THE JOURNAL OF WEATHER MODIFICATION

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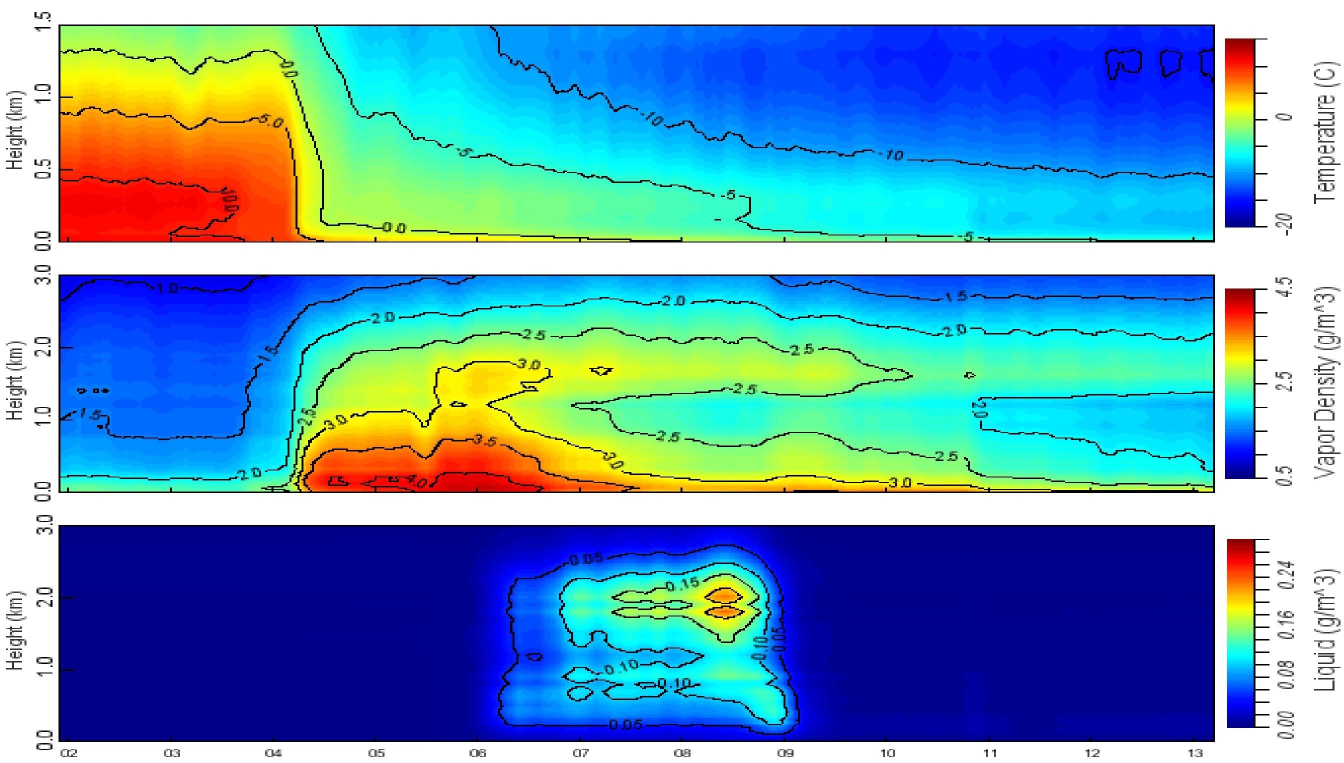

Supercooled liquid (bottom) at -3 to -15 C temperature (top) condenses at the expense of water vapor (middle) during 2008 Valentine's Day snowstorm at Denver. Snowflakes crystallize directly from vapor and further deplete vapor after 0900 UT, consistent with Bergeron process.

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THE WEATHER MODIFICATION ASSOCIATION

The Weather Modification Association was organized in 1950 to develop a better understanding of weather modification among program sponsors, the operators and members of the scientific community. In 1966, the first suggestion for a professional journal was proposed and Volume 1, No. 1, of the *Journal of Weather Modification* was published in March 1969. This series now includes 41 volumes (43 issues).

Originally called the Weather Control Research Association, the name of the organization was changed to the Weather Modification Association in 1967. During its 55-year history, the Association has:

- Pressed for sound research programs at state and federal levels.
- Promoted a better understanding of weather modification for beneficial use.
- Acted as a disseminating agent for literature.
- Provided extensive testimony before many federal, state and local committees and agencies in regard to all aspects of weather modification research and operations.
- Assumed an active role in the promotion of policy statements concerning all aspects of weather modification.
- Developed active positions on ethics, minimum standards for operations, and a strong certification program for operators and managers.
- Published the *Journal of Weather Modification*, the only professional journal in the world totally dedicated to the operational, societal, economic, environmental, legal and scientific aspects of weather modification.

The *Journal* is published annually and papers are always welcome for consideration in either the scientific paper or notes and correspondence sections. A nominal charge of $50 per black-white page is made for each page ($120 per color page) published in the final double-column format of the *Journal.* This fee is charged for all papers, foreign and domestic.

Additional information on the individual classes of membership can be found in the Articles of Incorporation found at http://www.weathermodification.org.

Applications for membership on a calendar year basis, as well as additional information, can be obtained by contacting the WMA at the permanent address of the Association:

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President's Message

Weather modification or cloud seeding has been the fascination and passion of many scientists since the 1940s. It should be no mystery why scientists have always had an obsession with clouds. Descriptively simple in composition, each cloud is merely a collection of tiny drops of water and ice crystals. Yet clouds are obviously so much more than that. Collisions of tiny drops of water conspire with continental-scale patterns of wind that bring in colder air aloft to produce an endless field of puffy cumulus, and violent towers of cumulonimbus.

An army of scientists study the curious behavior of clouds, slowly working out the details of cloud formation but still struggling to understand precipitation formation. A modification or change in the cloud environment will create a change in the cloud properties, the sizes and numbers of the tiny drops and the formation of ice crystals. This is weather modification in its simplest form.

The WMA was established in 1950 with the mission to promote research, development and understanding of weather modification technology for beneficial uses. Day-to-day operation of the WMA is managed by a close network of volunteer members of the Association. The Executive Board and Committees deserve to be acknowledged and praised for their commitment towards the Association. A note of great appreciation goes to WMA Executive Secretary Hilda Duckering whose tireless work is consistently outstanding.

The WMA is also grateful to the Government of Mendoza province in Argentina and Direccion de Agricultura y Contingencias Climaticas for hosting the WMA 2008 Semi-Annual Meeting that was held in the city of Mendoza on 1-3 October 2008. The hospitality of the Argentinians was very much appreciated by the Association.

Duncan Axisa

Editor's Message

The purpose of ***The Journal of Weather Modification*** is to be *"the only professional journal in the world totally dedicated to the operational, societal, economic, environmental, legal and scientific aspects of weather modification".* To fulfill this purpose it is important to communicate detailed results of original research; detailed and thoughtful reviews of results previously presented in the literature; preliminary results of experiments that are important to circulate to the community even before final results are available; summaries of work that is described in more detail in project reports that may not be widely available to the broad weather modification community; information on the status of various government programs and local, state, and federal laws; and discussion of ideas related to weather modification that fall into the realms of economics, the social sciences, and politics. It also is important to provide a forum for comment on previously published scientific work or other matters of importance to the community.

To better fulfill serve the community in these ways, we implemented with Volume 40 (2008) a new scheme for categorizing papers appearing in the Journal. These categories are *Scientific Papers* and *Technical Notes and Correspondence*. This structure supersedes the structure used for Volumes 1-39 in which papers were categorized either as *Reviewed* or *Non-Reviewed*. With Volume 41 we continue the new classification.

As a professional journal ***The Journal of Weather Modification*** needs to balance its function as a means of communication and vehicle for exchange of a wide range of results and ideas against the need to ensure that the material presented in the journal is scientifically and professionally sound. The structure of "Reviewed" and "Non-reviewed" papers has become less and less useful in fulfilling this function, in recent years. In fact, in recent years, all submissions to ***The Journal of Weather Modification*** have been peer-reviewed in order to validate their basic scientific and professional quality. Papers not adhering to the basic principles of science and professional communication have been rejected based on advice from peer-reviewers and the judgment of the editor. The distinction between the two current categories is that *Scientific Papers* adhere to the basic structure of a scientific presentation, include detailed discussions of how data are obtained and analyzed, the scientific background for theoretical developments, detailed discussion of how the results lead to the conclusions, etc. In principle, there is enough information in a Scientific Paper to allow independent replication of results presented.

Papers denoted as *Technical Notes* contain preliminary results that have not been fully validated scientifically, summaries of more detailed presentations contained in project reports or other hard-to-access literature, etc. *Correspondence* is a forum in which one may publish a discussion or critique of previously-published work and in which the author(s) of that original work can reply to the comments. *Correspondence* also serves as a means for non-technical discussions of social, economic, legal, or political issues of interest to the weather modification community.

The Editor appreciates the many Weather Modification Association members, and also several non-members, who served as peer-reviewers for submissions to Volume 41.

Andrew Detwiler

AN INDEPENDENT STATISTICAL EVALUATION OF THE VAIL OPERATIONAL CLOUD SEEDING PROGRAM

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Abstract. An independent target-control statistical evaluation of the Vail operational cloud seeding program over its period of operations from 1977 to 2005 was conducted using ratio statistics and, in particular, the bias-adjusted regression ratio. The water year (October-September) streamflow expressed in Acre-Feet (AF) served as the response variable in the evaluations. The effect of seeding on eight (8), closely-spaced sub-basins in the Vail watershed was evaluated using the controls that give the most precise evaluation results possible with the available data. Evidence for statistically significant seeding effects ranging from +6.3% to +28.8% was found for 5 of the 8 seeding targets. The maximum seeding effect is centered on Bighorn Creek (GBH) and decreases for targets both northwest and southeast of GBH. An analysis of the time evolution of the seeding effect suggests that the percent change in streamflow at each of the target sub-basins was about the same from water year to water year.

1. INTRODUCTION

The Vail operational cloud seeding program began during the last half of the 1976-77 winter season. The ski areas and water conservancy districts contracted Western Weather Consultants to mount a wintertime cloud seeding program in the Vail basin in an attempt to counter the effects of drought conditions and poor winter snowpack. The Vail Program has operated continuously since then with a regularly scheduled three-month program that starts on November first and continues to the end of January each winter season. A few of the operational seeding seasons have been extended into February and occasionally into March during winters of below normal precipitation. Only once has the seeding season been terminated early (in late December) during a winter with exceptionally above normal snowfall amounts. Brief periods of suspensions of seeding operations have occurred during periods of avalanche concerns or warnings.

The initial program at Vail had 8 ground-based silver iodide nuclei generators that could provide continuous seeding plume coverage over and around the Vail ski slopes with targeting wind directions varying from 240 degrees to about 350 degrees. In 1981, the target area was expanded to include the Beaver Creek ski area and the network of seeding generators was expanded to 14 seeding sites within the same approximate targeting wind direction envelope. Over the next few years an additional three seeding sites were added to the total generator network (for a total of 17) to further improve the total seeding plume coverage of cloud nuclei that would feed into the cloud systems forecast to move over the two ski areas. In the seeding methodology of Western Weather Consultants, the ground generators are located at sites that utilize upwind ridges and channeling valleys to push the seeding material into the lower cloud region with the most favorable seeded regions being downwind of the initial barriers.

In 2001, Western Weather Consultants completed a ten-year evaluation (Hjermstad, 2001) of the more recent operational years with the most complete sets of available precipitation data. A non-statistical analysis of the Snotel data suggested a seeded precipitation increase of 15% on all of the seeded days and an increase of 7% for the average seasonal precipitation. A non-statistical analysis of the Ski area data suggested an average 31% increase of the precipitation on seeded days in the ski areas and a 15% increase of the average seasonal precipitation. Western Weather Consultants (Hjermstad, Personal Communication) obtained its estimates of the non-seeded precipitation for each of the Vail targets by extrapolating the average precipitation value of 2 nearby non-seeded sites (one on each side of the target) to the Vail target by adjusting them for the differences in natural precipitation due to elevation and distance. The Vail operational cloud seeding program has never been subjected to a statistical evaluation. Until now, statistical

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evaluations of snowpack enhancement cloud seeding programs in the Colorado Rockies were all based on precipitation measurements taken over a period of several hours to several days as the response variable.

Both statistical and physical evidence are required to establish the success of any cloud seeding activity (AMS, 1998). Because the expected effects of cloud seeding are within natural meteorological variability, statistical methods are needed to detect a seeding effect with reasonable certainty. Physical evidence is needed to establish plausibility that the effects suggested by the results of the statistical evaluation could have been caused by the seeding intervention. This study is primarily concerned with assessing the statistical evidence in support of the Vail operational cloud seeding program. The purpose of this study is to conduct an independent statistical evaluation of the Vail operational cloud seeding program from water year 1977 through water year 2005. The objectives of the evaluation are (1) to determine if cloud seeding enhanced streamflow in the Vail Basin, (2) to provide information on the strength of the seeding effect and its confidence interval to allow informed judgments to be made about its cost-effectiveness, and (3) to identify follow-up physical studies that will help explain and support the plausibility of the statistical results.

2. EVALUATION PROCEDURES

The bias-adjusted regression ratio was used in a target-control evaluation of the effect of seeding on streamflow in the Vail River Basin. The water year (October-September) streamflow expressed in Acre-Feet (AF) served as the response variable in the evaluations. Silverman (2007) described and demonstrated the capability and merits of using ratio statistics and the bias-adjusted regression ratio, in particular, in evaluating the effectiveness of operational (non-randomized) cloud seeding programs. He showed that the bias-adjusted regression ratio is a more precise and more reliable method for evaluating operational (non-randomized) seeding programs than the traditional historical regression methodology used heretofore. He also showed that the bias-adjusted regression ratio results for the Kings River operational cloud seeding program (2007) and the Kern River operational cloud seeding program (Silverman, 2008) were statistically comparable to those from the re-randomization analysis. Following is a summary of the major concepts about the bias-adjusted regression ratio methodology and its application to the evaluation of operational cloud seeding programs. See Gabriel (1999, 2002) for a description of the ratio statistics methodology, and Silverman (2007) for a more complete description of its application to operational (non-randomized) cloud seeding programs.

The regression ratio (RR) is given by the relationship, $RR = SR / SR_{PRED}$ where the single ratio (SR) is the ratio of the average target streamflow during the operational period (TS_O) to the average streamflow for the seeding target during the historical period (TS_H), i.e., $SR=TS_O/TS_H$, and SR_{PRED} is the ratio of TS_O and TS_H that are predicted by the target-control regression relationship for the data over the entire period of analysis (including both the historical and operational periods). By dividing the SR by SR_{PRED}, the SR is adjusted for effects due to natural differences in streamflow between TS_O and TS_H, and thereby improves the precision in the estimate of the target streamflow.

The RR results are then adjusted for biases that can occur when operational data are compared to historical records in an *a posteriori* evaluation of non-randomized seeding programs. An adjustment is made to the RR results based on multiplying its computed P-value by an adjustment factor (Gabriel and Petrondas, 1983). For this study, the adjustment factor was found to be slightly less than 2. However, an adjustment factor of 2 was used so the calculated values of the bias-adjusted regression ratio are conservative estimates of the seeding effects. The results using the regression ratio that were adjusted for bias in this way are called RR_A.

The main emphasis in the presentation of the results is on confidence intervals because they infer a range within which the true effect lies whereas null hypothesis significance tests only assess the probability that an effect is due to chance (Gabriel, 2002; Nicholls, 2001). Confidence intervals were calculated as prescribed by Gabriel (2002). Use of confidence intervals provides information on the strength of the seeding effect to allow informed judgments to be made about its cost-effectiveness and societal significance. In this study, an evaluation result is considered to be statistically significant if its 90 percent confidence interval does not include the null hypothesis value of RR_A = 1 or zero percent change in streamflow, i.e., it satisfies a 2-sided level of significance of 0.10.

3. SELECTION OF THE TARGETS AND CONTROLS

3.1 Targets

The primary targets of the seeding operations were eight small basins in and directly adjacent to the Vail Ski Area that were all very likely seeded under most of the meteorological conditions for each operational season. They include Piney River (PNY), Booth Creek (GBO), Middle Creek (MID), Pitkin Creek (GPT), Bighorn Creek (GBH), Upper Gore Creek (GUP), Black Gore Creek (GBL) and Turkey Creek minus Wearyman Creek (TMW). These basins should give the best potential to represent the target area snowpack under all operationally seeded weather conditions.

3.2 Potential Controls

A potential control is a streamflow station that has not been seeded, is highly correlated with the target, and has a long enough record of full natural flow data during the historical and operational period to support a meaningful evaluation. All upwind, non-seeded basins within about 75 miles of the target area that met these criteria were selected as potential control sites. They include White River North Fork at Buford (WNF), White River South Fork at Buford (WSF), West Divide Creek (WDC) and the Fryingpan River Near Ruedi (FRR). WNF and WSF are about 75 miles west northwest of the target area. WDC and FRR are about 70 miles and 30 miles west southwest of the target area, respectively.

Table 1 gives the geographical characteristics, average water year streamflow and data record lengths of the selected targets and the potential control stations used in this study. Fig. 1 is a map of the Vail region showing the location of all the targets and controls, and the location of the ground generators used for the original Vail program and for the Vail-Beaver Creek program.

Table 1. Geographical characteristics, average water year streamflow and data record lengths of the seeding targets and the potential control stations used in this study.

Station Name	Sta. ID	USGS No	Latitude (° N)	Longitude (° W)	Elevation (feet)	Avg FNF[4]	Record WaterYrs
Primary Targets							
Piney River	PNY[1]	09059500	39.800	106.583	7,272	54,234	1948-2005
Booth Creek	GBO[1]	09066200	39.648	106.323	8,325	8,091	1965-2005
Middle Creek	MID[1]	09066300	39.646	106.382	8,200	3,944	1965-2005
Pitkin Creek	GPT[1]	09066150	39.644	106.302	8,525	7,395	1967-2005
Bighorn Creek	GBH[1]	09066100	39.640	106.293	8,625	5,842	1964-2005
Upper Gore Creek	GUP[1]	09065500	39.623	106.278	8,600	20,523	1948-2005
Black Gore Creek	GBL[1]	09066000	39.596	106.264	9,150	12,052	1948-2005
Turkey Creek [3]	TMW[1]	09034000	39.523	106.336	8,918	10,312	1965-2005
Potential Controls							
West Divide Creek	WDC[2]	09089500	39.331	107.579	7,060	22,582	1909-2005
NF White Rvr at Buford	WNF[2]	09303000	39.988	107.614	7,010	225,164	1909-2005
SF White Rvr at Buford	WSF[2]	09304000	39.974	107.625	6,970	189,524	1909-2005
Fryingpan Rvr -Ruedi	FRR[2]	09080400	39.366	106.825	7,473	177,090	1909-2005

1 Full natural flow data reported by the USGS
2 Full natural flow data provided by the Colorado Water Conservation Board (CWCB)
3 Full natural flow data for Turkey Creek minus that portion for Wearyman Creek

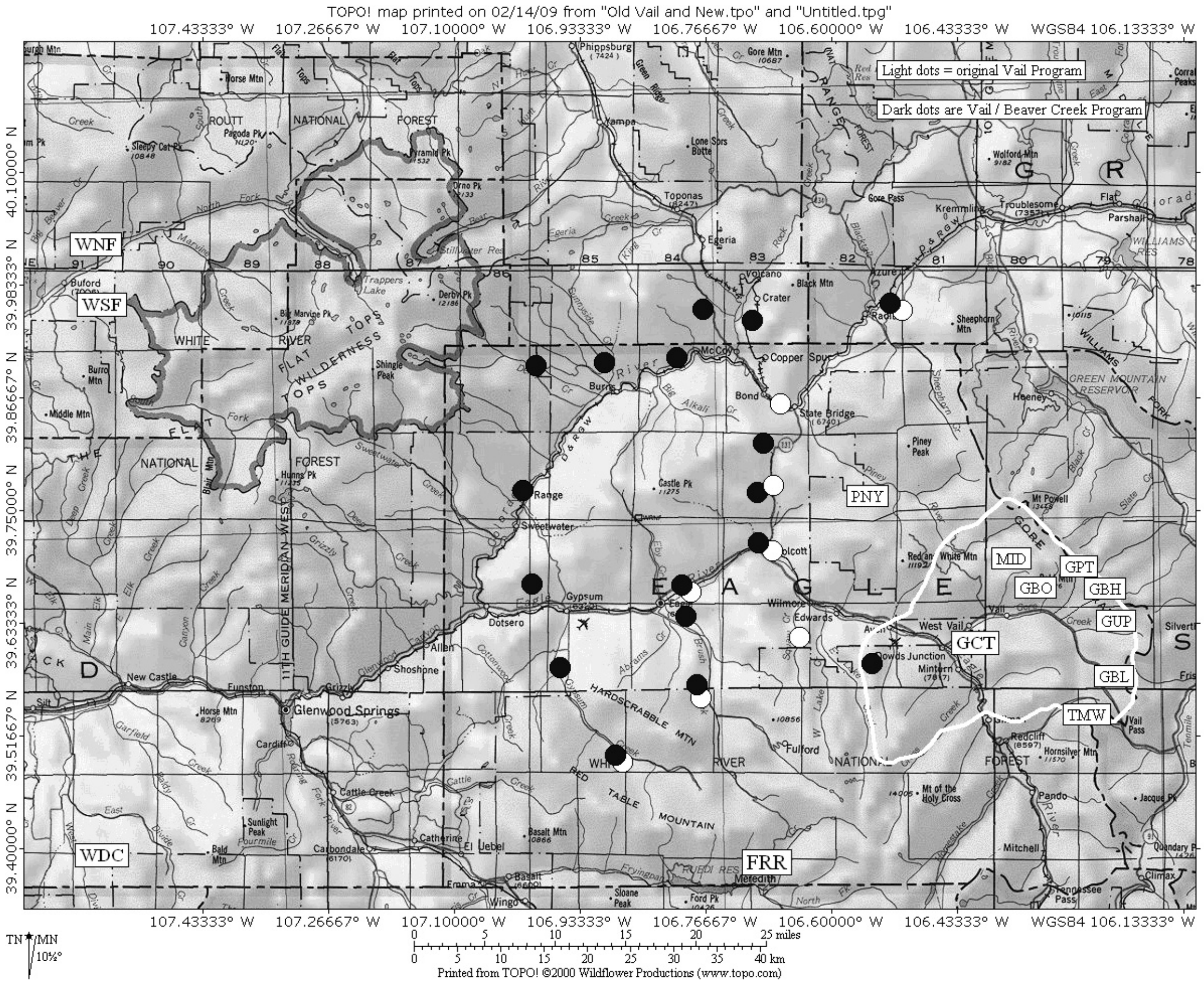

Fig. 1. Map of the Vail region showing the location of all the targets and controls, and the location of the ground generators used for the original Vail program (blank circles) and for the Vail-Beaver Creek program (shaded circles). The white "circle" encompassing the target stations is the intended target area.

3.3 Choosing the Best Control

Silverman (2007) showed that it is imperative to use as the control or controls, to the extent that available data permits, the streamflow station or stations that yield the most precise results. He showed the control or combination of controls that has the highest correlation with the target and, especially, the lowest standard deviation of the residuals (differences between the observed and predicted values) will yield the most precise evaluation results.

The four potential control basins, by themselves and in various physically meaningful combinations, were regressed against each of the targets to determine which had the highest correlation and, especially, which had the smallest standard deviation of the residuals. Since GBH is near the center of the overall Vail target, it is used to represent and illustrate the kind of results that were obtained. The resulting linear and multiple correlation coefficients, ρ, and standard deviations of the residuals, s_o, for GBH are given in Table 2.

It was found that the control that had the highest correlation with GBH and had the lowest standard deviation of the residuals was FRR. It was also found that FRR was the best control for each of the other targets. In accordance with the regression ratio method (see Section 2), regression equations were derived by the least squares method for each of the targets that predicts the streamflow at the target station as a function of the streamflow at the control station FRR. The regression results should be accurate and robust since there were no outliers in the data and the regression residuals exhibited homoscedacity (constant variance).

Table 2. Linear and multiple regression analysis results for GBH against each potential control alone and the indicated combination of controls, respectively, for the entire period of analysis (including both the historical and operational periods).

Control	Corr. Coeff. ρ	Std Dev Res s_o (AF)
WSF	0.679	1,602
WNF	0.718	1,520
WDC	0.703	1,551
FRR	**0.775**	**1,406**
WSF, FRR	0.766	1,420
WNF, FRR	0.771	1,407
WSF, WDC	0.732	1,505
WNF,WDC	0.716	1,543

4. EVALUATION RESULTS

The evaluation results for the primary targets are given in Table 3. It can be seen from Fig. 2 that the maximum seeding effect is centered on GBH and decreases for targets both northwest and southeast of GBH. The seeding effect for GBH and all the targets north of it are impressively large and statistically significant except for MID which is almost, but not quite, statistically significant. The seeding effect for targets south of GBH decreases rapidly with increasing distance from GBH. The seeding effect is large and statistically significant for GUP and modest but not quite statistically significant for GBL, but TMW indicates no seeding effect at all. Keeping in mind that the choice of the bias adjustment factor gave rise to conservative estimates of seeding effects, it is possible that the seeding effects for MID and GBL are statistically significant after all. The fact that the seeding effect changes rapidly over the very short distances between seeding targets suggests, as one possible explanation, that the silver iodide nuclei from the ground generators are channeled by the terrain into a focused plume, and not widely dispersed as intended. This possible explanation was motivated by the analysis of the Colorado River Basin Pilot Project by Elliott *et al.* (1978) who found that under low-level stable conditions the silver iodide was transported northwestward parallel to the mountain barrier instead of northeastward and up into the clouds over mountain as intended. This and other possible explanations warrant further investigation and verification through appropriate meteorological and hydrological studies.

Table 3. Results of the Vail evaluation for each of the primary targets. Results are given for the proportional effect of seeding, δ (%) = 100* (RR_A-1), where RR_A is the bias-adjusted regression ratio, ρ is the correlation between the indicated target and the control (FRR), and CI90L and CI90U are the lower and upper bound of the 90% confidence interval, respectively. Statistically significant results in accordance with a 2-sided level of significance of 0.10 are shown in bold.

Target	δ	CI90L	CI90U	ρ
PNY	**+6.3**	**+0.4**	**+12.5**	0.910
GBO	**+9.3**	**+1.1**	**+18.1**	0.836
MID	+7.9	-0.2	+16.7	0.909
GPT	**+18.5**	**+7.3**	**+30.9**	0.812
GBH	**+28.8**	**+16.6**	**+42.2**	0.775
GUP	**+11.1**	**+4.7**	**+18.0**	0.837
GBL	+4.6	-0.6	+10.1	0.918
TMW	-2.0	-11.5	+8.3	0.871

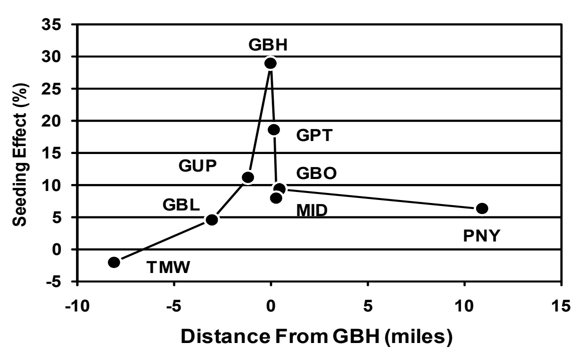

Fig. 2. Values of the seeding effect (%) as a function of the distance in miles northwest (positive) and southeast (negative) from the maximum effect at GBH.

The combined flows from GUP, GBL, GBH, GPT, GBO, and MID, hereafter called Gore Creek (GCT), flows into the Eagle River about 12 miles south of the target area at a point 3 miles downstream of Minturn, Colorado. An evaluation of the seeding effect for GCT indicates a statistically significant increase in GCT streamflow of +9.5% with 90% confidence that the true effect of seeding lies between +2.9% and +16.4%.

It can also be seen from Table 3 that the target-control correlation coefficients range from 0.775 to 0.918, accounting for about 58% to 85% of the variance of the target streamflows, respectively. There are two noteworthy aspects to this finding: (1) despite the fact that the targets are very close to one another, there is a big difference in their correlation coefficients with the control, and (2) the target-control correlation coefficients for the Vail targets are substantially smaller than those found for the evaluation of the operational seeding programs in the watersheds of the Sierra Nevada Mountains which ranged from 0.93 to 0.98. It appears that the spatial variability of annual runoff among watersheds in the Rocky Mountains is greater than that for watersheds in the Sierra Nevada Mountains. In view of the increased standard error of the estimate for the Vail targets, it is impressive that there is such strong statistical support for the estimated increases in streamflow due to seeding.

The +28.8% increase in water year streamflow at GBH is rather large compared to the results from similar seeding programs, especially when one takes into account that the water year streamflow is being affected by seeding during only 3 months of the year. Silverman (2007, 2008) evaluated the Kings River, Kern and San Joaquin operational cloud seeding programs and found that they produced a positive, statistically significant increase in water year streamflow ranging from +4.6% to +12.2%. Climax I and Climax II resulted in increases in precipitation of +9% and +13%, respectively, that could reasonably have occurred by chance (Grant and Kahan, 1974); however, for data stratifications of temperature and wind that are most favorable to seeding, statistically significant increases in precipitation as high as +55.2% were indicated (Mielke *et al.,* 1981). The evaluation of the Colorado River Basin Pilot Project resulted in no statistically significant increase in precipitation (Elliott *et al.,* 1978); however, a statistical reanalysis of the data suggested that, for data stratifications of wind direction that are most favorable to seeding, statistically significant increases in precipitation from +28% to +45% were apparent (Hjermstad and Mielke, 1976).

Lest the rather large seeding effect estimate for GBH be an anomalous function of the control that was used (FRR), the evaluation of GBH was repeated using several different controls. The results of the evaluations of GBH with all of the controls are shown in Table 4. It can be seen that the results of the evaluation using the other 7 controls are statistically comparable to the results obtained using FRR as the control. However, using FRR as the control yields the most precise result; i.e., the lowest standard error of the estimate of RR_A. Therefore, it is reasonable to conclude that the estimates of the seeding effect using FRR as the control for all of the targets, as given in Table 3, are statistically credible.

Table 4. Same as Table 2 except for the evaluation of GBH using different controls as indicated.

Control	δ	CI90L	CI90U	ρ
FRR	+28.8	+16.6	+42.2	0.775
WDC	+23.6	+10.9	+37.9	0.703
WNF	+26.8	+13.9	+41.2	0.718
WSF	+33.4	+19.2	+49.3	0.679
FRR,WSF	+28.7	+16.6	+42.0	0.766
FRR,WNF	+28.4	+16.4	+41.6	0.771
WDC,WSF	+27.9	+14.9	+42.4	0.716
WDC,WNF	+25.2	+12.8	+39.1	0.732

5. TIME EVOLUTION OF THE SEEDING EFFECT

The time evolution of the seeding effect for the Vail primary targets is shown in Fig. 3. In Fig. 3 the seeding effect calculated for each seeded water year is the value that would have been obtained if the evaluation were done for all seeded years up to and including that water year. It can be seen that the seeding effect appears to be consistent over time. For clarity of presentation, the 90 percent confidence limits are not shown. For each of the targets the 90 percent confidence limit lines follow the pattern of their point value plot and narrow with time as the standard error of

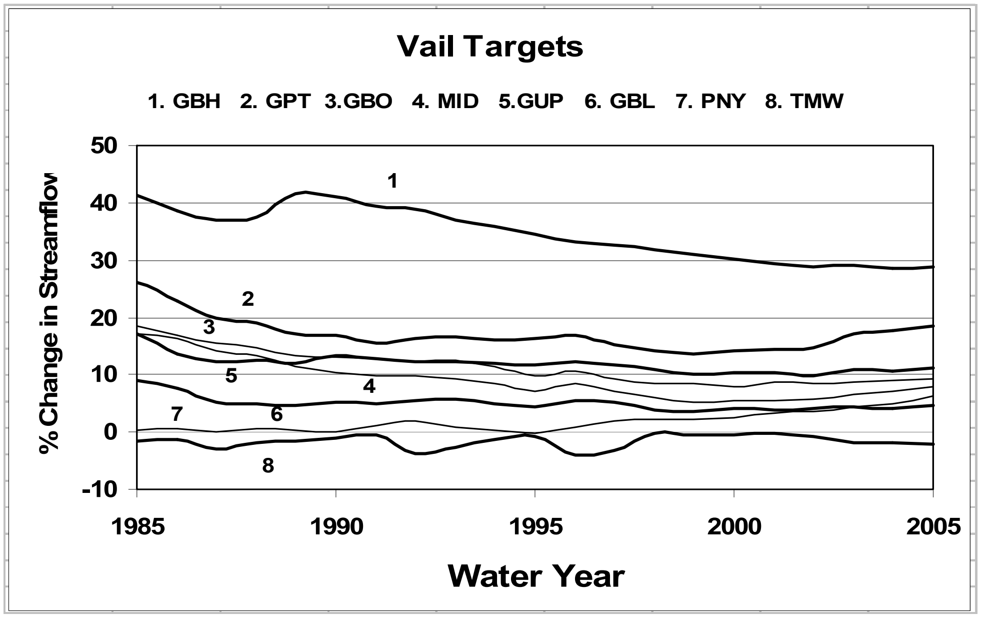

Fig. 3. Time evolution of the seeding effect (% change in streamflow)

estimate decreases with increasing sample size. See Table 2 for an indication of the 90 percent confidence limits for the final year (2005) of each target's evaluation.

It can be seen from Fig. 3 that there are no significant and/or abrupt changes in trend that might be indicative of a significant change seeding effectiveness and, in turn, a significant change in some aspect of the meteorology and/or seeding procedure that affected the seeding effectiveness.

6. SUMMARY

An independent statistical evaluation of the Vail operational cloud seeding program over its period of operations from 1977 to 2005 was conducted using ratio statistics and, in particular, the bias-adjusted regression ratio. The effect of seeding on eight (8) primary seeding targets in the Vail Basin was evaluated using the control that gives the most precise evaluation results possible with the available data. The following is a summary of the main findings of this evaluation study:

(1) The evaluation results suggests, as one possible explanation, that the dispersion of the silver iodide seeding agent tends to be narrowly focused rather than uniformly distributed across all the primary seeding targets. This and other possible explanations need to be investigated further through physical and hydrological studies such as silver iodide tracer experiments.

(2) Of the 8 primary seeding targets in the Vail Basin, statistically significant increases in streamflow due to seeding ranging from +6.3% to +28.8% was found in 5 of them (PNY, GBO, GPT, GBH and GUP); not quite statistically significant seeding-induced increases in streamflow was found in 2 of them (MID and GBL); and no seeding effect was found in one of them (TMW). The maximum seeding effect of +28.8% occurred at Bighorn Creek (GBH) and decreased rapidly with increasing distance for seeding targets both northwest and southeast of GBH.

(3) The time evolution of the seeding effect on the Vail primary seeding targets suggests that the seeding-induced changes in streamflow were steady and consistent over time.

7. REMARKS

It is emphasized that this study is an *a posteriori* evaluation of a non-randomized seeding operation. In addition, this evaluation is an exploratory study that involves consideration of a multiplicity of analyses, some of which are suggested by the results of previous analyses. With such a large number of tests, a few are likely to yield significant results purely by chance. In view of these considerations, the results of the evaluations in this study must be viewed with caution. It is emphasized that the results should be interpreted as measures of the strength of the suggested seeding effect. From a rigorous statistical standpoint, the suggested effects that are indicated must be confirmed through new*, a priori,* randomized experiments specifically designed to establish their validity.

Mindful that the results from *a posteriori* analyses might evince a physically interesting result that in fact might only reflect chance, strong statistical support for a result, as obtained in this study, provide incentive to do a more in-depth study of past seeding operations. The ultimate aim of these studies should be to obtain the statistical and physical evidence needed to declare the unequivocal success of the Vail operational cloud seeding program that, in turn, establishes the basis for optimizing the cost effectiveness of future seeding operations. New studies are needed to clarify and extend the results, and to resolve the uncertainties in the statistical and physical evidence obtained thus far. Physical understanding is clarified and advanced through follow-up statistical and physical studies and experiments prompted by promising findings such as those obtained in this study. Progress in physical understanding comes from noting the unexpected and following it up as well as from confirming the expected.

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AN EVALUATION OF THE SAN JOAQUIN OPERATIONAL CLOUD SEEDING PROGRAM USING MONTE CARLO PERMUTATION STATISTICS

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Abstract. An independent target-control statistical evaluation of the Southern California Edison (SCE) Upper San Joaquin River Basin Weather Modification Program, also known as the Big Creek Cloud Seeding Project, was conducted using Monte Carlo permutation statistics. The cumulative effect of seeding over the entire history of the project through water year 2006 was calculated in terms of confidence intervals because they provide information on the strength of the seeding effect and, thereby, allows informed judgments to be made about its cost-effectiveness and societal value. The effect of seeding on several targets in the Upper San Joaquin River Basin was evaluated using the control(s) that gives the most precise evaluation results possible with the available data. Evidence for positive, statistically significant and cost-effective increases in streamflow after 56 years of seeding was found for Mono Creek and Pitman Creek, but the results for Bear Creek were not statistically significant. Physical studies that help explain the statistical results and that could lead to more cost-effective seeding operations are suggested.

1. INTRODUCTION

The Upper San Joaquin River Basin Weather Modification Program, also known as the Big Creek Cloud Seeding Project, is an operational cloud seeding program sponsored by the Southern California Edison Company (SCE). The objectives of the cloud seeding program include enhancing streamflow for increased hydroelectric power generation with additional benefits to downstream agriculture and reservoir recreation. It is arguably the longest continuously operated cloud seeding program in the world. Operational cloud seeding began during water year 1951 and has been conducted every year since then. North American Weather Consultants (hereafter referred to as NAWC) conducted the cloud seeding operations during water years 1951-1987 and 1991-1992, and Atmospherics Incorporated (hereafter referred to as AI) conducted the cloud seeding operations during water years 1988-1990 and 1993-present. Although designed primarily to enhance snowpack and subsequent streamflow, both summer and winter storms have been seeded with silver iodide ground generators, airborne silver iodide generators, airborne silver iodide flares, and/or airborne hygroscopic flares.

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SCE and its seeding contractors conducted evaluations of the effectiveness of the Upper San Joaquin River Basin Weather Modification Program for individual years and for several blocks of years (see, for example, NAWC, 1966; NAWC, 1978; AI, 1991). The evaluations were primarily based on streamflow analysis using the historical regression method although evaluations for some of the years included radar and precipitation analyses as well. NAWC used various sites at various times as the target streamflow station (e.g., San Joaquin River below Hooper Creek, San Joaquin River at Miller Crossing, San Joaquin River near Florence Lake, and Bear Creek), and used the Merced River at Pohono Bridge streamflow station and various precipitation sites, usually in combination, as control stations. AI consistently used Bear Creek as the target streamflow station and the Merced River at Pohono Bridge and Cottonwood Creek in combination as the control. For some of the early years, NAWC and SCE also used double mass analysis of target and control streamflows to detect seeding effects and estimate their magnitude (see, e.g., NAWC, 1978). The results of the various analyses by the seeding contractors based on target-control comparisons suggested a positive effect of seeding ranging from 7%-9% depending on the period of evaluation and the choice of target-control sites. The Panel on Weather and Climate Modification to the Committee on Atmospheric Sciences, National Academy of Sciences conducted an evaluation of the first 14 years of the San Joaquin River Basin Operational Cloud Seeding Program (National Academy of Science,

1966) using an unspecified statistical method with streamflow as the test variable and reported a 7% increase at a significance level of 0.04. In his evaluation of the Kern River operational cloud seeding program, Silverman (2008) included for comparison and pooling an evaluation of the first 56 years of the San Joaquin operational cloud seeding program at Pitman Creek using the bias-adjusted regression ratio and found evidence for a positive, statistically significant and cost effective seeding effect.

The success of any cloud seeding activity requires (1) statistical evidence of a significant increase in the response variable (water year streamflow in this case) presumably due to seeding, and (2) physical evidence that establishes the plausibility that the effects suggested by the statistical evidence could have been caused by the seeding intervention (AMS, 1998). This study is primarily concerned with assessing the statistical evidence in support of the San Joaquin operational cloud seeding program. The purpose of this study is to conduct an independent statistical evaluation of the Upper San Joaquin River Basin Weather Modification Program in order to determine if the requisite statistical evidence exists. The objectives of the evaluation are (1) to evaluate the program over its 56 years of operation from water years 1951 to 2006 and, thereby, take advantage of the longevity of the data base, (2) to evaluate the operational seeding program using Monte Carlo permutation statistics, (3) to provide information on the strength of the seeding effect and its confidence interval to allow informed judgments to be made about its societal value and cost-effectiveness, and (4) to identify follow-up physical studies that will help explain and support the plausibility of the statistical results obtained thus far, and lead to the optimization of the cost-effectiveness of the seeding operations.

2. EVALUATION PROCEDURES

Permutation analysis, also known as re-randomization analysis, is a non-parametric method of analysis that is based solely on the experimental data itself. It does not depend on any assumptions about the distribution shape and its associated properties or about independence of the data from one time to another. Re-randomization (permutation) analysis involves the calculation of all permutations of the observed data to determine how unusual the observed experimental outcome is. Tukey *et al.* (1978) stated that re-randomization (permutation) analysis offers the most secure basis for drawing statistical conclusions and advocated its use in evaluating weather modification experiments, especially confirmatory experiments. This was emphasized by Gabriel (1979), who discussed some of the advantages of re-randomization tests over classical parametric tests.

A drawback to the application of permutation analysis by exact methods is they are computationally exorbitant. By the use of re-randomization inference, Gabriel (1999, 2002) developed the ratio statistics methodology for randomized experiments that is computationally practical and yields results that approximate those from re-randomization analysis. Silverman (2007) extended the ratio statistics methodology to non-randomized operational cloud seeding programs by introducing an empirical adjustment factor to account for biases that can occur when non-randomized, operational data are compared to historical records.

Monte Carlo permutation analysis will be the statistical basis for the evaluation presented in this study. The Monte Carlo permutation test is an asymptotically equivalent permutation test that is useful when there are too many permutations to practically allow for complete enumeration. This is done by generating a reference set of possible experimental outcomes by random Monte Carlo sampling, which consists of a small (relative to the total number of possible permutations) random sample of the possible experimental outcomes. However, the number of Monte Carlo random samples must be large enough to achieve the required accuracy of the test. In this study the Monte Carlo permutation test will be applied to the regression ratio (Gabriel, 1999) test statistic using a random Monte Carlo sample of 30,000 permutations. For an observed P-value of 0.05, the accuracy from 30,000 random permutations is, with 99% confidence, ±0.004. For larger values of the observed P-value, the use of 30,000 random Monte Carlo samples yields even more accurate test results.

The regression ratio (RR) is given by the relationship, $RR = SR / SR_{PRED}$ where the single ratio (SR) is the ratio of the average target streamflow during the operational period (TS_O) to the average streamflow for the seeding target during the historical period (TS_H), i.e., $SR=TS_O/TS_H$, and SR_{PRED}

is the ratio of TS_O and TS_H that are predicted by the target-control regression relationship for the data over the entire period of analysis (Gabriel, 1999). By dividing the SR by SR_{PRED} , the SR is adjusted for effects due to natural differences in streamflow between TS_O and TS_H, and thereby improves the precision in the estimate of the target streamflow. By taking advantage of the high correlation between the target and control streamflows over the entire period of analysis, the variance of the regression ratio is reduced with respect to the variance of the single ratio for the target. This enables the detection of smaller effects due to seeding with greater probability.

