighted Double Ratio	Combined P-Value (14 Downwind Months)
Precip Analysis	1.36	.0535

	Seeded Cases	Not Seeded Cases	Correlation	Double Ratio	P-Value
Snow Course Analysis					
South Facing Slopes					
April 1	2	21	.743	.840	.777
North Facing Slopes					
March 1	1	23	.671	1.184	.213
April 1	2	22	.817	1.208	.047
May 1	2	15	.762	1.492	.228

2. <u>High Uintas Downwind of the Wasatch Target When Western Uintas also Not Seeded</u>

When neither the High Uintas and the Western Uintas are not seeded and the Wasatch is seeded, the precipitation in the High Uintas was 46.4% greater than natural expectancy as shown in Table 6. There were too few cases involving snow course data available to justify a snow course analysis for this situation. These results could be considered positive for a precipitation increase, as distinct from a decrease, but are not statistically significant, and would not be expected to be with a small data sample.

Table 6

Downwind: High Uintas
(Neither High Uintas or Western Uintas Seeded and Wasatch Seeded)

	Weighted Double Ratio	Combined P-Value (5 Downwind Months)
Precip Analysis	1.464	.2140

3. <u>Downwind Arbitrary Area Northeast of Wasatch and Generally Northwest of Western Uinta</u>

Tables 7 and 8 show the results of the precipitation analyses for the arbitrary area downwind to the northeast of the Wasatch target and generally northwest of the Western Uintas seeding targets. This arbitrary area is basically not mountainous and snow course data is not available for analysis. When this area was downwind of seeding only from the Wasatch seeding target, the precipitation was less than expected by about 10 percent, but when it was downwind of seeding for both the Wasatch and Western Uintas targets the precipitation in this area was some 24.5 percent greater than chance expectancy. Neither of these differences are statistically significant, although they each have a chance expectancy of only around 12 percent.

Table 7

Downwind: Area Northeast of Wasatch Target
(Area Not Seeded and Downwind of Wasatch Seeding,
Western Uintas Not Seeded)

	Weighted Double Ratio	Combined P-Value (5 Downwind Months)
Precip Analysis	.901	.8824

Table 8

Downwind: Area Northeast of Wasatch Target
(Area Not Seeded and Downwind of either/or
Wasatch or Western Uintas Seeding)

	Weighted Double Ratio	Combined P-Value (16 Downwind Months)
Precip Analysis	1.245	.1213

V. DISCUSSION AND SUMMARY

The purpose of this analysis has been to make an estimation of the seeding effects "in" and "downwind" of cloud seeding operations in northern Utah. Highly definitive results could not be expected from this analysis due to the small number of treated cases, the restrictions in available control areas from other seeding projects in Utah and the varying seeding intervals and interaction of the Wasatch, Western Uintas and High Uintas seeding projects themselves. There are some consistent indications. For the <u>intentional designated seeding target</u> areas the precipitation has been consistently greater than expected by chance and, in a number of cases, the probability values of this occurrence are encouragingly low although not statistically significant. Statistically significant results could not be expected from the small and complex data sample. The only exception to this consistent finding is for the snow course analysis on the south side of the High Uinta where snowpack amounts have been about or somewhat less than would be expected. This exception is not consistent with the suggested greater amount of precipitation for the Uinta from the precipitation analysis. Such discrepancies can be expected from such small data samples.

For the areas <u>downwind of seeded areas and specifically in the Uinta Mountains and Basin</u>, the precipitation has also been consistently greater than expected by chance, and, in general, the indicated increases above chance are higher than those for targets intentionally seeded. This result is particularly true for the analyses of the precipitation data for the Uinta and for the snow course data for the northern portion of the High Uinta. Again the snow course analyses suggest a lesser amount of precipitation than could be suggested by chance on the southern portion of the High Uinta. But again this conflicts with the results of the High Uinta precipitation analysis which shows substantially greater precipitation than expected by chance when the area is downwind of cloud seeding, and the data input for that precipitation analysis is heavily influenced by precipitation stations in the Uinta Basin and on the south side of the High Uinta Mountains.

The analyses show larger than expected values of precipitation snowpack differences above chance expectancy, in general, for the downwind cases than for the intentionally seeded cases. While these values are not statistically significant with the small sample sizes available, they suggest a positive rather than a negative effect from seeding in the downwind areas.