The main emphasis in the presentation of the results is on confidence intervals because they infer a range within which the true seeding effect lies whereas null hypothesis significance tests infer only whether there is any effect at all (Gabriel, 2002; Nicholls, 2001). Use of confidence intervals provides information on the strength of the seeding effect to allow informed judgments to be made about its cost-effectiveness and societal value. The method of Fletcher and Steffens (1996) is used to calculate the confidence limits estimated by the Monte Carlo permutation test.

3. SELECTION OF THE TARGETS AND CONTROLS

The evaluation of the Upper San Joaquin River Basin Weather Modification Program was evaluated using unregulated "natural" or full natural flow (FNF) streamflow data. In particular, the water year (October-September) streamflow expressed in Acre-Feet (AF) served as the response variable in the evaluations. There is an intrinsic and unavoidable error of about ± 5% in the streamflow measurements. Since the measurement errors are random variables and apply to both the target and control data alike, they should not bias the evaluations and should not interfere with the detection of a seeding effect if one exists.

It is emphasized at the outset that the selection of target stations in the San Joaquin River Basin was limited to those streamflow gauging sites for which full natural flow (FNF) data was available in the public domain. This included FNF data that was available directly or could be derived from data available in the public domain. Thus, the target stations available for use in this study were limited to Bear Creek near Lake T.A. Edison (USGS site #11230500, hereafter referred to as BCK), Pitman Creek (USGS site #11237500, hereafter referred to as PIT) and Mono Creek (USGS site #11231500, hereafter referred to as MNO). The unregulated streamflow data for BCK and PIT were obtained from the USGS through their web site online at http://waterdata.usgs.gov/ca/nwis/nwis. The FNF data for MNO were obtained by making the appropriate storage and evaporation adjustments to the regulated streamflow data reported on the USGS web site using the reservoir storage data for Lake Thomas A. Edison Reservoir reported on the CDEC web site online at http://cdec.water.ca.gov and the evaporation rates suggested by Longacre and Blaney (1961).

Silverman (2007) showed that it is imperative to use as the control or controls, to the extent that available data permits, the streamflow station or stations that yield the most precise results. The control or combination of controls that has the highest correlation with the target and the lowest standard deviation of the residuals (differences between the observed and predicted values) will yield the most precise evaluation results. A potential control is a streamflow station that has not been seeded, is highly correlated with the target, and has a long enough record of full natural flow data during the historical and operational period to support a meaningful evaluation. There are four (4) potential control stations: the Merced River at Pohono Bridge (USGS site #11266500, hereafter referred to as MDP) and the Merced River at Happy Isles Bridge near Yosemite (USGS site # 11264500, hereafter referred to as MHI) in the Merced watershed, the Stanislaus River at Goodwin (hereafter referred to as SNS in the Stanislaus watershed), and Cottonwood Creek (hereafter referred to as CCR in the Eastern Sierra watershed).

The geographical characteristics, data record lengths and average water year streamflow for the target stations are given in Table 1. The geographical location of the seeding targets is shown on the streamflow map of the San Joaquin River Basin in Fig. 1. Fig. 2 is a map of the region that shows the relative locations of all the targets and all the potential controls.

Table 1. Geographical characteristics, average water year streamflow and data record lengths of the selected target and potential control stations used in this study

Station Name	Sta. ID	USGS No (1)	Latitude (° N)	Longitude (° W)	Elevation (feet)	Avg FNF (AF) (4)	Record Water Yrs
Targets							
Bear Creek	BCK	11230500	37.339	118.973	7,367	70,957	1922-2006
Mono Creek	MNO	11231500	37.361	118.991	7,380	117,547	1922-2006
Pitman Creek	PIT	11237500	37.199	119.213	7,020	31,068	1929-2006
Potential Controls							
Stanislaus R - Goodwin	SNS	(2)	37.852	120.637	252	1,155,497	1901-2006
Merced R at Pohono Bridge	MDP	11266500	37.717	119.665	3,862	475,832	1917-2006
Merced R at Happy Isles Br	MHI	11264500	37.732	119.558	4,017	270,314	1916-2006
Cottonwood Creek	CCR	(3)	36.439	118.080	3,779	17,472	1935-2006

(1) Data obtained from the United States Geological Survey (USGS) website online at http://waterdata.usgs.gov/nwis/nwis
(2) Data obtained from the California Data Exchange Center (CDEC) website online at http://cdec.water.ca.gov
(3) Data obtained from the Los Angeles Department of Water and Power (Personal Communication)
(4) Average water year full natural flow (FNF) in Acre-Feet during the historical period 1935-1950

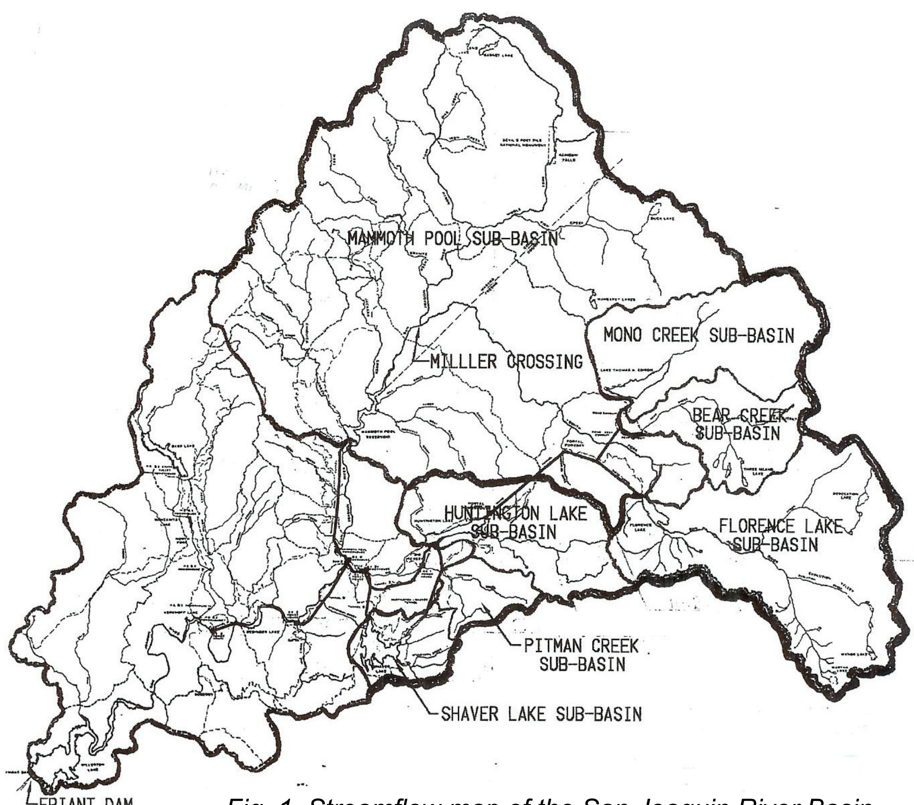

Fig. 1. Streamflow map of the San Joaquin River Basin

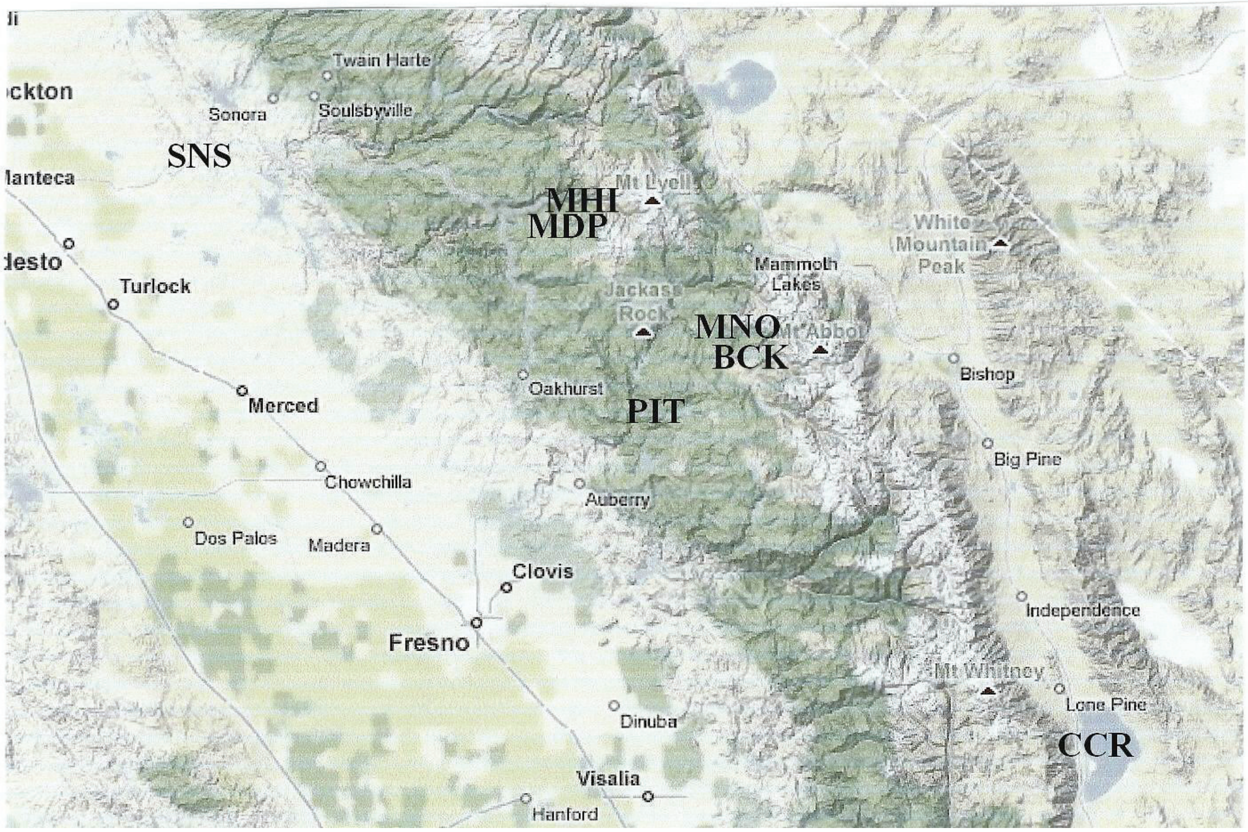

Fig. 2. Map showing the relative locations of all the targets and all the potential controls.

4. EVALUATION OF BEAR CREEK

At the outset it was decided to use BCK as the first target to evaluate because it was used by NAWC and AI as the target in their evaluations of seeding effects and, therefore, it afforded the opportunity to compare the results produced here with those of previous evaluations.

The four potential control stations were investigated by themselves and in physically reasonable combinations. The resulting linear and multiple correlation coefficients, ρ, and standard deviations of the residuals (differences between the observed and predicted values), s_o, are given in Table 2. It was found that the control having the highest correlation with BCK was the combination of MHI and CCR that yielded a multiple correlation coefficient of 0.984. In accordance with the regression ratio method, a multiple regression equation was derived for the 72-year period (1935-2006) that predicts the streamflow at the target station (BCK) as a function of the streamflow at the control station combination of MHI and CCR. The following equation for the water year streamflow at the target was obtained:

$$BCK(AF) = 0.19284 * MHI(AF) + 0.72487 * CCR(AF) + 7806.99\ AF$$

The regression equation was obtained using the least squares method. The regression results should be accurate and robust since there were no outliers in the data and the regression residuals exhibited homoscedacity (constant variance). This equation enabled the calculation of SR_{PRED} and, in turn, the calculation of RR as outlined in section 2. Applying the Monte Carlo permutation test as described in section 2, it was found with 90% confidence that the true effect of seeding lies somewhere between -1.18% and +3.00%. Thus, the null hypothesis can not be rejected and the result is not statistically significant.

Table 2. Linear and multiple regression analysis results for BCK against each potential control alone and the indicated combination of controls, respectively, for the entire period of analysis (including both the historical and operational periods).

Control	Corr. Coeff. δ	Std Dev Res s_o (AF)
MDP	0.972	6,861
MHI	0.974	6,654
SNS	0.945	9,615
CCR	0.882	13,806
MDP, CCR	0.983	5,462
MHI, CCR	**0.984**	**5,276**
SNS, CCR	0.973	6,862

5. EVALUATION OF ALL SELECTED TARGETS

The three (3) selected targets in the San Joaquin River Basin were examined in an effort to determine the area extent and magnitude of the seeding effects. The process of choosing the control site combination that yields the most precise results, as described in Section 4 for BCK, was repeated for the other 2 targets. While it was found that the combination of MHI and CCR was best for BCK, the combination of MDP and CCR was best for MNO and PIT. Therefore, the evaluation of the seeding effects on MNO and PIT was carried out with the combination of MDP and CCR, as described in section 4.

The results of the evaluation of seeding effects on the 3 target stations are shown in Table 3. The multiple correlation coefficients between the data for each of the target sites with their respective controls are also shown in Table 3. It can be seen in Table 3 that the seeding effect for MNO and PIT are positive and statistically significant at a 2-sided level of significance of 0.10. The observed experimental outcome for BCK is considerably weaker and not statistically significant. It is particularly important to note that the evaluation results based on Monte Carlo permutation analyses shown here confirms and reinforces the evaluation results based on the bias-adjusted regression ratio. It confirms that ratio statistics results approximate those from re-randomization analyses extremely well.

It is beyond the scope of this study to determine the physical cause(s) for the different levels of seeding effectiveness. One can, however, speculate that it is likely that targeting and seeding coverage of such a large drainage area as the Upper San Joaquin River Basin was not very uniform and that any increase in streamflow that may have been produced by seeding in some locations was diluted by the streamflow from those areas not efficiently seeded or not targeted for seeding.

The poorer seeding effectiveness at Bear Creek is consistent with the results of the silver-in-snow tracer study reported by McGurty (1999). Only silver iodide seeding chemicals released by aircraft were found in the Bear Creek sub-basin while none were found that were released by the ground generators. Thus, the increase in streamflow at Bear Creek appears to be the result of the aircraft seeding alone, supplemental seeding that did not start until 1975. In the Mono Creek sub-basin, tracers indicated that the source of the silver iodide was from both the aircraft and ground generators, with the majority coming from the ground generators.

Table 3. Water year seeding effects on the selected San Joaquin River Basin targets. The proportional effect of seeding is $\delta(\%) = 100*(RR-1)$, where RR is the Regression Ratio, and LB and UB are the lower and upper bound of the Monte Carlo permutation test 90% confidence interval, respectively

	Bear Creek	Mono Creek	Pitman Creek
Correlation with Controls	0.984	0.975	0.980
90% Conf. Interval			
LB (%)	-1.18	+1.99	+1.53
UB (%)	+3.00	+8.80	+9.26

6. SUMMARY AND CONCLUSIONS

An independent statistical evaluation of the Upper San Joaquin River Basin Weather Modification Program over its period of operations from 1951 to 2006 was conducted using Monte Carlo permutation analyses. The stated objectives of the evaluation were achieved. Additional results obtained were insightful and enhanced the stated objectives. The following is a summary of the main findings of this evaluation study:

(1) The Monte Carlo permutation analysis of water year streamflow for Bear Creek, the target chosen for the first evaluation, indicated with 90% confidence that the true effect of seeding lies somewhere between –1.18% and +3.00%, a statistically non-significant result.

(2) Three (3) streamflow stations in the San Joaquin River Basin were examined to determine the area extent and magnitude of the seeding effects. Evidence for positive, statistically significant and cost-effective increases in streamflow after 56 years of seeding was found for MNO and PIT, but the results for BCK were not statistically significant.

(3) The evaluation results based on Monte Carlo permutation analyses shown here confirms and reinforces the evaluation results based on the bias-adjusted regression ratio. It confirms that ratio statistics results approximate those from rerandomization analyses extremely well.

It is emphasized that this study is an *a posteriori* evaluation of a non-randomized seeding operation. In addition, this evaluation is an exploratory study that involves consideration of a multiplicity of hypotheses/analyses, some of which are suggested by the results of previous analyses. In view of these considerations, the results should be interpreted as measures of the strength of the suggested seeding effect and not as measures of statistical significance. Nevertheless, the estimated effects of seeding should be of considerable value to SCE in determining the past, present and future value of their cloud seeding operations according to risk criteria used in their business operations. As Boe *et al.* (2004) state, "… if a potential sponsor of a cloud seeding program, following careful deliberation, decided they had an 80% likelihood of obtaining a 10% increase in precipitation that would yield a benefit/cost ratio of 10:1, they would probably choose to support the program." According to Henderson (2003) an increase in streamflow of only 1.5% in the Sierra Nevada Mountain watersheds would yield a benefit/cost ratio of 10:1 where the benefits include both non-consumptive hydroelectric power generation and other downstream consumptive uses such as agricultural irrigation.

7. REMARKS

Additional studies are needed to clarify and extend the results of this evaluation, and to resolve the uncertainties and deficiencies in the statistical and physical evidence obtained thus far. Progress in physical understanding comes from noting the unexpected and following it up as well as from confirming the expected. Scientists should be mindful that the results from *a posteriori* analyses might evince a physically interesting result that in fact might only reflect chance. Nevertheless, strong statistical support for a result alerts the physical scientist even though there is no ready theory to explain the results or the findings run counter to the postulated seeding conceptual model or the findings appear to be inconsistent with the findings of previous physical studies. Physical understanding is clarified and advanced through follow-up statistical and physical studies and experiments prompted by such findings.

Follow-up physical studies that are needed to help explain the statistical results obtained thus far include, but are not limited to, analyses aimed at understanding:

(1) why Cottonwood Creek, as an additional control, captures an important part of the target variability, especially during the past 10 years,

(2) why there is a difference in seeding effect among the various targets, and

(3) what are the relative roles of ground and aircraft seeding.

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30+ WINTER SEASONS OF OPERATIONAL CLOUD SEEDING IN UTAH

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Abstract. North American Weather Consultants (NAWC) has conducted operational winter cloud seeding programs in many of the mountainous areas of Utah since 1974. The goal of these programs has been to enhance winter snowpack accumulation in several mountainous target areas throughout the State. Studies have demonstrated that a large majority of the annual runoff in Utah streams and rivers is derived from melting snowpacks, which explains the focus on wintertime seeding. Augmented water supplies are typically used for irrigated agriculture or municipal water supplies. Programs are typically funded at the county level with cost-sharing grants from the Utah Division of Water Resources.

Cloud seeding is accomplished using networks of ground-based, manually operated silver iodide generators located in valley or foothill locations upwind of the intended target mountain barriers. As such, these programs are classified as orographic winter cloud seeding programs. Orographic winter cloud seeding programs are typically categorized as those with the highest level of scientific support based upon capability statements of such organizations as the American Meteorological Society, the World Meteorological Organization, and the Weather Modification Association.

NAWC historical target/control evaluations of these Utah programs based upon high elevation precipitation and snow water content observations indicate a range of apparent increases in target area average precipitation or April 1st snow water content of 3-21%.

The Utah Division of Water Resources conducted an independent assessment of the seeding programs in 2000. That assessment confirmed the NAWC indicated increases in snow water content, and then took the additional step of estimating the increases in annual streamflow resulting from the estimated increases in snow water content. Average annual increases from four seeded areas were estimated to total 249,600 acre-feet. Factoring in the cost of conducting these programs resulted in an estimate of the average cost of the augmented runoff to be $1.02 per acre-foot.

1. BACKGROUND

An early winter cloud seeding program was conducted in southern Utah during the period of 1951 through 1955. The University of Utah Meteorology Department (Hales *et al.*, 1955) and the American Institute of Aerological Research (1955) made evaluations of the effects of this seeding program. The two evaluations resulted in conflicting results, and the program ended.

North American Weather Consultants was contracted by a group of central and southern Utah Counties to initiate a winter cloud seeding program in the mountainous areas of central and southern Utah. This program began in the 1973-74 winter season and continued in the 1974-75 winter season. The initial impetus to initiate this program was drought conditions that impacted southern Utah during the 1972-73 winter season. The participating counties provided funding for the program. The Utah legislature passed a comprehensive weather modification law in 1973 (73-15-3 through 8) (Stauffer, 2001). This legislation authorized the Utah Division of Water Resources to both regulate and develop cloud seeding programs within the State. The Division of Water Resources began cost sharing with the local supporters of the Central/Southern cloud seeding program during the 1975-76 winter season. That program has continued to the present except for a break from 1983-1987, which was an extremely wet period throughout the State of Utah. Figure 1 provides a map of Utah Counties for reference purposes.

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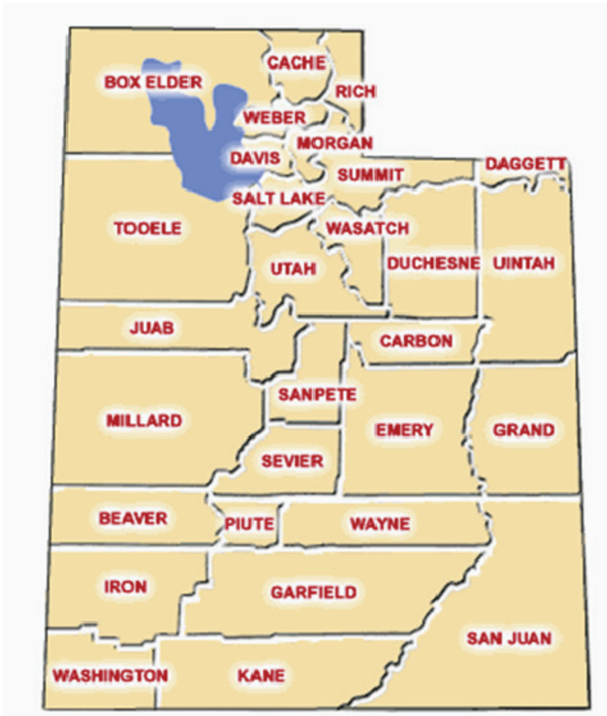
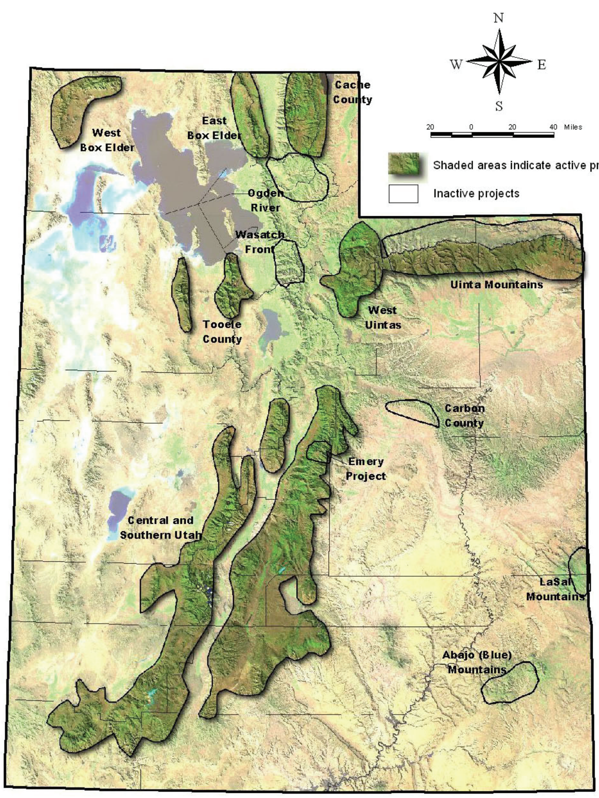


Fig. 1. Utah Counties



Winter Cloud Seeding Project Areas

Fig. 2. Current and Historical Utah Cloud Seeding Program Target Areas

A dry winter, 1987-88, led to an expansion of the seeding activities into northern Utah beginning with the 1988-89 winter season. One program area, encompassing the mountainous areas of two northern Utah Counties (Box Elder and Cache) has been operational most winters from the 1988-89 winter season to the present. Another operational area encompassed the mountainous areas that ring the east side of Salt Lake County. That program operated during the 1987-88 through the 1994-95 winter seasons. Another program was developed to target the Western Uinta Mountains located in northeast Utah. It began in the 1988-89 winter season and has operated during the following winter seasons: 1988-1993, 1994-95, and 2000 to the present. One other program has been developed to target the south slopes of the High Uinta Mountains located in two northeastern Utah counties (Duchesne and Uintah). The program began during the 2000-01 winter season and has continued to the present. There have been other short duration programs conducted in other parts of the State. For example, a program was conducted for a few winter seasons to affect the La Sal Mountains located in southeastern Utah. Figure 2 provides the locations of all historical cloud seeding programs in Utah since 1974.

2. ORGANIZATION

The cloud seeding programs are supported at the county or multi-county level. A non-profit group, Utah Water Resources Development Corporation, was organized to represent a number of the central and southern Utah counties. County Commissions or Water Conservancy Districts represent each of the counties that participate. A commitment is made each fall by these counties or conservancy districts to conduct a program for the approaching winter season.

All of these programs have received cost sharing support from the Utah Division of Water Resources since 1976. The typical portion of the costs funded by the State in recent years has ranged from 37 to 50% of the total program costs. Figure 3 provides the amount of State and local funding support since 1974. Figure 4 provides the participation by Utah counties since the beginning of the winter cloud seeding programs in 1974.

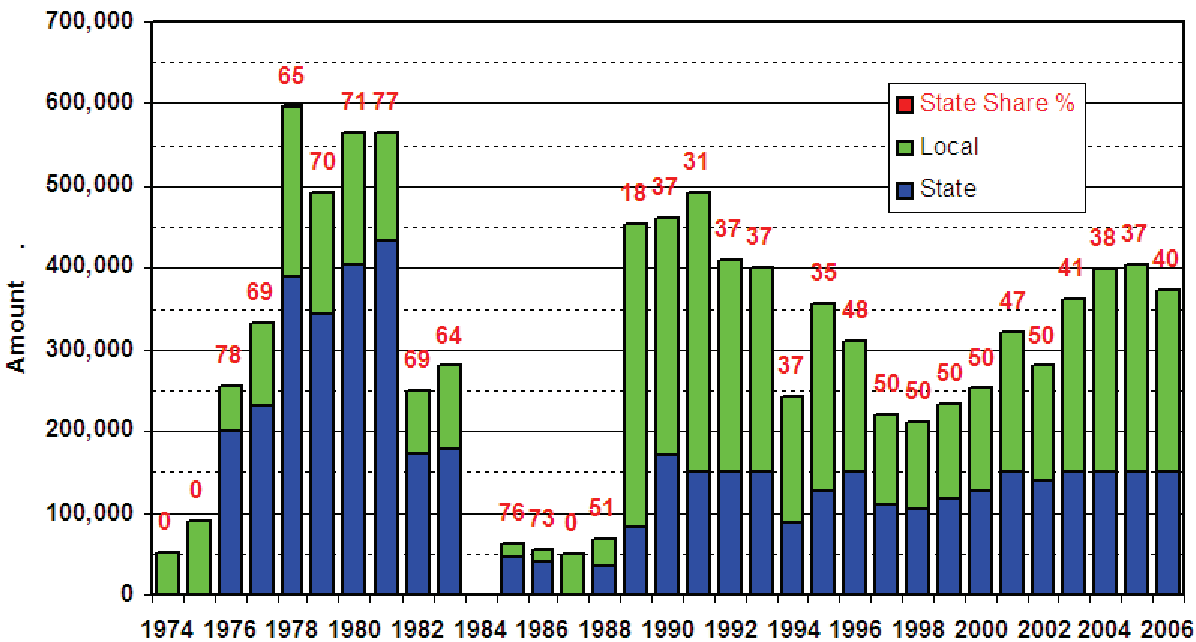


Fig. 3. State and Local Funding of Utah Cloud Seeding Programs, 1974-2006

County	73-74	74-75	75-76	76-77	77-78	78-79	79-80	80-81	81-82	82-83	83-84	84-85	85-86	86-87	87-88	88-89	89-90	90-91	91-92	92-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01	01-02	02-03	03-04	04-05	05-06	06-07
Beaver	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Emery	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Garfield	x	x	x	x	x											x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Iron	x	x	x	x				x	x	x							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Juab	x	x	x	x	x	x	x	x	x	x							x						x	x	x	x	x	x	x	x	x	x	x	x
Millirad	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Piute	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
San Juan			x	x	x	x	x	x	x	x							x	x	x	x														
Sanpete	x	x	x	x	x	x	x	x	x	x					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sevier	x	x	x	x	x	x	x	x	x	x								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Tooele			x	x	x	x	x	x	x	x							x	x	x				x	x	x	x	x	x	x	x	x	x	x	x
Washington	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Wayne	x	x	x	x	x	x	x	x	x	x						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Kane	x	x																																
Grand					x	x	x	x	x	x							x																	
Carbon					x	x	x	x	x	x							x																	
Duchesne				x	x											x														x	x	x	x	x
Uintah				x	x											x														x	x	x	x	x
Daggett				x	x											x																		
Davis				x																														
Weber				x														x	x	x														
Salt Lake				x											x	x	x	x	x	x	x	x	x											
Morgan				x														x	x	x														
Summit				x												x	x	x	x	x		x						x	x	x	x	x	x	x
Utah				x																														
Box Elder																x	x	x	x	x	x	x	x	x			x	x			x	x	x	x
Cache																x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Rich																	x	x																
Wasatch				x												x	x	x	x	x		x						x	x	x	x	x	x	x

Fig. 4. Cloud Seeding Program Participation by Utah Counties by Year

3. SCIENTIFIC BASIS

The Utah programs were originally designed based upon results obtained from research-oriented weather modification programs in the western United States conducted in the 1960's through 1980's (e.g., Climax I and II, the Colorado River Basin Pilot Project, and the Bridger Range Experiment). Designs were updated based upon results obtained from more recent research programs such as the Utah NOAA Atmospheric Modification Program (AMP) conducted from 1990-1998. Research funded under the Utah NOAA AMP program was conducted in two different areas in Utah, the Tushar Mountains located in south central Utah and the Wasatch Plateau located in central Utah (Super, 1999). Unfortunately, there have been no relevant research programs conducted in the United States since the late 1990's that could be used to update the design being used in the conduct of the Utah programs. A new five-year research program is in progress in Wyoming. The results obtained at the conclusion of that five-year program will be examined for possible refinements to the Utah design.

4. CONCEPTUAL MODEL

The basic conceptual model upon which the Utah seeding programs is based can be summarized as follows:

Some winter storms or portions of naturally occurring winter storms that pass over Utah contain/produce supercooled water droplets. Some of these droplets are not converted to ice crystals as they pass over the mountainous areas of Utah. The transport of supercooled water droplets over the crests of these mountain barriers indicates that these storms or portions of storms are inefficient in the production of precipitation. This inefficiency is attributed to the lack of sufficient natural ice nuclei (also called freezing nuclei) to convert these supercooled water droplets to ice crystals which, given the right conditions, could develop into snowflakes that would fall on the mountain barriers. The deficit in natural ice nuclei occurs primarily in the range of cloud temperatures in the 0°C to –15°C range. Introduction of artificially generated silver iodide particles into cloud systems that contain supercooled water droplets in approximately the –5 to –15°C range will artificially nucleate some of the supercooled water droplets. The –5°C temperature is considered the nucleation threshold of silver iodide. The resultant ice crystals then have the potential to grow into snowflakes through vapor deposition and riming processes. If the ice crystals are generated in the right geographic locations, the artificially generated snowflakes will fall onto the targeted mountain barriers, resulting in increases in precipitation above what would have occurred naturally.

Research conducted in Utah and other Intermountain West locations (e.g., Super, 1999; Reynolds, 1988) has verified the presence of supercooled water droplets over or upwind of mountain barrier crests in a large number of winter storm periods. Research in a variety of locations has indicated the background concentrations of ice nuclei are low in the warmer portions of the atmosphere but increase exponentially at colder temperatures. Prior research conducted in cloud chambers and in the atmosphere have demonstrated the ability of silver iodide nuclei to serve as ice nuclei in significant concentrations beginning near the –5°C level and increasing exponentially to the –20 to –25°C level.

5. PROGRAM DESIGN

The program design is based upon the results obtained from previous research programs in which the results are felt to be transferable to Utah and implementation is based on methods that are compatible with the conceptual model. The Utah design is consistent with criteria established by the American Society of Civil Engineers (ASCE, 2004). Seeding relies upon the use of ground based seeding, although some airborne seeding was attempted during a few winter seasons. Key problems encountered with airborne seeding were the relatively high altitudes (approximately 4.3 km, 14,000 feet MSL) aircraft had to be flown based upon FAA approved routes and the difficulty in effectively covering the large Utah target areas even with multiple aircraft. It was theorized that seeding plumes released at these higher altitudes would miss the supercooled liquid water regions that research in Utah and California indicated to be predominantly located over the upwind slopes of mountain barriers at low elevations (perhaps only extending to 0.15 to 0.3 km, 500-1000 feet, above the mountain crests). An analysis of one winter of seeding in southern Utah when there were four seeding aircraft available suggested that a seeding aircraft was upwind of a ground station that was reporting precipitation only about 10% of the time.

5.1 Silver Iodide Generators

The operational winter cloud seeding programs in Utah rely upon the release of silver iodide nuclei from strategically placed, manually operated ground generators located in valley or foothill locations (see Figure 5). The current seeding solution contains a 3% solution of silver iodide complexed with sodium iodide and paradichloro-benzene dissolved in acetone that is burned in a propane flame. The emission rate of silver iodide is approximately 12 grams per hour. Sodium iodide and paradichlorobenzene are added to the seeding solution based upon results from tests performed in the Colorado State University cloud chamber. A paper published by Finnegan (1999) indicates that this formulation is superior to others that produce pure silver iodide particles. The modified particles produced by combustion of the revised formulation act as ice nuclei much more quickly (probably through a condensation-freezing mechanism), and there are somewhat larger numbers of effective nuclei at warmer temperatures (e.g., about -5 to -10°C). Figure 5 provides a photograph of one of these manually operated ground-based generators.

Fig. 5. Ground Based, Manually Operated Silver Iodide Generator

Some would argue for higher elevation, remotely operated ground based generators to be used on these Utah programs. In a strictly technical sense this approach would seem to have merit, based primarily on the concern that effluent released from lower elevation sites might become trapped by low-level atmospheric conditions (e.g., inversions). There are a number of considerations important in this discussion; we will touch on a couple of the more important ones: economics, feasibility, and observations.

North American Weather Consultants, Inc. had 148 manually operated ground generators installed for the 2007-2008 winter season in Utah (for locations refer to Figure 6). The cost of remotely controlled ground generators is approximately $40,000 each without any consideration of installation or maintenance costs. A network of 148 remotely controlled generators that would match the number of NAWC's lower elevation generators would cost approximately $5,920,000 just to cover the acquisition costs. There are additional complications regarding the implementation of a large, remotely controlled generator network. Suitable sites must be found and leases arranged for these locations. Often, these suitable sites will lie on National Forest or Bureau of Land Management lands which may well make the approval for such use problematic. Remote locations may require over the snow or helicopter servicing during the winter, which can be an expensive proposition.

Analyses of observations from the Utah NOAA AMP research program indicated that valley released silver iodide plumes might be trapped in lower elevations 37% of the time based upon an analysis of 46 rawinsonde observations collected during three winter seasons (Super, 1999). The critical missing information in this analysis was how often supercooled cloud droplets were occurring over the mountain barrier during these periods. In other words, the trapping of silver iodide under these conditions may have frequently been in pre-frontal conditions with little seeding potential. This supposition on our part receives strong support from this same Utah research program which indicated from an analysis of 100 hours of data from seven relatively wet storms in

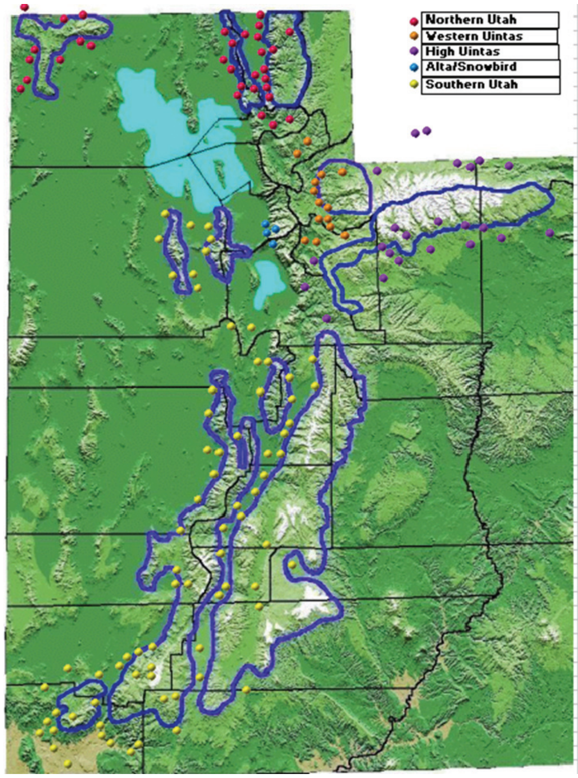


Fig. 6. 2007-2008 Active Target Areas and Generator Locations
(black lines indicate county lines)

which supercooled liquid water was present and several of NAWC's lower elevation generators were being operated that silver iodide was present over the targeted mountain barrier 90% of the time. The following statement was made in this paper: "This is remarkable when it is realized that valley-based inversions are common during winter storms. However, most hours with supercooled liquid water amounts of 0.05mm or greater had weak embedded convection present, which likely assisted vertical silver iodide transport."

We do agree that cloud seeding from remotely controlled ground generators may be more effective under certain conditions, but the cost of implementing a large remotely controlled ground generator network to impact the large target areas in Utah is not practical in the economic sense. The design of programs using remotely controlled ground generators for smaller target areas, in Utah or elsewhere, where the resultant water has significant value (say, greater than several hundred dollars per acre-foot) may be justified. Water in Utah for agricultural purpose is worth perhaps $10-15 per acre-foot and perhaps $50 to a few hundred dollars per acre-foot for municipal water supplies (Utah State Water Plan, 2001). Contrast these values with the value of municipal water in parts of California, which may be worth several hundred dollars to near $1000 per acre-foot (California State Water Plan, 2005).

5.2 Generalized Seeding Criteria

The NAWC has developed some generalized seeding criteria for use by our meteorologists in deciding whether a specific weather event should be considered potentially seedable. These criteria consider two basic questions:

1. Is it likely that supercooled liquid water is present?
2. Can some of the installed generators be used to effectively target this seeding potential?

Table 1 provides these generalized seeding criteria.

Table 1. NAWC Winter Orographic 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 RELEASE POINTS 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 OR COLDER.
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) .

5.3 Suspension Criteria

Cloud seeding suspension criteria have been developed between the Utah Division of Water Resources and NAWC. These criteria are primarily concerned with:

1. Rain-induced winter floods.
2. Excess snowpack accumulations.

The potential for wintertime flooding from rainfall on low elevation snowpack is fairly high in some of the more southern target areas during the late winter/early spring period. Every precaution must be taken to insure accurate forecasting and timely suspension of operations during these potential flooding situations. The objective of suspension under these conditions is to eliminate both the real and/or perceived impact of weather modification when any increase in precipitation has the potential of creating or adding to a flood hazard.

Snowpack begins to accumulate in the mountainous areas of Utah in November and continues through April. The highest average accumulations normally occur from January through March. Excessive snowpack becomes a potential hazard from snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snow pack measurement sites in the State of Utah. This network is known as SNOTEL. SNOTEL observations are routinely available at several times per day. The following set of threshold snow water content criteria, based upon observations from the SNOTEL site observations, has been developed as a guide for possible suspension of operations.

- 200 % of average on January 1st
- 180 % of average on February 1st
- 160 % of average on March 1st
- 150 % of average on April 1st

Possible suspensions are determined on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria.

Streamflow forecasts, precipitation forecasts, height of the freezing level during storms with high precipitation amounts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors which are considered when deciding whether seeding operations should be suspended.

These suspension criteria have been invoked for varying periods over the years. One of the more notable events occurred in early January 2005 when seeding was suspended due to the excess snowpack criteria and the outlook for an impending warm storm pattern. A few days later a warm, heavy rain event impacted southern Utah. This rain on snow event resulted in flooding near St. George, Utah. Rather vivid video showed entire homes falling into the Santa Clara River near St. George due to this flooding. Had excess snowpack criteria not have been exceeded, seeding would still have been suspended on this storm system due to the rain-induced winter floods criteria. Suspensions continued in a large portion of southern Utah during the latter part of the 2005 winter season due to the snowpack suspension criteria.

6. PROGRAM OPERATIONS

An array of information available via the internet is used to make real-time seeding decisions to determine whether to operate and, if so, which generators to activate. Types of data or analysis utilized include: weather satellite visual and infrared photos, surface and upper-air analyses (especially those at the 700 mb level), rawinsonde skew-t plots, surface observations, video cameras, weather radar displays, weather forecasts and weather forecast model output, and NRCS SNOTEL observations (temperature, precipitation). The project meteorologist considers this information to determine if the generalized seeding criteria are met and that no suspension criteria are met, and then determines which generators are to be operated, primarily as a function of low-level winds that determine the targeting of the seeding effects. Different generators may be operated as the winds evolve with the passage of the storm through the target area.

7. PROGRAM EVALUATIONS

Evaluations of the effects of operational cloud seeding programs are rather challenging. Since program sponsors wish to derive the maximum potential benefits from a cloud seeding program, operations are focused on seeding every potentially seedable event. Thus, operational program sponsors are typically unwilling to employ some form of randomization of seeding decisions, which could assist in evaluating the effects of seeding. Essentially these sponsors have sufficiently high confidence that cloud seeding can produce positive effects to warrant moving ahead with an operational program. They generally do not see the necessity of conducting a program to "prove" that the cloud seeding is "working" as would be one of the primary goals in the conduct of a research program.

This is not to say that sponsors of operational cloud seeding programs are not desirous of having a reasonable indication that the program is working, only that the indication need not be as rigorous as that from a research program where a 5% or better significance level attached to any indicated results is required. Sponsors of operational programs are accustomed to dealing with much more uncertainty than this on almost a daily basis.

What types of evaluations can then potentially be applied to operational programs? There are three basic categories of possible evaluation techniques:

1. Statistical Approaches
2. Physical Approaches
3. Modeling Approaches

7.1 Statistical Approaches

One commonly employed statistical technique is the "target" and "control" comparison. This technique is one described by Dr. Arnett Dennis in his book entitled "Weather Modification by Cloud Seeding" (1980). This technique is based on selection of a variable that would be affected by seeding (e.g., precipitation, snowpack or streamflow). Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites should be selected in an area meteorologically similar to the target, but one that would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period as that of the proposed or previous seeding.

The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression) that estimates the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded periods to estimate what the target area precipitation would have been without seeding, based on that observed in the control area(s). This allows a comparison between the predicted target area natural precipitation and that which actually occurred during the seeded period, to determine if there are any differences potentially caused by cloud seeding activities. This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are in terms of elevation and topography, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

It should be understood that the measurement of precipitation in mountainous areas is extremely difficult for a variety of well-documented reasons (e.g. gage bridging due to snow, wind causing reductions in gage catch, and wind causing drifting that may impact snow pillows). Some of the uncertainty in these evaluations is reduced since the same measurement techniques are being used in both the target and control locations and target and control are located at similar elevations, but the basic values of the amounts of precipitation and snow water contents in mountainous areas can be only considered approximations of the true values.

7.2 Physical Approaches

The results from a statistical evaluation, such as a target/control analysis, can be strengthened through supporting physical studies, as recommended in a response to a National Research Council Report (2003) by the Weather Modification Association (WMA, 2004). One technique that has been employed by the Desert Research Institute (DRI) in the assessment of the effectiveness of at least the targeting of seeding material, if not the magnitude of seeding effects, in winter programs is that of analyzing samples of snow from the target area during seeded periods to determine whether silver is present in projects that use silver iodide as the seeding agent (Warburton *et al.,* 1995 and 1996). The following contains a summary of this technique.

Occasionally, samples of newly fallen snow are collected for an analysis of silver content. This is an evaluation technique encountered more frequently in research projects due to the expense involved. Snow samples collected prior to cloud seeding or from non-seeded storms are analyzed to establish the natural background silver content (if measurable with available analysis techniques) for comparison with snow samples taken from seeded storms. This technique is only valid for projects using silver iodide as the cloud seeding agent, although some analysis techniques are applicable to other possible cloud seeding agents as well (e.g, lead iodide). Several analytical techniques have been developed for use in such analyses, including neutron activation, proton excitation, and flameless atomic absorption. An example of an analysis of the downwind transport of silver iodide outside of primary target areas is given by (Warburton 1974). Warburton *et al.,* 1996 demonstrates how trace chemical assessment techniques strengthen traditional target and control precipitation analyses.

7.3 Modeling Approaches

Sophisticated atmospheric computer models have the potential to estimate the amounts of natural precipitation for short intervals (e.g., 6 hours, 12 hours) in mountainous areas. If these predictions are validated as accurate, they could be compared with the amount of precipitation that fell during seeded periods within the intended target area to determine the impact of seeding on target area precipitation. An attempt to verify the output of the RAMS computer model developed at Colorado State University versus observed and predicted modified precipitation due to cloud seeding was made for the 2003-2004 winter season in central Colorado, with rather mixed results. This work was done under the Colorado Weather Damage Mitigation Program. Some of the conclusions from the final report (Colorado Water Conservation Board, 2005) were:

- When model simulated precipitation was compared to measured 24-hour precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88.
- Comparison of model-predicted precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals.

The report listed the following possible reasons for the lack of differences between seed and control precipitation:

- The model-predicted seedability could be real; however, because of the model over-prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby underestimating seedability.
- A low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent in the model.

In spite of the rather mixed results, Colorado State University is to be commended since this is apparently the first time that any modeling group has attempted a real-time winter season time scale evaluation with a model.

The Wyoming Water Development Commission is using a high-resolution model known as WRF for guidance and evaluation of their currently active five-year pilot cloud seeding research project. To the best of our understanding, it has not been demonstrated whether simulations from this model are sufficiently accurate to discern seeding effects from natural precipitation, or to accurately predict the transport and dispersion of seeding material in complex terrain.

7.4 NAWC Evaluations

North American Weather Consultants has frequently utilized the first of these approaches (statistical) in evaluating the apparent effects of our operational programs. Two types of data are normally used in developing these equations relating target and control areas: (1) some accumulation of monthly precipitation data representative of the seeded period (e.g., December through March), and (2) April 1st snow water content. The agency that has collected the most useful data is the NRCS (formerly the Soil Conservation Service).

The NAWC has typically selected potential target and control sites close to the inception of each operational program. In the process, data have been obtained from possible target and control stations to develop the regression equations. Some quality control procedures were then employed to determine whether some sites should be dropped from consideration due to missing data or relocation of stations, causing a change in the observations. Control sites were selected to avoid including sites that may have been impacted either historically or currently by other cloud seeding programs. Data were spatially averaged for the potential target and control sites and linear regression equations were developed from these data. The goal was to find the mix of possible control sites that provide the highest correlation with the target sites. The regression equations developed using these procedures were then used in subsequent seeded seasons without change except in two situations. First, if a station was discontinued we developed a new regression equation, which often consisted of the addition of just one alternate site to replace the location that had been discontinued. Second, we recalculated all of the April 1st snow water content equations in 2004 to utilize NRCS-estimated data that attempted to normalize data collected by two different means. Monthly snow course measurements were the norm before the advent of the NRCS SNOTEL program. SNOTEL site installations began in the west in the early 1980's. SNOTEL sites were typically established at prior snow course sites. Normally a ten-year overlap period using both types of observations was obtained. The NRCS then used this overlap period to provide estimates of what the prior snowcourse data would have been had the SNOTEL measurements been available historically.

As an example of the target/control evaluation technique, Figure 7 provides the locations of target and control stations that have been used for a number of years in the evaluations of the Central/Southern Utah program. The linear regression equation relating the target and control areas for this program is: $y = 1.66x - 2.79$ where y is the predicted average target area December through March precipitation and x is the control station average December through March precipitation. The r^2 value for this regression equation is 0.92. Table 2 summarizes the indications of seeding effects on the Central/Southern program and other on-going, longer-term Utah seeding programs. An earlier evaluation of the Central/Southern program December through March precipitation indicated the same apparent 14% increase as now shown in Table 2 (Griffith *et al.*, 1991). Figure 2 provides the locations of the various target areas. The range of indicated seeding effects from Table 2 for precipitation is 3-21% and 3-17% for April 1st snow water content.

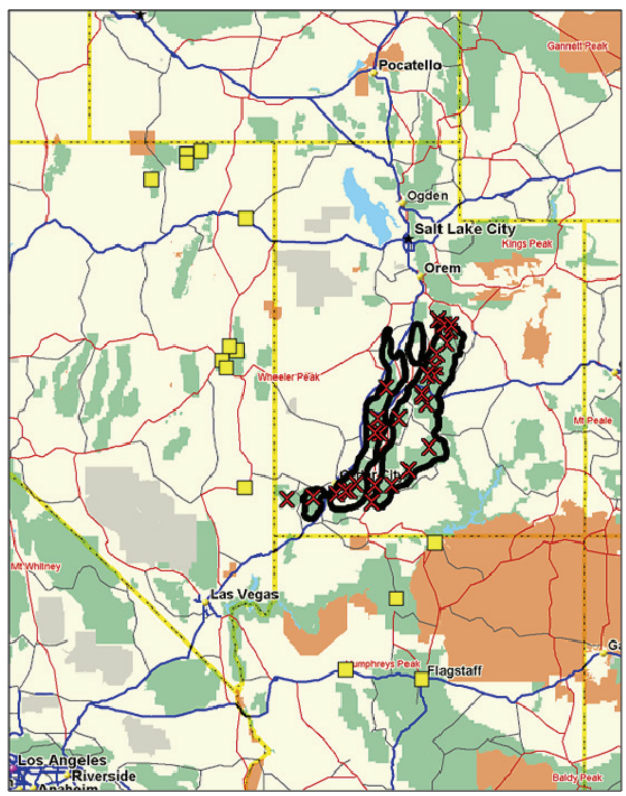


Fig. 7. Precipitation Target Sites (red x's) and Control sites (yellow squares), *Central/Southern Utah Program*

Table 2. Summary of Historical Target/Control Evaluations of Various Target Areas in Utah

Target Area	Number of Seasons	Precip. r^2 value	Precip. Inc. %	Precip. Difference cm/inches	Snow Water r^2 Value	Snow Water Inc.%	Snow Water Difference cm/inches
NW Box Elder	15	----	---	---	.83	+17	6.6/2.6
E. Box Elder/ Cache	19	.81	+17	5.3/2.1	.83	+10	5.6/2.2
E. Tooele	23	.74	+21	4.6/1.8	.68	+16	5.1/2.0
Western Uintas	13	.75	+5	1.5/0.6	.77	+5	2.0/0.8
South Slope High Uintas	5	.89	+3	1.0/0.4	.65	+3	1.0/0.4
Central/ Southern	29	.92	+14	3.6/1.4	.87	+4*	1.5/0.6

* NAWC's annual project report for the 2003-2004 winter season indicated that a change (reduction) in indicated results was primarily due to our decision to use NRCS adjusted snow water content data in this evaluation. The precipitation evaluations are considered more representative for this target area.

Lower percentages in the Uinta Mountains program may be due to possible impacts of air pollution from the Salt Lake City/Provo complex. Pioneering work by Dr. Rosenfeld (2000) demonstrated that winter orographic precipitation downwind of major metropolitan areas in Israel and the western United States has been declining. The NAWC conducted a study similar to those conducted by Rosenfeld to determine if similar impacts were occurring downwind of the Salt Lake City/Provo complex (Griffith *et al.,* 2005). The 2005 study did indicate a decline in winter precipitation in the western end of the Uinta Mountains, located east of Salt Lake City. Figure 8 provides a plot from the study, demonstrating the decline at the Trial Lake NRCS SNOTEL site (located approximately 80km east of Salt Lake City). That site sits on a divide between two cloud

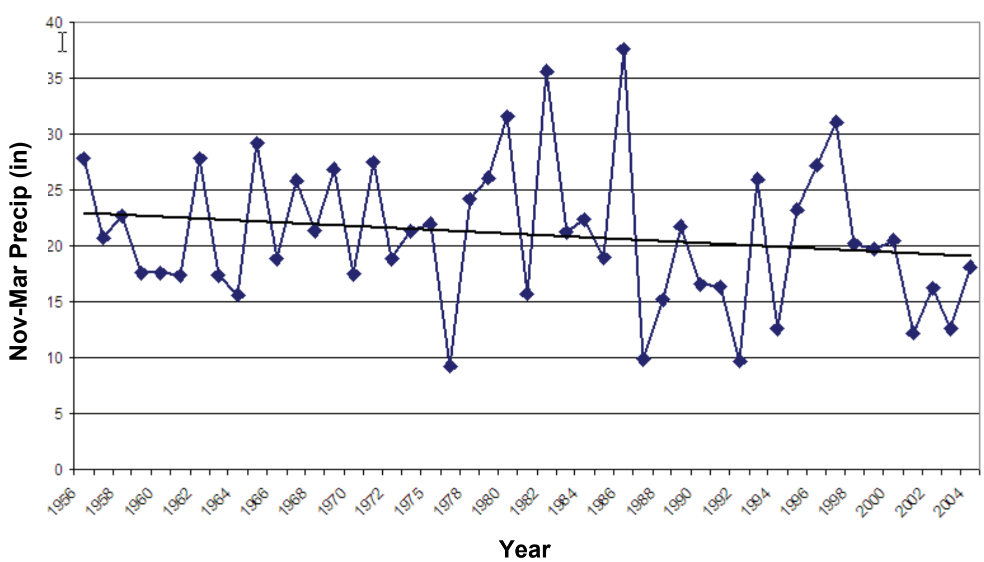


Fig. 8. Plot of November – March Precipitation at Trial Lake, Utah

seeding programs (western Uintas and south slope of the High Uintas). The study documented how this decline in precipitation could reduce the indicated effectiveness of the seeding programs in this area. Other more rural areas of the State were also analyzed. Declines in winter mountainous precipitation in the more rural areas were not observed. It was therefore concluded that the estimated seeding effects in other areas of the State would not be impacted similarly to those downwind of Salt Lake City.

Figure 9 provides an example of the apparent consistency in positive seeding effects for December through March precipitation in the Central/Southern program. This figure provides a plot of the ratios of the actual precipitation divided by the predicted precipitation for the historical, not-seeded seasons (18) and for the seeded seasons (30). This figure indicates that only 2 of the 30 seeded seasons had ratios less than 1.0. In other words, 28 out of 30 seasons have indications of a positive seeding effect.

A recurring question regarding cloud seeding programs is whether the cloud seeding program is reducing precipitation downwind of the intended target area. This question is sometimes referred to as whether you are "Robbing Peter to pay Paul." The NAWC attempted to at least partially answer this question by analyzing precipitation downwind of one of the Utah winter programs. The program selected for analyses was the Central/Southern Utah program since it is the region with the longest period of cloud seeding activities within the state. The same target/control regression technique applied to an evaluation of the Central/Southern target area was used to examine predicted versus observed December through March precipitation in areas downwind of the intended target area. This downwind area included precipitation observation stations located in southeastern Utah and southwestern Colorado. Figure 10, taken from a paper summarizing this analysis (Solak *et al.,* 2003), provides ratios of observed to predicted precipitation during 25 seeded seasons. Ratios greater than 1 (which are widespread in the figure) suggest increases in precipitation in this downwind area, contrary to the often stated concern that precipitation would be less in downwind locations. Table 3, taken from the referenced paper, demonstrates the apparent seeding effects in the downwind area as a function of distance from the intended target area. This table indicates that apparently positive seeding effects extend downwind for approximately 100 miles. It should be noted that even though the ratios found in Figure 10 suggest apparent increases in downwind precipitation on the order of an average of 10-15%, the actual amounts of increased precipitation are relatively low since southeastern Utah is an area that normally receives low amounts of precipitation.

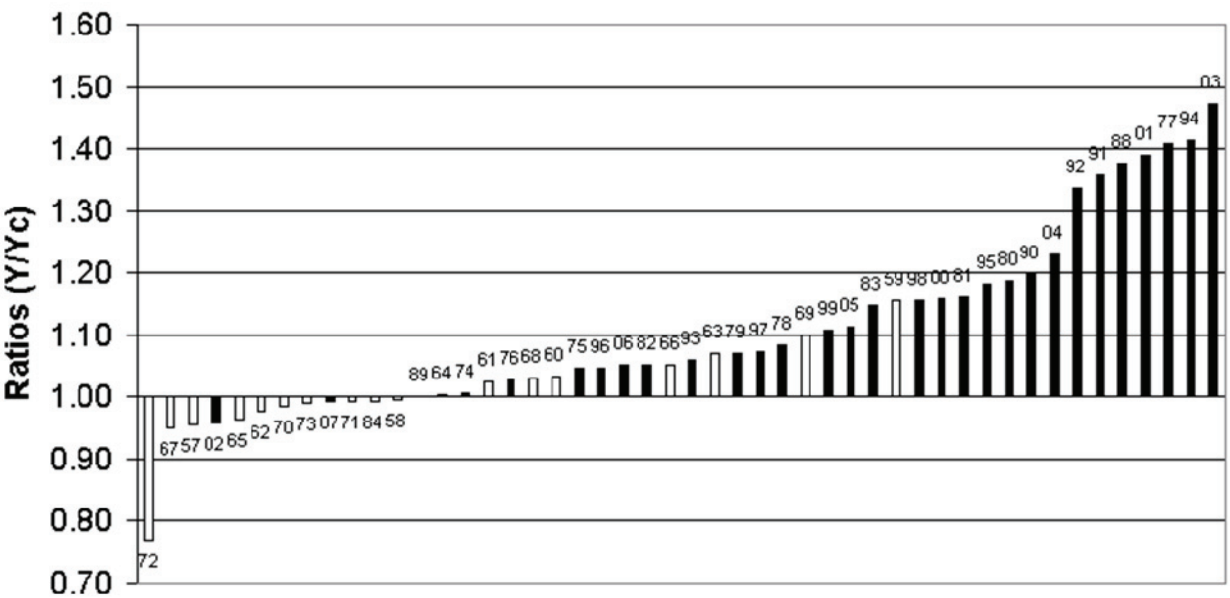


Fig. 9. Plot of December- March Actual Precipitation Divided by Predicted Precipitation (Open bars are historical seasons, solid bars are seeded seasons)

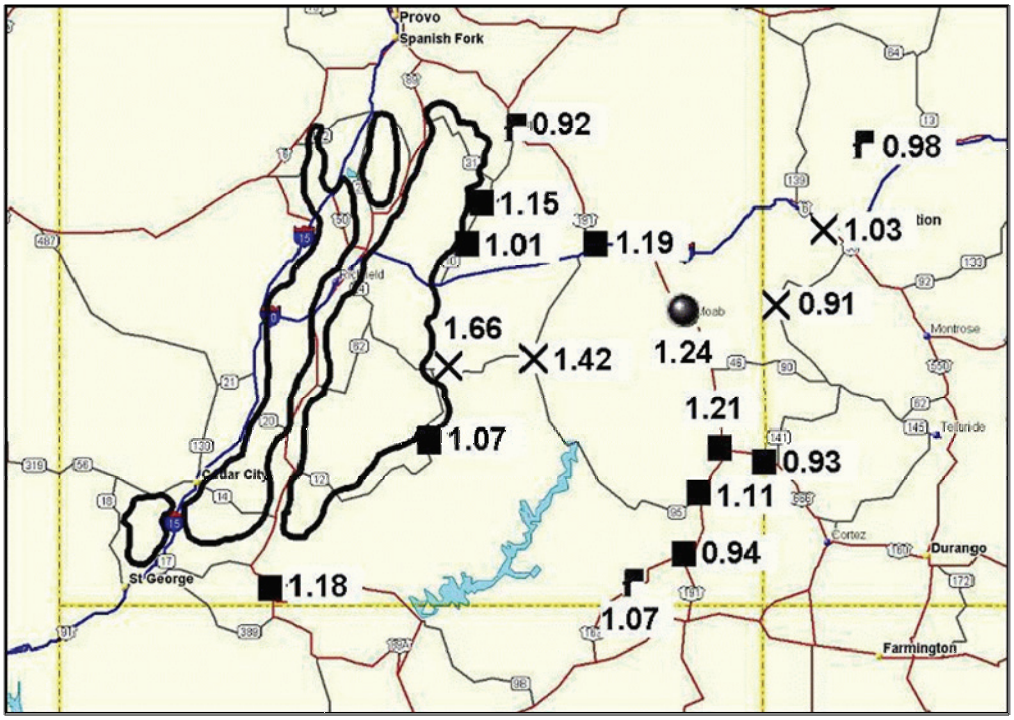


Fig. 10. Average Site Ratios of Actual Over Predicted November – March Precipitation (Central/Southern Target Area Outlined in Black)

Table 3. Results of Grouping Precipitation Ratio Data into 50 mile (80km)-wide

Distance From Target	No. of Sites	Ratio 0bs/Pred	Precip. Diff. cm/in.	Correlation (r)
Seeding Target	27	1.14	3.53/1.39	0.97
0-50 miles (0-80km)	7	1.14	0.96/0.38	0.91
50-100 miles (80-160km)	3	1.17	0.86/0.34	0.82
100-150 miles (160-240km)	7	1.03	0.25/0.10	0.91

8. ESTIMATED INCREASES IN STREAMFLOW

Dr. Norman Stauffer of the Utah Division of Water Resources reported on some work he had conducted in an attempt to estimate increases in streamflow that could result from estimates of increases in April 1st snow water content attributed to cloud seeding (Stauffer and Williams, 2000). The procedures used to make these estimates were as follows:

1. Estimate the average annual runoff from the areas that are being seeded (target areas).
2. Estimate the increase in April 1st snow water content attributed to seeding.
3. Determine the relationship (equations) between annual runoff and April 1st snow water content for major gaged rivers and streams in the target areas.
4. Estimate the increase in average annual runoff due to cloud seeding, based on 1, 2, and 3 above.

The Stauffer study focused on four target areas that were active during the 1999-2000 winter season. The areas were: Western Box Elder County, Eastern Box Elder and Cache Counties, Eastern Tooele County, and Central/Southern Utah. Refer to Figure 2 for the locations of these four areas. This analysis estimated the average annual increase in streamflow from these seeded areas to be 249,600 acre-feet. The resulting cost of producing the estimated additional water (for WY 2000) was $1.02 per acre-foot.

9. SUMMARY

Winter cloud seeding programs have been conducted in Utah during the early 1950's and most years from 1974 to the present. In recent years most of the mountainous areas in Utah have been targeted. These programs are designed to increase higher elevation snowpacks, the goal being to enhance spring and summer runoff that benefits a variety of users. The cost of these programs has been shared between the State of Utah, Division of Water Resources and local entities consisting of Counties or Water Conservancy Districts.

The NAWC utilized an historical target/control regression analysis technique to estimate the effects of cloud seeding in the various target areas in Utah. These analyses suggest average seasonal effects ranging from 3-21%.

A Utah Division of Water Resources study, completed in 2000, independently validated NAWC estimates of increases in April 1st snow water contents for four different target areas in the State then estimated average annual increases in streamflow based upon these estimated increases in snow water contents. This study estimated an average annual increase of 249,600 acre-feet attributed to the cloud seeding program at an estimated cost of $1.02 per acre-foot.

Acknowledgements. A number of directors, engineers and meteorologists with the Utah Division of Water Resources have supported these cloud seeding programs since 1976. These include Todd Adams, Larry Anderson, Lloyd Austin, David Cole, Paul Gillette, Robert King, Daniel Lawrence, Ann Merrill, Clark Ogden, Barry Saunders, Norman Stauffer, Dennis Strong, Paul Summers, Clint Warby and Kevin Williams.

Alan Frandsen, Bryce Jackson and Robert Nielson have served as President of the Utah Water Resources Development Corporation, a non-profit organization that has represented a number of the central and southern Utah Counties that have sponsored the longest operational cloud seeding program in the State of Utah.

A number of water conservancy district directors and county officials have supported these programs in their areas of interest including Randy Crozier, Keith Denos, Voneene Jorgensen, Lynn Lemon, Frank Nishigushi, David Pitcher and Scott Ruppe.

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SIX HOUR ANALYSES OF THE BRIDGER RANGE RANDOMIZED WINTER OROGRAPHIC CLOUD SEEDING EXPERIMENT

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Abstract. The Bridger Range winter orographic cloud seeding experiment was conducted during the early 1970s. Published post hoc exploratory statistical analyses used 24 h experimental units. However, 6 h precipitation observations exist which have not been previously tested with non-parametric statistics. They should be better represented by available 6 h partitioning data. This experiment produced high quality precipitation data and was one of few with associated physical studies adding credibility to statistical suggestions. Use of control gauge data substantially reduces natural variance in target precipitation. Two independent statistical approaches were applied to the 6 h dataset. Results strongly suggest that seeding was effective when conditions were conducive to orographic cloud formation with near-crestline temperatures sufficiently cold for adequate nucleation with silver iodide. Specifically, the null hypothesis (seeding had no effect) was rejected with one-tailed P-values near 0.001 for the single partition of seeded zone temperatures less than the median. That subpopulation was further reduced by about 50% with the requirement of rawinsonde observations, launched only when clouds existed near or below crestline elevations. Similar very low P-values resulted from this dual partition with much reduced sample size, and for an even smaller population with 700 mb dew point depressions less than their median value. These results are physically reasonable. Partitioning by cloud-top temperature and cloud thickness suggested that seeding could be effective even when thick clouds with cold tops were present. It is stressed that these results are based on post hoc exploratory analyses so they can only be viewed as suggestive and not conclusive proof. Suggestions are given for future randomized winter orographic experimentation.

1. INTRODUCTION

Cloud seeding for mountain snowpack augmentation has been operationally applied for six decades but the field remains controversial (National Research Council 2003; Boe *et al*. 2004; Huggins 2009). The 1998 American Meteorological Society Policy Statement (AMS 1998) may be considered cautiously optimistic about future potential but does not indicate a proven technology. The Statement recommended, “Whereas a statistical evaluation is required to establish that a significant change resulted from a given seeding activity, it must be accompanied by a physical evaluation to confirm that the statistically observed change was due to the seeding.”

The Bridger Range Experiment (BRE), conducted in southwestern Montana during the early 1970s, is described in detail by Super and Heimbach (1983), hereafter SH83. Review of the peer-reviewed literature indicates that no more recent randomized winter orographic experiment (RWOE) has met the above AMS statement recommendation as well as the BRE (Reynolds 1988; Huggins 2009). Given this state of affairs and continued lack of research funding, the authors decided to statistically analyze 6 h BRE data in an attempt to provide further insight beyond the 24 h analyses of SH83.

It is well established that randomized experiments are required to provide credible statistical inferences. Dennis (1980), Gabriel (2000), Super and Heimbach (2003) and others show that statistical results from historical target-control analyses or other non-randomized approaches can have serious potential sources of bias.

Credible short-term physical evidence of seeding effects over mountains was reported by Hobbs (1975b) with radar detection shown by Hobbs *et al*. (1981). Several more recent physical experiments which demonstrated seeding-caused snowfall were summarized by Huggins (2009). A detailed case study including apparent detection by radar was presented Huggins (2007). Such brief (~ 1h) experiments provide convincing evidence that some types of seeding can enhance snowfall under some conditions. However, they cannot provide credible estimates of *seasonal* changes. Therefore, randomized experimentation is emphasized herein.

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This paper presents post-hoc exploratory analyses of 6 h periods from the BRE, the shortest interval for which routine precipitation and rawinsonde (rawin) observations were collected. It also addresses whether resulting statistically significant results are physically credible. Statistical analyses of the original 24 h experimental units (EUs) were presented by SH83 along with considerable supporting physical evidence including AgI plume tracking, airflow studies and silver-in-snow analyses. Physical evidence obtained in the same area after the BRE was reported by Heimbach and Super (1988) and Super and Heimbach (1988).

Six-hour intervals should be better represented by associated partitioning data than was the case for the original 24 h EUs. A similar idea was proposed by Mielke (1995) who stated with respect to the Climax Experiments, "At the time the analyses were accomplished, it seemed important to have analysis and experimental units be identical (i.e., 24-h periods). I now feel this notion of identical units may have hindered improved analyses. A suggestion by L. O. Grant to imbed eight 3-h analysis units on each 24-h experimental unit would yield a vast improvement since the atmospheric conditions are more uniform during a 3-h period than a 24-h period."

It is fundamental that certain conditions be satisfied for winter orographic cloud seeding with AgI to succeed. Supercooled liquid water (SLW) cloud, the necessary "raw material" for seeding to be effective, must exist in the spatial zone intended for treatment, upwind of and perhaps over the target area. The AgI must frequently be transported and widely dispersed into that zone in sufficiently high *effective* concentrations to produce meaningful snowfall rates. Silver iodide effectiveness is highly temperature dependent especially above about -10°C. Moreover, the rate of AgI nucleation varies significantly depending upon the specific formulation of the seeding solution and SLW cloud conditions (Chai *et al.* 1993; DeMott *et al*. 1995)

The BRE did not have instrumentation for direct measurements of SLW. Ice crystal observations were occasionally made on the target area which frequently showed riming. Later icing rate sensor observations atop the Main Ridge (MRO on Fig. 1) during the months of January, February and March 1985 detected SLW during 9, 8 and 7% of all hours with data, respectively, with a median Main Ridge temperature (MRT) of -8.5°C (Super and Heimbach 1988). An operational seeding project attempted to increase snowfall on a ski area immediately to the lee of the Main Ridge during the 1986-87 winter (Heimbach and Super 1988). The northern BRE seeding site, just upwind of the ski area (see Fig. 1), was reactivated for this purpose. Additional icing rate sensor observations detected SLW during 7% of all hours during that dry winter with locally record low snowpack. Heimbach and Super (1988) summarized microphysical observations from that crestline location and stated, "Photography showed that during periods of significant snowfall rates, there was riming of the crystals, indicating that even with seeding, not all the available supercooled liquid water was being processed

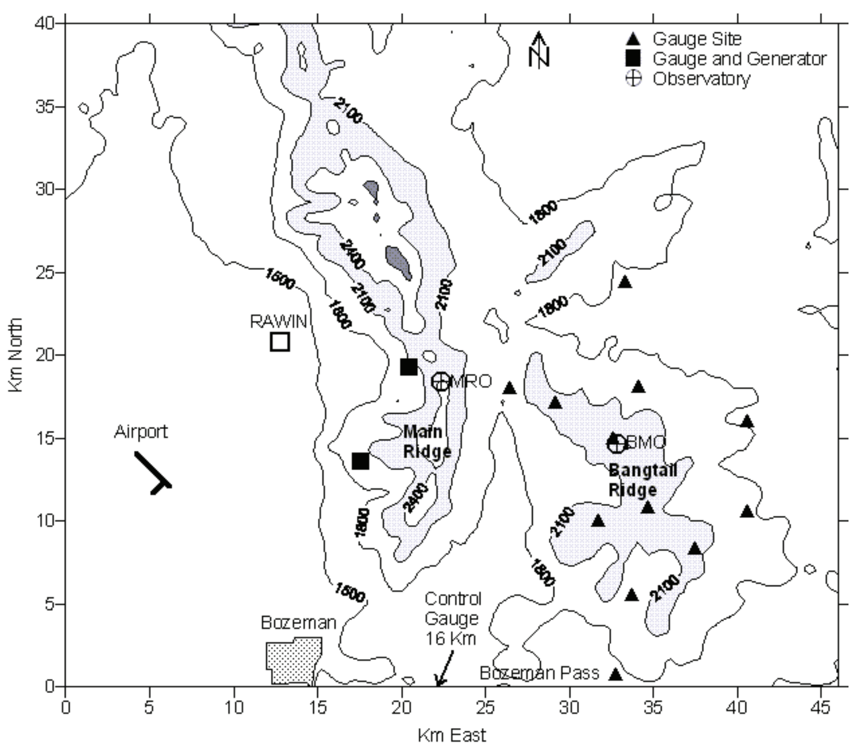

Fig. 1. Map of Bridger Range experimental area showing Main Ridge and Bangtail Ridge, location of gauges, seeding sites and facilities. Contours are meters MSL.

and some accretional growth was helping the precipitation process."

Observations of SLW cloud have been made over several mountain ranges since the BRE. Studies summarized by Huggins (2009) show that a common feature has been predominance of SLW over windward slopes and crests due to orographic lift with most SLW found <1 km above mountain crests. The SLW decreases further downwind due to conversion to precipitation and/or evaporation in descending air (Hobbs 1975a; Huggins 1995). Huggins (2009) noted that the overall conclusion of each study of SLW availability was that significant cloud seeding potential existed in winter storms over mountainous terrain if seeding could be properly applied. Availability of SLW cloud does not appear to be a limitation for seeding effectiveness over the course of many storms (Super and Huggins 1993; Super 1994). But measurements have consistently documented considerable SLW variability over periods of a few hours or less (Rauber *et al*. 1986; Boe and Super 1986; Super 1999).

2. OVERVIEW OF BRIDGER RANGE EXPERIMENTATION

Bridger Range experimentation was accomplished by Montana State University (MSU) researchers under the Bureau of Reclamation's Project Skywater. The MSU research and some contemporary projects were partially motivated by the apparent success of ongoing experimentation at Climax, Colorado. Funding for the BRE and other western state field research projects was unexpectedly terminated during 1972 when resources were concentrated on a large Reclamation "pilot project."

The randomized BRE was designed to test whether seeding could enhance the seasonal snowfall on a broad secondary downwind ridge by seeding clouds over the somewhat higher primary upwind ridge (see Fig. 1). The upwind Main Ridge and downwind Bangtail Ridge Target Area (BRTA) both have a generally north-south axis and are separated by a narrow mountain valley. Both ridges can be expected to produce near-terrain SLW cloud. Seeded crystals formed over the Main Ridge may encounter a secondary SLW zone upwind and over the target ridge, potentially enhancing the snow production process. Embedded gravity waves may sometimes have an important role in SLW production (Heimbach and Hall 1994; Reinking *et al.* 2000). The BRE design was unusual in that most experiments (and operational projects) have attempted to seed a single downwind barrier.

Available resources did not permit testing over a larger area and only two seeding sites were used. But the limited target area was sufficient to test the seeding hypothesis discussed in SH83. The BRE had two top field priorities: (a) insuring that orographically-enhanced (hereafter simply orographic) clouds over the upwind Main Ridge were actually seeded on a routine basis with AgI ice nuclei (IN) and, (b) observing melted snow water equivalent (SWE) as accurately as practical over and downwind of the expected target area. Super *et al*. (1972; 1974) produced a comprehensive two-part final report, hereafter Part I and Part II, which discussed Bridger Range experimentation in detail including design, field equipment and operations and several auxiliary studies such as radar observations, airflow and AgI plume tracking investigations and attempts to directly detect seeding effects. Printed or microfiche copies of Part I and Part II are available from the National Technical Informational Service. Part II contains listings of all data used in this paper, available in ASCII format upon request of either author.

Although the BRE was discussed by SH83, details of seeding operations and snowfall observation are presented herein because of their importance in conducting a successful RWOE and to have this paper stand alone. Large variations exist among various programs in the application of "cloud seeding" due to different release methods, rates, seeding agents and their transport and dispersion, and variations in topography. The resulting uncertainties, and those related to the difficulties in accurately measuring snowfall in mountainous terrain, are often not fully appreciated.

The BRE expended considerable effort and resources to insure seeding reliability by using improved silver iodide (AgI) generators monitored at 3 to 4.5 h intervals day and night. Field technicians climbed about 600 m vertically from the upwind valley to man the remote high elevation sites for 3-day shifts. All major supplies and equipment had to be lifted in by helicopter. Use of foothill generator sites was abandoned after initial testing during the 1968-69 winter. Wind and temperature profile observations showed a high frequency of persistent stable conditions below about midway up the west (windward) slope of the Main Ridge (Super *et al*. 1970) so seeding sites were later established about 2/3 of the way up that slope (Fig. 1). Commercially-obtained generators were used during preliminary testing but proved unsatisfactory. Improved "MSU Skyfire" generators were locally-fabricated in time for the BRE. Unlike the commercial generators, the MSU units permitted fine spatial adjustment of the hypodermic needle used to inject seeding solution into the propane jet permitting complete solution atomization upon entering the burner chamber. Wind shields were added to minimize flameouts although typical seeding site winds proved to be light. At the time the MSU generators were among the highest yield ground-based units tested by the Colorado State University Cloud Simulation Laboratory, particularly at warmer temperatures (Garvey 1975).

Considerable documentation exists that high elevation Bridger Range generators provided routine transport and dispersion of seeding plumes over the Main Ridge and downwind BRTA (Super 1974; Part II; SH83). Numerous aircraft missions documented AgI plumes over both the Main Ridge and BRTA during visual flight rules conditions, usually with a mid-level and/or high overcast to reduce solar heating. Acoustical counter sampling at the Bangtail Mountain Observatory (BMO) frequently detected AgI (Part I). In-cloud aircraft sampling during a January 1985 NSF-sponsored experiment detected AgI plumes over the BRTA during all six missions as well as co-located seeded ice crystals during the three missions with detectable SLW (Super and Heimbach 1988). Further evidence that seeding plumes frequently passed over the intended target was provided by seasonal snowpack samples which showed silver concentrations well above background over the BRTA for both BRE winters (SH83). Those observations combined with seasonal SWE data suggested that much of the silver emitted during snowfall ended up in the BRTA snowpack. Similar sampling for a 1986-87 winter operational seeding project demonstrated high silver levels on the ski area target just to the lee of the Main Ridge and near the previous BMO target location (Heimbach and Super 1988). Later sampling of plumes released from similar high elevation sites on the Grand Mesa of Colorado and Wasatch Plateau of Utah also showed routine transport and dispersion over the barriers (Huggins 2009).

Snow water equivalent was measured by a dense network of Universal (Belfort) weighing gauges then in common use by the National Weather Service (NWS) and other agencies. Initial testing with the standard 8-inch diameter gauge orifices revealed they were unsuitable for snowfall observations in protected clearings because of frequent partial or total snow bridging over the orifices, known as "capping." Replacement gauge shells were locally manufactured for the BRE with 11.3-inch diameter orifices providing twice the standard orifice area. The larger orifices eliminated capping and doubled the resolution from 0.01 to 0.005 inch SWE. This facilitated reading Universal gauge charts to the nearest 0.01 inch, the NWS standard, as did extraction at 6 h intervals rather than hourly as sometimes done by the NWS. The BRE practice was more realistic and less prone to false readings given the high frequency of hours with very light snowfall in the Rocky Mountains. For example, all nonseeded 6 h periods with rawin data and a westerly wind component at 700 mb were selected for examination of a representative target gauge, near the BMO shown on Fig. 1. Of the 138 periods with detectable SWE, 23% had 0.01 inch, the smallest value extracted from the gauge charts. The median 6 h amount was only 0.04 inches. Careful consideration should obviously be given to gauge characteristics and protection from wind-caused undercatch when measuring such low snowfall rates.

Gauge mechanisms were carefully calibrated with standard weight sets prior to each field season. After field installation each calibration was again checked and mechanisms were adjusted when outside of specifications. Prior to end-of-season gauge removal, a final weight set check was made. These revealed that all units stayed in calibration during each winter season. Gauge chart clocks were also carefully adjusted prior to field use. Start and stop times were marked on each 24 h rotation chart during approximately weekly service visits and clocks were soon replaced if needed. All gauges were operated in the field for at least a month prior to each season and the large majority of problems were resolved during those shakedown periods. These procedures minimized missing data.

Numerous publications over many decades have addressed the difficulties of obtaining accurate measurements of SWE, especially in the presence of wind. Brooks (1941) stated, "It has been generally recognized for more than a century that the more precipitation gages are exposed to the wind the less they catch; and that the catch of snow in an unshielded gage gives a very unreliable indication of the precipitation." He also pointed out the importance of using Alter wind shields to improve catch. All BRE gauges used Alter shields. But a 5 m s^{-1} wind speed will reduce the catch of even an Alter-shielded Universal gauge by 50% (Goodison 1978) with unshielded gauges having significantly poorer performances. Wilson (1954) reported results of a five winter comprehensive study of mountain snowfall measurements. He analyzed the catch of several gauges against snow course measurements and concluded that small protected clearings provided the best gauge sites. Brown and Peck (1962) compared seasonal gauge catch with snow course observations in the mountains of Utah and provided a subjective scheme for selecting sites with limited wind effects. Small clearings in conifer forest, which they called "overprotected," were sought out for BRE gauges. The 3 control gauges and 10 of 12 BRTA gauges were in such clearings where wind speed was minimal. For example, average wind speeds were 0.6 m s^{-1} in the BMO gauge clearing during days with snowfall. Agreement was excellent between that gauge and two nearby snowboards with a correlation coefficient of 0.99 for 54 daily SWE totals during the 1969-70 winter (Part I). The linear regression equation with the gauge as the dependent variable had a slope of 1.05 and intercept of -0.02 inch indicating minor undercatch by the gauge.

Two BRTA target gauges were on the lee slope below conifer forest but were shielded from wind as much as practical by terrain and brush. Gauges further downwind in the broad and windy Shields Valley are not analyzed in this paper. They had much greater exposure to wind effects due to lack of forest cover, and received substantially lower precipitation amounts due to the "rain shadow" effect. Valley gauges had a high frequency of 6 h periods with no precipitation detected. Use of 6 h totals becomes problematic under such conditions.

Ideally, collection and reduction of SWE data would have been contracted out to an independent agency to minimize human bias. This was not considered practical during conduct of the modestly-funded BRE for both operational and economical reasons. Data from each gauge chart was reduced twice by separate teams of MSU data clerks (work study students) who had no knowledge of seeded periods. Any differences were resolved by the data clerk supervisor. Approximately 96% of all data were complete. The remaining 4% were estimated by the first author as discussed by SH83, using all available data plotted on contour maps by data clerks. The maps were coded with no date or seeding information on them. It is believed that human bias was eliminated by these procedures.

Analyses of BRE 24 h EUs and associated studies are described in detail by SH83. Seeding during the 1969-70 winter, just prior to the BRE, used a single high elevation site with a different AgI generator and seeding solution. Only one control gauge south of the Bridger Range was operated that winter (Fig. 1) which provided a shakedown period for field procedures and equipment. A second high elevation seeding site was selected prior to the BRE, 6.4 km crosswind from the southern site (Fig. 1). Both generator sites were near 2150 m (all elevations MSL) where generators burned 3% by weight AgI in a solution of acetone complexed by NH_4I. The resulting rather pure AgI particles are known to nucleate by contact-freezing, a relatively slow process (DeMott *et al*. 1995) unless generators were within sufficiently cold SLW cloud enabling rapid forced condensation-freezing nucleation (Finnegan and Pitter 1988). BRE generators were often in cloud but the frequency of in-cloud seeding is unknown. Control gauges were installed in forest clearings near each seeding sites prior to the 1970-71 winter to supplement the original control gauge in mountains south of the Bridger Range (Fig. 1).

The intended target was the BRTA about 5 to 20 km east of the Main Ridge crestline (Fig. 1). The latter had an average elevation of 2600 m. Rawins launched about 10 km west of the Main Ridge crest indicated that 700 mb (about 3050 m) winds should have transported seeding plumes toward the BRTA in the large majority of cases. Aircraft tracking over both the Main Ridge and BRTA revealed AgI plumes were seldom transported higher than 3050 m so 700 mb wind directions approximate plume top transport but not necessarily lower plume portions.

Twenty-four hour EUs beginning at local noon were declared by the simple criterion of a special NWS precipitation probability forecast ≥ 30% for the upwind valley airport (Fig. 1). The main statistical suggestions of the 24 h analyses were that AgI seeding was effective when the MRT was less than about -9°C, and that operational seeding would likely increase target area seasonal snowfall by approximately 15%.

3. STATISTICAL TECHNIQUES

The natural variation of precipitation in RWOEs can be several orders of magnitude larger than the seeding signal requiring a large number of EUs to find probabilities (P-values) small enough to reject the null hypothesis that seeding is ineffective. The statistical convention used in this paper follows. A Type I error, i.e., erroneously rejecting the null hypothesis and claiming a seeded effect when none exists, is expressed as a probability level and is symbolized by α. An α-level of 0.05 has traditionally been used in weather modification and is termed *significance level* if expressed as a percentage. The P-value is the specific probability of a Type I error derived by a statistical test that is compared to the specified α-level to judge the null hypothesis. A Type II statistical error, which is the incorrect acceptance of a false null hypothesis, has its probability symbolized by β. Heimbach and Super (1996) used BRE 24 h SWE data show that the power of a test, i.e., the probability of not having a Type II error, (1-β), is difficult to quantify if response to seeding is variable among EUs. That seems likely given SLW variability and other factors.

The large natural variability of SWE, the primary response variable, makes it essential to use covariates that are strongly correlated with target snowfalls. Otherwise, the number of EUs and, therefore, seasons needed to detect a treatment effect can be prohibitive while the risk of undetected Type I errors remains. The best covariates are upwind and crosswind control gauges (Gabriel 2000). Properly sited control gauges appropriate for snowfall measurement can remove half or more of the natural SWE variance, improving the efficiency of detecting a treatment effect.

Early analyses of Bridger Range data in Parts I and II used control gauge observations only for detection of “bad draws.” These were partitions for which the randomization procedure failed to provide similar distributions of *natural* SWE amounts for seeded and nonseeded EU populations as shown by comparison of control gauge amounts. Wilcoxon testing was applied to individual gauges. If P-values were low at control gauges as well as target gauges the particular partition was considered flawed by a bad draw. The authors of Part II concluded that, “It was found that portions of the total observed ranges for several of these parameters (used to partition) were subject to a bad draw. Therefore, nothing could be determined regarding seeding effects in these instances.”

Evidence that the entire BRE had a bad draw is provided by SWE observations from the three available control gauges, all at mountain locations (Fig. 1). The BRE produced 185 experimental days, 90 seeded and 95 nonseeded. But even with this large population the randomization scheme produced dissimilar seeded and nonseeded distributions of natural SWE amounts. The control gauges’ nonseeded mean and median daily amounts were 0.116 and 0.050 inch, respectively, while corresponding seeded values were 0.095 and 0.037 inch. Thus, the mean (median) SWE amounts on nonseeded days were 22% (35%) larger because of the bad draw, greater than typical claims of seeding-enhanced SWE. The bad draw was even more pronounced for the 44 seeded and 56 nonseeded days with MRT ≤ -9.0°C, suggested by SH83 as most affected by seeding. Control gauge nonseeded mean and median daily amounts were 0.118 and 0.067 inch, respectively, compared with seeded values of 0.084 and 0.043 inch. Without reference to control gauges or other covariates unaffected by seeding, analyses of target SWE could have produced a Type I error incorrectly suggesting that seeding decreased snowfall. Even with larger populations, Climax I and Climax II were each influenced by bad draws in the opposite sense with seeded days receiving more natural snowfall than nonseeded days (Mielke *et al*. 1981).