The results for both the seeded target and downwind areas are consistent with the results of analyses of other research and operational cloud seeding programs of wintertime cloud seeding in mountainous areas. These analyses in other areas have generally shown precipitation increases in such seeded areas to be in the range of 10-15 percent, considerably higher under some weather situations but lower or negligible under others. These results are also compatible with consistent indications of an increase in precipitation in the 25 to 100 mile area downwind of wintertime, orographic cloud seeding programs in other areas. These authors know of no analysis reported in the literature where this has not been the case. As with this analysis, many of the other analyses of downwind effects have shown greater indicated increases in the downwind areas than in the seeded targets.

There have been some studies of the physical mechanisms by which cloud seeding may cause extra area effects. Most of these studies, as concluded by Mulvey (1977) show "...the existence of at least two mechanisms through which mountain orographic clouds can affect the precipitation..." Mulvey's studies also outline the meteorological conditions under which the mechanisms investigated are operative.

Jensen et al. (1990) place in perspective the role played by large scale dynamics in the control of precipitation and droughts in Utah. Some weather patterns are just not favorable for precipitation in the Uinta Mountains of Utah. A very few patterns are highly favorable. Most precipitation comes from patterns that are not highly favorable or highly unfavorable. These other patterns produce 98 percent of the precipitation events. Jensen et al. (1990) point out that a relatively small small percentage of the storms from a westerly direction produce precipitation in the Uinta Basin, but that all storms do with southeasterly flow. The major impact of precipitation, however, remains with the storms from westerly directions since, according to Jensen et al.'s data, that while 100 percent of the events will flow from the southeast produce precipitation, this constitutes only 1.5 percent of the total number of precipitation events that occur in the Uinta Basin. As can be derived from the Jensen et al. data, the following are the percentages of the precipitation events in the Uinta basin produced by different weather patterns: dry pattern 0.4 percent, west through northwest flow 22.7 percent, southwest flow 75.3 percent, southeast flow 1.5 percent. Thus, while the frequency of events with precipitation in the Uinta Basin is relatively low for storms from the westerly directions, the ones that do produce precipitation account for nearly all of the precipitation events due to their much higher frequency of occurrence. Weather modification operations cannot change the large scale atmospheric dynamics that produce favorable or unfavorable conditions for precipitation or drought in the Uinta Mountains of Utah. They are designed to hopefully add an additional increment with whatever large scale dynamic pattern nature provides.

VI. FURTHER ANALYSIS

It is recommended that Utah consider the use of computed volume precipitation as generated by the Rhea or other orographic models in conjunction with available precipitation, snow course, and streamflow data as covariates to develop the strongest feasible statistical prediction equations for the evaluation of Utah operational cloud seeding programs. While it is essential that the precipitation, snow course, and streamflow data come from areas considered relatively free from contamination from any cloud seeding programs, the volume precipitation output from the model is not so constrained. Refined analyses should be feasible for a number of Utah projects that have already run for a number of years, and increasingly so for projects with limited past seeding operations as future programs take place.

It is likely an orographic model brought on line for volume precipitation computation can have value for making continuous accumulating snowpack forecasts for value to Utah water users independent of its use for weather modification evaluations.

VII. REFERENCES

Brown, Keith J., Robert Elliott and Max W. Edelstein, 1978: Transactions of Workshop on Total-Area Effects of Weather Modification. August 8-12, 1977, Fort Collins, CO. North American Weather Consultants Report to NSF, Goleta, CA, 227 pp.

Jensen, D.T., Gail E. Bingham, Gaylen L. Ashcroft, Esmaiel Malek, Greg D. McCurdy and William K. McDougal, 1990: Precipitation Pattern Analysis Uinta Basin - Wasatch Front. Office of State Climatologist, Utah State University, Logan, Utah, 40 pp.

Medina, Jonnie G., 1981: Techniques for Assessment of Nonrandomized Weather Modification Programs in the Colorado Mountains. Masters Thesis, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 90 pp.

Mulvey, Gerald J., 1977: Physical Mechanisms of Extra-Area Effects from Weather Modification. Atmos. Sci.Paper 276, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 138 pp.