While the authors realized a bad draw had occurred, the techniques for incorporating control gauge data were not available until Mielke *et al*. (1981). That paper described a nonparametric inference technique which adjusted for such errors and applied it to the Climax Experiments. In this method, control gauge observations are used to predict target precipitation and the seed and nonseed residuals (departures) from the regression are input to one or more statistical inference tests. SH83 applied the techniques of Mielke *et al*. (1981; 1982) to the BRE 24 h data and found strong suggestions of a seeding effect with small P-values for partitions that were physically reasonable.

The high variability of meteorological conditions within the 24 h EUs warrants subdividing into 6 h periods, the shortest intervals for which BRE observations are available. The independence of 6 h periods was conservatively tested by calculating the lag correlation for all 339 available adjoining 6 h pairs of nonseeded target area precipitation, that is, each pair was from a continuous 12 h block. Calculations were based on averages of the 12 BRTA gauges, called Zone 1 by SH83. With 54 pairs of 0, 0 precipitation included (excluded), variance explained was only 8.5% (6.4%). These values suggest that the 6 h periods are not entirely independent; however, the amount of dependence is small. Conversely, the natural variance explained by the 6 h control data in the analyses herein is substantial, far overshadowing that explained by autocorrelation. Consequently, the 6 h SWE amounts can be considered independent for practical purposes, producing at most minor errors in probability estimation. Such errors have little consequence here as post-hoc analyses are being applied to an exploratory experiment so tests of statistical significance do not have the level of certainty provided by *a priori* rigorously controlled confirmatory experiment (Dennis 1980; Gabriel 2000). Given that caveat, some latitude is appropriate for exploratory analyses. Accordingly, adjectives like "suggestive" and "strongly suggestive" are applied to statistical results herein as the term "proof" would be inappropriate.

To form a basis of comparison, portions of the 6 h analyses described in this paper mimic those done earlier by SH83 to 24 h data by applying the well-known Wilcoxon non-parametric test. Another statistical technique is applied based on rerandomization of ratios (described below). Since there is no evidence that BRE seeding decreased precipitation (Super 1986 and this paper), only 1-tailed inferences are used.

3.1. Applying the Wilcoxon Test

The Wilcoxon test is also known as the Mann-Whitney test because ranks to the first power are summed. Residuals were calculated from the median regression line which minimizes the sum of absolute deviations and is of the form $\hat{T} = b\overline{C}$ where $\hat{T}$ is the predicted average of the 12 BRTA gauges, and $\overline{C}$ is the average of the three control gauges. The fit was forced through the origin to minimize the influences of periods when either the control or target SWE, but not both, were zero (Mielke *et al.* 1981). The seeded and nonseeded target-control pairs were pooled to define the median fit following Mielke *et al*. (1982) and SH83. The seeded ranks of the rank-ordered residuals were summed to give a test statistic (Mann and Whitney 1947). The test statistic's null distribution is approximately normal if N_S and N_{NS} are each 8 or more where "S" refers to seeded and "NS" to nonseeded. This was not an issue for the current paper because all reported partitions met this requirement. Handling tied residuals was described by Mielke (1967).

3.2. Rerandomized Ratio Test (RRT)

The simplest ratios are the mean (median) single ratio which is the mean (median) seeded divided by the mean (median) nonseeded SWE. Control data are not involved in single ratios. Therefore, inferences drawn from the single ratio can be misleading because there is no compensation for the inherent large natural variance. There are several double ratios which involve control data. These include the mean double ratio (MDR) and median double ratio (MedDR).

$$\text{MDR} = \frac{\text{(Mean Target Single Ratio)}}{\text{(Mean Control Single Ratio)}}$$

$$= \frac{\overline{T}_S}{\overline{C}_S} \Big/ \frac{\overline{T}_{NS}}{\overline{C}_{NS}} . \qquad (1)$$

The MedDR is Eq. (1) with "Median" substituted for "Mean".

The MedDR is affected less by outlying values than the MDR, but is unstable if there are a large number of zero precipitation accumulations, and undefined if half or more of the T_{NS}, C_S, and/or C_{NS} SWEs are zero. Only the MDR is presented herein as it has been widely applied and provides an estimate of the proportional increase due to seeding.

The MDR can have its null distribution derived analytically through a logarithmic transformation to produce an approximately normal distribution provided >100 EUs are in the sample (Gabriel 1999). This size criterion could not be met for several of the partitions in the current paper so rerandomization was applied. Gabriel (2000) discusses the importance of using rerandomization to provide valid statistical inferences without transformation or parameterization (Mielke *et al*. 1981).

The rerandomization process pooled the observed 6 h S and NS periods, and then the seeded status of each was randomly reassigned, keeping the number of S and NS the same as the actual sample. A rerandomized MDR (hereafter, MDR_j) was derived from this synthesized sample. This process was repeated to derive a total of 10,000 rerandomized double ratios, $MDR_{j=1,10000}$, for each partitioning. These were ordered to produce a null distribution.

A P-value was derived by comparing the sample MDR to the null distribution. For example, if 500 out of 10,000 MDR_js were ≥ the sample MDR, then the 1-tailed P-value was 0.05. P-values were interpolated when the sample MDR was between two ordered MDR_js.

The same rerandomized null distribution is used to derive confidence intervals. The null distribution is transformed into MDR_j' by centering it on the sample's MDR,

$$MDR'_j = MDR_j + (MDR - \overline{MDR_j}). \qquad (2)$$

The lower bound for the (1-α) = 0.95 1-tailed confidence interval is the point bounding the lowest 0.05 X 10,000 MDR_j's.

$MDR'_{j=0.05*10000}$ ≤ 1-tailed 0.95 confidence interval. (3)

The upper 1-tailed limit is unbounded. For the 2-tailed confidence interval (not applied in the current paper), the 0.95 bounds are defined by (α/2) and (1-α /2) corresponding to the value of the ordered points in the null distribution,

$MDR'_{j=0.025*10000}$ ≤ 2-tailed 0.95 confidence interval ≤ $MDR'_{j=0.975*10000}$. (4)

Statistical significance can also be inferred through the application of confidence intervals. If the confidence interval includes MDR = 1 or 0% proportional increase due to seeding, i.e., the null effect, then the null hypothesis cannot be rejected at the specified α-level (Gabriel 2002). All 1-tailed confidence intervals reported in this paper use the 0.95 level meaning there are 95 chances out of 100 that the indicated MDR lower limit was achieved or exceeded.

The RRT and Wilcoxon test provide different approaches for statistical examination of the same data sets. Differences in the results can be expected because the Wilcoxon deals with linear ranks, whereas the rerandomization of target-control pairs involves the magnitude of the double ratios. The RRT is sensitive to outliers because of their influence on the magnitude of the MDR. Because the Wilcoxon test deals with ranks, not magnitudes of EUs, it reduces the distortion caused by outliers, i.e., is "resistant" (Wilks 2006). Low RRT P-values smaller than Wilcoxon P-values from the same dataset suggest the seeding signal may be dominated by periods with larger precipitation amounts.

4. STATISTICAL ANALYSES OF 6 H PERIODS

The 6 h analyses are limited to the 12 BRTA gauges and the 3 available control gauges (Fig. 1), all operated specifically for the BRE. The limited non-BRE gauges which existed in the general area are inadequate for the analyses herein. All but a few were at cooperative stations which provided only daily precipitation totals. The few with hourly data were operated in open valley locations, some without wind shields, and consequently subject to serious undercatch under windy conditions and numerous 6 h periods without detectable precipitation.

The 185 daily EUs produced a sample of 740 6 h periods. With the exception of Sec. 4.7, all analysis results are based on the Wilcoxon and RRT tests discussed in Sec. 3.

4.1. Partitioning by Main Ridge Temperature

The MRT distribution was used to subdivide the 6 h periods into halves, thirds, quarters and fifths shown in Table 1. As done by SH83, fractions are consistently used to partition populations throughout this paper in order to reduce bias by eliminating the possibility of "cherry-picking" results for more favorable (lower) P-values. One-tailed P-values less than or equal to α = 0.10 are in bold type in all tables to follow.

The Wilcoxon test provided a relatively low P-value of 0.06 for the entire population while the RRT had a somewhat suggestive value of 0.11. Both tests provided extremely low P-values of 0.001 or less for the colder half of the population with MRT ≤ -9.3°C, the 6 h median value. These results suggest only about one chance in a thousand of falsely rejecting the null hypothesis that seeding is ineffective in the colder temperature range. For comparison, corresponding values were 0.01 for both the Wilcoxon and the multiresponse permutation procedures tests applied to 24 h EUs in the SH83 study.

The presumed seeding signal in Table 1 is associated with colder temperatures, less than about -9 or -10°C. It is impractical to precisely estimate the higher MRT boundary for seeding effectiveness because each tested sample is made up of a range of temperatures. Low P-values are seen to exist for the coldest third, and two coldest quarters and fifths of the entire population. There is no indication of colder temperatures limiting seeding effectiveness. Only 4% of all periods had a MRT less than -20°C.

Table 1. Main Ridge temperature partitions by fraction of all 6 h periods.
MDR is the mean double ratio.

MRT (°C)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
-35.6 ~ +5.8	360 / 380	0.75	**0.06**	0.11	1.15	0.98 ~ ∞
Halves						
≥-9.2	191 / 178	0.74	0.72	0.63	0.95	0.69 ~ ∞
≤ -9.3	169 / 202	0.78	**0.001**	**< 0.001**	1.54	1.33 ~ ∞
Thirds						
≥ -6.8	117 / 129	0.68	0.84	0.61	0.93	0.56~ ∞
-11.5 ~ -6.9	135 / 114	0.86	0.57	0.35	1.05	0.86 ~ ∞
≤ -11.6	108 / 137	0.79	**< 0.001**	**< 0.001**	1.91	1.66 ~ ∞
Quartiles						
≥ -5.6	91 / 94	0.69	0.66	0.66	0.88	0.45~ ∞
-9.2 ~ -5.7	100 / 84	0.87	0.77	0.36	1.06	0.83 ~ ∞
-13.2 ~ -9.3	88 / 98	0.77	**0.09**	**0.03**	1.44	1.15 ~ ∞
≤-13.3	81 / 104	0.79	**0.003**	**0.003**	1.70	1.41 ~ ∞
Quintiles						
≥ -4.7	71 / 75	0.60	0.60	0.49	1.00	0.45 ~ ∞
-7.8 ~ -4.8	69 / 76	0.81	0.88	0.70	0.88	0.55 ~ ∞
-10.6 ~ -7.9	88 / 66	0.86	0.18	0.17	1.16	0.92 ~ ∞
-14.2 ~ -10.7	70 / 80	0.73	**0.09**	**0.005**	1.84	1.49 ~ ∞
≤-14.3	62 / 83	0.77	**0.006**	**0.03**	1.44	1.14 ~ ∞

4.2. Partitioning by Control Gauge Detection of SWE

Table 2 documents the effect of requiring detectable 6 h SWE at none, one, two or all three control gauges, done to address concerns about the numerous periods without detectable precipitation at one or more control sites. Results are shown only for periods with MRT ≤ -9.3°C as no seeding signal was suggested for the warmer periods. Only partitions with both P-values ≤ 0.10 will be listed in this and the remaining tables with the single exception of Table 7.

A strong seeding signal is suggested by low P-values in each row of Table 2. The tendency for the P-values to increase with reduction in sample size would be expected. The decrease in correlation coefficient (R) with more control gauges receiving snowfall is related to the reduction of T=C=0 SWE cases. Table 2 suggests that seeding was effective no matter how many control gauges detected snowfall, if any.

4.3. Partitioning by Cloud Presence and 700 mb Westerly Wind Component

Rawins were released at the midpoint of each 6 h period only when broken to overcast cloud cover was observed over the Main Ridge with bases estimated below 3050 m. A total of 364 rawins provided usable data during the BRE with some observations missing due to equipment and other problems. All but 9 rawins had 700 mb wind observations. Directions (not speed) were estimated for those nine by reference to other data including synoptic charts. Estimates ranged from 235 to 320 deg (all directions referenced to true north), all typical of storm periods.

Table 3 presents statistical results for 700 mb wind direction partitions with and without the 6% of periods with an easterly wind component. The top row shows analyses using all 364 periods with rawins. Simply partitioning by having a rawin available, meaning cloud criteria were met, provided P-values of 0.03 and 0.05, respectively, with a mean double ratio of 1.24. This is an impressive result, given the strong temperature dependence of seeding effectiveness previously discussed. However, P-values for warmer periods with MRT ≥ -9.2°C were insignificant at 0.62 and 0.43, respectively, compared with ≤ 0.001 values for colder periods shown in Table 3. The suggested seeding signal is clearly associated with colder temperatures.

Results including or excluding easterly winds are very similar as might be expected since only 22 (16) periods had an easterly component for all temperatures (colder temperatures). It is physically implausible that easterly winds would transport AgI toward the BRTA so such periods are not considered in analyses to follow. The median 700 mb wind direction is 279° for periods between 180 and 360° (actual observations were from 192 ~ 359°).

The colder periods have smaller P-values, larger MDRs and tightened confidence intervals, compared with inclusion of all temperatures. These results would be expected with the previously demonstrated strong temperature dependence.

Partitioning was done with the 700 mb wind speed component normal to the north-south Main Ridge. This parameter might be expected to be correlated with SLW production. All 331 periods with rawin speed data and a westerly wind component were subdivided into halves, thirds and quarters. There was no indication of a seeding effect for any partition indicating the normal wind speed component had no detectable relationship with seeding.

4.4. Partitioning by Cloud-top Temperature and Thickness

A common opinion is that the most seedable orographic clouds are shallow with relatively warm tops, perhaps no colder than about -20°C, while deep cold-topped clouds are naturally efficient in converting SLW to snowfall. As a result, the latter are considered to have negligible seeding potential. Grant and Elliott (1974) presented the concept of a cloud-top "temperature window," arguing that seeding can increase precipitation when tops range from about -10 to -24°C. Analyses were based on simple seed/noseed precipitation ratios compared with estimated cloud-top temperatures from seven randomized experiments. Diverse cloud environments and seeding approaches were included ranging from all-season airborne seeding of convective and mixed clouds in Australia to ground pyrotechnic flare seeding of convective bands over California's low coastal ranges to ground-based AgI generator seeding over the Rocky Mountains. The authors of this paper believe there is good

Table 2. Statistical results with different numbers of control gauges detecting SWE and MRT ≤ -9.3°C.

Control Gauges w / SWE	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
0 ~ 3	169 / 202	0.78	**0.001**	**<0.001**	1.54	1.33 ~ ∞
1 ~ 3	92 / 125	0.74	**0.006**	**0.003**	1.46	1.25 ~ ∞
2 ~ 3	61 / 96	0.72	**0.004**	**0.006**	1.41	1.20 ~ ∞
3	35 / 63	0.70	**0.02**	**0.02**	1.35	1.11 ~ ∞

Table 3. Statistical results for noted 700 mb wind direction and MRT ranges. Each period had rawin data implying clouds existed over the Main Ridge.

Wind Dir. Range (°)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Temperatures						
1 ~ 360	181 / 183	0.71	**0.03**	**0.05**	1.24	1.04 ~ ∞
180 ~ 360	169 / 173	0.70	**0.02**	**0.04**	1.28	1.07 ~ ∞
MRT ≤ -9.3°C						
1 ~ 360	88 / 102	0.74	**0.001**	**<0.001**	1.62	1.38 ~ ∞
180 ~ 360	79 / 95	0.74	**0.002**	**<0.001**	1.64	1.39 ~ ∞

reason to doubt the validity of the Grant and Elliott (1974) concept given the broad range of cloud types and seeding methods they included, the lack of controls in the analyses approach, and later published challenges to the Climax I, II and Wolf Creek Pass experiments.

Evidence certainly exists that shallow, warm-topped orographic clouds can have abundant SLW. Examples include Rauber and Grant (1986; 1987). But their 1986 article also presents conceptual models of deep stratiform and convective cloud phases having significant SLW over and upwind of mountain crest-lines, in agreement with Cooper and Marwitz (1980).

Instrumentation to routinely monitor SLW was not available to the BRE although several physical experiments discussed in Part I showed frequent rimed ice crystals on the target area. An icing rate sensor and microphysical observations of ice crystals showed evidence of SLW atop the Bridger Range Main Ridge during a later operational program (Heimbach and Super 1988). Measurements of SLW since development of the microwave radiometer have indicated abundant and frequent SLW during major storm passages at other Rocky Mountain locations. For example, two winters of microwave radiometer-sensing of SLW over the Grand Mesa of western Colorado were summarized by Boe and Super (1986). They noted that SLW production was usually linked to the passage of short-wave troughs or low-pressure centers, and that substantial SLW was often present even during periods with significant natural snowfall.

Super and Huggins (1993) presented SLW flux estimates, based on microwave radiometer and wind observations, and compared them with winter precipitation observations from four mountain ranges in Arizona, Colorado and Utah. None of the data sets supported the concept that large precipitation-producing storms are highly efficient in converting SLW flux to snowfall. The reverse was indicated; i.e., storms with larger precipitation totals tended to have greater SLW flux. This indication suggests that large SLW flux-producing storms may be efficient in snow production during some phases and inefficient during other phases. A case study of a moderate-sized Utah storm supported this conceptual picture.

Huggins (2009) described some important characteristics of SLW in winter storms. He noted that SLW is present at some stage of nearly every winter storm but it exhibits considerable temporal and spatial variability. A number of SLW periods may be interspersed with other periods with none during a given storm passage.

SH83 discussed use of radiosonde temperature-dew point differences for estimation of cloud base and top temperature and cloud thickness. The estimates were approximations at best, especially during 1970-71 winter daylight periods, because of improperly-shielded and ducted relative humidity sensors then in use (Hill 1980). The BRE began using improved humidity ducts as soon as they became available near the beginning of the final 1971-72 winter (exact date unknown). Partitioning of 24 h EUs by cloud-top temperature by SH83 found little if any correlation between suggested seeding effects and cloud-top temperatures. They concluded, "This (these results) does not support the notion that cold cloud tops, with presumed naturally high ice crystal concentrations, reduces or eliminates seeding potential near Bridger Range mountain-top levels."

The influence of cloud-top temperature on seedability was revisited for the present 6 h analysis and cloud thickness was also considered. Original radiosonde data were discarded long ago and the only observations available to SH83 and this paper are listed in Part II. They are pressure level height, temperature, dew point, wind speed and direction at 800, 700, 600 and 500 mb, respectively; estimated cloud base and top temperature and cloud thickness (last three without reference to altitude or pressure level), 800 mb equivalent potential temperature and the lapse rate between the mean seeding site elevation and 700 mb.

All available 6 h periods with westerly flow and estimates of cloud-top temperature (CTT) and cloud thickness (CTH) were partitioned into halves, thirds and quarters. Results are shown in Tables 4 and 5. Since CTT and CTH are inversely related, with a correlation coefficient of 0.76 for the 315 periods with CTT available, results are similar. A total of 342 periods exist for CTH because 27 cases had no detectable cloud by the criterion used, i.e., estimated thickness was zero.

Tables 4 and 5 show P-values from 0.02 to 0.05 for the entire populations with MDRs of 1.25 and 1.28. These results could be anticipated from Table 3 since populations are the same or very similar. Other P-values near or below 0.05 by both tests were found for the coldest and thickest clouds in each partitioning with MDRs in the range 1.40 to 1.57. The single exception was the 2nd quartile for cloud thickness, from 1068 ~ 1970 m, which has P-values of 0.04 and 0.08 with a MDR of 1.64, suggesting relatively shallow clouds may be seedable. But the results also suggest that seeding was most effective during passage of deep, cold-topped cloud systems. Such results may be unanticipated as cold cloud regions can be expected to naturally nucleate ice crystals. Possible explanations may be that (1) natural crystals formed at high levels did not settle down to the near-terrain zone of orographically-produced SLW before being transported beyond the BRTA and/or (2) natural ice crystal production rates were insufficient to convert all the low-level SLW to snowfall.

Table 4. Cloud-top temperature partitions by fraction of all 315 six hour periods with a westerly wind component at 700 mb. Only partitions with both P-values ≤ 0.10 are listed.

Cloud Temperature (°C)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
-52.3 ~ -0.2	156 / 159	0.70	**0.05**	**0.05**	1.25	1.03 ~ ∞
Halves – (none qualified)						
Thirds						
-52.3 ~ -31.2	51 / 54	0.77	**0.06**	**0.02**	1.41	1.15 ~ ∞
Quartiles						
-52.3 ~ -35.2	36 / 42	0.79	**0.009**	**0.006**	1.53	1.26 ~ ∞

Table 5. Like Table 4 except cloud thickness partitions by fraction of all 342 six hour periods.

Cloud Thickness (m)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
1 ~ 5689	79 / 95	0.74	**0.002**	**<.001**	1.64	1.39 ~ ∞
Halves						
1 ~ 2119	40 / 47	0.77	**0.03**	**0.06**	1.52	1.13 ~ ∞
2120 ~ 5689	39 / 48	0.69	**0.02**	**0.005**	1.66	1.37 ~ ∞
Thirds						
1 ~ 1399	28 / 30	0.83	**0.02**	**0.02**	1.78	1.36 ~ ∞
2960 ~ 5689	23 / 35	0.71	**0.03**	**0.002**	1.94	1.59 ~ ∞
Quartiles						
1 ~ 1129	21 / 22	0.85	**0.01**	**0.05**	1.79	1.30 ~ ∞
3565 ~ 5689	15 / 29	0.74	**0.05**	**0.01**	1.91	1.53 ~ ∞

The results of partitioning by cloud thickness and MRT ≤ -9.3°C are presented in Table 6. Low P-values are apparent for all periods and for both the thinner and thicker halves, all with substantial MDRs. Examination of the thirds and quartiles (not shown) revealed insignificant P-values (inconclusive results) for the mid-thickness periods, possibly related to the unusually low target-control correlation coefficients for the middle third and two center quartiles. They ranged only between 0.42 and 0.56, well below more typical values ≥ 0.7. Table 6 suggests seeding was effective, if MRT was sufficiently cold, for both the thinner and thicker cloud periods. The results in this section do not support the view that seeding is necessarily ineffective if thick clouds with cold tops are present.

4.5. Partitioning by Dew point Depression

The 700 mb dew point depression might be expected to provide a better indication of cloud presence upwind of the Bridger Range than just the existence of rawin data. For typical winds and ascent rates rawins would reach the 700 mb level about 8 km upwind of the Main Ridge crestline. Cloud boundaries were estimated by a dew point depression of 3°C or less at 700 mb (Part II, p. 40). The accuracy of that approach is uncertain. However, it can be generally stated that smaller dew point depressions have a higher likelihood of cloud existing over the Bridger Range.

For this analysis the median dew point depression of 2.7°C for the population of 342 rawins (easterly flow excluded) was used in Table 7. Results applying higher MRTs and greater dew point depressions are not listed because none were significant. Table 7 shows that partitioning only by the smaller half of dew point depressions results in P-values of 0.01 and 0.03 and a respectable MDR of 1.39, whatever the MRT. Although P-values are similar in the two upper rows, the sample size is halved in the second row suggesting the seeding signal was concentrated within periods with smaller dew point depressions. Additional partitioning by the colder MRTs reduces the P-values by an order of magnitude, increases the MDR to 1.90, and narrows the confidence interval to 1.58 ~ ∞. This dual partition strongly suggests a seeding effect primarily in the colder periods (as previously shown) but also associated with small dew point depressions indicative of moist air and/or clouds extending several kilometers upwind of the mountains where rawin sampling was done. This particular partition is likely the best approximation of the existence of cold SLW cloud over the Bridger Range that can be provided by existing observations. The low P-values of 0.002 by both tests are particularly impressive given the limited sample size. SLW cloud was not monitored during the BRE but later observations atop the Main Ridge detected SLW during 7-9 % of all hours as discussed in Sec. 1.

Table 6. Like Table 5 except by fraction of all 174 six hour periods with MRT ≤ -9.3°C.

Cloud Thickness (m)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
1 ~ 6231	169 / 173	0.70	**0.02**	**0.04**	1.28	1.07 ~ ∞
Halves						
1971 ~ 6231	84 / 87	0.68	**0.04**	**0.01**	1.42	1.18 ~ ∞
Thirds						
2754 ~ 6231	55 / 59	0.69	**0.05**	**0.01**	1.48	1.21 ~ ∞
Quartiles						
1068 ~ 1970	43 / 43	0.75	**0.04**	**0.08**	1.64	1.14 ~ ∞
3265 ~ 6231	36 / 50	0.69	**0.04**	**0.008**	1.57	1.28 ~ ∞

Table 7. Statistical results for noted dew point depression and MRT partitions.

Dew point Depression (°C)	MRT (°C)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All	All	169 / 173	0.70	**0.02**	**0.04**	1.28	1.07 ~ ∞
≤ 2.7	All	79 / 95	0.67	**0.01**	**0.03**	1.39	1.12 ~ ∞
≥ 2.8	All	90 / 78	0.73	0.21	0.34	1.10	0.77 ~ ∞
≤ 2.7	≤ -9.3	40 / 51	0.59	**0.002**	**0.002**	1.90	1.58 ~ ∞

4.6. Partitioning by Individual Winters and Halves of Day

In addition to analyses of the combined two winters of the BRE, SH83 analyzed each winter separately for colder MRTs. This approach approximately halved the sample size, providing a demanding test. Analogous tests are presented here with 6 h periods providing larger sample sizes, but limited to periods with a westerly wind component. Table 8 shows results for MRT ≤ -9.3°C. The BRE was suspended during the month of March 1971 because of well-above normal snowpack, partially explaining the smaller sample size that winter.

Table 8 is divided into two portions. First considered is the upper portion which partitions the total sample by individual winters. It is shown that low P-values and high MDRs result for each winter. Target-control correlation coefficients were high with the control gauges explaining 55% of the natural variance in each winter. Finding strong statistical suggestions of effective seeding for separate winters adds to the credibility of the overall results. It is less likely that a Type I error occurred since each winter showed low P-values.

The lower portion of Table 8 examines 6 h populations split from the first and last half of each 24 experimental day. Partitioning by each 6 h time period (e.g., 1200 - 1800 MST) was attempted but the results were unstable with widely differing P-values and MDRs. This was likely due to small sample sizes, ranging from 34 to 48. It is seen that approximately halving the entire population, in this case by splitting 24 h days, again resulted in low P-values and high MDRs. This provides further evidence that a Type I error was unlikely for analyses of the overall population.

Comparison of the markedly lower P-values in the combined middle row with those by partitioning by individual winters, or by first and last half of each day, illustrates the sensitivity of statistical analysis to sample size.

4.7. Testing by Least-squares Regression

Given the previous discussion, a seeding effect should be evident in the relation between the target and control data. A widely-known and easily understood relation is the linear least-squares regression where for this application the target SWE, $\hat{T} = a + b\overline{C}$.

Table 8. Statistical results for partitioning by separate winters (upper 2 rows) and 12 h periods from the first and last half of each 24 h EU (lower 2 rows). The MRT was ≤ -9.3°C with the 700 mb wind direction

Winter	**N_s / N_{ns}**	**Pooled R**	Wilcoxon P-value	**RRT P-value**	**MDR**	**Confidence Interval**
1970/71	24 / 45	0.74	0.02	**0.08**	1.42	1.07 ~ ∞
1971/72	55 / 50	0.74	0.02	**0.004**	1.79	1.45 ~ ∞
Combined	79 / 95	0.74	0.002	**<0.001**	1.64	1.39 ~ ∞
Noon to Midnight	44 / 50	0.82	0.03	**0.02**	1.57	1.24 ~ ∞
Midnight to Noon	35 / 45	0.62	0.01	**0.01**	1.75	1.39 ~ ∞

The average control SWE is indicated by $\overline{C}$. If there is a positive seeding effect, the seeded slope, $b_{S,}$ will be greater than the nonseeded slope, b_{NS}. One way to test the null hypothesis of homogeneity among the slopes is to apply an analysis of variance (ANOVA) to find an F_s statistic (Sokal and Rohlf 1969),

$$F_s = \frac{MS_{\text{Variation Among Regressions}}}{MS_{\text{Unexplained by Regression}}}. \quad (5)$$

F_s is compared to critical values of $F_{á[1,s+ns-4]}$ to determine the P-value of a Type I error. Since an ANOVA cannot differentiate variance due to positive or negative effects, the test is 2-tailed.

Application of this ANOVA to the partitioned data of the last line of Table 3 produced a 2-tailed P-value of 0.042. The 1-tailed P-value is half this or 0.021, suggesting that the two slopes are not from the same population, i.e., there is a seeding effect. This simple regression analysis confirms the encouraging results from the more robust Wilcoxon and rerandomized ratio tests.

5. DISCUSSION

5.1. Summary of Statistical Suggestions

Post-hoc exploratory analyses of BRE 6 h data strongly suggest that AgI seeding was effective in enhancing snowfall in the sample population with MRT ≤ -9.3°C, the median value. This is essentially the same result reported by SH83 using 24 h EUs (N = 92) but the statistical significance is greater with the larger 6 h sample size (N = 371) and tighter association with weather parameters. It was impractical with the statistical testing to precisely estimate the warm temperature limit for *effective* seeding which, in any event, might only apply to the particular AgI complex, generator type, release rate, terrain configuration and cloud conditions of the BRE. But the best statistical evidence from Table 1 is that the limit was near -9°C. Seeding likely produced some effective IN at temperatures a few degrees warmer but in concentrations too low for meaningful snowfall production, unless AgI was released within SLW cloud ≤ -6°C allowing forced condensation-freezing to occur. It may not be coincidence that -6°C at the seeding sites corresponds to a MRT near -9°C for in-cloud lapse rates. Claims that AgI seeding with newer complexes can produce meaningful snowfall rates at higher temperatures may be true but have yet to be documented.

A seasonal SWE increase of 15% was suggested by the mean double ratio for all 6 h periods with a 54% increase indicated for the colder half. The mean (median) nonseeded target SWE for the colder half was 0.620 (0.178) mm per 6 h so a 54% increase is equivalent to a *hourly* rate of 0.056 (0.016) mm. Actual seeding increases per individual periods are unknown but could be expected to range from zero to several times the above rates. That range is in reasonable agreement with the survey by Huggins (2009) which indicated that short-term seeding experiments revealed precipitation rate increases of a few hundredths to >1 mm h^{-1}.

Analyses of periods with available rawin observations (cloud cover observed) produced low P-values by both tests regardless of temperature. The MDR for westerly flow component periods was 1.28 (28% increase). Including the requirement of MRT ≤ -9.3° indicated about one chance in a thousand of incorrectly rejecting the null hypothesis with a suggested 64% SWE increase from seeding. The associated 1-tailed confidence interval (1.39 ~ ∞) showed a 95% chance that the increase was at least 39% for this dual partition. It had a sample size of 174 or about half of the single partition of MRT ≤ -9.3°. This favorable dual partition was further tested by applying ANOVA to compare seeded and nonseeded slopes from least-squares regression. This simple approach resulted in a 1-tailed P-value of 0.02.

A reviewer raised the possibility of a natural sample bias (bad draw) for the colder periods in spite of substantially reducing (but not eliminating) natural variance with control gauges. Statistical testing cannot totally rule out that possibility. An attempt was made to address that concern by further testing the same dual partition by approximately halving the overall sample by (1) separately testing each winter and (2) testing the first and last half of each day. Impressive results were calculated for all four of these subdivisions, each with relatively small sample sizes. This stringent testing adds credibility to the hypothesis that suggested seeding effects were real and not the result of multiplicity or natural sampling bias.

Partitioning by estimated cloud-top temperature or cloud thickness suggested that presence of deep, cold-topped clouds does not necessarily rule out seeding effectiveness. A number of investigations have suggested that large SLW flux-producing storms may be inefficient in snow production during some phases but efficient during other phases (Huggins 2009).

Dual-partitioning by westerly wind component and 700 mb dew point depression ≤ the 2.7°C median resulted in P-values of 0.01 and 0.03 with a 1.39 MDR. Including the additional partition of MRT ≤ -9.3° decreased P-values to 0.002 by both tests with a MDR of 1.90. The sample size for the latter was limited to 91 periods, about half the 174 size of the dual partition and a quarter of the single colder MRT partition with N = 371. Consequently, the results suggest that seeding was especially effective if moist air and/or cloud was present just upwind of the Main Ridge, sufficiently cold for AgI nucleation. This would be expected from physical reasoning and thereby adds credibility to the statistical suggestions.

5.2. Physical plausibility

The most fundamental element for any RWOE should be a demonstrated capability to target clouds as intended. Yet, based on review of several other RWOEs and various plume tracing studies, it is the authors' opinion that most previous RWOEs had frequent failures to seed as planned. Orographic clouds have either been infrequently seeded (mistargeting, trapping, generator failures), seeded with effective IN concentrations too low for meaningful snowfall production (Super 1999), and/or seeded with generators too widely spaced resulting in untreated gaps between AgI plumes (Griffith *et al*. 1992). In discussing the results of a propane-seeding RWOE in the Sierra Nevada, Reynolds (1996) concluded, "Again, it would seem imperative that detailed transport and dispersion studies be preformed prior to the onset of any long-term snowfall enhancement program in order to confirm that successful targeting is possible for a majority of storm periods when liquid water is observed." The authors of this paper fully agree.

The most important physical evidence in support of the BRE is the considerable documentation that orographic clouds were regularly seeded. Moreover, sufficiently high concentrations of effective AgI IN resulted with colder seeded zone temperatures. As discussed by Super (1974) and SH83, many below-cloud aircraft passes over the Bridger Range showed AgI plumes were consistently transported over both the Main and Bangtail Ridges as detected by an acoustical IN counter. The AgI was largely confined to within ~ 450 m of the Main Ridge crestline. Such low level aircraft sampling over mountain peaks is not permitted within cloud because of safety concerns. Plume widths from the southern generator, 4.7 km upwind of the crestline, were usually in the 10-30° range over the Main Ridge. Long after the BRE, in-cloud sampling of AgI plumes from the southern generator site was done as low as 300 m above the highest (2433 m) BRTA terrain (Super and Heimbach 1988). Plume widths ranged between 5-8 km (16-26°) while tops were detected from 2.7 to 3.3 km on each of six aircraft missions. Orographically-produced SLW cloud is concentrated in this same zone, within 1 km over mountainous terrain, as shown by studies summarized by Super (1999) and Huggins (2009).

Further evidence of appropriate AgI targeting was discussed by SH83, and Heimbach and Super (1988). To briefly summarize, numerous pilot balloons (pibals) of known still air ascent rates were tracked by the dual-theodolite method from each seeding site. The observations demonstrated that the vertical wind speed just west of the Main Ridge crestline was essentially forced by the terrain slope. The 3050 m wind direction was a good predictor of the mean wind direction for the layer in which AgI was transported up the west slope of the Main Ridge. There was little indication of changes in wind direction near plume tops between the Main Ridge and BRTA. However, prevailing southwest winds were measured at the BMO which may have transported AgI and seeded crystals more northward than suggested by 700 mb winds.

End of season silver-in-snow analyses during the BRE (SH83), and later sampling reported by Heimbach and Super (1988), showed widespread Ag concentrations well above background levels over intended targets. Large fractions of the total Ag released during the BRE while snowfall was detected near the BMO were found in the BRTA snowpack. Scavenging by natural snowfall could explain an unknown fraction of the observed silver enhancement. But finding increased Ag in the seasonal snowpack provides further evidence that the AgI plumes were often transported over the target areas. Finally, acoustical ice nucleus counter observations at both the BMO and MRO observatories (see Fig. 1) frequently detected AgI plumes atop the Bangtail Ridge (Part I) and Main Ridge (Heimbach and Super 1988). There is no reason to doubt that AgI plumes were routinely transported over the BRTA with widths sufficient to affect much of the target area at any given time. Meandering winds and wind shear would be expected to further broaden the affected area.

The question remains whether *effective* AgI particle concentrations were sufficiently high to result in meaningful snowfall rates. On the Grand Mesa of Colorado (Super *et al*. 1986) and the Wasatch Plateau of Utah (Super and Heimbach 2005b) many hours with "trace" precipitation, < 0.13 mm (0.005 inch) or less, contributed only a few percent to the total seasonal SWE and can be considered trivial. Seeding-caused snowfall must often exceed trace rates to be meaningful, which leads to discussion of required seeded ice particle concentrations (hereafter IPCs).

Holroyd and Super (1998) used observations from a wind vane-mounted 2D-C optical array probe and nearby high resolution gauge on the Wasatch Plateau to show that most natural ice particle concentrations (IPCs) exceeded 10 L^{-1} when precipitation rates were more than trivial. The same instrumentation and location were later used by Super and Heimbach (2005a). They concluded that a minimum of 20 L^{-1} was probably a more realistic threshold for seeded snowfall to exceed hourly trace amounts. These threshold values are similar to the low end of the 10 to 100 L^{-1} effective seeding range calculated in the classic paper by Ludlam (1955). The BRE attempted to achieve that range for typical conditions as discussed by Super (1974). He showed that aerially-sampled AgI plumes passing over the Main Ridge would, for average conditions, be exposed to temperatures from about -13 to -10°C. Given AgI generator calibrations results and aircraft-observed AgI plume widths and depths over the Main Ridge, it was estimated that approximately 10 to 100 effective IN L^{-1} would result for typical temperatures during snowfall. Discussion in the 1972 Part I report stated, "A recent calibration of one of the generators used on the Bridger Range experiment has revealed that the number of effective nuclei per gram of silver iodide decreases rapidly as the temperature is increased above about -10ºC. Thus, little nucleation is to be expected for temperatures warmer than -10ºC." Statistical analyses done by SH83 and herein suggest that long-ago expectation was met.

Direct IPC observations with an aircraft 2D-C particle imaging probe were made over the BRTA in January of 1985 (Super and Heimbach 1988). Three missions had clear evidence that the AgI plume encountered SLW cloud over the BRTA when the MRT was between -9 to -10°C. Twenty crosswind passes showed AgI-caused IPC increases ranging from 3 to 21 L^{-1} with only two values below 7 L^{-1} and a median of 14 L^{-1}. These are very likely conservative values because a large fraction of seeded crystals should have fallen below safe aircraft sampling altitudes. These observations and the above estimates of effective AgI IN all suggest that BRE seeding should have produced sufficient IPCs for meaningful snowfall production when SLW cloud temperatures were less than approximately -10°C. These physical results are in excellent agreement with the statistical suggestions presented herein which indicate seeding was effective for MRTs colder than about -9°C, with corresponding AgI plume top temperatures below -12°C. This apparently effective seeding temperature range coincides well with the rapid ice crystal mass growth range, peaking between -11 to -17°C according to Redder and Fukuta (1989), providing further physical plausibility to the statistical suggestions.

A nucleation process unknown at the time of the BRE offers another plausible reason to expect effective BRE seeding during some storm conditions. The rapid "*forced*-condensation freezing" mechanism functions immediately downwind of AgI generators operated in ice or water saturated conditions if the ambient temperature is less than -6°C (Finnegan and Pitter 1988; Chai *et al*. 1993). Combustion of acetone and propane releases considerable water vapor resulting in a local zone of high supersaturation. The BRE seeding sites were often in-cloud during storms and had temperatures < -6°C when the MRT was ≤ -9°C. Ice crystals formed just above the generators should have been transported upslope in the SLW cloud production zone. Such early nucleation would significantly prolong the period available for seeded crystal growth and fallout, and might explain suggested near-source increases in snow on the lee slopes of the Main Ridge (SH83, Sec. 8; Heimbach and Super 1988).

Partitioning by availability of a rawin observation with a westerly wind component at 700 mb strongly suggested that seeding was particularly effective within the subpopulation with broken to overcast cloud cover over the Main Ridge and bases below 3050 m. Further partitioning by dew point depression provided even stronger evidence for the half of periods most likely to have moist air or cloud upwind of the Main Ridge. Such conditions could be expected to likely have SLW cloud production in forced uplift over the Bridger Range. These are physically plausible results since SLW cloud is the "raw material" necessary for seeding to be effective. When those partitions were combined with MRT less than or equal to the median of -9.3°C, even more significant P-values resulted as expected from the previously demonstrated temperature dependence of seeding effectiveness.

6. CONCLUSIONS AND RECOMMENDATIONS

The strong statistical suggestions from two independent analyses of BRE 6 h periods can be briefly summarized as follows:

- Seeding appeared to be most effective when atmospheric conditions favored orographic production of SLW cloud over the Bridger Range with crestline temperatures colder than the median of -9.3°C. Corresponding AgI plume top temperatures would be less than -12°C.

- There was no evidence that seeding decreased snowfall, even with the coldest temperatures experienced. Seeding apparently increased snowfall for both small and large storms since low P-values resulted no matter how many control gauges detected snowfall, how cold cloud tops were, or how thick the clouds.

- Mean double ratios and confidence intervals suggested the relative increase was larger for smaller storms.

- The seasonal increase to be expected from operational seeding was estimated as 15% by the MDR calculated for all 6 h periods.

It is strongly recommended that a relatively small RWOE be conducted using a simple design with EUs declared only by real-time observations of SLW cloud near the windward crest. Such observations make it practical to totally automate an experiment on a 24/7 basis as demonstrated by Super and Heimbach (2005a). The experimental area should be carefully selected to permit practical over-snow travel to a dense precipitation gauge network and other surface instrumentation sites. Sufficient conifer forest should exist to provide well-protected locations for snowfall observations. As a matter of practicality the target area should be limited in crosswind extent so that it can be regularly impacted by no more than four high elevation seeding sites spaced 4-5 km crosswind. A minimum of one target and one crosswind or upwind mountain observatory should be maintained for microphysical observations because cloud microphysics is still imperfectly understood even though it is fundamental to understanding variations in seeding effectiveness. Experimental unit duration should be no longer than about 3 h given known variability in SLW and natural snowfall. At least one winter should be devoted to a complete "shakedown" of all design and observational aspects, definitely emphasizing seeding plume tracking, prior to initiation of a randomized experiment.

Modern remote-sensing instrumentation and model simulations should, of course, be part of any future RWOE. But care should be taken so that the related high expense does not reduce funding needed to accomplish the fundamentals of proper seeding, monitoring transport and dispersion of seeding plumes and the primary response variable of snowfall on the ground. Scientists have a natural tendency to give a high priority to what is new, different, "cutting-edge," and of particular interest to them. The overall goal of some past RWOEs has not been met in part because of misplaced priorities with the fundamentals taken for granted.

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EVALUATION PLAN FOR A SNOW ENHANCEMENT EXPERIMENT IN AUSTRALIA

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Abstract. A comprehensive suite of tests is developed to evaluate the Snowy Precipitation Enhancement Research Project, a cloud seeding project in south eastern Australia aimed at increasing snow fall. The project will use both physical and chemical observations for its primary evaluation. An analysis of historical data shows that there is an 80% chance that more than 100 five-hour experimental units will occur over the five-year duration of the project. Moreover, although there is a significant amount of natural variability in the properties of experimental units, it is appropriate to treat all experimental units as members of the one class of event. A bootstrap analysis of the historical data shows that there is about a 75% chance that a 20% increase in precipitation will be detected at the 10% significance level. On the basis of bootstrap analysis, the primary analysis for the project is taken to be the identification of a positive seeding impact at the 10% significance level in the primary target area, together with snow chemistry results showing at the 5% significance level that ice nuclei have been activated in the primary target area. A number of secondary analyses are identified to support the results of the primary analysis.

1. INTRODUCTION

Huggins *et al*. (2008) describe the overall design of the Snowy Precipitation Enhancement Research Project (SPERP), which commenced in 2004 with the aim of increasing snow fall over an area of about 1,000 km^2 in the Snowy Mountains of south eastern Australia. Ground-based generators are used to disperse silver iodide into suitable cloud systems. Following a year of experimentation, the formal operation commenced in 2005 using a 2:1 seeded:unseeded randomised sequence of experimental units (EUs). The randomised sequence is known only to the technical operators of the seeding-material generators, and it will be revealed only at the end of the five-year operational phase of SPERP. Huggins *et al*. provide a description of the instrumentation deployed in SPERP and a summary of some initial results of the snow chemistry observations taken during the Project. The plan for evaluating SPERP is described only briefly in their paper.

The purpose of the present paper is to describe the development of a systematic plan for evaluating the experiment based on analysis of historical data. The approach follows the well-established practice of carrying out numerical simulations of the impact of seeding (for example, Twomey and Robertson, 1973). However, the evaluation plan recognises the potential role of snow chemistry in providing information on the targeting of seeding material, while using statistical analysis of precipitation gauge data to determine quantitative information on the impact of seeding on snow amount.

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The specific nature of the statistical evaluation is designed on the basis of analysis of historical data across the region. In order to maximise the number of seeding opportunities and to localise the period in which seeding may be effective, EUs of 5 hours (with an operational purge period of at least 1 hour between EUs) have been selected for SPERP (Huggins *et al*., 2008). An initial analysis is therefore an examination of the spatial and temporal variation of precipitation across the region from historical data. This analysis suggests that the precipitation in the target area can be reasonably well represented by a simple arithmetic mean of individual observations, and so bootstrap simulations of the mean precipitation are used to estimate the probability of detection of a seeding impact over the five-year duration of SPERP.

In order to mitigate the effects of multiplicity (that is, false positive results from the application of many tests), the evaluation of SPERP is split into primary and secondary analyses. The primary analysis is designed to determine whether there has been an impact of seeding on the amount of precipitation in the target area, while the secondary analyses should provide supporting evidence and physical understanding of the results of the primary analysis.

2. SELECTION OF TARGET AND CONTROL AREAS

The key areas for consideration in SPERP are shown in Figure 1, where the locations of precipitation measurements are shown as black dots. The primary target area (red outline) is the region where snow is consistently the predominant form of precipitation in winter, and it lies on the highest ridge of the region with site elevations extending from 1560 m to 1950 m. From use of the GUIDE model (Rauber *et al.*, 1988), it is expected that solid precipitation induced by seeding will fall in the primary target area. To allow for uncertainty in the targeting of seeding material, a secondary target (blue outline) area is specified to the east and west of the primary target with site elevations from 1000 m to 1630 m. Together the primary and secondary target areas form the overall target area, which is expected to have increased precipitation due to seeding.

The control area (green outline) includes all the sites outside the secondary target area and westward of 148.41°E. The control area is selected to provide precipitation measurements in a region unaffected by seeding material but with a similar climatology to that of the target (see Section 3). If sites in the control area are occasionally affected by seeding then the outcome is to reduce (rather than increase) the estimated impact of seeding. It is noted that there is an absence of sites to the south of the target area.

An extended area is specified to include sites outside the target and control areas at which potential impacts of seeding will be investigated. Sites in the extended area lie mainly downwind of the target area.

Figure 1 shows that there are 9 sites in the primary target area and an additional 8 sites in the secondary target area so that there are 17 sites in the overall target area. The control area has 13 sites, and the extended area has 24 sites generally to the east of the target. Hourly data from the sites in the target and control areas are used for the primary analysis of the impact of cloud seeding on precipitation.

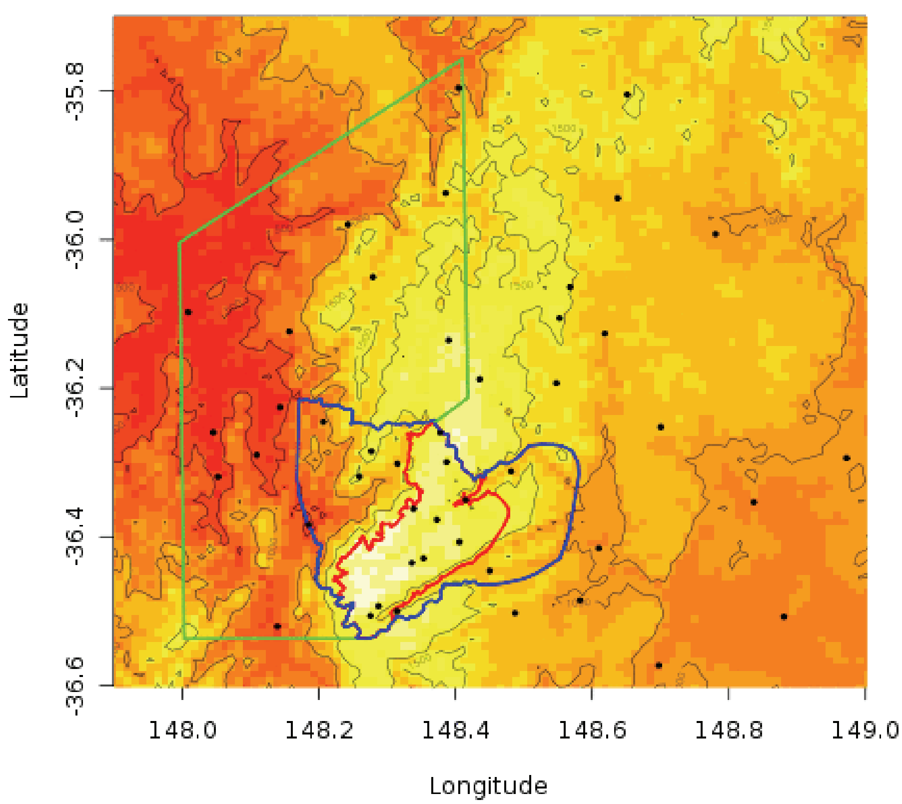

Fig. 1. Sites (black dots) at which precipitation measurements are taken in the primary target (red), overall target (blue), control (green) and extended areas; orography contours shown at 500, 1000 and 1500 m; the overall target area is abut 40 km wide.

3. CLIMATOLOGICAL STUDIES

In designing a cloud seeding project, it is usual to conduct detailed analyses of historical precipitation records across the region in order to determine the spatial and temporal variability of precipitation and to ensure that the project aims can be achieved in a reasonable time. An initial study of the probability of detection of a seeding impact was carried out by Shaw and King (1986). That study used daily data at sites that were largely outside the selected target and control areas, and it suggested that about 100 EUs (days) should yield sufficient data to detect a seeding effect within five or six years. Further analysis of historical data by Snowy Hydro Ltd (2004) showed that about 100 EUs of 5 hours duration should be obtained in a period of five years.

3.1 Historical data set

The present study aims to determine more accurately the probability of detection of a statistically significant result over the specified five-year duration of the project. In order to refine the analysis of Shaw and King (1986) which used daily data, it is necessary to develop a precipitation time series that has at least 1-hour resolution to identify 5-hour EUs. As most of the sites used in SPERP have been established at the start of the project, it is found that only 13 of the 30 sites in the target and control areas have at least a decade of historical hourly data, as shown in Figure 2. It is seen that there are 3 sites in the primary target area, 3 in the secondary area, 5 in the control area, and 2 in the extended area. A consistent historical record is obtained from all sites over the period from May 1995 through to September 2003, bearing in mind that snow falls consistently only in the winter period (May to September) and that SPERP operations began in May 2004.

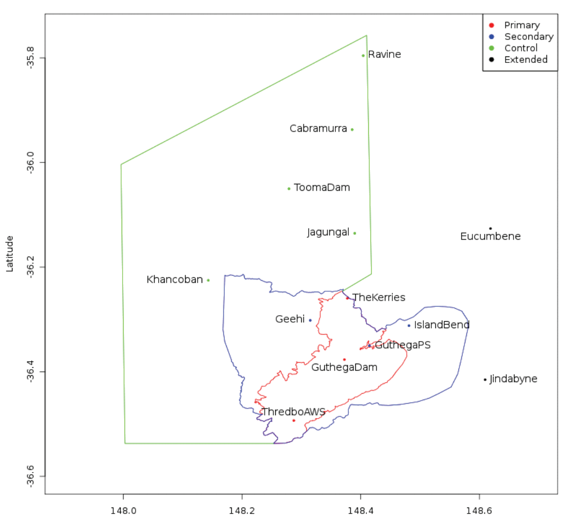

Fig. 2. Sites at which there are historical hourly precipitation data

In order to develop a climatology of precipitation during EUs, an historical time series of EU occurrence is generated by analysis precipitation data from Guthega Dam, temperature data from Cabramurra and upper-air data from Wagga Wagga (147.47 E, 35.17 S) over the period from May 1995 through to September 2003. The criteria for the start of an historical EU are specified to closely match the formal criteria used for an EU during the experimental phase of SPERP. The criteria for an historical EU can be summarised as:

- Measurable precipitation for 5 consecutive hours
- Freezing level less than or equal to 1600 m
- Surface temperature less than or equal to 1°C
- Wind (average of 850 and 700 hPa) has a westerly component (i.e. between 180° and 360°).

An historical EU data set is generated containing the start data and time of each EU, wind direction, wind speed, and the total (5-hr) precipitation at each site. A total of 214 EUs are found over the period from May 1995 through to September 2003. The validity of the selection process is checked by extending the analysis to 2004 during the start-up period of SPERP. It is found that the method is valid because the estimated EUs coincide well with the operational times (even though a small portion can be missed). We can therefore be confident in using the historical data set to estimate the climatology of EUs.

3.2 Statistical properties of EUs

To examine the basic climatology of EUs we use the precipitation data from Guthega Dam alone. Figure 3 shows histograms for each of the EU variables over that 9-year period. It is seen that the total precipitation during an EU varies from 1 to 26 mm, with a mean value of 5.4 mm. Fifty percent of the values lie between 2.6 and 6.9 mm.

The freezing level varies from 480 to 1600 m, with a mean value of 1260 m. Figure 3 shows that the distribution of the freezing level appears to be truncated at 1600 m, and so it would seem that the criterion of a freezing level lower than 1600 m is eliminating a number of possible EUs. However, the mode of the distribution is around 1300 m, suggesting that the rain-producing events are in the tail of the overall distribution of 5-hr precipitation events with a westerly component. Further analysis is needed to determine the actual impact of the criterion that removes rain-producing events.

It is apparent that the wind tends to be from the south west during the historical EUs, with 50% of the values lying between 240 and 270 degrees. The wind speed varies from 10 to 100 km/hr, with a mean value of 57 km/hr. Although there are no significant correlations between the EU variables, there is a suggestion that higher precipitation occurs when the freezing level is lower and the wind speed is higher, both of which suggest more intense storms. An analysis of the synoptic conditions during EUs would clarify the overall meteorological environment during EUs.

3.3 Inter-annual variability of EUs

There is clearly a considerable amount of variability in the precipitation associated with each EU, and we find that this variability (as with total precipitation in eastern Australia) occurs on annual as well as shorter time scales. To quantify this variability, we first consider the year-to-year variations of each of the key EU variables. It is found that the number of EUs each year varies from 10 to 36 with a mean of 24, while the annual average intensity of EUs varies from 4.5 to 6.6 mm with a mean of 5.4 mm. There is a weak positive correlation (0.51) between the annual intensity and the annual-average wind speed, suggesting that large events are associated with high winds.

The climate of the Snowy Mountains region is complex and there are a number of large-scale factors that affect the precipitation (Murphy and Timbal, 2007). However, it is useful to consider whether any major external factors have a domi-

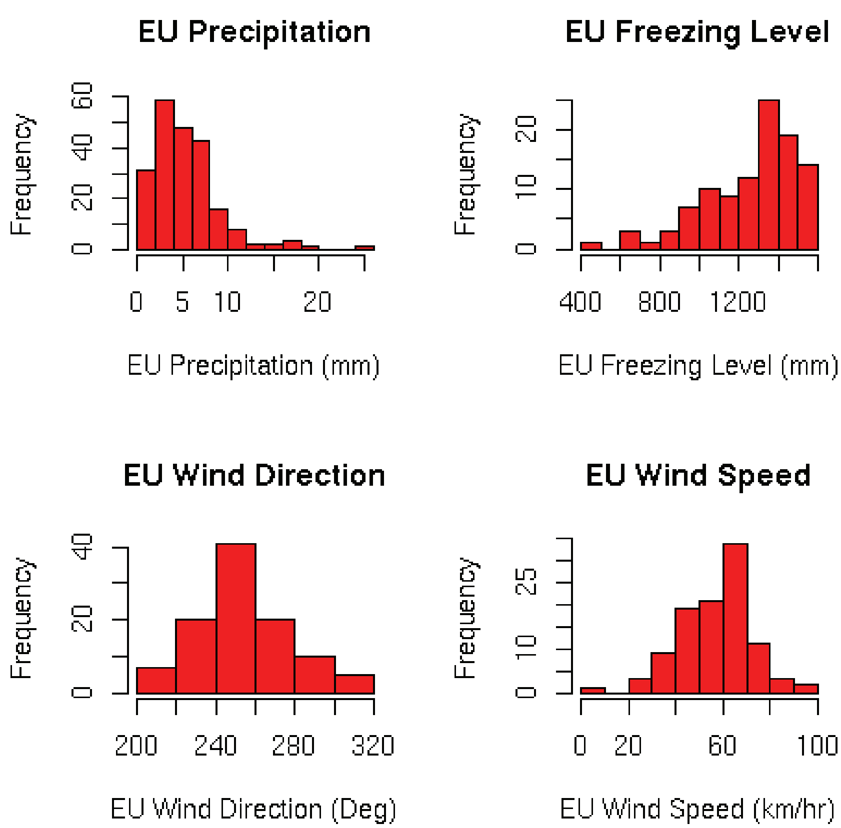

Fig. 3. Histograms of historical EU variables; the ordinate shows the number of counts in each bin of the histogram

nant impact on the inter-annual variability of EUs, as they may provide a predictor of EUs a season ahead. The Snowy Mountains lie in the south eastern sector of the Murray Darling Basin. Three factors known to influence climate in the Murray Darling Basin are the Southern Oscillation Index (SOI), which represents the El Nino influence of the Pacific Ocean, the Dipole Mode Index (DMI), representing a sea-surface temperature index in the Indian Ocean, and the Southern Annular Mode (SAM), which represents the large-scale pressure pattern around the south pole. We should note that these three factors are not entirely independent (for example, Allan *et al*., 2001), and there is a significant correlation of -0.61 between the SOI and the DMI over the nine-year period of the historical EUs. The data source for the SOI is Bureau of Meteorology (2008), for the SAM is British Antarctic Survey (2008), and for the DMI is Frontier Research Centre for Global Change (2008). It is found that there are no significant correlations with the SOI. On the other hand, there is a positive correlation at the 5% level between the DMI and the mean wind direction during EUs. This result suggests that the wind has a more northerly aspect when the DMI is positive, which may correspond to weaker synoptic systems. Indeed Verdon and Franks (2005) find that eastern Australia tends to have higher rainfall in years with a negative DMI. On the other hand, the winter-mean EU precipitation is found to have a weak positive correlation with DMI. The influence of the DMI is therefore not altogether clear. There is a significant (p-value of 0.006) negative correlation between the SAM and the winter-mean freezing level. This result does not appear to be consistent with the finding of Hendon *et al*. (2007) that positive SAM values are associated with higher rainfall in the summer in south eastern Australia, but with lower rainfall in winter.

From this very preliminary analysis, it would seem that the large-scale factors affecting the properties of EUs are not revealed by a linear regression analysis over a 9-year period. More detailed studies and longer time series may provide a greater insight into the large-scale controls on EUs.

3.4 Seasonal variability of EUs

While we have found that there is large variability in the number of EU events each year, the properties of each EU do not show the same degree of variation from year-to-year. This result gives us some confidence that all EUs can be treated as coming from the same class. However, confirmation of this hypothesis requires us at least to consider whether there are seasonal variations in the properties of EUs.

It is found that there is a strong seasonal cycle in the occurrence of EUs, with a peak in July and reduced numbers in the early and late months of the five-month winter season. However, this expected seasonal variability in the frequency of EUs does not mean that individual EUs vary significantly with the seasons. Indeed the month-to-month variations in EU properties are less than the variability within each month. As may be expected, the mean amount of precipitation in an EU tends to be less in May and September than in mid-winter, but even here the differences in the monthly means are well within the standard deviation for each month.

From the climatological analysis, it is appropriate to treat all EUs as coming from the same class of event, and so the analysis of the impacts of cloud seeding should not have to take into account either large-scale climatological factors or seasonal variations.

3.5 Variability of total number of EUs

We have found that there is substantial inter-annual variability in the number and intensity of EU events. This variability may tend to reduce the total number of cloud seeding opportunities, and so it is useful to examine the total number of events that are expected over the five-year duration of SPERP. We first note that annual precipitation in south eastern Australia has substantial decadal variability (Nicholls and Wong, 1990), and so the 9-year historical record is really too short to provide precise estimates of probabilities. Nonetheless we use the historical EU record to provide an estimate of the total number of events in a 5-year period.

There are only weak correlations between the EU variables and the large-scale climate factors, and so a basic estimate of the total number of events is found by sampling five-year ensembles from the historical EU data set. The 9-year data set means that there are only five real (but overlapping) 5-year runs to be considered. It is readily found that these runs imply there is a 50% chance that the total number of EUs over a 5-year period will lie between 100 and 122, with a mean of 112. In order to get a more robust estimate of the distribution of 5-year runs, we use a simple bootstrap technique to randomly select (with replacement) 5 years from the overall data set. It is found that the resulting distribution of total number of EUs implies that there is an 80% chance that the total number will be greater than 100. The range of the total number is from 50 to 180, which correspond to repetitions of the lowest (10) and highest (36) annual number of events. The 5% confidence limits are from 83 to 154 events.

Given the short length of the historical data set, the present analysis implies that there is a good chance that there will be around 100 EU events over the five-year period of SPERP.

3.6 Spatial variability of EU precipitation

A key feature of a cloud seeding experiment is a comparison of precipitation in the target area with that in a neighbouring control area. It is therefore appropriate to consider the spatial variability of precipitation during EUs in order to determine how best to represent the precipitation in the target and control areas. For example, if there is substantial spatial variability across the region then it may be necessary to compare detailed spatial patterns of precipitation, rather than simply the area-mean value.

To analyse the spatial variability of precipitation during EUs, we first select only EUs for which there are valid precipitation observations at all of the 13 historical data sites. This condition reduces the number of available EUs from 214 to 138.

Figure 4 shows the spatial patterns of the mean and standard deviation of EU precipitation. There is a considerable degree of consistency in both mean and variance across the target and control areas. There is a suggestion of reduced precipitation in the south of the target area, but this result may be a reflection of the under-catch of precipitation gauges in the high-wind regions of the mountains. On the other hand, there is a clear rain-shadow to the east of the high mountains in the extended area of SPERP.

A test of spatial variability is a principal component analysis (Becker *et al.*, 1988), in which we identify the dominant spatial patterns of variability. The first principal component represents the most consistent spatial pattern. It is found that the first principal component (PC) explains nearly 80% of the variance of precipitation across the region and the pattern of that PC is very similar to pattern of the mean precipitation in Figure 4.

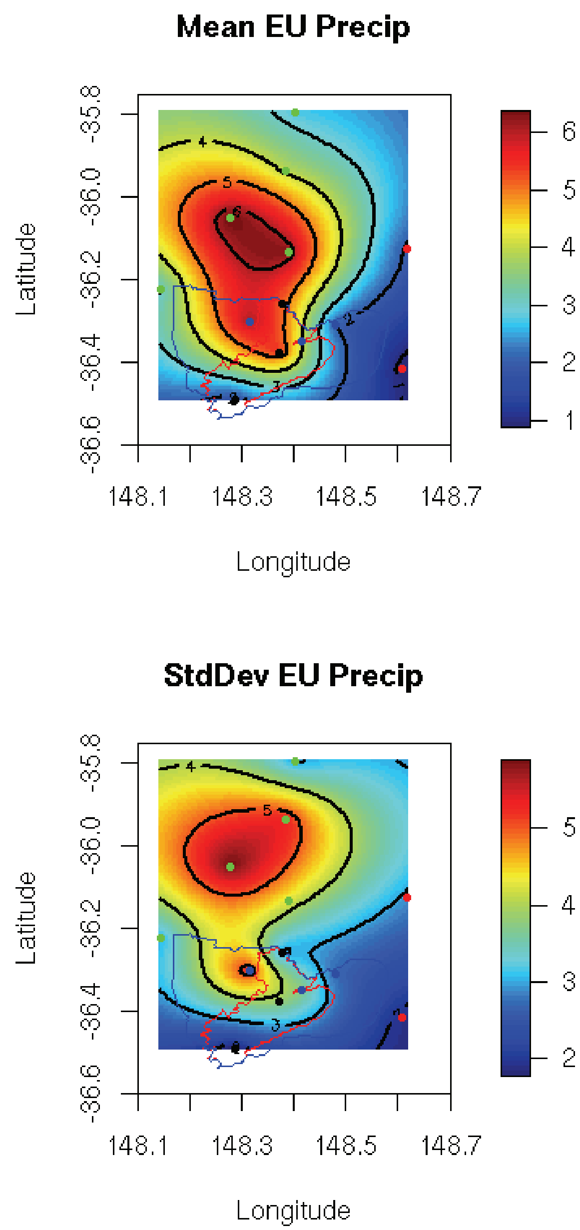

Fig. 4. Spatial variation of mean and standard deviation of precipitation during historical EUs; dots show location of precipitation sites; the overall target area is about 40 km wide.

If we extend the analysis to sites in the target and control areas separately, then it is found that the first PC in each of these areas also explains about 80% of the variance. All these results suggest that, at least to a first approximation, the primary analysis of a seeding impact may be carried out using area-mean values of precipitation, rather than more complex variables that reflect the spatial variability of precipitation across the region.

4. PROBABILITY OF DETECTION OF SEEDING IMPACT

It is shown in Section 3 that, while there is a significant amount of natural variability in the properties of EUs from month-to-month and from year-to-year, it is appropriate to treat all EUs as members of one class of event. We therefore can use the historical EU data set to estimate the probability that a seeding impact can be detected over the 5-year lifetime of SPERP.

Before considering the detailed analysis of the probability of detection, we first establish that there are significant correlations between the precipitation in the target and control areas during EUs. The analysis of spatial variability in Section 3.6 suggests that such correlations exist. However, this test must be carried out to ensure that the basic assumption of a detection analysis (that is, that the control area can be used to estimate the natural precipitation in the target area) is valid.

Based on the analysis of Section 3.6, we use the most basic measure of precipitation over an area: the arithmetic mean of the available observations in the area. The EU precipitation time series are calculated from hourly data at each site using the timing of events from the historical EU data set. All the correlations between the areas of interest are found to be significantly different from zero. However, because of the variability in precipitation across the region, the correlations are not particularly high. The correlation between the primary target and control areas is found to be 0.71, but the correlation increases to 0.79 when the control is compared with the overall target area. Because the spatial correlations are not especially high, the detection of an impact of seeding in the target area is not expected to be straightforward. On the other hand, it is expected that the increased number of observing sites in the target and control areas (from 11 to 30) during the operational phase of SPERP will provide greater statistical robustness to the analysis.

4.1 Detection of seeding impact

Having established that all EUs can be treated as being from the one class and that the correlations between the target and control areas are significantly different from zero, it is appropriate to carry out simulations of a cloud seeding experiment, in which the precipitation in some EUs is artificially increased (for example, Twomey and Robertson, 1973). The simulations use the three data sets of historical EU precipitation in the primary target, the overall target and the control areas. Each record has 214 EUs over the period from 1995 to 2003. A bootstrap method (Davison and Hinkley, 1997) is used to estimate the probability that the impact of cloud seeding will be detected. The impacts of specified increases of 5, 10, 20 and 40% are investigated.

From the analysis of Section 3.5, it is apparent that the expected number of EUs over the 5-year duration of the operational phase of SPERP is between about 100 and 130. The seeding strategy of SPERP is to seed twice as many EUs as are left unseeded; that is, the seeding ratio is 2:1. In order to make a conservative estimate of the outcome of SPERP and to have a convenient number of events for the specified seeding strategy, we assume that there are 99 EUs in the simulations.

For each simulation, 33 EUs are randomly selected (with replacement) from the total of 214 EUs as unseeded events, and 66 are selected as seeded events. The precipitation in the target is T(t) and in the control is C(t), where t is the EU number. For the unseeded EUs, we have the target precipitation TU(t) and the control precipitation CU(t) given by

$$TU(t) = T(t) \text{ and } CU(t) = C(t).$$

For the seeded EUs, we increase the natural precipitation by the seeding impact (s), and so the target TS(t) and control CS(t) precipitation are given by

$$TS(t) = (1 + s) * T(t) \text{ and } CS(t) = C(t)$$

where s = 0.05, 0.10, 0.20 or 0.40.

We consider two alternative approaches to measure the calculated impact of seeding. The first is the well-known double ratio (Smith *et al.*, 1963) and the second is based on a regression analysis. The double ratio approach compares the ratio of the target to control precipitation in seeded and unseeded periods; in particular, we calculate the double ratio

$$D = \frac{[\text{sum}\ (\text{TS}(\text{t})\text{sum}\ (\text{CS}(\text{t})]}{[\text{sum}\ (\text{TU}(\text{t})\text{sum}\ (\text{CU}(\text{t})]} \qquad (1)$$

The ratio on the denominator of DR is assumed to normalise the numerator by accounting for the natural relationship between precipitation in the target and control areas. It is clear that if there is a seeding impact then DR should be greater than one, and DR-1 is an estimate of the seeding impacts.

For the regression approach, we use linear regression to estimate the "natural" precipitation in the target area; in particular, we calculate

$$TU \sim a + b * CU$$

where the coefficients a and b are estimated by a linear regression of the target and control precipitation in the unseeded EUs. Then the impact of seeding is estimated by the "error" variable

$$ES(t) = TS(t) - a - b * CS(t), \qquad (2)$$

which is the difference between the actual and natural precipitation in the target area for the seeded EUs. It should be found that the distribution of ES has a positive bias when compared with the unseeded EUs, for which the error variable is

$$EU(t) = TU(t) - a - b * CU(t). \qquad (3)$$

The overall precipitation increase is given by

$$PI = sum(ES(t)), \qquad (4)$$

while the fractional increase in natural precipitation is estimated by

$$FI = PI / [sum(TS(t)) - PI].$$

The variable PI is useful in providing a quantitative estimate of the actual increase in precipitation across the target area, while FI is a normalised variable that provides an estimate of the seeding impacts.

The regression analysis outlined here is slightly different from the approach taken by Smith *et al*. (1979) and Mielke *et al*. (1982). The earlier analyses essentially used all the data to estimate the basic regression between the target and control precipitation. The current approach is based on the physical argument that the unseeded EUs provide the only unbiased data for estimating the 'natural' relationship between precipitation in the target and control areas. Having established that relationship, it can be applied to estimate the natural precipitation in the target area during seeded EUs. Thus the statistical analysis is based on a simple physical argument.

It is found that stable results are obtained using 600 simulations for each value of the seeding impact. The simulations yield statistical distributions for DR, PI and FI, and so it is straightforward to estimate the probability that DR>1, PI>0 and FI>0. The precipitation increase (PI) is included in the analysis as it provides an estimate of the explicit impact of seeding, independently of whether the impact is multiplicative or additive. However, as PI and FI are almost linearly related, the results for PI are similar to those for FI. Moreover, most evidence suggests that the impact of seeding is multiplicative, and so we will focus attention on FI rather than PI.

The simulations discussed at this stage consider only the question of the likelihood that the estimated impact of SPERP will be positive. Another important question is whether analysis of one realisation of the experiment can yield a robust estimate of the seeding impact; that is, can we get accurate estimates of the uncertainty associated with the observed value of the fractional increase (or double ratio). For this question, we carry out an additional bootstrap analysis within each simulation. This analysis corresponds to the statistical analysis to be carried out on the actual observed data during the operational phase of SPERP (when there is clearly only one experimental result).

From any given simulation, we have one estimate of the fractional increase (FI) and the double ratio (DR). These estimates are based on the 99 "measurements" of precipitation in the target and in the control area for each event. To test the significance of the estimates of FI and DR, we randomly select (with replacement) 66 events as "seeded" events and 33 as "unseeded" events. The "unseeded" events are used to estimate the natural precipitation in the target area by regression. From the "seeded" and "unseeded" events, values for FI and DR can be computed. The random selection is repeated to build up the statistical distributions of FI and DR. Analysis of the distributions of FI and DR yield estimates of the significance of the observed value of FI and of DR; for example, the one-sided significance of FI is estimated by the fraction of the distribution having values greater than the observed value of FI (Smith *et al*., 1979). It is found that stable estimates of the significance levels are obtained with 400 replications.

The results of the simulations are summarised in Table 1. As expected, the chance of finding a significant seeding effect increases as the actual seeding impact increases. However, the chances are not greatly increased by using the overall rather than the primary target area. This result is reflected in the relatively small increase in the correlation of precipitation in the control area with the target when the target is enlarged from the primary to the overall area. Table 1 does not include the results for the PI, as the probabilities for PI are essentially the same as for FI owing to the almost linear relationship between them.

The results for the double ratio (DR) and fractional increase (FI) are found to be similar. However, the probability of DR>1 is found to be a little less than the probability of FI>0. Moreover, the chance of obtaining a significant result is found to be generally larger for the FI than for the DR. This result suggests that the fractional increase method may be a little more sensitive than the double ratio for this problem, and so it is appropriate to use the fractional increase for the primary analysis.

A feature of Table 1 is that the probability of detecting a seeding impact at the 5% level is not large unless the seeding impact is greater than about 0.2. For example, there is only about a 65% chance of finding a significant result at the 5% level when the actual impact is 0.2; on the other hand there is an 85% chance that a positive result will be found. The chance of having a significant result at the 10% is substantially greater than at the 5% level. This observation suggests that, recognising the limited number of EUs expected in the 5-year duration of SPERP, it is appropriate to seek an impact of seeding at only the 10% level. This level of significance may be questioned by statisticians. On the other hand, if there is other evidence (arising from secondary analyses) supporting a positive impact then the relatively low statistical significance can be acceptable (for example, Nicholls, 2001).

5. PRIMARY ANALYSIS OF SEEDING EFFECTS

Many variables are measured in a cloud seeding experiment in order to ensure the scientific integrity of the results. All these data can be used to conduct many different tests of the results of the experiment. However, Mielke *et al*. (1982) points out that, as there is a substantial random component in a cloud seeding experiment, the application of many different statistical tests leads to the problem of multiplicity; that is, the application of many tests can lead to false positive results.

In order to minimise the risk of multiplicity, the analysis for SPERP is separated into primary and secondary tests. The primary analysis is seen as the key test of whether there has been an impact of seeding on the amount of precipitation in the target area. If a positive result is obtained from the primary analysis then the secondary analyses are used to confirm the scientific integrity of the primary result. If the primary analysis yields a negative or uncertain result then the secondary analyses are used to clarify where and how the seeding hypothesis broke down. An important purpose of the secondary analyses is to support scientific advice to assist policy decisions on potential future cloud seeding activity.

The primary analysis for SPERP has two components. The first is the detection of a seeding im-

Table 1. Results of simulations of specified impacts (SI) of cloud seeding using 99 EUs; DR is the double ratio and FI is the fractional increase of precipitation

Target	SI	Prob DR>1	Prob DR	Prob DR	Prob FI>0	Prob FI	Prob FI Sig
Primary	0.05	0.68	0.13	0.22	0.72	0.16	0.27
Primary	0.10	0.79	0.22	0.36	0.85	0.28	0.42
Primary	0.20	0.95	0.53	0.67	0.97	0.63	0.77
Primary	0.40	1.00	0.96	0.98	1.00	0.98	0.99
Overall	0.05	0.69	0.13	0.26	0.73	0.14	0.25
Overall	0.10	0.85	0.27	0.46	0.87	0.32	0.46
Overall	0.20	0.98	0.63	0.76	0.99	0.68	0.81
Overall	0.40	1.00	0.98	0.99	1.00	0.98	1.00

pact on precipitation based on the regression analysis to determine the fractional increase in precipitation (FI) in the primary target area, used in Section 4.1 in simulation experiments of historical data. A bootstrap analysis for Section 4.1 will also yield confidence limits on the observed value of FI. The second component of the primary analysis is the confirmation that activated seeding material has reached the target area, based on the measurements of the silver (Ag) and indium (In) at the ground during each EU (Huggins *et al*., 2008).

5.1 Targeting of seeding material

Analysis of the precipitation data provides an estimate of the physical impact of seeding. To ensure that any impact is consistent with the seeding hypothesis, snow chemistry data are also analysed as part of the primary evaluation. The basic technique is described by Chai *et al*. (1993). Snow chemistry measurements of the concentration of Ag and In in 2-cm slices of snow are taken at eight sites in the primary target area. At least two important factors need to be clarified in order to obtain quantitative estimates from the snow chemistry data. The first factor is the estimation of the time associated with each snow slice, and the second is the selection of the most appropriate variable associated with Ag and In.

The timing of the period associated with each snow slice can be estimated from alignment of each snow slice within the total snow depth of a profile against the timing tips of a collocated precipitation gauge. The number of slices that fall within an EU depends upon the rate of precipitation, but the number is likely to be small in any 5-hour period. Indeed it is possible that no well-defined snow slices can be obtained during an EU, and so chemistry data may not be available for all EUs.

Chai *et al*. (1993) suggest that the Ag:In ratio is a suitable indicator of the microphysical impact of seeding in the target area. However, this ratio can vary greatly in both seeded and unseeded cases. Such variability is partly caused by substantial variations in the background level of Ag. On the other hand, observations in the Snowy Mountains region in 2004 (Snowy Hydro Ltd, 2004) suggest that the presence of In at concentrations above 1 ppt is indicative of the presence of tracer material from a seeding generator.

Given the uncertainties associated with the chemistry measurements, it is appropriate to take a simple indicator as the variable for use in the primary analysis. For data from a specific site in the target area to be used in the chemistry analysis for a specific EU, we first require that the chemistry sample can be identified unambiguously with the specific EU. Secondly we require that the In concentration is greater than 1 ppt to indicate that material from a generator has impinged on the site. The concentration of Ag is then taken as the variable indicating whether Ag has been active in nucleating ice particles that fell in the target area. It is anticipated that this variable will be significantly larger in seeded EUs than in unseeded EUs. The peak value of Ag across all valid measurements is chosen as a sensitive indicator of activated seeding material reaching the target area. In principle, the mean value may be more statistically robust. On the other hand, the technical difficulties associated with the snow chemistry suggest that it may not be possible to obtain consistently valid estimates of Ag over the target area. The use of peak values is a pragmatic decision to identify whether activated seeding material has fallen somewhere in the target area.

In summary, the second component of the primary analysis is required to demonstrate that the peak value of Ag is on average larger during seeded EUs than in unseeded EUs. There will be two distributions of the peak value of Ag: one from seeded EUs and one from unseeded EUs. Bearing in mind that the samples of Ag may be limited in number and that the observed values of Ag can vary widely, a Wilcoxon rank-sum test (Bauer, 1972) will be used to demonstrate the differences between the means of the two distributions. The primary analysis will require the difference to be significant at the 5% level.

5.2 Interpretation of primary analysis

A fully successful outcome of SPERP will be achieved if both components of the primary analysis are achieved; that is, the precipitation analysis shows a positive seeding impact at the 10% significance level and the snow chemistry analysis that ice nuclei have been activated in the primary target area at the 5% significance level. These two tests are physically independent in that the first test seeks evidence of a macro-scale impact of seeding across the primary target area, while the second seeks evidence of microscopic impacts of seeding. Thus the second test aims to confirm the physical hypothesis (that the seeding material reaches the target area and that it activates additional ice particles) underpinning any observed increase in precipitation in the primary target area.

In Section 4.1 it is noted that the limited duration of SPERP implies that, while it is likely that a positive seeding impact will be detected, the statistical significance of the result may not be high. For example, analysis of the historical data suggests that there is a less than 30% chance that a 10% increase in precipitation will be detected with a significance level of 5%. The inclusion of the second (and independent) component of the primary analysis aims to consolidate the detection of a seeding impact at only the 10% significance level.

6. SECONDARY ANALYSES OF SEEDING EFFECTS

The purpose of the secondary analyses is to support the results of the primary analysis if it yields positive results or to help explain the sources of uncertainty if the primary results are negative or uncertain. The natural variability of precipitation and the inherent uncertainties associated with cloud seeding processes mean that there is no guarantee of a positive result from the primary analysis, and so the secondary analyses are vital elements in the overall assessment of a cloud seeding experiment such as SPERP. The secondary analyses assist our understanding of the physical basis of the impact of seeding. The secondary analyses should also provide a basis for refinement of the operational procedures used in future cloud seeding experiments in the region. It is expected that additional secondary analyses to those enumerated in this section will be carried out as part of SPERP as new data and insights are gained during the execution and analysis phases of the experiment.

The primary analysis is very specific, and there are a number of variations that would be worthwhile secondary analyses; for example:

- Repetition of primary analysis using the overall target area (rather than the primary target)
- Comparison of the distributions ES and EU, given by Eq. (2) and Eq. (3), to demonstrate the differences in the deviations from the estimated natural precipitation in the target
- Analysis of the double ratio (DR) given by Eq. (1)
- Analysis of the precipitation increase (PI) given by Eq. (4).

As SPERP extends over five years and as we know that precipitation in the Snowy Mountains region has high inter-annual variability, a useful secondary analysis is to investigate the inter-annual variations in the estimates of the parameters FI, PI and DR. The small numbers of samples means that the year-to-year estimates are not individually robust. However, the time series can identify outliers and so determine whether a result (positive or negative) is affected by a small number of "anomalous" events. Indeed, Mielke *et al*. (1981) points out that the magnitude of the double ratio can be dominated by a few extreme values, and a similar criticism could be applied to FI. This sensitivity to extreme values can be reduced either by taking the logarithm of the single ratios of target to control precipitation (Gabriel, 1999) or by using the median (rather than mean) precipitation for the area averages (Super and Heimbach, 1988). Adderley (1961) describes a number of statistical tests that can be applied to the double ratio data to estimate the significance of the result.

In theory the most direct method of assessing the impact of seeding is to simply compare the ratio of the total precipitation in the target area during seeded EUs to that during unseeded EUs. This approach would be valid provided that the precipitation in each EU is represented by a stationary random variable, with no serial correlation and with no trends or long-term variability. In practice, it is found that serial correlations, trends and long-term variability ensure that such an analysis is not statistically robust. Nonetheless, it will be instructive to compute this statistic at the conclusion of the field phase of SPERP, and Gabriel (1999) provides an analysis of the statistical properties of the "singe ratio".

All the analyses described at this stage are aimed at identifying differences between the area -average precipitation in the target area during seeded and unseeded events. The following analyses use more detailed information from SPERP to resolve spatial and temporal differences between seeded and unseeded events.

6.1 <u>Sensitivity studies of primary analysis</u>

The primary analysis described in Section 5 is aimed at determining that seeding material is found in the target area during seeded EUs and that the impact of seeding is an increase in precipitation in the target area. If a positive impact of seeding is established from the primary analysis then the following secondary analyses should provide results that enhance our understanding of the scientific basis of the positive impact. If, on the other hand, the primary analysis is inconclusive then the secondary analyses can provide supplementary evidence of the impact of seeding as well as clarifying the science of the processes associated with seeding.

One set of secondary analyses should involve repetitions of the primary analysis with additional predictor variables to help identify the sources of the seeding impact. Moreover, such analyses can sometimes demonstrate why the primary seeding impact is masked by other factors. Although these regressions are listed individually, it would be appropriate to use a stepwise regression to identify possible compounding effects of subsets of the predictor variables. Thus the primary analysis can be repeated, with additional independent variables set to:

- wind direction
- wind speed
- height of the freezing level
- temperature of cloud top
- temperature of cloud base
- ice particle size and concentration
- amount of supercooled liquid water (SLW)
- flux of SLW
- number of seeding generators used.

The ice particle size and concentration and SLW are taken from the 2D probe and radiometer at a site (Blue Calf near Guthega Dam in Figure 2) in the primary target area (Huggins *et al*., 2008), and upper-air variables are taken from the soundings at Khancoban to the west of the target area (Figure 2).

6.2 Time history of key variables

An important aspect of the secondary analyses of SPERP is the clarification of the physical processes occurring during seeding. Variables that characterise the physical processes are SLW and ice particle size and class. The source of any precipitation enhancement is the SLW, and it is measured at Blue Calf well within the target area. It may therefore be found that the level of SLW decreases during an EU, and so the ratio of SLW at the start to that at the end of an EU may be an indicator of seeding effect, if the ratio is significantly different in seeded and unseeded EUs. If an interesting result is apparent from this analysis, then a more detailed time-history of SLW over an EU should be investigated using the basic key data set (with at least half-hour time resolution).

It is not clear *a priori* how the nature of precipitation should vary during an EU, except that seeding should lead to an increase in precipitation over an EU. On the other hand, seeding is assumed to act at the microphysical level, and so it is appropriate to investigate any changes in microphysical properties over an EU. Thus, the ratio of ice particle size and concentration between the start and end of an EU should be analysed for seeded and unseeded EUs. A contingency table analysis (Press *et al*., 1986) can be carried out on changes in the particle class between the start and end of an EU, and between seeded and unseeded EUs. Results from other cloud seeding experiments (for example, Super, 1999) suggest that microphysical changes should be observed during seeded EUs.

In addition to the calculation of indicator variables, such as the ratio of SLW at the start and end of an EU, it is also important to consider the detailed time variation of key variables over the lifetime of an EU. Composite time histories, with at least half-hour resolution, should be prepared for seeded and unseeded EUs covering such variables as precipitation, SLW, particle size and particle class. It is expected that differences between the seeded and unseeded composites should be apparent.

6.3 Spatial variability of precipitation

Having considered the temporal variations in total precipitation and related variables in the target and control areas, it follows that the detailed spatial variability of the precipitation in seeded and unseeded EUs should also be examined. This comparison should involve a study of the variations of the principal components, in order to reduce the number of variables to be considered.

The technique of principal component analysis (Johnson and Wichern, 1988) is often used in meteorology and other fields to identify the main modes of variability among a set of variables. Mielke *et al*. (1971) and Smith *et al.* (1979) employ principal components to represent rainfall across the control areas of cloud seeding experiments. It is commonly found that the number of modes (or principal components) needed to describe most of the observed variability is much fewer than the number of variables. Using the data from the unseeded EUs, the principal components for the primary target, control and overall target areas can be calculated. Only the components needed to describe the bulk of the observed variability will be retained in the subsequent analysis to evaluate the impact of seeding.

Inspection of the weightings of the principal components should provide some insight on the main sources of spatial variability across the target and control areas.

If significant differences are found between the seeded and unseeded weightings, then it would be appropriate to extend the analysis to examine the temporal variability of the dominant precipitation patterns in the target and control areas in seeded and unseeded EUs. For example, Hart *et al*. (2006) use a cluster analysis to determine the dominant combinations of principal components for the spatial variability of surface ozone. This technique could be applied to identify changes in the dominant precipitation patterns in seeded and unseeded periods. In order to investigate the possible contamination of the control area by seeding, the analysis could be carried out using the overall target plus the control area as a single region.

6.4 Spatial variability of snow chemistry data

Aircraft observations of the dispersion of silver iodide (Stewart and Marwitz, 1982) and passive tracers (Bruintjes *et al*., 1995) show that well-defined plumes of seeding material are expected to evolve downwind of the ground-based generators. We therefore expect to be able to observe spatial signatures of the impacts of seeding across the target area.

The primary analysis (Section 5.1) should indicate whether the activated seeding material has been effective in the target area. Secondary analyses are proposed to investigate further the spatial and temporal variations in targeting. These analyses will involve the measurement of Ag and In at various sites across the areas where snow is expected in each EU. Snow chemistry data are collected at 9 sites in the target area, 1 site in the control area, and 1 site in the extended area.

The first analysis should extend the primary analysis to investigate the spatial variability of the targeting over all sites at which snow chemistry is obtained. For EU number t and site x, we can generally observe the peak value of the Ag, S (t,x). The primary analysis is an examination of the temporal distribution of the maximum value of S across all sites in the target area at each EU. The simplest secondary analysis is to examine the spatial pattern of S(t,x) for seeded and unseeded EUs. It is expected that the patterns will be quite different. The value of S should be uniformly close to zero at all sites in the unseeded EUs, while S should be high in the target area during the seeded EUs. The values of S should be close to zero at all times in the control and extended areas.

If it is found that the patterns of S are inconclusive or inconsistent with the basic seeding hypothesis, then a principal component analysis should be carried out. By considering the variance explained by each principal component, we can decide how many components are needed to adequately describe the spatial variation of the snow chemistry; this number is expected to be very much less than the total number of sites. For each of these key components, the weighting given to sites in the target, control and extended areas can be inspected, and so we can consider the apparent connections between variations across the target, control and extended areas.

6.5 Hydrological impacts

Since SPERP is aimed at increasing snow-pack, hydrological impacts of seeding cannot be analysed over the EUs of 5-hour duration. Therefore, hydrological impacts of seeding will be investigated through studies of differences in annual streamflow in catchments in the target area with that in potential 'control' catchments outside the target area. Three catchments in the target area and three control catchments have been identified, and a 'double-ratio' analysis will be carried out on data from these sites using historical records before 2004 as the unseeded years. However, such analyses are fraught with problems, especially because the historical record is far from being statistically stationary; major external forces such as bushfires have imposed significant spatial and temporal variations across the catchments of the region.

6.6 Persistence effects

Since cloud seeding commenced in Australia, the possibility of a persistent effect of seeding has been recognised (Bigg and Turton, 1988; Bigg, 1995), but not fully documented or explained (Long, 2001). If such effects are significant, then a controlled experiment, like SPERP and most other experiments around the world, would be unable to identify the effect of seeding. It is therefore important to conduct some investigations on the possibility of persistent effects in SPERP.

Persistent effects are defined to be physical and biological processes that cause the effects of seeding to persist well beyond the period of seeding. Thus the target area could be contaminated during unseeded periods, and even the control and extended areas could be contaminated as random winds move ice nuclei from one place to another. In this section, we concentrate on indicators of persistence in the target area. Extra-area effects are considered in Section 6.6.

The highest level of persistent effects may be seen at annual scales. In order to enhance the robustness of the results the primary analysis in Section 5 is carried out on all the available EUs. It may be interesting to carry out this analysis on each individual year, without concern for the lack of significance of each result. Indeed each result can be treated as a random variable, which would be analysed for a trend using a regression against year. This analysis is recommended earlier in Section 6 in order to identify outliers rather than trends.

The impact of any persistent effect is seen to decay with a time scale of days to months (Bigg and Turton, 1988), and so another analysis could be focused on trends within each year. For example, annual time series of the ratio of target to control precipitation for seeded and for unseeded EUs could be generated. The first test of each ensemble would be to identify any consistent trend over the five months of operations each year. The second test would be to identify differences (or lack of differences) between the ratios in the seeded and unseeded EUs.

Any persistent effects are assumed to be associated with the generation of secondary ice nuclei (Bigg, 1995). It would therefore be appropriate to investigate the time series of the microphysical measurements in each EU over the annual cycle. If persistence leads to secondary ice nuclei, then the ice nucleus concentration level should essentially become saturated as more and more secondary particles are generated. This effect should lead to a decrease in SLW as the annual cycle moves on, and indeed the frequency of seedable EUs should decrease with time. Studies of the particle size, concentration and class should also show convergence of these variables between seeded and unseeded EUs as time goes on.

6.7 Downwind effects

Section 6.4 describes how the snow chemistry data can be used to investigate some possible downwind effects of seeding. Similar analyses of the precipitation data can be carried out to determine whether there are discernible effects of seeding on the amount of precipitation downwind of the target area. The aim is to look for coherent patterns in the rainfall downwind of the target.

We first consider all the precipitation data PS(t,x) obtained during seeded EUs and the data PU(t,x) from the unseeded EUs. The time-means of these variables are PSM(x) and PUM(x). These data will display a lot of spatial variation due to the inherent variability of natural rainfall. However, the data will be more coherent spatially if they are normalised with respect to the local climatological mean value, PCM(x). (In some circumstances, it may be necessary to approximate PCM by PUM.) If the impact of seeding is primarily a multiplicative effect then the ratio

$$M(x) = PSM(x) / PCM(x)$$

provides a map of the apparent impact of seeding across all areas. The ratio

$$A(x) = PSM(x) - PCM(x)$$

provides a map of the impact if seeding leads primarily to an additive effect.

As discussed earlier, it is not expected that the maps M and A will be statistically robust because of the high natural variability of precipitation in space and time. However, it will be of interest to note if there are any consistent patterns in M and A that extend from the target area into the control or downwind areas.

Similar maps to M(x) and A(x) can be produced for the unseeded EUs during SPERP. Comparison of all these maps should help estimate the robustness of any apparent patterns in M and A. That is, the maps from the unseeded EUs should yield some estimate of the natural variability of M and A.

As for the snow chemistry in Section 6.4, it may be appropriate to use a principal component analysis to investigate changes in the patterns of the leading modes of spatial variability in the precipitation.

Having carried out these analyses for data collected in the 5-hour EUs, it would be instructive to repeat the analysis for a period following each EU to account for the transport time of any effects from the target area. From these calculations, it should be apparent whether (i) the patterns of variability in and after the EUs are similar, and (ii) there is an apparent seeding impact after an EU in the downwind area. We note that it is possible for the period after one EU to overlap with the following EU, and so care will need to be taken to restrict this analysis to distinct EUs.

7. CONCLUSIONS

This paper outlines a comprehensive suite of tests to identify and quantify the effects of seeding in the target area of SPERP in a rigorous manner. Secondary analyses use data from all the instruments in the SPERP to help understand the physical processes associated with seeding. The analyses should also help identify whether there are discernible downwind effects from the seeding, and whether there are signs of persistent seeding effects. As the analysis proceeds, it is expected that the range of secondary analyses will increase in order to explore unexpected results.

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AN ASSESSMENT OF THE ENVIRONMENTAL TOXICITY OF SILVER IODIDE – WITH REFERENCE TO A CLOUD SEEDING TRIAL IN THE SNOWY MOUNTAINS OF AUSTRALIA

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Abstract. The objectives of the Snowy Precipitation Enhancement Research Project are to determine the technical, economic and environmental feasibility of augmenting snowfalls in the Snowy Mountains region of New South Wales. The project commenced during 2004, following proclamation of special enabling legislation, the *Snowy Mountains Cloud Seeding Trial Act 2004* (NSW). Amongst other things, the legislation prescribed a target area of approximately 1000 square kilometres (mostly within the Kosciuszko National Park), and scheduled completion date of 2009. The legislation also mandated the use of silver iodide as the seeding agent. The *Snowy Mountains Cloud Seeding Trial Act 2004* (NSW) was amended in May 2008, expanding the size of the target area to around 2150 square kilometres, and authorising the continuation of cloud seeding activities until April 2015. An extensive review of the literature was undertaken prior to commencement of the project to determine if the use of the silver iodide (AgI) seeding agent would have an adverse impact on the environment. Although silver ions from water-soluble silver salts have been shown to be toxic to aquatic species, this is not the case for the insoluble silver iodide. Many studies have shown that the toxicity of silver ion in water is significantly ameliorated by the presence in water of chloride ion, carbonate ion, sulfide ion and dissolved organic carbon. In addition, silver has been shown to strongly adsorb onto particulate matter in water. Recent research has shown that silver ion concentrations in natural waters are negligibly small, and an investigation in the study area has confirmed many of these ameliorating factors to be present. Consequently the bioavailability of silver is unlikely to change from the current background levels. Extensive investigations undertaken prior to the commencement of the project confirmed background levels of silver, and the presence of many ameliorating factors known to limit toxicity of silver the ion. An analysis of ecotoxicity monitoring data collected over the first four years of the SPERP has shown that the monitoring program has sufficient power to detect any adverse trend in silver concentration well before a level of environmental concern is reached. The SPERP monitoring results to date have all shown mean concentrations of total silver to be well below any level of concern, and we consider the risk of an adverse ecotoxicological impact resulting from the use of silver iodide for this project to be negligibly small.

1. INTRODUCTION AND BACKGROUND

The Snowy Precipitation Enhancement Research Project ("SPERP") is an eleven year cloud seeding research program designed to assess the technical, economic and environmental feasibility of augmenting snowfalls in the Snowy Mountains Region of New South Wales ("NSW").

The SPERP commenced during 2004, following proclamation of special enabling legislation, the *Snowy Mountains Cloud Seeding Trial Act 2004* (NSW) (the "Act"). Amongst other things, the Act prescribed a target area of approximately 1000 square kilometres, and a scheduled completion date of 2009. The legislation also mandated the use of silver iodide (AgI) as the seeding agent.

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The Act was amended in May 2008, expanding the size of the target area to approximately 2150 square kilometres, and providing for a continuation of cloud seeding activities until April 2015.

Most of the SPERP target area lies within the Kosciuszko National Park ("KNP"), a place with legislated Australian National Heritage Significance, and also a UNESCO declared World Biosphere Reserve. A large proportion of the SPERP infrastructure and monitoring equipment is located within the KNP.

Given the environmental setting of the SPERP target area, a comprehensive investigation of the potential environmental impacts was undertaken prior to commencement of the project in 2004. This investigation included an extensive review of the literature:

- To determine if the use of AgI would result in a significant adverse impact on the environment; and
- Design a monitoring program and environmental management plan appropriate to the project setting and environmental risks identified.

In this paper we present the key elements of the literature review and its relevance to the SPERP, and provide a brief overview of the SPERP ecotoxicity monitoring program and brief interpretation of the monitoring results to date.

2. GENERAL CHEMICAL AND PHYSICAL PROPERTIES OF SILVER AND SILVER COMPOUNDS

The element silver occurs naturally in the earth's crust at a concentration of $7x10^{-2}$ mg/kg (Handbook of Chemistry and Physics) and is found in the free state as the metal, and as ores such as the sulfide, arsenide and chloride (Cotton and Wilkinson, 1962). The metal is not soluble, but salts such as silver nitrate ($AgNO_3$) are very soluble. Other silver salts, such as the sulfide (Ag_2S), chloride (AgCl) and iodide (AgI) are insoluble in water (Purcell and Peters, 1998).

Insoluble or complexed silver compounds were found to be much less toxic or essentially non-toxic to a range of terrestrial and aquatic vertebrates (Ratte, 1999). Silver thiosulfate was found to be 15,000 times less toxic, and AgCl 11,000 times less toxic than silver nitrate (Ratte, 1999). Particulate AgCl is described as virtually non-toxic (Bury *et al.* 1999; Rodgers *et al.* 1997). The importance of speciation of trace metals such as silver is well understood (Allen and Hansen 1996).

The silver cation (Ag^+) binds strongly with ligands found in natural waters, hence its toxicity will be reduced by the presence of substances with which it can associate or form covalent bonds. Some silver complexes and silver ions are readily adsorbed to particulate matter to the extent that only some 25% of total silver is estimated to be dissolved as either ion, colloid or complex (Wen *et al.* 1997).

Free silver ion is known to be fungicidal, algicidal and bactericidal at relatively low doses. Typically, bactericidal concentrations are of the order of 0.01 to 1.0 mg/L, which are well below human health hazard levels. Soluble silver compounds are used in medicine and for sterilising potable water, in part due to the sensitivity of bacterial metabolism to Ag^+ inhibition of the thiol functionality in enzymes.

2.1 Solubility of Silver Salts

Silver is known to be a particular hazard in aquatic environments, however research over the last decade and more has shown that the toxicity is essentially a function of silver speciation, rather than total dissolved silver ion concentration (Bowles *et al.* 2002, Shafer *et al.* 1998, and others). Nevertheless, a consideration of solubility is a useful starting point in an assessment of its likely bioavailability.

The solubility in water of some selected silver compounds is shown in Table 1 below.

In solution, the silver ion (Ag^+) has been shown to be toxic to aquatic plants and a range of animals (see for example Table 3), however the toxicity has been clearly demonstrated to be dependent on the chemical form, and has been shown to correlate with free ionic silver (Ag^+).

For silver salts such as silver nitrate (which dissociate strongly) the concentration of silver ion equates to the concentration of the silver salt.

Table 1: Solubility of Selected Silver Salts

Salt	Solubility (in g/100 ml)	
	Cold water	**Hot water**
Silver nitrate $AgNO_3$	122	952
Silver chloride AgCl	0.000089	0.0021
Silver iodide AgI	insoluble	insoluble
Silver sulfide Ag_2S	insoluble	insoluble

Most importantly, as Ratte (1999) has noted *inter alia*, "…the perception of high silver toxicity has long been due to the fact that most laboratory toxicity trials used $AgNO_3$, which readily dissolves releasing the highly toxic free silver ion".

Since water solubility generally controls bioavailability, silver compounds that are not readily soluble or insoluble are of less environmental concern, a point emphasized by Karen *et al.* (1999).

The concentration of Ag^+ derived from an insoluble silver salt is determined by the dissociation constant K_{SP} which (in the case of silver iodide) limits the concentration of silver ion to ca. $9x10^{-9}$ M. This means that the concentration of Ag^+ in a solution containing silver iodide cannot be greater than this value. In contrast, the Ag^+ concentration derived from silver nitrate (as shown in Table 1), is many orders of magnitude greater than that of silver iodide.

For the insoluble silver salts, the concentration of silver ion in equilibrium with the solid silver salt can be determined from the solubility product constant. The solubility product constants for the silver salts of interest are shown in Table 2 below. The calculated silver ion concentrations that would exist in aqueous solution (at equilibrium) are also shown.

The significance of the data in Table 2 is that for silver iodide, the maximum concentration of silver ion in an aqueous solution in equilibrium with solid silver iodide is $9.2x10^{-9}$ M ($9.84x10^{-7}$ g/L). In comparison, the maximum silver concentration that can be reached for silver sulfide is $2.56x10^{-17}$ M ($2.73x10^{-15}$ g/L).

This means that solid silver iodide is an extremely poor source of silver ions in solution.

3. TYPICAL LEVELS OF SILVER IN THE ENVIRONMENT

Silver is a widely distributed element, and until relatively recent times used for many applications and extensively in the photographic industry. Waste water from that industry is known to have accounted for significant silver fluxes into the environment (Hirsch, 1998). Although that use is declining, silver is being used more widely in medicinal applications. Silver ions have also been reported in waters adjacent to silver mine sites and municipal waste waster treatment plants (Kramer *et al.* 1999).

Silver is a normal trace constituent of many organisms. Terrestrial plants for example usually contain silver at less than 0.1 mg/kg dry-weight, with seeds, nuts, and fruits containing higher concentrations than other plant parts (USEPA (1980), cited in The Concise International Chemical Assessment Document 44 (2002) ("CICAD 44") and Irwin (1997).

3.1 Soils, Sediments and Water

The CICAD 44 monograph reports silver levels for various environmental matrices. For pristine, unpolluted areas such as rivers, lakes and estuaries, levels of about 0.01 µg/L were found, while for urban and industrialised areas the levels were typically 0.01 to 0.1 µg/L.

Estuarine waters in San Francisco Bay were found to range from 6 to 250 pM (0.65 to 27 ng/L), while in a number of Wisconsin rivers, silver concentrations ranged from 1.2 to 72 ng/L. Wen *et al.* (2002) note rapid removal rates in freshwater environments of the Ag^+, with a one to two weeks half-removal time even for pristine environments.

Table 2: Solubility Product Constants for Some Silver Salts (Handbook of Chemistry and Physics)

Salt	Solubility product constant K_{SP} at 25°C	Silver ion concentration (M)
Silver chloride AgCl	$1.77x10^{-10}$	$1.33x10^{-5}$
Silver iodide AgI	$8.51x10^{-17}$	$9.2x10^{-9}$
Silver sulfide Ag_2S	$6.69x10^{-50}$	$2.56x10^{-17}$ M

Silver is more bioavailable under conditions of low anion concentrations, low levels of reactive sulfide or sulfur containing ligands, low concentrations of organic ligands (humates), lower suspended sediment and lower pH (Hogstrand and Wood, 1998). In soils and fresh water, the primary silver compounds under oxidizing conditions were believed to be chlorides, bromides and iodides. Under reducing conditions the free metal and silver sulfide are the principal species (CICAD 44).

Recent published work (Bowles *et al.* 2002a) has shown that sulfides are very important regulators of silver ion concentration, even under oxic conditions.

For brackish and marine environments, increasing salinity leads to increasing concentrations of silver-chloro complexes because of the affinity of free silver ion for the chloride ion. Contemporary research has shown that levels of reactive sulfide in oxygenated natural waters are stable and high enough to ensure that silver sulfide or silver thiol complexes dominate (Bowles *et al.* 2002; Bowles *et al.* 2002a; Bielmyer *et al.* 2002).

Although they did not report silver levels in the ocean generally, Martin *et al.* (1983) showed that silver levels in the north-eastern region of the Pacific Ocean were ca. 1 pmol/kg (1.07 x 10^{-7} mg/L) and increased with depth to 23 pmol/kg at 2440 m.

Sunda and Huntsman (1998) have pointed out that photochemical and biological reduction of Ag+ leads to a substantial decrease in biological uptake and toxicity. Redox conditions play a role in determining bioavailability because the elemental form is unreactive towards complex formation. Adams and Kramer (1998) found that silver (Ag^+) is not reduced to the metal when complexed to ligands for which it has a high affinity.

Tsiouris and co-workers (2002) reported on the silver content of agricultural soils in Greece following a number of years of cloud seeding using silver iodide. They surveyed soils from two areas of Greece, one of some 200,000 ha to which 469 kg of AgI had been applied, and the other some 100,000 ha to which 361 kg AgI had been applied. However the silver concentrations found in the soils from the treated areas were within the range found for the three control areas.

Silver concentrations in the treated soils ranged from 37.2 to 44.5 µg/kg, compared with the concentrations in the control areas which ranged from 30.4 to 6.7 µg/kg.

Contamination by silver in aquatic environments has been reviewed by Flegal *et al.* (1997).

3.2 Air

Concentrations of silver in air have been reported from time to time. For example, silver concentrations in air near a smelter have been measured at 36.5 ng/m^3 and a level of 2.0 µg/m^3 in atmospheric dust (CICAD 44). Concentrations of up to 0.075 ppm (0.075 mg/kg) Ag in dust collected over the SPERP target area have been observed by Kamber *et al.* (2009). It is clear from this work that silver travels great distances from its source.

The level of silver in the air in polluted environments has been reported by Bowen (1986) for both Britain (0.0001 to 0.001 µg/m^3) and the US (0.01–0.02 µg/m^3). It is worth reiterating that the levels allowed in air are typically much higher than levels reported in snow following cloud-seeding operations (Warburton *et al.* 1995b, Snowy Hydro Limited 2008).

Estimating acceptable exposures in non-occupationally exposed populations can be difficult, as data or recommended exposures are lacking. The US workplace airborne limit for silver is 0.1 g/m^3 (NOHSC 1995).

3.3 Silver Concentrations in Snow

The metal composition of snow has also been studied in a number of environments including the US and the Antarctic. For example, Warburton *et al.* (1981) have examined trace metal levels in snow in the Antarctic and concluded that the silver found was derived from marine sources. They also reached the same conclusion following a study of levels of metals in snow across the continental US.

The natural background level of silver in snow in the Snowy Mountains Main Range was determined during the course of an earlier study on snow enhancement (Snowy Mountains Council Meteorology Working Group 1989). Typical levels were reported to be 5 ng/L (5x10^{-12} g/L) and generally were less than 2 ng/L.

Detection limits were stated to be between 2 to 5 ng/L. One site, next to an alpine village, showing between 3 to 10 times background (10 to 30 ng/L), was believed to reflect emissions from over-snow vehicles, chair lifts and fossil fuel emissions. The silver concentration in stream runoff was below the detection limit of $1x10^{-7}$ g/L (SMHEA 1993).

4. TOXICITY OF SILVER ION

The toxicity of the silver ion (Ag^+) in water to a range of aquatic species has been the subject of a great number of studies reported in the scientific literature. These studies have been comprehensively reviewed by Eisler (1996), Ratte (1999) and others.

4.1 Acute Silver Toxicity

Reviewing the toxicity of Ag^+ to algae, bacteria and macroinvertebrates, Taylor (cited by Bell and Kramer, 1999) recorded silver concentrations in the nanomolar (10 µg/L) range for threshold effects. More subtle effects were found at concentrations of 10 to 100 ng/L.

Eggs of rainbow trout continuously exposed to silver ions at 0.17 µg/L had increased embryotoxicity and hatched prematurely. The fry also had a reduced growth rate (Davies *et al.* 1978).

CICAD 44 notes that aqueous concentrations of silver in the range 1 to 5 µg/L killed sensitive species of aquatic organisms including representative species of insects, daphnids, amphipods, trout, flounder and dace. Wood *et al.* (1996) noted that 96-hr LC_{50} values for freshwater fish generally lie in the range 6.5 to 65 µg/L.

In a detailed study of the mechanism of toxicity of silver ion (using silver nitrate), Grosell *et al.* (2000) found a difference in tolerance to free silver ion between European eels and rainbow trout of 3 to 4 fold. The 96-hr LC_{50}'s ranged from 5 to 70 µg/L. For trout, the silver ion inhibited both sodium ion and chloride ion influx whereas for eels only the sodium ion influx was inhibited.

The key target of inhibition in trout and eels was found to be branchial Na^+, K^+-ATPase, an enzyme that drives uptake of Na^+ needed to counter diffusive loss of Na^+ to the hypo-osmotic environment. This is similar to the findings of Webb and Wood (1998) and Wood *et al*. (1999), who examined physiological responses in rainbow trout rather than toxicity. In each case the source of the silver ion was silver nitrate.

In the Australian context, acute silver ion toxicity is generally considered to be of the order of $1x 10^{-7}$ g/L, although the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and AMRCANZ 2000) give 0.005 µg/L as a Guideline Trigger Value ("GTV"). The Australian Drinking Water Guidelines (National Health and Medical Research Council 2004) cite a guideline value of total dissolved silver of 0.1 mg/L.

In the US the EPA has set a guideline of 4.7 µg total Ag/L in water with a hardness of 120 mg/L as the acute toxic limit. There is no chronic guideline value.

Freshwater fish and amphibians appear to be the most sensitive vertebrates to dissolved silver. The leopard frog, *Rana pipiens*, is among the most sensitive amphibians with an LC_{50} of 10 µg/L silver ion. The most sensitive fish species are even less tolerant with LC_{50}'s between 2.5 and 10 µg/L.

The CICAD 44 monograph has tabulated the range of aquatic species that have been used in toxicity tests with silver ion. The toxic silver concentration for each species is also given in CICAD 44.

4.2 Chronic Toxicity of Silver Ion

The importance of exposure pathways in sub-lethal toxicity testing of silver on zooplankton has been examined by Hook and Fisher (2001).

In their paper detailing a study on the physiology of silver ion toxicity to freshwater rainbow trout, Wood *et al.* (1996) note that during chronic exposure to 0.5 µg/L Ag^+ (as silver nitrate) the principal sub-lethal effect was a small depression of plasma Na^+ and Cl^-.

Diamond *et al.* (1990) carried out a series of chronic silver toxicity tests using a range of representative aquatic species including six invertebrates and three fish species. Their results suggested that some of the invertebrates were more sensitive than the fish species tested. As a general statement they concluded that for water of moderate hardness a chronic value could be obtained by multiplying the acute value by 0.5. Chronic tests are significantly influenced by the binding of silver ion to the food used during the test period.

Guadagnolo *et al.* (2001) showed that silver concentrations in different compartments of rainbow trout eggs were greatest just before hatch. However, they noted that the silver burden was not correlated with mortality.

5. FACTORS AFFECTING THE BIOAVAILABILITY AND TOXICITY OF SILVER

5.1 General Discussion

It is now clear from a large number of studies, that the toxicity of silver ion in water is significantly ameliorated by the presence in water of species such as chloride ion, sulfide ion, carbonate and dissolved organic carbon. In addition, silver is strongly adsorbed onto particulate matter. Where the number of moles of each of these ameliorating factors in total, is greater than the number of moles of silver added there is a negligible risk of toxicity due to silver occurring. The explanation for this is discussed below.

Bell and Kramer (1999) found that in the aqueous phase, silver at the lowest concentrations exists either as a simple sulfydrate (AgSH) or as a simple polymer HS-Ag-S-Ag-SH. Many studies have shown that because of the possibility of binding to colloids or through the formation of covalent and other complexes, the toxicity of dissolved silver ion in the environment is generally less than that found in laboratory tests.

It has recently been shown by Bianchini *et al.* (2002), Bowles *et al.* (2002) and others, that reactive sulfides occur at concentrations ranging from picomolar to nanomolar concentrations in natural oxygenated waters. These concentrations are sufficient to strongly bind soft metals such as Ag(I) (Bowles *et al.* 2002).

Bianchini *et al.* (2002) have observed that these reactive sulfides probably account for the fact that waterborne chronic silver toxicity has never been shown for natural field situations.

Attempts to extrapolate current laboratory results to field sites where silver is found have resulted in extremely low regulatory limits (Karen *et al.* 1999). Differences in laboratory test methods and local water quality characteristics are further confounding factors in the application of laboratory results to field situations.

It is worth reiterating that the source of the silver ion used in these studies was generally derived from the readily soluble silver nitrate ($AgNO_3$) which dissociates completely and gives essentially free silver ion.

In contrast to the situation found in most laboratory studies, Hogstrand and Wood (1998) note that only a small proportion of total dissolved silver in natural waters, <40%, exists in the free form, and very often will be much less.

In studies where the silver ion was derived from silver salts that are insoluble, such as silver thiosulfate $Ag_2(S_2O_3)$ and silver chloride (AgCl), the toxicity decreased significantly as the solubility decreased. No studies have been reported for silver iodide, presumably due to its insolubility. For silver chloride, for example, the 96-hr LC_{50} was reported as > 100 µg/L (Wood *et al.* 1996).

LeBlanc *et al.* (1984) reported that for fathead minnows, silver ion was 300 times more toxic than silver chloride, 15,000 times more toxic than silver sulfide and 17,500 times more toxic that the silver thiosulfate complex.

Similar results were found by Hogstrand *et al.* (1996), who also reported that toxicity decreased as hardness was increased from 50 to 250 mg $CaCO_3$/L. Increasing concentrations of humic acid were also found to decrease silver ion toxicity, as noted elsewhere in this review.

From time to time silver toxicity studies have been attempted using the insoluble silver salts, but the researchers had to resort to indirect methods to achieve the desired silver salt's concentration, see for example, Wood *et al.* (1996). A number of researchers investigating the toxicity of insoluble silver salts have attempted to circumvent the problem of the very low solubility by preparing the required silver salt in solution by chemical reaction prior to toxicity testing. For example, adding silver nitrate to a solution of sodium chloride to produce silver chloride.

This overlooks the fact that these anions, often in some excess, will act to reduce the available silver ion concentration in solution (K_{SP}) leading to AgCl (precipitate) and or may produce a silver ion complex $AgCl^{2-}$ which is negatively charged (Pavlostathis *et al.* 1998).

Each factor is discussed in more detail in the following sections.

5.2 Dissolved Organic Carbon

Many published studies have identified Dissolved Organic Carbon ("DOC") as a significant factor in reducing the bioavailability of silver ion. For example, Karen *et al.* (1999) studied the effect of DOC (as humic acid) on the toxicity of silver nitrate to rainbow trout (*Oncoryhyncus mykiss*), fathead minnows (*Pimphales promelas*) and water fleas (*Daphnia magna*).

For all three species, increased concentrations of humic acid, measured as the percentage of carbon, significantly increased the LC_{50} values in all treatments. In other words as the dissolved organic carbon concentration increased, the silver ion became much less toxic. This clearly illustrates the protective effect of DOC.

In a study on the toxicity of silver to fathead minnows and water fleas, reported by Erickson *et al.* (1998), the researchers were able to demonstrate that for the fathead minnows, increasing the organic carbon to 2.5 mg C/L increased the 96-hr LC_{50} by 350%, and increasing organic carbon to 10 mg C/L increased the 96-hr LC_{50} by 450%.

As they noted, this is similar to other metals for which complexation by organic matter also reduces bioavailability.

Furthermore, Erickson *et al.* (1998) also found that the toxicity of silver ion to both organisms was much reduced when water from the St. Louis River was used in the test rather than normal laboratory water. The reduction in toxicity was some 60-fold for water fleas, although this is regarded as a more sensitive organism than the fathead minnow. The researchers surmised that the higher organic carbon content in the St. Louis River water was responsible for the reduced toxicity.

The data are shown in Table 3 below.

In a study of silver complexation in river waters in central New York, Whitlow and Rice (1985) had noted that the determined values for silver in the river waters were lower than calculated from a speciation model. They attributed the discrepancy to additional complexes formed with dissolved organic carbon and or colloids that were not further identified.

The importance of DOC complexes with silver, has also been emphasized by Hogstrand and Wood (1998) in their review of the bioavailability, physiology and toxicity of silver in fish. They noted that Janes and Playle (1995) have estimated a log K ~ 9 for natural DOC collected from a marsh.

The greater protectiveness of DOC compared with that due to hardness, is seen as particularly important for regions of soft-water which contain much organic carbon.

Table 3: Acute toxicity of silver nitrate to juvenile fathead minnows and < 1-d-old Daphnia magna in laboratory water and St. Louis River water

Test Organism	Test Water	LC_{50}[1] (mg Ag/L)	95 % Confidence Limits
Pimphales promelas	Laboratory	10.4	8.6 – 12.5
	River	106	97 – 114
Daphnia magna	Laboratory	0.58	0.56 – 0.61
	River	35	32 - 39

[1]LC_{50} = median lethal concentration

Because of the importance of DOC in ameliorating silver toxicity, it is relevant to note an important example of a so-called "hot moment" (McClain *et al.* 2003) which could be expected to occur in the KNP. A "hot moment" is an isolated zone of enhanced biogeochemical cycling (referred to as a "hotspot"), which is itself "hot" in a temporal dimension (referred to as a "hot moment").

In this specific case, the "hot moment" is the pulse of DOC that leaches from near-stream soils during snowmelt in alpine areas and which would be expected to play a key role in binding any silver ions arising from the silver iodide associated with the snowpack.

Boyer *et al.* (2000) reported that in Deer Creek, Colorado, DOC increased rapidly from 1 to more than 4 mg/L on initiation of snowmelt, remained high for about one month then decreased quickly as runoff peaked. The effect of snowmelt is to flush DOC accumulated under the snowpack, and this DOC then binds to silver.

5.3 Chloride Ion and other complexes

In their review, Hogstrand and Wood (1998) point out that the ability of native chloride and sulfide to significantly reduce the toxicity of silver by precipitating it out of solution in natural waters should not be overlooked. Silver ion forms complexes with chloride ion including $AgCl_2^-$, $AgCl_3^{2-}$ and $AgCl_4^{3-}$.

Increasing the chloride ion concentrations will increase the concentration of these chlorocomplexes. There is some evidence that the neutral AgCl may represent the most bioavailable form as suggested by Bryan and Langston (1992) and others.

It has been suggested by some researchers that chloride levels >35 mg/L will affect silver solubility in fresh waters. However, as we now show lower concentrations can also be effective.

In their study examining the toxicity of silver to seawater-acclimated rainbow trout, Ferguson and Hogstrand (1998) note that in brackish water, with a typical chloride concentration of 50 mM NaCl (1775 mg/L Cl^-), total silver at a concentration of 0.1 g/L was not toxic over 168 hr. These silver concentrations however are well outside the ranges expected in the planned trial.

In a study on rainbow trout (*Oncorhynchus mykiss*), Galvez and Wood (1997) showed that increasing calcium by 100-fold increased the median lethal time by a factor of 10. However, increasing chloride ion levels by 100-fold increased the median lethal time by a factor of at least 100-fold. As they observed in their paper, "… complexation processes are expected to reduce silver ion concentrations to well below acute toxicity concentrations".

The importance of complexes in reducing silver toxicity is well illustrated in the study of silver thiosulfate toxicity to freshwater rainbow trout (Wood *et al.* 1996). In this study, rainbow trout were able to tolerate a 3000-fold higher concentration of silver where it was complexed as $Ag(S_2O_3)^{n-}$ compared with free Ag^+ from silver nitrate.

During exposure to silver thiosulfate there was a doubling of silver concentrations compared with that found for silver nitrate. This may reflect the increased octanol-water partition coefficient of these neutral species (Ratte 1999, Reinfelder and Chang 1999, and Fortin and Campbell 2000).

5.4 Sulfides and Sulfur Containing Ligands

There is a growing recognition that because reactive sulfides are found in oxic as well as anoxic environments, silver -"sulfide" complexes may have a greater impact in reducing acute silver toxicity than many, if not most, of the factors described above.

Probably the most important chemical fact to note is the strength of the silver – sulfur bond. The presence in the environment of tiny concentrations of inorganic sulfides and organic mercaptans plays a major role in the environmental behaviour of silver. As mentioned earlier, silver binds strongly to the sulfide ion (see K_{SP} data), which results in nanogram per litre concentrations of aqueous dissolved silver. This outcome is also found for sulfide ion associated with inorganic and organic species.

Occluded mercaptans as well as HS^- or H_2S trapped within colloids or particulate matter will act as reaction sites for Ag^+. Silver sorbs rapidly onto amorphous FeS giving an aqueous silver ion concentration similar to that for Ag_2S solubility.

Trace levels of dissolved silver in the presence of FeS are rapidly adsorbed (Bell and Kramer 1999) with any silver remaining in solution as silver sulfide. Silver thiolate complexes are often the dominant dissolved species in waters with high levels of natural organic matter (Adams and Kramer 1998).

At low silver concentrations, when silver is adsorbed onto sulfide particles, the local presence of a high concentration of an organic mercaptan can lead to an exchange reaction leading to the formation of a silver thiolate. This process will move silver into solution phase as either a silver thiolate or as a silver-other-metal thiolate at levels of the order of <5 nM. This “dissolved silver” is not bioavailable however.

In their study, Adams and Kramer (1998) showed (using X-Ray Diffraction) that dissolved silver ion in the presence of amorphous iron sulfide rapidly equilibrated, to give ultra-trace levels (~ 5 ng/L) of silver ion. This concentration is consistent with that calculated from the solubility product constant (see earlier). They also calculated that sulfur containing ligands, especially thiols, are more important than chloride until the total sulfur species is less than 10^{-13} M (~3.2×10^{-9} mg/L).

Bielmyer *et al.* (2002) have argued that silver thiol complexes dominate all other dissolved silver species when organic molecules containing sulfur are present and other metal sulfide concentrations are negligible. Silver thiol complexes are bioavailable due to increased lipophilicity and have shown chronic effects in *Ceriodaphnia dubia* at lower concentrations than for silver ion.

In a comprehensive (ultra-clean) study of silver concentrations in tailings and stream sediments and rooted vegetation associated with an old mining site in Canada, Kramer *et al.* (1999) looked at, *inter alia*, the association of silver to acid volatile sulfide (“AVS”) ratio. They found AVS at the nanomolar concentration in most samples.

The procedure they used detected many colloidal sulfides, soluble sulfides and part of the polysulfides but not the thiols. Concentrations ranged from <1 nM to 570 nM. Interestingly, corresponding dissolved oxygen levels were between 6.8 to 10.2 mg/L with dissolved organic carbon levels of 3.2 to18.7 mg/L. They noted that, although all water samples were nearly saturated with respect to atmospheric oxygen, over half the samples had measurable AVS ranging from tens to hundreds of nM.

They concluded that the silver is strongly bound to the solid phase and is at low nanogram per litre concentrations in the apparent soluble phase. Their data indicate that the majority of the operationally defined soluble (<0.45 µm) silver ion occurs in the colloidal phase. One conclusion from their study was that as long as the AVS (mole) >Ag^+ (mole), Ag^+ should not accumulate in plant material.

Hirsch (1998) looked at the toxicity of silver sulfide to the juvenile freshwater amphipod (*Hyalella azteca*), an epibenthic organism that burrows into the sediment surface. Using sediments from a non-contaminated source, spiked with varying amounts of silver sulfide, there was no difference found in survival rates between treatments and controls up to a level of silver of 753.3 mg Ag/kg sediment. The sediments had average AVS concentrations of 5.35 µmol/gm and total organic carbon values of the order of 1.5%. Hirsch noted that the concentration of AVS in the sediment would have favoured the formation of Ag_2S had any free silver ion been present. The relationship between acid volatile sulfides and metals is important in predicting bioaccumulation in benthic macroinvertebrates (Ankley 1996).

Call *et al.* (1999) showed that the capacity of river sediments to bind silver effectively occurs at relatively low levels of Total Organic Carbon (“TOC”) and acid volatile sulfides. This capability is important in reducing silver bioavailability in pore waters to which benthic organisms would be exposed.

Sediments were spiked with silver nitrate until silver ion was detected in the pore water. One sediment, with a TOC of 0.87% and an AVS of < 0.1 µmol/g was spiked at 2.2 g Ag per kilogram before silver appeared in the pore water.

In contrast, the other sediment with a TOC of 0.22% and AVS < 0.1 µmol/g showed silver in the pore water at a spiking level of only 0.08 g Ag /kg. The authors believed that the differences might in part be explained by the interaction of several sediment characteristics such as particle size distribution and geochemical composition.

It should be noted that this work involved sediments, which are very likely to be anoxic, whereas the work reported by Kramer *et al.* (1999) involved oxic waters which were shown to contain AVS.

Other research groups have found that in more oxic sediments, amorphous Fe oxides or manganese oxides or colloids are important sinks for binding silver and other metals.

Because of the large stability constants found for metals such as silver sulfide, the importance of a pool of sulfides including zinc and iron sulfides (AVS) in detoxifying metals such as silver in natural waters cannot be overstated.

In a recent study of multinuclear sulfide clusters in natural waters, Rezan *et al.* (2000), showed that the most abundant metal sulfides were iron sulfides and that they were composed mainly of a soluble FeS cluster. They found that FeS predominated in rivers that drained less-urbanised watersheds. Metal sulfide clusters were kinetically stable and as a result persisted in oxic waters.

On the basis of their observations it was suggested (Rezan *et al.* 2000) that sulfur complexation might dramatically lower the acute toxicity of "b"-class metals including silver.

5.5 Hardness

Water hardness, principally in the form of calcium, was recognised by the USEPA (1980) (cited in CICAD 44) as having a critical role in reducing harm to aquatic organisms from acute silver toxicity.

The maximum total recoverable silver in water was related to hardness by the equation:

$$\text{Max. total recoverable Ag } (\mu g/L) = e^{(1.72[\ln \text{hardness}] - 6.52)}$$

More recently however, it has become clear that this expression is under-protective at high hardness levels, and is overly conservative where waters have low hardness (Galvez and Wood, 1997). In the study reported by Galvez and Wood (1997), they found that the protective effect of chloride is much more significant than that due to calcium. CICAD 44 notes that silver is less toxic to fathead minnows when water hardness increased from 50 to 250 mg $CaCO_3$/L.

The current view however is that hardness due to calcium ion is now thought to be less effective in modifying the toxicity of silver ion than the other factors discussed, unless it is the only significant ameliorating factor present.

Recent work by Bianchini and Wood (2008) identified both hardness and sulfides as being important in protecting against lethal acute effects as well as chronic silver toxicity in terms of mortality, whereas sulfide alone showed a protective effect against the sub-lethal chronic silver effects on growth and reproduction.

5.6 Colloids

The strong affinity of silver for suspended particulates in river and estuarine water was demonstrated in a study reported by Wen *et al.* (1997). In experiments to determine phase speciation, they used cross-flow ultrafiltration to separate water samples into particulate >0.45 µm or >0.1 µm, colloidal (0.1 – 0.45 µm), or truly dissolved (<0.1 µm) fractions. They were able to show that between 33-89% of the silver was bound to the particulate fraction.

The high affinity of silver for suspended particulates was reflected by a high mean particle/water partition coefficient of log K_D = 5.0. They also noted that the ratio of colloidal silver to filter-passing silver was similar to the ratio of colloidal organic carbon to total dissolved organic carbon.

They further concluded that silver is complexed by organic macromolecules and that the functional groups with affinity for silver are evenly distributed across the different molecular weight fractions.

In their detailed study, the particulate silver was found to be associated mainly with an iron – manganese oxyhydroxide/sulfide phase. Because of the close relationship between silver and iron in both the colloidal and particulate phases, a common surface complex (believed to be sulphydryl groups) was proposed. Of particular relevance to this project was their finding that particulate silver from riverine inputs was rapidly removed from water.

Further support for the effectiveness of colloids in removing silver from water is provided by Shafer *et al.* (1998) and Benoit *et al.* (1994). They examined the removal of silver from influent water in Publicly Owned Treatment Works and found that more than 94% of the influent silver was removed during treatment. The percentage of filterable silver was directly related to DOC.

The amount of silver passing a 0.4 μm filter (often regarded as the dissolved fraction) represented just 2% of the total Ag in the sample.

They found that 92% of dissolved silver was associated with colloidal particles. In their study, DOC concentrations were typically 4.5 to 11.6 mg/L, and log K_D values ranged between 4.75 and 6.14.

A useful illustration of the operational significance of all these factors on the bioavailability of silver, following the release of silver iodide into the environment over a 40 year period, is shown in the report on the Mokelumne watershed lake water and sediment survey (Stone *et al.* 1995).

This report showed that, although there were detectable concentrations of silver in the lake sediments (average value 0.035 mg/kg), the silver level in the watershed averaged 6.7×10^{-12} g Ag/mL.

Importantly, no detectable free silver could be measured in leachates of the sediment samples at pH 5 showing that the silver in the sediments was tightly bound.

6. POTENTIAL ENVIRONMENTAL FATE

6.1 Uptake of Silver by Terrestrial Plants

Accumulation of silver by terrestrial plants is low even when the plants are grown on silver amended sewage sludge or mine spoil (Hirsch, 1998). Where uptake occurs, the silver is found mainly in the root systems (Ratte 1999). As a general rule most of the toxicity testing on plants, reported in the recent literature, involved the use of appropriate concentrations of silver nitrate giving (Ag^+) concentrations in the mg/L (ppm) range.

In sensitive plant species, growth and germination were reported to be affected at a concentration of 7.5 mg/kg with germination the most sensitive stage. As expected, soluble silver salts were markedly more toxic than insoluble silver salts.

Silver uptake by seedlings of perennial ryegrass (*Lolium perenne L.*) and white clover (*Trifolium repens L.*) was studied in detail by Ward *et al.* (1979). They found that some 90% of the silver was immobilised in the root systems of both species.

Uptake was rapid and essentially complete after 10 days. While the silver concentrations in the roots of both species approached that of the added silver, the aerial parts of the plants were much lower, and seldom exceeded 10% of that in the roots.

The silver concentrations used in this study ranged from 0 to 1000 mg/L (ppm) which are significantly higher than expected for the SPERP. More importantly, they concluded that there would be little danger to stock grazing on pastures with these high levels of plant silver.

In some much earlier work Freeman (1979), looked at silver levels in algae and emergent aquatic plants in an alpine lake in Colorado and found concentrations of the order of 0 to 2.6 mg/kg in several species. However, this work was well before the introduction of ultra-trace techniques and no detail was given of the analytical procedures used.

Hirsch (1998) has looked at the germination of a range of crop plants grown on soils amended with silver-laden sludge derived from photographic industry waste. It was found that germination or emergence in all crop species studied was not adversely affected. And further, for silver levels up to 106 mg Ag/kg in the sludge, the growth and yield of corn and oats was not different from the controls.

Hirsch (1998) also reported that yields of plant species such as lettuce, cabbage and spinach were affected at amended soil levels greater than 14 mg Ag/kg. With the exception of lettuce, there was no difference in silver concentrations in the tissues of the treated crops compared with the controls. Hirsch's conclusion was that land application of silver rich sludge would not adversely affect plant growth.

Sensitive aquatic plants were found to grow poorly at 3.3 to 8.2 μg Ag/L and died at concentrations greater than 130 μg Ag/L (CICAD 44).

6.2 Bioaccumulation of Silver in Organisms

Bioaccumulation of substances occurs via body surfaces (often referred to as bioconcentration) and through intake of food often referred to as biomagnification). Bioconcentration factors ("BCFs") are given by the ratio of the concentration of the compound in the organism with that of the surrounding medium, usually water (also food). For terrestrial plants, uptake is generally through the roots and leaves. For terrestrial animals uptake occurs via the surface or the gastrointestinal tract ("GIT").

For aquatic vertebrates uptake is possible via the body surface or the GIT, or in the case of fish, via the gills. Uptake from water can be due to passive diffusion, active transport and adsorption. There is no significant evidence of substantial silver uptake via food for aquatic organisms.

It is clear that BCFs appear to be correlated with the solubility of the silver compound.

In his review of bioaccumulation and toxicity of silver compounds, Ratte (1999) has tabulated the silver bioconcentration factors, the silver compound and the species studied.

The US EPA (1980) (cited in CICAD 44) has reported BCFs of 210 in diatoms, 240 in brown algae, 330 in mussels, 2300 in scallops and 18700 in oysters. In contrast, bluegills showed no significant accumulation when exposed to 0.5 µg/L silver (Coleman and Cearley, 1974).

Concern over the possible accumulation of silver in both marine and freshwater environments has arisen because of bioaccumulation observed in benthic organisms (Bell and Kramer, 1999).

Silver is a soft or "b"-class metal and would be expected to coordinate and complex strongly with soft bases which, in this context, are organic molecules containing sulfur (S) or nitrogen (N) atoms. Silver exhibits a great affinity for sulfur-containing ligands (organic compounds) (Frausto da Silva and Williams 1991).

This is reflected in the higher stability constants (K) between silver ion (Ag^+) and organosulfur complexes such as thiols, $K \sim 10^{13}$ compared to those of Ag^+ carboxylate complexes (monodicarboxylic acids, $K \sim 10^2 – 10^4$ and polycarboxylates such as EDTA, $K \sim 10^7$).

In biological systems thiolate complexes include mercaptans, glutathione and cysteine and for many of these complexes stability constants are available (Bell and Kramer 1999). Higher stability constants indicate strong binding between silver and the complexing agent which in turn decreases bioavailability.

Fisher and Wang(1998), in their review of trophic transfer of silver, note that trophic transfer has been shown to be insignificant in several aquatic animals, for example particularly oysters and shrimp. Oysters were able to accumulate dissolved silver but did not acquire silver from various phytoplankton species. Shrimp could accumulate dissolved silver but did not acquire silver from planktonic or detrital food.

Uptake from marine sediments was reported by Bryan and Langston (1992), leading to the view that sediments are an important source of silver. However, in a reported laboratory exposure experiment over some 20 days, net uptake of silver only occurred when the concentration of silver in the sediment exceeded 1 mg/kg.

Connell *et al.* (1991) found that incorporated silver was tightly bound to the cell membrane and was not released by mechanical disruption. They also observed that food-chain biomagnification was unlikely at concentrations normally found in the environment.

6.3 Bioaccumulation by Algae, Pelagic and Benthic Food Chains

The accumulation of dissolved silver into algae is very high. Uptake into algal cells would be expected to influence biogeochemical cycling if the algae are subsequently consumed by animals. Algae show BCFs, although differences in experimental conditions can significantly influence the value.

In the pelagic food chain, typically including protozoans, rotifers and small crustaceans, significant bioaccumulation is not likely. For example, bioconcentration was markedly lower in daphnids than in algae.

The benthic food chain, typically including snails, some insect larvae, bivalves and worms, feed on algae on the bottom of the water body. For gammarids such as midge larvae and chironomids, the BCF exceeded the BCF found for daphnids.

In contrast, bivalves showed BCFs that corresponded to the daphnid BCF.

6.4 Bioaccumulation by Fish

Pelagic carnivores such as fathead minnows showed low bioaccumulation potential compared with their prey. Other studies involving fish have shown that concentration of metals was dependent on its contact with sediment or contact with the sediment by its prey, rather than trophic position within the food chain (Ratte 1999).

The toxicity of rainbow trout to dissolved silver has been the subject of many studies into the toxicity of silver ion. These studies have generally used the highly soluble silver nitrate and have largely focused on laboratory conditions although some researchers have considered the effect of water parameters such as hardness and DOC (Hogstrand and Wood 1998, Erickson *et al.* 1998, Rodgers *et al.* 1997).

Where bioavailability in the presence of these ameliorating factors has been considered, toxicity was shown to be reduced.

6.5 Bioaccumulation by Terrestrial Animals

Studies into the effects of silver ions on terrestrial species are limited. Exposure of earthworms to increasing concentrations of Ag_2S in artificial soil did not lead to an accumulation of silver, but there was evidence of reduced growth. The No Observed Effect Concentration ("NOEC") was given as 62 mg Ag/kg (Hirsch 1998).

Silver has also been found in fur seals and sea lions in the North Pacific Ocean (Saeki *et al.* 2001). Some 70% of the body burden was found in the liver with the remaining silver associated with body hair and other organs. Their data suggested that bioaccumulation increased with age.

Given the extremely low levels of bioavailable silver expected to arise from the trial, toxic effects and bioaccumulation for terrestrial species are considered unlikely.

7. SNOWY PRECIPITATION ENHANCEMENT RESEARCH PROJECT

The Act requires that the SPERP must only use silver iodide as the ice nucleating agent. This is dispensed through a network of 23 ground generators placed to the west of the main range of the Snowy Mountains.

When in operational mode, each generator burns a ~2% solution of silver iodide in acetone (w/w), at a rate of 1.25 litres per hour. Approximately 20g of silver iodide with an average particle size of 0.06μm is released from each generator for each hour of operation.

The average mass of silver iodide used each year (2004 through 2008) is 17.6 kg, dispensed from 13 separate locations across a target area of approximately 1000 square kilometres. A summary of reagent use statistics are shown in Table 4 below.

A good overview of the SPERP can be found in Heggli *et al.* (2005) and Huggins *et al.* (2008), although the reader should note that these papers pre-date the project expansion described in Section 1 above.

7.1 Preliminary Investigations

Given the location and environmental significance of the SPERP target area, an extensive assessment of the ameliorating factors described in Section 5 above was undertaken prior to the commencement of cloud seeding experiments. The factors examined are shown in Table 5.

Samples were collected from a large number of sites including proposed generator locations, and likely points of accumulation in the landscape. Background levels of total and bioavailable silver were also determined for all of these samples.

Table 4: SPERP AgI Use Statistics[3]

Year	Total mass of AgI dispensed (kg)
2004[4]	20.1
2005[5]	23.2
2006	6.8
2007	15.6
2008	20.1

[3] These statistics relate to the original target area of approximately 1000 km^2
[4] Twelve generators in operation during 2004
[5] Thirteen generators in operation for the period 2005 through 2008

In the following Sections we discuss the relevance of these factors to the SPERP.

7.2 Soil and Soil Organic Matter

Organic matter in soil will bind silver ions in the same way as dissolved organic matter in water binds silver ion, as discussed in detail earlier. As part of a recent study on the influence of aeolian dust deposits in the KNP, Johnston (2001) reported that the percentage of organic carbon in the ten centimetres of soil profiles from Mt. Clark and Mt. Twynam (within the KNP) to be 12.1% and 12.7% respectively. Concentrations of organic matter of this order would be expected to be very significant in immobilising silver in the ecosystem.
The pH of soils in the Kosciuszko alpine area, also reported by Johnston (2001), fall within the range (pH 4.5 – 4.8) levels found by Spark *et al.* (1997) to facilitate formation of metal-humate species due to increased dissolution of humic substances.

Costin (ISC 2002) has noted that the alpine humus soils in the KNP reflect an accumulation of soil colloids and nutrients in the surface soils. And, that the "soil building processes involve recycling by deep-rooted snow grasses and other major herbs (possibly in association with soil mycorrhiza), accretion of windblown dusts, and vigorous decomposition and redistribution of plant remains by soil organisms, particularly invertebrates…".

The role of groundwater in soils is controlling the spreading and filtering of catchment run-off before it enters streams was noted by Costin (ISC, 2002).

Silver also adsorbs to manganese dioxide, ferric compounds and clay minerals meaning that these compounds are involved in silver sequestration in soil and sediments.

Data reported by Johnston (2001) confirms a modest cation exchange capacity ("CEC") for soils in the KNP. This means that some binding of silver to clay minerals would be expected for the soils in the study area.

The relatively high organic nature of the soils in the SPERP target area (see Snowy Hydro Limited 2005 and others) suggests that DOC and soil organic matter will be one of the most significant factors regulating the bioavailability of silver ion. Concentrations of organic matter of this order would be expected to be very significant in immobilising silver in the ecosystem.

The significance and relevance of each of the ameliorating factors in regulating the bioavailability of silver ion in the present trial cannot be overstated.

7.3 Water chemistry

In the Independent Scientific Committee's ("ISC") report (ISC 2002) on the KNP, Marchant (Chapter 6) has noted that the water in the alpine lakes is very fresh, with extremely low salinities (< 3 ppm) and slightly acid with pH's ranging from 6.0 to 6.2. Furthermore, at least for Lake Albina and Blue Lake, significant amounts of decomposed leaves and twigs occurred in the bottom sediments.

Table 5: Assessment of Ameliorating Factors

Description	Acronym	Matrix Assessed
Chloride	Cl	Soil, Water
Specific Conductance	SPC	Water
Dissolved Organic Carbon	DOC	Water
Hardness	HD	Water
pH	pH	Soil, Water
Cation Exchange Capacity	CEC	Soil
Total Organic Carbon	TOC	Soil

Marchant also notes that "… it is well known that water quality problems (e.g. low water temperatures, low oxygen concentrations and high concentrations of toxins such as hydrogen sulfide) can occur below the deep dams that release bottom water". This indicates, qualitatively at least, that sulfur-containing ligands are present in the ecosystem.

The significance and relevance of each of these ameliorating factors in regulating the bioavailability of silver ion in the present trial cannot be overstated.

7.4 Silver Levels in Snow

Cloud seeding operations make very small additions of the insoluble silver iodide to the KNP. For silver iodide to mobilise in the environment, it must first dissolve and dissociate, leading to extremely low levels of silver ions. The silver ions produced will then be subject to the factors described below, which in turn act to ameliorate their bioavailability.

The proportion of this ultra-trace concentration of added silver ion that would become bioavailable will be determined by the relative importance of each of the ameliorating factors described in detail below. These factors affect the bioavailability of silver ions in both soil and water environments.

Warburton and co-workers (1985) have shown that if silver iodide aerosols are released at rates of 10^{13} to 10^{15} nuclei per second, the concentration of silver found in the precipitation is in the range 10^{-12} to 10^{-9} g/ml (corresponding to one part per trillion (ppt) to one part per billion (ppb) in snow). This concentration was similar to that found in a much earlier study by Warburton and Young (1972), where snow in seeded areas had a median concentration of the order of $5x10^{-9}$ M silver.

In separate studies associated with cloud seeding experiments around Lake Almanor (US), Warburton and co-workers (1995a, 1995b), found the amount of silver deposited in snow ranged from about 8 $x10^{-12}$ to 245 $x10^{-12}$ g/cm^2.

7.5 Other Relevant Factors Affecting the Fate of Silver

The study area has been subjected to extensive bushfires in the past, the most recent notable example having occurred in the summer of 2003. During the early planning stages for the SPERP, some stakeholders raised concerns with respect to likely environmental fate of any silver iodide as a result of bushfire.

It is reasonable to expect that any silver iodide associated with cloud seeding reaching the ground would be incorporated into the top organic-rich soil layer (in the first instance). The miniscule number of silver ions arising from dissociation of the solid silver iodide would then become bound to humic and other components as described above. While combustion would presumably destroy the organic matter to which the silver iodide is bound, the trace levels of silver iodide would remain in the ash or be volatilised depending on fire temperature.

The melting point of silver iodide is recorded as 558°C (Handbook of Chemistry and Physics) and its boiling point as 1506°C and it has a negligible vapour pressure (MSDS). At the levels this compound is being used in snow augmentation, it is difficult to see any environmental issue arising from the impact of fire. It is possible that at extremely high flame temperatures there could be some dissociation of silver iodide but the levels of iodine atoms formed would be insignificant.

8. MONITORING PROGRAM

8.1 Objectives

The specific objectives of the SPERP ecotoxicity monitoring program (Snowy Hydro Limited 2008b) are:

- To be able to detect any increases in the concentrations of silver in environmental matrices, compared to baseline concentrations and compared to natural variability;
- To be able to assess concentrations of silver against the relevant GTV for further investigation if required; and
- To provide an early warning of any adverse trend in silver concentration, allowing for timely and effective management intervention.

8.2 Overview of Monitoring

As described earlier in this paper, the following work was undertaken prior to commencement of the SPERP

- An assessment of factors known to ameliorate toxicity of silver ion; and
- Determination of background levels for total silver and bio-available silver.

This data was analysed to confirm that the presence of the ameliorating factors discussed earlier in this paper, and to verify that GTV for silver in each environmental matrix to be monitored was appropriate.

Annual monitoring of total silver concentrations in soils, sediments, potable water supplies and peat and moss is undertaken at a large number of locations across and downwind of the study area. These include:

- Generator sites (sites from which silver iodide is dispensed);
- Potential points of accumulation in the landscape (for example sediments in glacial alpine lakes, peat bogs, stream sediments);
- Potable water supplies; and
- Randomly selected locations across the study area.

Monitoring of potable water supplies is undertaken on a number of occasions throughout the winter, typically following significant snowfall and run-off events. Monitoring of other matrices commences following the cessation of cloud seeding operations for the season, usually in October each year (Snowy Hydro Limited 2008b).

8.3 Preliminary Interpretation of Results

A statistical analysis of the silver data for various environmental matrices being monitored was undertaken for the period 2004 through 2007. The data were compared to the relevant GTVs for each matrix, and also between periods and locations of sampling.

A statistical power analysis undertaken for generator sites (the locations from where silver iodide is dispensed, and the most likely to show any change) was used to assess the likelihood of being able to detect an increase in concentrations of silver before the GTV was reached (Snowy Hydro Limited 2008a).

The key outcomes of these investigations include the following:

- Measurable concentrations of silver occurred at all locations and in all matrices sampled prior to commencement of the cloud seeding trial. Importantly, there was a measurable baseline of silver present in the local environment prior to commencement of the SPERP;
- The sampling design had sufficient power to detect any statistically significant increase well before the GTV was reached. This provides an important level of confidence to stakeholders that management intervention could be implemented in a timely manner if ever required;
- The analysis of the silver data showed mean concentrations and upper 95% confidence limits of silver to all be well below the GTV in all matrices, and all locations and for all periods of sampling;
- Generally, mean concentrations of silver were less than 20% of the relevant GTV, and in many cases less than 10% of the GTV.

Detailed results and interpretations from the monitoring program for the period 2004 through 2009 (prior to expansion of the SPERP target area) are presently being prepared for publication.

9. CONCLUSIONS

The Act mandates that the SPERP must use silver iodide as the seeding agent. We consider the risk of an adverse ecotoxicological impact for the project to be negligibly small for the following reasons:

- Although silver ions from soluble silver salts have been shown to be toxic to aquatic species, this is not the case for the insoluble silver iodide;
- Since water solubility generally controls bioavailability, silver compounds that are not readily soluble or insoluble are of much less environmental concern;
- Where silver toxicity studies have been attempted using the insoluble silver salts, researchers have had to resort to indirect

methods to achieve the desired concentration of silver ion;

- The majority of studies into acute and chronic effects of silver ion have used soluble silver nitrate;
- A number of studies have shown that the toxicity of silver ion in water is significantly ameliorated by the presence in water of chloride ion, carbonate ion, sulfide ion (reactive and other forms) and dissolved organic carbon. In addition, silver is strongly adsorbed onto particulate matter in water. Findings from recent studies point to the fact that silver ion concentrations in natural waters are negligibly small;
- The study by Johnston (2001) has shown that many of these factors exist in the KNP and, as a result, the bioavailability of silver would be expected to be of the order of current background levels;
- The research results reported by Johnston have been validated by extensive additional sampling and analyses for the relevant parameters;
- Background levels of silver occurring in snow in the KNP are generally less than $2x10^{-9}$ g/L, while background level of silver in stream runoff was below the detection limit of 1x10 g/L for silver. This level is several orders of magnitude below the chronic toxicity level;
- The Snowy Hydro Limited (2005) assessment of background levels also showed silver to be present in the environment at concentrations ranging from 0.47 mg kg^{-1} in soil at generator sites to 0.09 mg kg^{-1} in alpine humus in the target area;
- The average mass of silver iodide used each year is 17.6 kg, dispensed from 13 separate locations across a target area of approximately 1000 square kilometres. The likelihood of any environmental impact, even in potential zones of accumulation is minimal because of the small quantities and because silver iodide is not water soluble and not readily bioavailable. Hence no acute or chronic toxic effects are expected;
- The SPERP monitoring program has a high probability of detecting any adverse trend in silver concentration well before the GTV is reached. A statistical power analysis of the SPERP monitoring data for generator sites has shown the monitoring design to have sufficient power to detect any statistically significant change in silver concentrations; and
- Mean silver concentrations have all been shown to be well below the GTV for all matrices, at all locations and for periods of sampling during the SPERP.

The conclusion of this review of the literature, assessment of ameliorating factors and interpretation of results to date provides compelling evidence that the use of silver iodide for the SPERP will not result in an adverse ecotoxicological impact on the environment of the study area.

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AN 'AEROSOL EFFECT' DETECTED IN WINTER OROGRAPHIC CLOUDS BUT AN EFFECT ON PRECIPITATION COULD NOT BE DETERMINED

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Abstract. Analyses of a 22-year record (1984/85 - 2005/06) of wintertime (December - February) measurements at Storm Peak Laboratory (SPL) in the northern Colorado Rocky Mountains have shown aerosol particle concentrations were directly related to cloud droplet concentrations, the droplet concentrations were inversely related to mean diameters and the mean diameters were not related to the precipitation rates. A direct relationship between mean diameters and precipitation rates was expected due to snow crystal riming; the measurements were too variable to establish a relationship. Additionally, no significant trends in precipitation rate and snowfall water content were detected; at least a 40-year record is required. Nevertheless, the record defines average wintertime cloud and precipitation properties at SPL.

1. INTRODUCTION

At Storm Peak Laboratory (SPL) in the northern Colorado Rocky Mountains during the winters of 1984/85 through 2005/06 (a 22-winter period), cloud and snow physical and chemical measurements were made to determine if expected increasing anthropogenic emissions would increase droplet concentrations, decrease mean droplet diameters and decrease cloud pH and, through the snow crystal riming mechanism, increase snow pH values.

From the first 20 winters, Hindman *et al.* (2006) reported an aerosol effect opposite that expected: significant trends occurred of decreasing cloud droplet concentrations, increasing mean diameters and initially increasing cloud and snow pH values then more recent decreasing values. Decreased condensation nucleus (CN) concentrations, and most likely cloud-condensation nucleus concentrations as well, caused the decrease in droplet concentrations. However, CN concentrations and precipitation rates were not related. Thus, the inverse relationship between aerosol concentration and precipitation rate reported by Borys et al. (2003) for two storms at SPL was not detected in the long-term record.

Two additional winters of data have been collected (winters of 2004/05 and 2005/06) since the Hindman *et al.* paper. The purpose of this paper is to add the new data to the long-term record, repeat the analyses and report that there was no significant trend in either precipitation rates or snowfall water contents in the record. Due to the large variability in precipitation, a 40-year record is required to detect significant trends.

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2. MEASUREMENTS

The 2004/05 and 2005/06 cloud droplet, pH, CN, precipitation rate, temperature and wind measurements were collected and analyzed following exactly the procedures detailed by Hindman *et al.* (2006). Please refer to that publication for a description of the instruments and procedures. The temperature and wind measurements, not mentioned in that publication, were made from a 10 m tower attached to SPL using deiced sensors. As with most of the previous measurements, the data were collected for two-week periods during the month of January 2005 and 2006.

Additionally, at a mid-mountain site directly upwind and below SPL, personnel from the Steamboat Ski Patrol made daily snow depth and water equivalent measurements (from which snow water content was derived using standard methods). These measurements were made for an entire ski season (November-April). These data have been included in the long-term record.

The measurements in the long-term record were made during cloud episodes (immersions) at 3-hour intervals during two-week periods in December, January or February. The individual measurements were used to produce seasonal averages and their standard deviations/standard errors (see the Table). Seasonal averages were determined to identify trends in the record.

Table

Average values, standard deviations (StDev) and standard errors (StError) from the SPL 22-year winter (December – February) record: number of samples (n), droplet number concentration (N), droplet mean diameter (D_{bar}), liquid water content (LWC), cloud pH, condensation nucleus concentration (CN), snowfall water-equivalent precipitation rate (Ppt. Rate), snow pH, air temperature (T) and wind speed and direction.

Winter	n (699)	N (cm^{-3})	StError	D_{bar} (μm)	StError	LWC (gm^{-3})	StError	Cloud pH	StError	CN (cm^{-3})	StError	Ppt. Rate (mm/h)	StError	Snow pH	StError	T (C)	StError	Speed (m/s)	StError	Direction (degrees)	StError
1984-85	89	235	15	8.5	0.3	0.092	0.008	4.13	0.06	5049	337	2.20	0.30	4.46	0.050	-8.5	0.3	10.4	0.4	260	5
1985-86	31	499	28	7.2	0.3	0.134	0.023	3.44	0.07	3562	911	1.30	0.20	4.29	0.100	-9.4	0.5	8.0	0.4	287	4
1986-87	14	306	28	7.6	0.3	0.089	0.012	3.87	0.09	100	0	0.22	0.31			-9.7	0.2	5.6	0.5	294	6
1987-88	12	303	45	6.4	0.3	0.053	0.011	3.70	0.06			3.90	1.50			-9.5	0.9	7.2	0.6	254	20
1988-89	10	261	50	6.0	0.2	0.035	0.007	3.99	0.03	4710	1213	4.50	5.70			-14.1	1.8	5.7	0.4	296	7
1989-90																					
1990-91	45	313	24	7.9	0.3	0.098	0.013	4.32	0.07	7758	616	0.85	0.30	4.30	0.100	-10.9	0.2	5.5	0.5	296	3
1991-92	34	221	21	6.6	0.3	0.040	0.006	4.42	0.07	1311	208	0.46	0.13	5.08	0.140	-13.2	0.4	5.4	0.3	297	3
1992-93	52	220	15	6.4	0.2	0.041	0.004	4.98	0.06	742	69	0.86	0.15	4.99	0.059	-10.5	0.4	6.3	0.3	267	5
1993-94	71	281	21	7.5	0.3	0.063	0.005	4.81	0.04	1117	97	1.18	0.17	5.35	0.068	-11.7	0.3	6.4	0.2	303	2
1994-95	55	212	19	7.7	0.2	0.059	0.010	4.96	0.05	1483	185	0.12	0.04	5.39	0.042	-11.3	0.5	6.8	0.3	291	4
1995-96																					
1996-97	33	125	14	7.1	0.5	0.038	0.004	4.42	0.14	1374	230	0.50	0.18	5.15	0.130	-12.4	0.6	9.1	0.4	294	5
1997-98	57	70	6	9.8	0.3	0.030	0.007	4.40	0.06	718	80	0.82	0.12	5.10	0.094	-10.3	0.4	11.6	2.1	272	6
1998-99	33	137	24	9.7	0.5	0.039	0.009	5.56	0.13	834	159	3.00	0.54	6.38	0.190	-9.3	0.6	8.9	0.5	269	6
1999-00	29	206	18	7.3	0.5	0.046	0.015	5.63	0.16	866	154	1.54	0.49	6.13	0.130	-7.1	0.7	13.5	1.0	261	13
2000-01	30	193	18	10.2	0.4	0.092	0.009	4.63	0.15	1476	257	0.43	0.12	4.60	0.075	-8.3	0.5	8.4	0.3	277	5
2001-02	19	108	34	11.5	0.8	0.067	0.012	4.24	0.07	1174	208	1.27	0.22	4.67	0.067	-8.4	0.6	7.2	0.5	286	7
2002-03	21	144	21	9.6	0.6	0.068	0.012	3.83	0.07	1086	151	1.90	0.40	4.44	0.110	-11.1	0.6	8.0	0.6	289	6
2003-04	4	133	13	6.7	0.9	0.022	0.008	3.96	0.09	1415	127	0.09	0.01	4.29	0.011	-8.6	1.0	4.9	0.7	309	9
2004-05	8	160	26	11.4	0.6	0.099	0.019	4.29	0.07	1916	666	1.08	0.99	4.94	0.050	-7.3	0.6	7.8	0.6	291	6
2005-06	22	88	12	11.0	0.6	0.059	0.012	5.47	0.07	816	205	2.76	1.12	5.49	0.057	-11.9	0.6	7.4	0.7	281	6
Average		211		8.3		0.063		4.45		1974		1.45		5.00		-10.2		7.7		284	
StDev		100		1.8		0.029		0.62		1932		1.25		0.62		1.9		2.2		15	
StError		23		0.4		0.007		0.14		455		0.29		0.15		0.4		0.6		4	

Measurements were not obtained for two winters during the 22-winter period (1989/90 and 1995/96). The number of measurements was not constant each winter because of the variable durations of the cloud episodes which ranged from a few hours to a few days.

3. RESULTS

The average values in the Table, due to the small standard errors, define the wintertime (December – February) cloud and precipitation properties at SPL. For example, the average 1.45 mm/h precipitation rate illustrates that it must snow frequently with substantial duration at SPL to produce the average 2100 mm of wintertime precipitation.

The values in the Table were analyzed producing the following results.

3.1 Trends

Upon addition of the winter 2004/05 and 2005/06 data, the cloud droplet concentration, mean diameter and LWC values now produce statistically significant trends of decreasing concentrations and increasing diameters (Figs. 1a and b). Further, the significant LWC trend remains consistent with the decreasing droplet concentrations and increasing mean diameters: an initial decreasing LWC trend in the early years but an increasing trend in the later years as the mean diameters became larger (Fig. 1c).

The statistically significant trends of initially increasing cloud and snow pH values then more recent decreasing values reported from the 20-winter record, upon addition of the winter 2004/05 and 2005/06 data (Figs. 2a and 2b), remain significant but with a reduced correlation coefficients: respectively, from 0.70 to 0.58 and from 0.61 to 0.49.

The addition of the winter 2004/05 and 2005/06 CN and precipitation rate measurements to the record (Figs. 2c and 2d) did not change the marginally significant decreasing trend in CN concentrations but did change the insignificant decreasing trend in precipitation rate to an insignificant increasing trend in recent winters.

3.2 Relationships

The series of relationships in the 'aerosol effect' at SPL (Borys *et al.,* 2003) is as follows: aerosol concentrations are directly related to cloud droplet concentrations, the droplet concentrations are inversely related to droplet mean diameters and the droplet mean diameters are directly related to the precipitation rates. The mean diameters and precipitation rates are related through snow crystal riming. So, increasing the aerosol concentra-

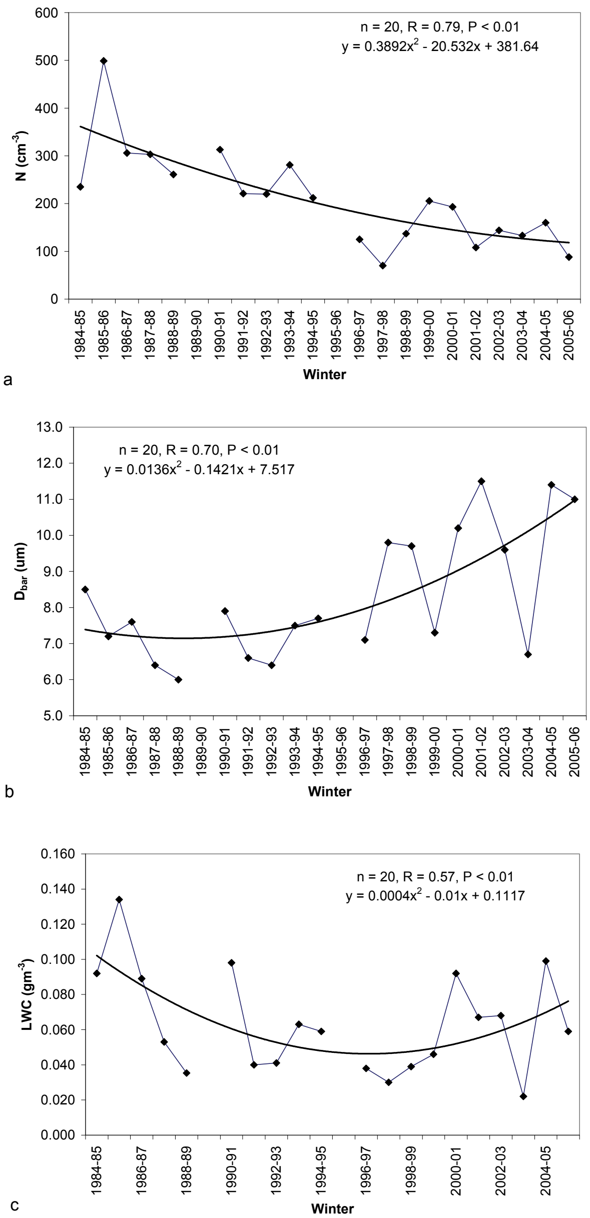

*Fig. 1: **a.** Cloud droplet concentration (N), **b.** cloud droplet mean diameter (D_{bar}) and **c**. cloud droplet liquid water content (LWC) as a function of winter. R represents the correlation coefficient and P the significance level. A polynomial-fit was the lowest order that produced the best R value in this figure and in subsequent figures.*

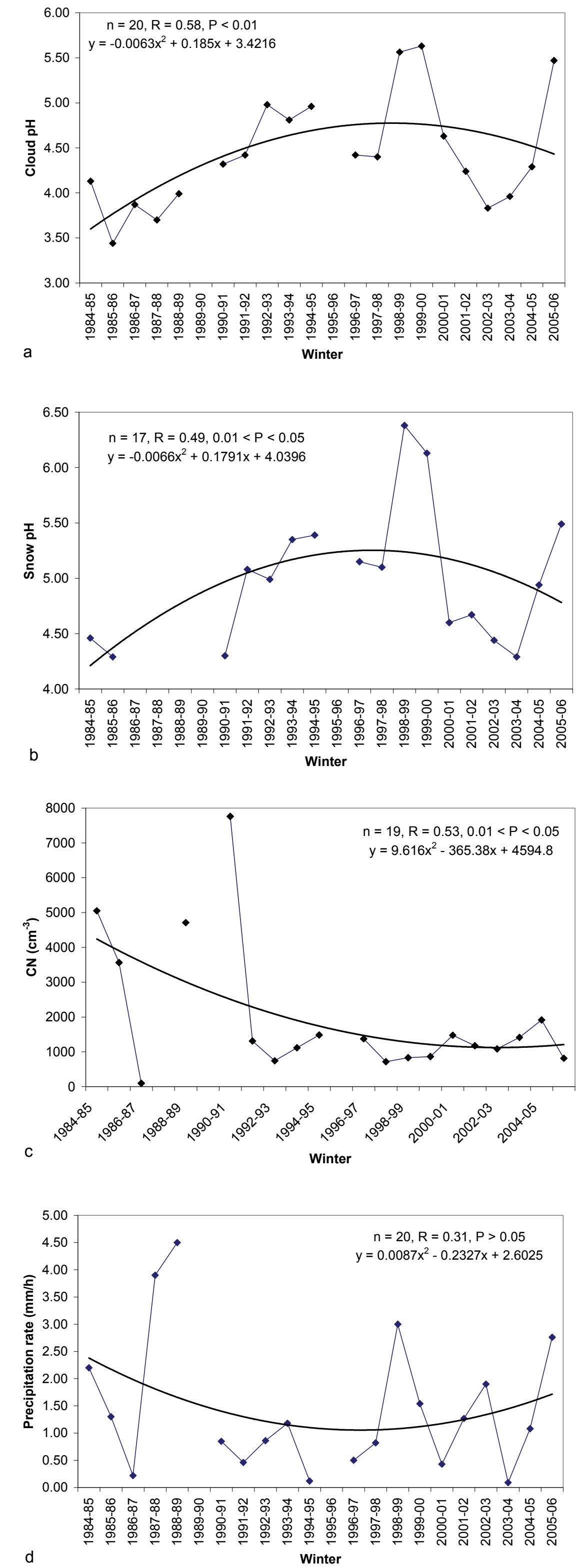

*Fig. 2. **a.** Cloud droplet pH, **b**. snow pH, **c**. interstitial condensation nucleus concentrations (CN) and **d**. snowfall water-equivalent precipitation rate as a function of year.*

tion is expected to increase droplet concentrations, decrease mean droplet sizes causing decreased crystal riming and decreased precipitation rates, and vice versa.

Addition of the winter 2004/05 and 2005/06 measurements to the long-term record and reanalysis of the relationships produced the following results.

The marginally significant relationship between aerosol concentration (CN concentration, considered the 'surrogate' CCN concentration) and cloud droplet concentration did not change but increased the correlation coefficient slightly from 0.46 to 0.49 (Fig. 3). In support of this relationship, the inverse relationship between cloud pH and CN concentrations became significant at better than the 1% level (Fig. 4). To check the cloud pH-CN relationship, cloud pH was correlated with droplet concentration (Fig. 5). It can be seen that as droplet concentration increased (due to increased aerosol particle concentrations) the cloud pH decreased supporting the Borys *et al.* (2000) finding that the more pollution-derived aerosol particles at SPL, the larger the droplet concentrations and vice versa.

The marginally significant inverse relationship between cloud droplet concentration and mean diameter became statistically significant with an improved correlation coefficient: from 0.48 to 0.63 (Fig. 6). This result is consistent with the fact that keeping LWC constant and increasing the droplet number concentrations decreases the mean droplet diameter and vice versa.

The highly significant relationship between cloud and snow pH values was maintained (Fig. 7) demonstrating the importance of riming to crystal chemical composition.

The statistically insignificant relationship between droplet mean diameter and precipitation rate did not change (Fig. 8).

4. DISCUSSION

The 'weak link' in the aerosol effect detected in the long-term record is the lack of a statistically significant relationship between droplet mean diameter and precipitation rate.

The most likely cause is meteorological variability. From first principles, the precipitation rate is

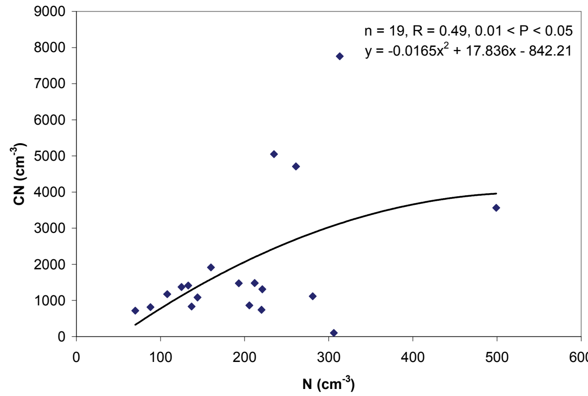

Fig. 3. Correlation of cloud droplet concentration (N) and interstitial condensation nucleus concentration (CN) from, respectively, Figs. 1a and 2c.

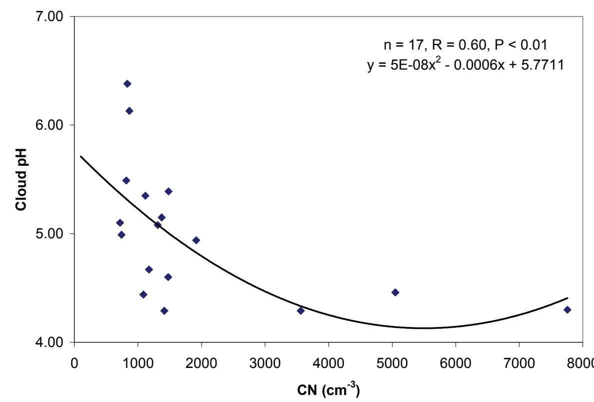

Fig. 4. Correlation of cloud pH and interstitial condensation nucleus (CN) concentration from, respectively, Figs. 2a and 2c.

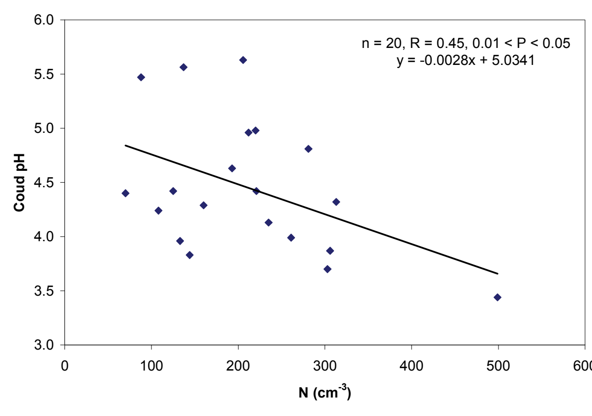

Fig. 5. Correlation of cloud pH and cloud droplet concentrations (N) from, respectively, Figs. 1a and 2a.

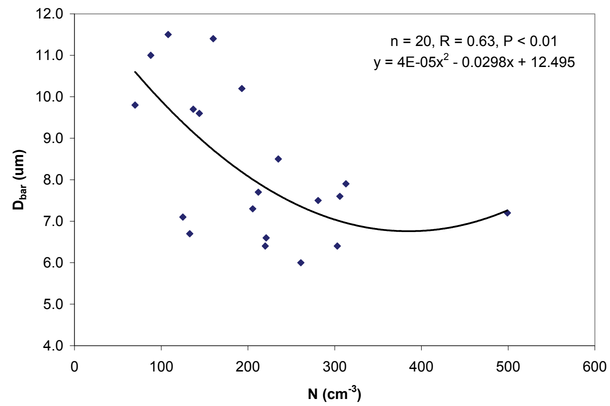

Fig. 6. Correlation of cloud droplet concentration (N) and mean droplet diameter (D_{bar}) from, respectively, Figs. 1a and 1b.

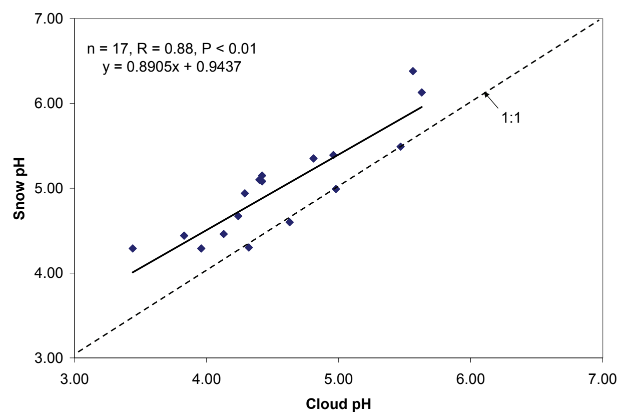

Fig. 7. Correlation of cloud pH and snow pH values from, respectively, Figs. 2a and 2b.

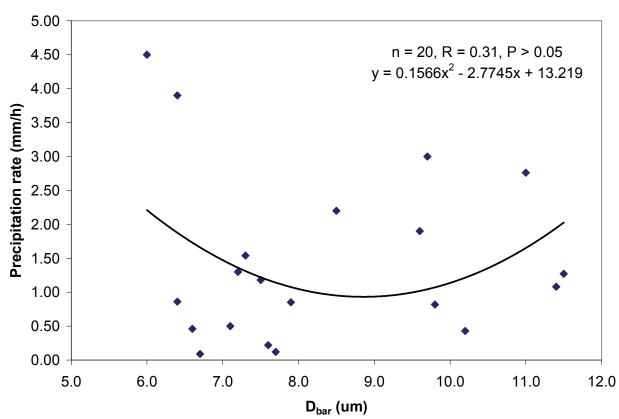

Fig. 8. Correlation of mean droplet diameter (D_{bar}) and snowfall water-equivalent precipitation rate from, respectively, Figs. 1b and 2d.

related to the following meteorological factors: the depth of the orographically-induced liquid cloud at and above SPL, the absolute humidity (which is determined by cloud-base temperature) and the upslope component of the wind speed. The aerosol particles only modulate these major factors.

The meteorological factors were correlated with precipitation rate in an attempt to estimate the effects of meteorological variability. The cloud depth was not measured due to the lack of a suitable instrument. So, temperature and wind speeds were correlated with precipitation rates. The results are shown in Figs. 9a and 9b. The best fits to the data illustrate an initial increase in the precipitation rates as temperatures and wind speeds increased, then a reduction of temperatures and speeds for the largest rates. These non-linear relationships illustrate the difficulty of extracting meteorological variability from the data in the Table. The variability may be accounted for if the 699 individual measurements summarized in Table are analyzed as independent variables; a project which is not possible at this writing.

There was no significant trend in precipitation rates in the long-term record (Fig. 2d). Additionally, the measurements corresponding to the period of the Ski Patrol snowfall water equivalent measurements (Winter 1987/88 through Winter 2005/06) are shown in Fig. 10. The Ski Patrol measurements are shown in Fig. 11. It can be seen in Figs. 10 and 11, no significant trends in precipitation were identified. The lack of significant trends in the precipitation measurements is due, in part, to the large variability in the values. To determine a significant trend in such variable data at less than the 5% significance level, it would take at least a 40-year record (Snedecor and Cochran, 1956).

From a 50-year record (1950-2000) of precipitation measurements from Steamboat Springs (at the base of the Park Range upon which SPL is located) and Hayden (an 'upwind' station on the plains 20 km to the west), Rosenfeld and Gavati (2006) report a suppression of orographically-induced precipitation due to the 'aerosol effect'.

5. CONCLUSIONS

The addition of the 2004/05 and 2005/06 measurements to the SPL long-term record reported by Hindman *et al.* (2006) strengthened some re-

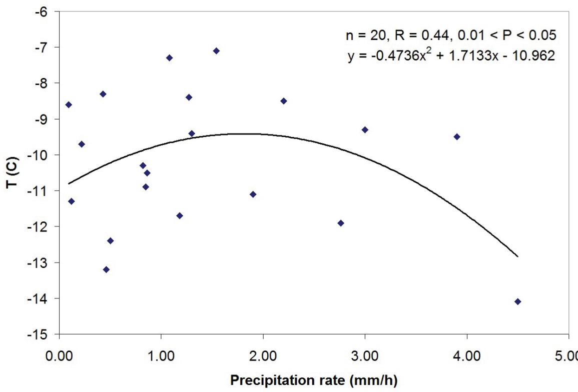

Fig. 9a. Correlation of the SPL temperature with the precipitation rate from the Table.

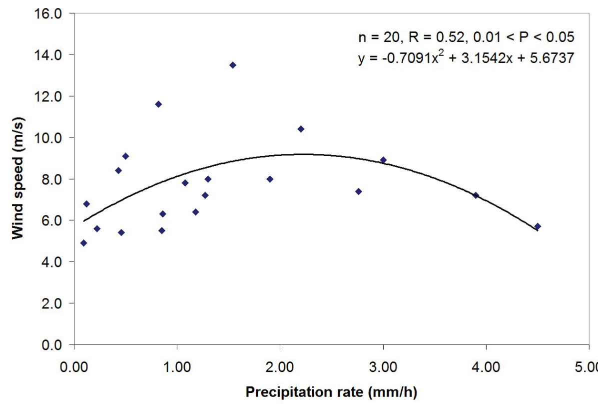

Fig. 9b. Correlation of SPL wind speed with precipitation rate from the Table.

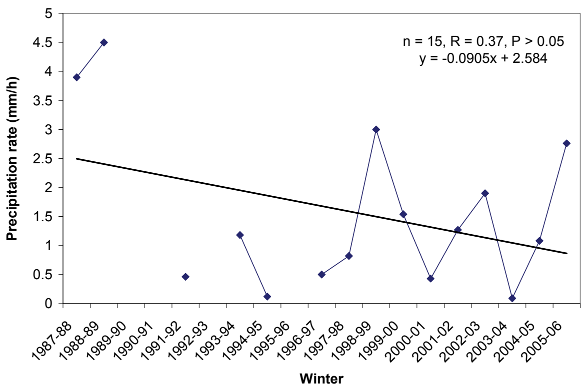

Fig. 10. Snowfall water-equivalent precipitation rate values that correspond to the period of the Ski Patrol measurements of snow water contents shown in Fig. 11.

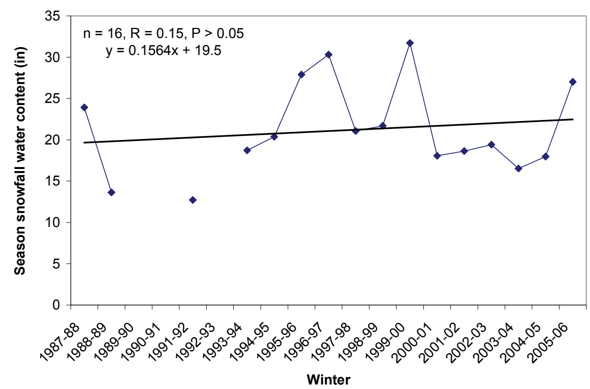

Fig. 11. The Ski Patrol measurements of snow water contents.

lationships and weakened others. But, the conclusions remain the same: the variations in CN concentrations (perhaps CCN concentrations as well) were directly related to droplet concentrations, the droplet concentrations were inversely related to droplet mean diameters and the mean diameters were not related to the precipitation rates. Thus, the long-term record supports the 'aerosol effect' for cloud droplets but, due to meteorological variability, no correlation between droplet mean diameter and precipitation rate could be established. Thus, the effect of the aerosol particles on precipitation rates could not be determined.

There was no significant trend in either precipitation rates or snow water contents in the long term -record. To determine a significant trend in such variable data at less than the 5% significance level, it would take at least a 40-year record.

There may be other factors that determine precipitation rate as much as snow crystal riming, eg. snow crystal type, size and concentration. For example, Meter *et al.* (2007) have reported pollution aerosol may be a rich source of ice-forming nuclei; perhaps crystal concentrations increased to offset the apparent reduction in crystal riming at SPL reported by Borys *et al.* (2003) and Rosenfeld and Givati (2006). Crystal collections were made as part of the long-term record following Hindman and Rinker (1967) but these data have not been reduced and analyzed. The average values in the Table, due to the small standard errors, define the wintertime (December

– February) cloud and precipitation properties at SPL.

Acknowledgments. Support for the long-term record was received from NSF, CUNY, NOAA-CREST and personal funds. R. Borys, former Director of SPL, D. Lowenthal of the Desert Research Institute and N. Phillip of the City University of New York provided data to the long-term record. J. Hirschboeck, formerly of the Steamboat Ski Patrol, assembled the daily snow-depth and water-equivalent measurements.

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SEEDING OPTIMIZATION FOR HAIL PREVENTION WITH GROUND GENERATORS

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Abstract: An evaluation method of hail prevention by silver iodide ground seeding generators is developed. The method is based on correlations between the point hailfall intensities measured with hailpads and the silver iodide released prior to the hailfalls in the "feeding areas" where the hail cells developed. The time unit for the correlations is the day, but days can be aggregated together after data normalization. Former evaluations have shown that the number of hailstones larger than 0.7 cm is mainly responsive to the amount of seeding material released in a 13-km radius area centered on the place where the storm was developing 80 min before the hailfall, and that the seeding effect can be detected only for the days with at least 15 hailed pads.

In this paper, the method is applied to 24 major hail days with seeding recorded in the past 20 years in a hailed region north of the Pyrenees. For each day, 15 to 42 point hailfalls have been recorded, and they are used to compute the best negative daily correlation between hailfall intensity and seeding amount by moving the feeding area around its first approximate position. With this seeding area optimization, all the daily correlations are negative (more seeding, less hail), but they are weak, with a correlation coefficient reaching about r = -0.3 in only half of the cases. For the whole hailfall sample (561 hailfalls), the correlation computed with the ideal feeding areas determined as indicated above is r = -0.22, significant at the 0.01 level, subject to the data independency hypothesis. In average, the distance from the middle of the feeding area to the hailfall corresponds to a storm travel time of 66 min, but a numerical simulation of the seeding particle trajectories with the Meso-NH model suggests that the generators must be started at least 45 min before the storm travels above them.

1. INTRODUCTION

In France, seeding hailstorms from silver iodide ground generator networks has a long practice, since the ANELFA (Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques) has been developing its field experiment since 1952 without interruption. It was only a few years ago, however, that the evaluation of the project was physically quantified by comparing the point hailfall measured parameters to the silver iodide amounts released before the hailfall time in the area where the hail cell was developing.

The evaluation of the seeding effect is made with an *a priori* hypothesis: greater amounts of seeding material presumably delivered to the storm lead to smaller hail intensities (as measured either by hailstone number or kinetic energy). After observing that, in general, hail is less severe at points located at the NE of well-seeded areas (most of the hailstorms are moving from SW to NE in France), the following method was designed when hailpad data became available. For a day with several hailfalls, to each point hailfall determined by its number of hailstones larger than 0.7 cm is associated the silver iodide amount released in a circle centered where the hail cell was presumed to be developing before the hailfall (the "feeding area"). Data normalizations with the mean daily values of these parameters allow to aggregate hail days together.

With the first 10 years of hailpad data, the hailfalls were determined to be mostly responsive to the seeding performed in a circle where the hail cell is located T = 80 min before the hailfall, and the circle area including the most efficient seeding stations was found to have a radius of R = 13 km (Dessens 1998). A refinement of the method was developed later, when a sensitive test showed that a significant effect is detected only for the major hail days with at least 15 point hailfalls recorded (Dessens et al. 2006). The present work is a re-examination of these major hail days with seeding activity. Since it is most probable that the position and the radius of the circle giving the best correlation between the seeding and the hailfall intensity change from one day to the next, the daily correlations will be computed with the first approximation parameters (T = 80 min, R = 13 km), then with parameters varying around these values. The circle will also be moved to the right and left of the storm trajectory.

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Table 1. Storm and hailfall parameters for the 24 major hail days. From left to right: case number (with asterisk for supercells), date, storm propagation (direction and velocity), number of point hailfalls, maximum hailstone diameter, mean number of hailstones larger than 0.7 cm, mean kinetic energy, storm travel time between the feeding area and the hailfall, correction for the direction, feeding area radius, and seeding/hail correlation coefficient.

	Day	α °	V km/h	n	Dmax cm	N /m²	Em J/m²	T min	Δα °	R km	r
1	17/05/90	261	34	22	2.5	1007	50.2	60	10	13	-0.20
2	13/08/90	280	36	17	1.5	296	13.3	60	10	10	-0.37
3	27/09/92	205	30	28	3.0	2077	165.8	60	10	13	-0.32
4*	05/07/93	263	49	16	3.7	645	131.5	90	0	13	-0.16
5	16/05/94	234	64	20	2.0	803	32.3	70	0	13	-0.36
6*	18/06/94	244	46	20	4.4	1392	177.7	70	-10	10	-0.31
7	31/07/94	230	36	16	3.7	1318	90.0	50	10	10	-0.42
8*	02/07/95	244	50	26	4.0	1682	183.6	50	10	16	-0.21
9	17/05/97	221	33	15	1.7	1144	52.9	60	0	13	-0.20
10*	02/07/98	263	65	40	3.3	2054	147.8	90	0	10	-0.30
11	26/09/98	227	62	15	3.3	1091	129.8	70	0	13	-0.21
12	29/04/99	247	40	43	2.6	1479	87.1	70	0	13	-0.48
13*	07/05/99	261	55	25	4.4	2024	191.2	80	0	13	-0.10
14	18/05/99	215	38	42	2.1	1211	63.2	90	-10	13	-0.14
15	02/06/99	258	59	23	2.5	1661	95.3	60	10	16	-0.36
16	13/05/00	280	33	20	2.0	1036	52.6	60	10	16	-0.23
17	01/06/03	230	23	21	4.0	843	55.7	60	0	10	-0.28
18*	28/08/03	245	59	36	3.3	1317	122.5	60	10	13	-0.23
19*	13/05/05	232	44	18	1.6	2091	78.1	70	-10	16	-0.21
20	28/07/05	228	48	19	3.9	831	189.6	90	0	13	-0.29
21	15/04/06	282	47	16	2.4	2723	137.3	50	0	10	-0.17
22	21/07/06	270	33	23	4.3	1911	158.6	50	0	13	-0.39
23*	27/07/06	235	55	18	2.4	2019	103.8	60	10	13	-0.29
24	17/04/07	108	15	22	1.6	727	32.2	50	10	13	-0.01

2. DATA SAMPLE

The Midi-Pyrenees region is one of the most heavily hailed areas of France (Dessens 1986). It is there that the ANELFA has had its longest experience in seeding operation and hailpad measurements, with 152 ground generators and 336 hailpad stations operated in an area of 16,000 km². The climate is oceanic, but altered by the Pyrenees in the south and by the Mediterranean in the east. The topography is marked by the Garonne valley and by many smaller valleys coming from the Pyrenees. Except near the mountains, the altitudes range from 100 to 600 m above sea level. At the end of the 2007 hail season, 2495 point hailfalls have been recorded in this area, 561 of them having occurred on 24 days with seeding activity and at least 15 point hailfalls (Table 1). For details concerning the seeding and the hail measurement, one can refer to Dessens et al. (2006), and only a brief description of these activities is given below.

2.1 Point hailfall intensity

Each point hailfall measured with the hailpad network is characterized by the total number of hailstones larger than 0.7 cm, Ni (m^{-2}), or by the total kinetic energy computed with all the hailstones, including those from the 0.5-0.7 cm diameter range. Since the data normality is, in general, better with the first parameter, the correlations are computed with it, but the seeding efficiency will also be estimated from the kinetic energy because this parameter is of a more general use. When days are aggregated together, the Ni values are replaced by their normalized values, Ni – Nm, Nm being the daily mean value of Ni (Dessens 1998).

2.2 Storm propagation

Since the object is to compare the hailfall intensity with the seeding material injected in the hail producing cells, the propagation parameters of the storm (direction and velocity) must be known. These parameters are, in general, well determined for the long trajectory hailstorms, usually of the supercell type. The direction is defined at a precision better than 5° with the observation of crop damages, and the velocity is computed from the hailfall time recorded by the observers. The direction and velocity of the multicell storms are not so easy to determine, and it is, in general, necessary to estimate at least one of these parameters from the sounding data after determining a general propagation rule for the hailstorms. This rule indicates that a severe hailstorm in southwestern France moves in a direction of 31° to the right of the wind at the 600 hPa level, and at a speed 18% lower that the wind velocity at the same level (Dessens 1998). In a further evaluation (Dessens et al. 2006), it was however observed that a 27° deviation gives better correlations between the seeding and the hail intensity, so this value is used in the present study.

The data sample examined in this paper is relative to 24 hail days for which the storm direction was directly observed in 11 cases and the velocity in 8 cases. In the other cases, the parameters were computed from the wind data of the nearest sounding made in the upflow air mass at 00UTC and 12 UTC at Bordeaux, Zaragoza, or, in one case, Nîmes. Table 1 gives the propagation parameters, α and V, for each of the 24 hail days.

2.3 Seeding amount.

The seeding stations are equipped with a vortex generator burning 1.1 l/h of a silver iodide-sodium chloride solution, which corresponds to a release of 8.6 g/h of pure silver iodide in the atmosphere. The seeding parameter, Si, used for the correlation with a point hailfall parameter is the total weight of silver iodide burnt for the 3 hours preceding the hailfall by the generators included in the circle considered as the hail cell development area. For example, for a circle with a 13 km radius, if there are 5 generators really burning during the 3 hours, the seeding amount is 5 x 8.6 x 3 = 129 g/531 km². In case of a late warning or generator deficiencies, this amount can be reduced, even down to 0. The Si values are replaced by their normalized values, Si – Sm, when days are aggregated together.

3. LOCALIZATION OF THE RESPONSIVE SEEDING AREA

In order to locate the feeding area, the method first consists in computing the point-to-point correlations between the number of hailstones larger than 0.7 cm at each hailfall point, Ni, and the seeding amount released during the 3 hours preceding this hailfall in the circle with a 13 km radius centered where the hail cell was presumably developing 80 min before the hailfall, Si. There is one data pair for each hailed pad, and the adjustments regarding travel time and direction and size of circle are the same for every hailpad included for a given day. It is worthy to note that the pads possibly receiving no hail as a consequence of the seeding are not included in the analysis.

Figure 1 illustrates the method for a day with 20 hailfalls recorded between 14.45 and 19.30 local time. The axis center is one of the 20 points, it received Ni = 39 m^{-2} hailstones. With the propagation parameters given in table 1, Fig. 1a locates the generators in the 13-km radius area centered at the place where the storm was 80 min before. For that day and that hour, the generator activity reports give a seeding amount Si = 224 g/3hr (one generator was not correctly running). The correlation coefficient computed with the 20 data pairs is found to be r = -0.31. The first step of the optimization consists in computing the correlations with the seeding amount in the circles located nearest and farthest from the hailfall point, at distances corresponding to travel times of respectively 70 and 90 min. If the correlation is found to be better (that means nearest to -1) for example at 70 min, then the correlation is computed at 60 min, and so on until the correlation stops decreasing (Fig. 1a). In the illustrated case, the correlation increases to r = -0.36 for 70 min (Si = 127 g/3h), but decreases to r = -0.20 for 90 min. A travel time of 70 min is then retained for the second step.

In the second step, one checks if the correlation improves when moving the circle with a deviation of 10° to the right and to the left of the direction from which the storm comes (Fig. 1c). In the last step, the circle with a 13 km radius giving the best correlation is changed for circles with a radius of 10 and 16 km (Fig. 1d). In the illustrated case, the correlation does not increase during the second and third steps. Table 1 gives the correlation coefficients, r, computed with the ideal parameters. For the example of May 16, 1994 presented in Fig. 1, the most responsive area is a circle with a 13 km radius and a center at 74 km in the exact direction of the incoming storm.

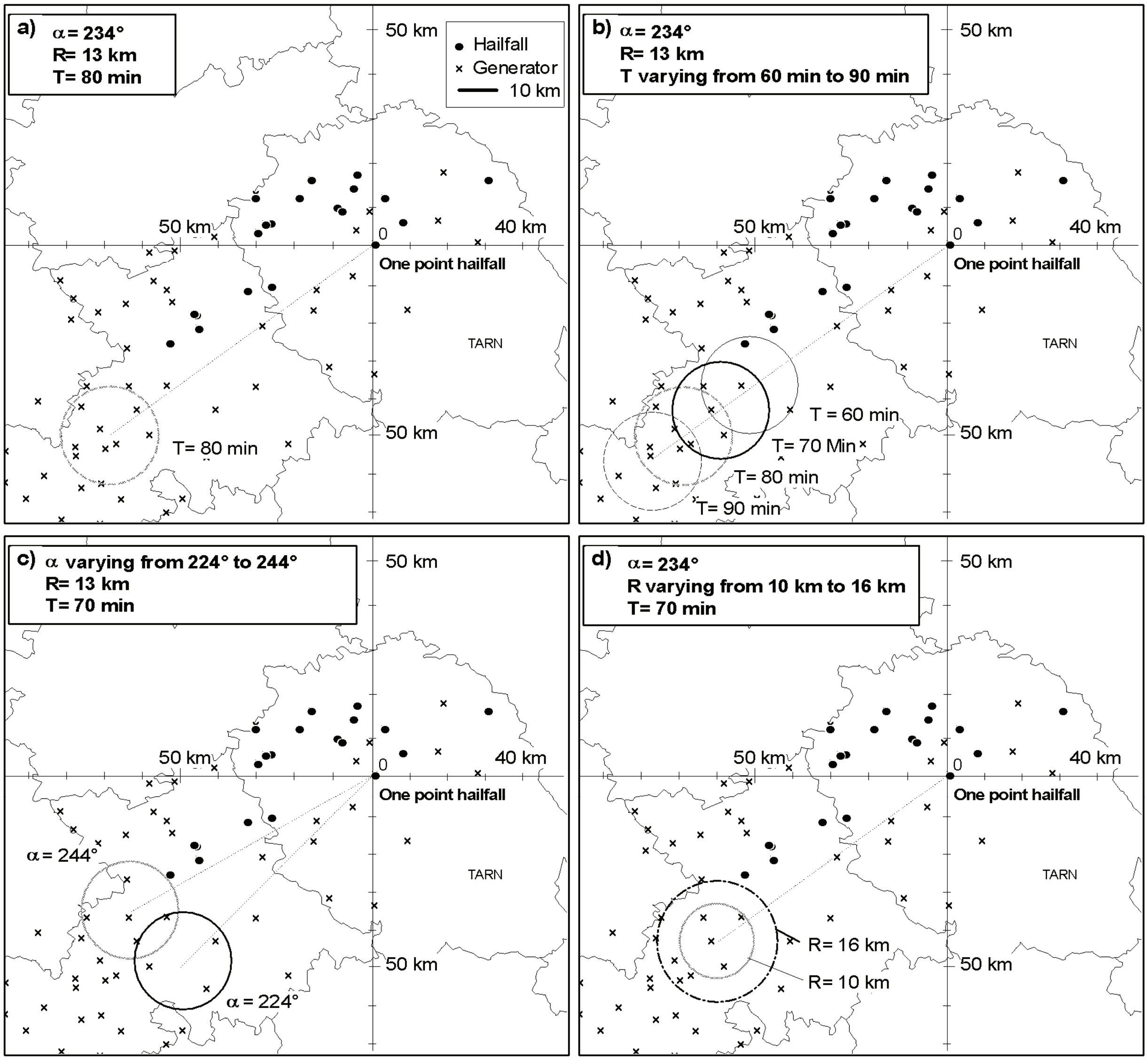

Fig. 1. Daily adjustment of the circle giving the best seeding/hail correlation. Example for May 16, 1994. The point hailfall location at the center is Cadalen, Tarn, hailed at 19.00 local time.
a) circle corresponding to the standard 80 min storm travel time
b) circles tested for longer and shorter travel times
c) circles tested for different directions
d) circles tested for different radiuses

Considering the most responsive areas defined as described above, all the daily r values are negative (Table 1), but they are weak, being statistically significant at the 0.05 level in only two cases. These negative correlations, however, seem sufficient to correctly locate the area where the seeding is most efficient. The average time between the seeding and the hailfall decreases from 80 to 66 min. The correction for the storm direction is 3°, which could mean either that storms are more feeding on their left side, or that their deviation from the wind at the 600 hPa level is 30° rather than 27°. The mean circle radius determining the most sensitive area, R = 13 km, remains unchanged. In fact, a detailed examination of the correlations shows that the correlations are very sensitive only to the first parameter (time).

Figure 2 shows the relative positions of the circle centers corresponding to the best seeding conditions for each day. With the axis origin as the geographical position of a hailfall, the points give, for each day, the center of the best seeding area relative to this hailfall. The gravity center of all the points is at (x = -42 km, y = -18 km).

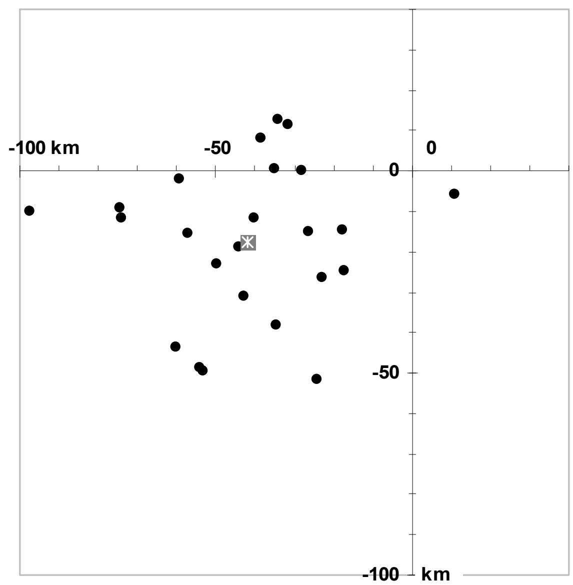

Fig. 2. Centers of the best feeding areas relative to a hailfall at point (x = 0, y = 0) for the 24 hail days. The gravity center is pointed with an asterisk.

4. STORM TYPE CORRELATIONS AND AVERAGE RESULTS

As everywhere in the world, damaging hail in France is produced by supercell storms, multicell storms, and storms intermediate between these main two types. The days with one or several supercell storms are marked with an asterisk in the first column of Table 1. Since, by definition, the supercell storms produce long trajectories of damages, their propagation parameters are, in general, available from the observations, and, in the absence of radar data, it is not necessary to infer them from the soundings. In three cases (Nos 16, 22, 24), most of the hailfalls occurred after local midnight local time (22.00 UTC), while, in general, the maximum frequency of hailfalls is in the late afternoon.

It appears from Table 1 that the seeding response is comparable for the supercell and the other hailstorms, and also for two of the three night cases. For the third night case N° 24 with a nearly zero correlation, the propagation parameters are doubtful: the velocity was low, and, in the middle of the night, the hailfall times are not well recorded by the observers. Moreover, for this case only was the wind flow from the east, so the radiosounding data of Nîmes, about 300 km away from the hailstorms, are used.

For each of the No 10 and No 12 days, the correlations are significant at the 0.05 level. The storm of July, 2, 1998 was absolutely characteristic of an isolated supercell. It moved at 65 km/h over more than 140 km. On the contrary, the storm of April, 29, 1999, was rather a multicell storm moving at 40 km/h over a diffuse trajectory of 60 km. This last case has been the subject of a detailed numerical simulation by Wobrock et al. (2003).

With the normalized values (Si – Sm) and (Ni – Nm), one can draw a scatter plot of the 561 hailfalls (Fig. 3). The interesting first observation is that the strongest hailfalls (large Ni – Nm values) are concentrated on the left side of the figure (less-than-average seeded hailfalls). The linear regression has a correlation coefficient r = -0.22, a value statistically significant at the 0.01 level if the data are independent. This problem of independence is discussed in a former paper (Dessens 1998). With a mean distance of 7 km

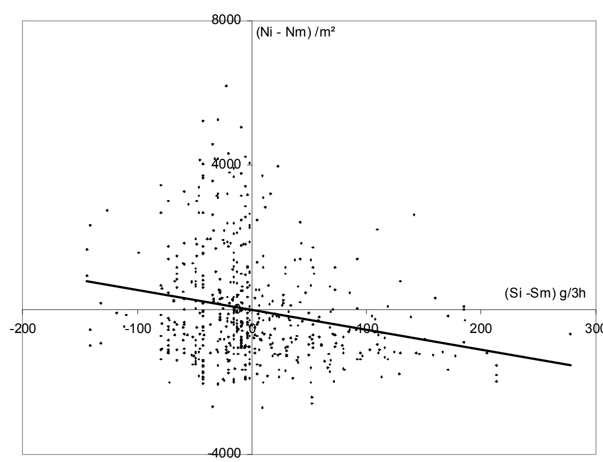

Fig. 3. Scatter plot of the hailstone number as a function of the seeding amount for the 561 hailfalls.

between two hailpads, the dependence of the data appears to be low but can lead to some overestimation of the significance of the correlation between seeding and hail.

If one wonders what happens if the regression line is extrapolated to estimate how much seeding would be required to drive the hail amount to zero, even if it is pure speculation, the regression equation is:

$$Ni - Nm = -5.57\ (Si - Sm), \qquad (1)$$

with Nm = 1430 m^{-2}, Sm = 50.3 g/3h, which gives Ni = 0 for Si = 307 g, a seeding obtained with 12 generators per 531 km^2. This extrapolation is evidently highly hazardous due to the correlation weakness.

The seeding effect can be computed more reasonably by comparing the hailfalls seeded less than average to those seeded more than average. The detailed computation is given in Dessens et al. (2006). For the 24 days taken together, the reductions in the hailstone number and in the kinetic energy amount to 41 and 48% respectively, these reductions being obtained by a seeding amount of 137 g of silver iodide burning for 3 hours in an area of 531 km^2, which corresponds to 5.3 generators located in the same area. These results are not much better than those found by Dessens et al. (2006) with a smaller data sample, but their statistical significance level is better (0.01 instead of 0.05, always subject to the independency hypothesis). They concern the most serious hailfalls recorded during the 20 years of measurements since their mean kinetic energy is 108 Jm^{-2}, to be compared with 67.8 Jm^{-2} for the other hailfalls.

5. PHYSICAL MEANING

The fact that a hailfall appears to be mainly responsive to the generators burning under the storm about one hour before the hailfall requires some physical interpretation. Yuter and Houze (1995) proposed a conceptual model of a multicellular storm based on radar observations made in Florida. This model introduces the notion of "particle fountains" in order to explain the concurrent microphysical evolution of the storm. A particle fountain is an updraft having its root in the surface layer. Updraft parcels stopping at warmer levels might contain a hydrometeor mass in the form of liquid water droplets. Updraft parcels that reach upper levels progressively contain more ice. The particles (droplets or ice) that fall out of the updraft parcels continue their fall through the environment of a predominantly weak vertical velocity that dominates the region between the few strong updrafts and downdrafts. There are so

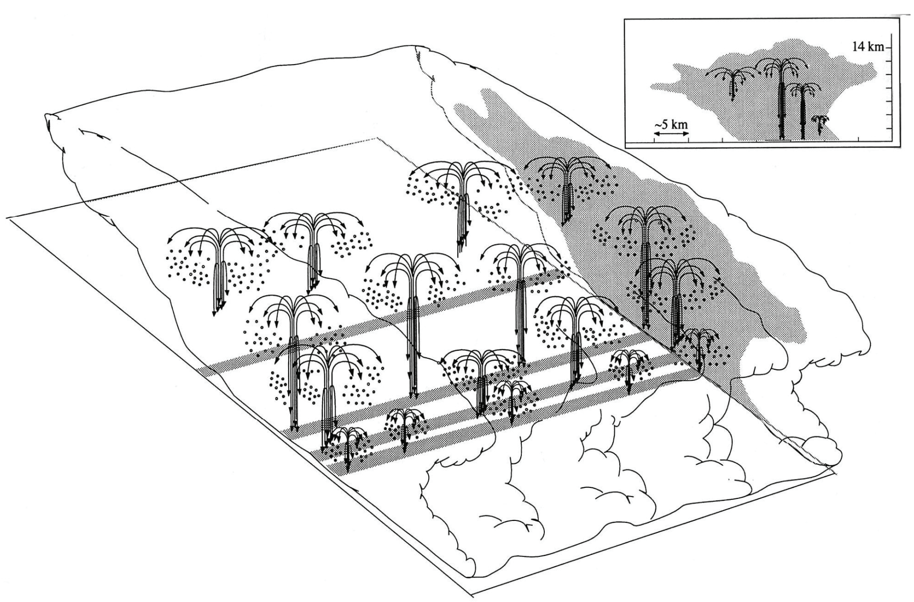

Fig. 4. Conceptual model of a set of particle fountains in a multicellular storm in perspective view. Shaded area represents radar reflectivity echo along a cross section perpendicular to the line of the storm. Cloud boundary indicated by scalloped outline. Inset shows approximate scales and arrangement of largest particle fountains relative to radar echo (from Yuter and Houze, 1995).

many particle fountains in this model (Fig. 4) that the seeding of all the updrafts can be performed only from generators that have been started early enough to seed the whole boundary layer before the storm develops.

A numerical simulation made for the ANELFA at the Laboratoire d'Aérologie of the Université de Toulouse (Lascaux and Richard 2006) will complete the description of the seeding process. The French non-hydrostatic model, Meso-NH (Richard et al. 2003), has been used to determine the back trajectories of the particles reaching the core of a storm. Two simulations have been performed in a preliminary research, one for the ideal simplified case described by Klemp and Wilhelmson (1978), the other for the severe hailstorm of May 21, 2004, in the Midi-Pyrénées region. The simulation considers two interlinked domains of respectively 8 and 2 km horizontal resolution, and has 55 altitude levels with the first one at 10 m above the ground. For the real storm, the model is initialized and forced with the ARPEGE data of Météo-France. The simulation correctly reproduces the observations made on that day: 22 point hailfalls have been recorded in the afternoon, and the day is not included in the 24-day sample only because there was no seeding at all in the network. The storm was of an intermediate type between the supercell and the multicell. According to the radiosounding of Bordeaux, 12.00 UTC, the cloud base and the 0°C isotherm level were respectively at 1000 m and 2800 m above the mean ground level.

Two main results can be drawn from both simulations:

- The air trajectories finishing inside the hail cloud at an altitude of 5 km come either from the same level behind the advancing cloud, or from the boundary layer (below 1 km) in front of the storm. The existence of the horizontal trajectories is interesting for the purpose of aircraft seeding, while the ground seeding is concerned by the trajectories coming from the lower levels.

- In the simulation of May 21, 2004, where the storm was moving at about 40 km/h, 45 to 60 min are needed for a particle released near the ground to reach the cloud. While the correlation method presented in this paper correctly locates the efficient seeding area, it seems that the nuclei entering the cloud are those produced in the same area 45 to 60 min before the passing of the cloud (Fig. 5). Once again, this observation justifies that the seeding must begin at least 3 hours before the hailfalls.

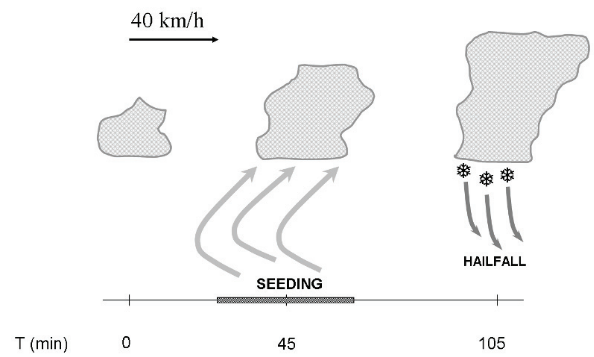

Fig. 5. Schematic disposition of ground seeding relative to hailfall. It takes 45 to 60 min for the seeding material to reach the cloud before it passes above the seeding area (numerical simulation), then 60 to 70 min more to affect the hailfall (seeding/hail correlation).

6. CONCLUSION

The work presented in this paper aims at a better understanding and targeting of hail prevention by silver iodide ground seeding. It started from previous results showing that, in average, hailfalls are responsive to silver iodide emissions from ground generators located in a circle of 13 km radius located where the developing hail cells are 80 min before the hailfall. The present study consisted in considering only the major hail days and in trying to determine if the correlation between seeding and hail intensity improves when the circle is moved around this mean position and when its radius is changed.

For the 24 major haildays examined in this paper, the correlation is mainly sensitive to a change in the time parameter. The mean value for this parameter reduces from 80 min to 66 min, which suggests that hailstones are growing faster in the most severe hailstorms. When the storm propagation is deduced from the wind velocity at the 600 hPa level, a mean shift of 30° to the right for these severe storms appears to be more appropriate than the 27° deviation considered before. For the third parameter, the former evaluation of R = 13 km for the radius of the area most responsive to the seeding remains unchanged. The implication for hail prevention of this new evaluation is that, in the Midi-Pyrénées region, the seeding should be concentrated about 45 km to the southwest of the areas to be protected from the most severe hailstorms.

With the ideal circles as the seeding areas, the correlation computed for all the days together remains weak (r = -0.22 for the 561 data pairs) but indicates a positive association between seeding and reduced hail defined by the number of hailstones larger than 0.7 cm. This average result confirms a former one based on a smaller sample of severe hail days. In the future, the ANELFA control method of seeding prevention should be improved thanks to a more exact knowledge of the silver iodide emissions obtained by continuously measuring the temperature of each generator chimney. Moreover, the storm propagation will be determined from radar data, and not only from ground observations or sounding measurements.

Acknowledgements. The three reviewers and the Editor are gratefully acknowledged for their remarks and suggestions.

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AN ATMOSPHERIC THERMODYNAMIC MODEL OF THE CONVECTIVE STORM PROCESS TYPES IN MENDOZA (ARGENTINA)

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Abstract: The DCPIM (Deep Convection Process Identification Model) index uses only surface meteorology data to forecast the convective storm class of Mendoza (Argentina). The DCPIM model did not guess right the forecast in about five percent of the studied cases. Then in order to improve the forecast model, we are adding vertical atmospheric information at the index calculation using the radiosonde on Santiago (Chile) and El Plumerillo (Mendoza). This index is calculated by correlating four surface variables: pressure P_S (mb), temperature T_S (°C), dew point DP_S (°C) and ground ultraviolet solar radiation index UV. Furthermore, two additional atmospheric variables at the 500 mb level were considered: temperature T_{500} in °C, and dew point DP_{500} in °C at 500 mb pressure level. The data was taken from radiosonde over Mendoza and Santiago (Chile). We collected 1551 samples, between September 2007 and April 2008. These data were statistically processed, obtaining a multivariate model for each storm convective process class (TPC) in Mendoza. From this correlation, we can observe that the class and severity of the storm convective process do not depend on the dew point at the 500 mb level (DP_{500}), but depend on surface dew point value. This is associated with the fact that the vertical ascendant movement of the circulating air feeds the storm process carrying the water vapor from the ground to upper levels. Moreover, the class and severity of the convective process depends on the vertical temperature difference between both levels T_S and T_{500}, and is associated with the heat flux transfer by thermal conductivity and natural convection. We conclude from the above result, that for higher values of the temperature difference and surface dew point, a more complex and severe storm convective process in Mendoza is expected. The thermodynamic calculations performed by the multivariate model were consistently compared with GOES satellite image, the C and S band radar, and its TITAN system.

1. INTRODUCTION

During the validation of the DCPIM index (Pérez and Puliafito, 2007), we find that during 5% of the studied cases the calculation failed to give a proper forecast. Therefore we began deeper research work in order to explain or improve the DCPIM model.

The previous version of the DCPIM index was developed only with surface meteorology data: surface pressure P_S (mb), surface temperature T_S (°C), surface dew point DP_S (°C) and ground ultraviolet solar radiation index UV. Therefore, vertical atmospheric variables at the 500 mb level from radiosonde launches (Mendoza, Argentina and Santo Domingo, Chile), were considered in the model. This study used 1551 samples from September 2007 to April 2008. These data were to improve the prediction ability of the storm convective process in Mendoza.

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2. HYPOTHESIS

In order to complement the results of our previous research in the DCPIM work, we assumed that the storm convective process class does not depend only on surface conditions, but also strongly on 500mb atmospheric variables. This atmospheric pressure level is roughly coincident with the mean altitude of Los Andes Mountains. Every atmospheric system that comes from the west (Chile), passes over Mendoza at 500 mb, with the consequent production of mountain waves. Moreover the relationship between both levels (surface and 500 mb) is a strong indication of the convection possibility in Mendoza, and thus a way to improve the DCPIM results and the storm convective forecast model.

3. METHODOLOGY AND EQUIPMENT

Data sources used were as follow:

- **The web site www.weather.co:**

In this web site it is possible to find hourly surface meteorological data of Mendoza, measured at El

Plumerillo Airport. We obtained the following surface data: dew point (R), atmospheric pressure (P), temperature (T) and the ultraviolet solar index (UV).

- **The web site www.contingencias.mendoza.gov.ar/rada:**

Here on-line TITAN system images from the radars of Mendoza are available. These images are upgraded every five minutes (Figure 1). From this site, it is possible to characterize and classify the convective process of Mendoza and also obtain important parameters like the maximal reflectivity.

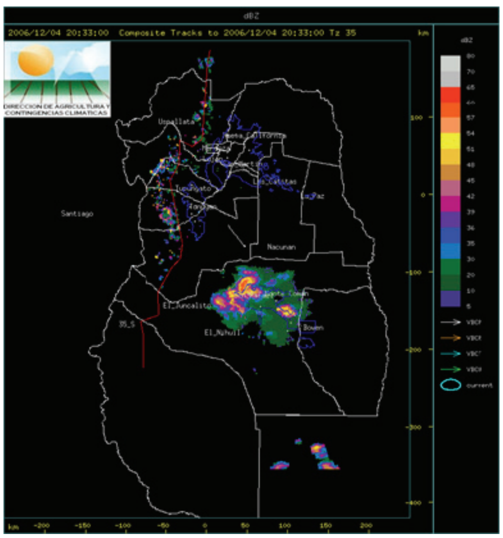

Fig. 1. www.contingencias.mendoza.gov.ar/radar web page with the TITAN systems images of Mendoza. The blue lines on the map show the limits of the hail defense area.

- **The web site www.meteofa.mil.ar:**

On this web site it is possible to access the GOES-12 satellites images (Figures 2 and 3).

- **The web site www.weather.uwyo.edu/upperair/sounding.htm:**

This page shows the radiosonde data. From this site we get all radionsonde information for both stations at Santiago de Chile and Mendoza (Argentina).

All this information was used to correlate the vertical sounding meteorological data, surface and 500 mb level information with the storm convective class present each day. The data was compiled in order to find a statistical relationship between them. For this study we have used surface hourly data and daily vertical data between September 2007 and April 2008.

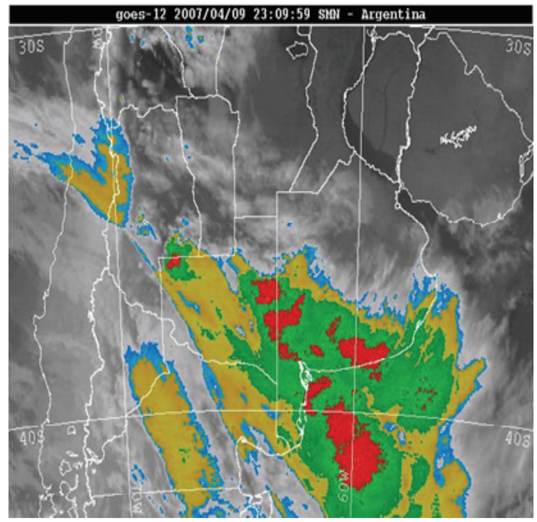

Fig. 2. www.meteofa.mil.ar web page with the GOES-12 image in the infrared frequency band.

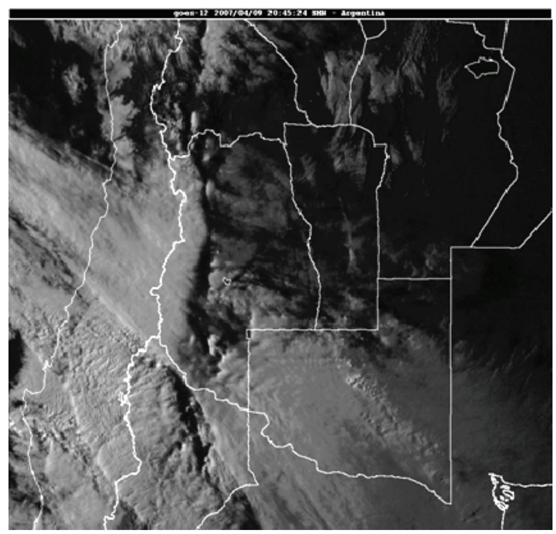

Fig. 3. www.meteofa.mil.ar web page with the GOES-12 image in the visible frequency band.

4. RESULTS

4.1 Statistical analysis

The correlation of surface and vertical information provided the estimation of a new index. This index was calculated by correlating four surface variables: pressure P_S (mb), temperature T_S in (°C), dew point DP_S (°C) and ground ultraviolet solar radiation index UV, and two additional vertical atmospheric variables at the 500 mb level. These were: temperature T_{500} (°C), and dew point DP_{500} (°C) at the 500 mb pressure level taken from radiosonde data over Mendoza and Santiago (Chile). The reasons for this choice are:

1. The 500 mb. level is coincident with the dumping of the west wind that come from Chile over Los Andes.

2. The previous studies determined that only temperature T_{500} and P_{500}, of all 500 mb level parameters have important correlation with the storm convective process class.

The data were statistically processed (Table 1 and Table 2); obtaining a multivariate model for each storm convective process class (TPC) in Mendoza.

A multiple linear regression fits the following relation between TPC and 3 independent variables:

$$TPC = -1.22422 + 0.0339936 \times T_S - 0.012635 \times T_{500} + 0.0896674 \times DP_S \quad (1)$$

$$TPC = -1.22422 + 0.012635\,(2.69 \times T_S - T_{500}) + 0,0896674 \times DP_S \quad (2)$$

The P-value in the ANOVA is less than 0.01, meaning that there is a statistically significant relationship between the variables at the 99% confidence level. The R-Squared statistic indicates that the model as fitted explains 34% of the variability in TPC. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is also 34 %. The standard error is 0.80 and shows the standard deviation of the residuals. The mean absolute error (MAE) of 0.63 is the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in the data file. Since the DW value is less than 1.4, there may be some indication of serial correlation. Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level. Consequently, it is convenient not to remove any variables from the model.

Table 1: Multiple Regression Analysis

Dependent variable: TPC (Standard T)

Parameter	Estimate	Error	Statistic	P-Value
CONSTANT	-1.22422	0.125033	-9.79115	0.0000
TS	0.0339936	0.004024	8.44771	0.0000
T500	-0.012635	0.00398971	-3.1669	0.0015
DPS	0.0896674	0.00558786	16.0468	0.0000

Table 2: Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	384.694	3	128.231	200.73	0.0000
Residual	733.36	1148	0.638816		
Total (Corr.)	1118.05	1151			

R-squared	34.4075 %
R-squared (adjusted for d.f.)	34.2361 %
Standard Error of Est.	0.799259
Mean absolute error	0.633167
Durbin-Watson statistic	0.72772

The evaluation of TPC can be interpreted as follows. When TPC is lower than 1, severe hailstorm process are not present in Mendoza. A TPC value between 1 and 2, indicates that monocell process will be present in the region. If the value is between 2 and 3, we should expect unorganized multicell convective processes (Figure 4 a) in Mendoza. Values of TPC between 3 and 4, it indicate the presence of organized multicell convective process in the province (Figure 4 b). If TPC has values between 4 and 5, it indicates intermediate cell processes (Figure 4 c) in the zone. Finally, when the value is bigger than 5, we should expect the formation of a supercell process in Mendoza (Figure 4 d).

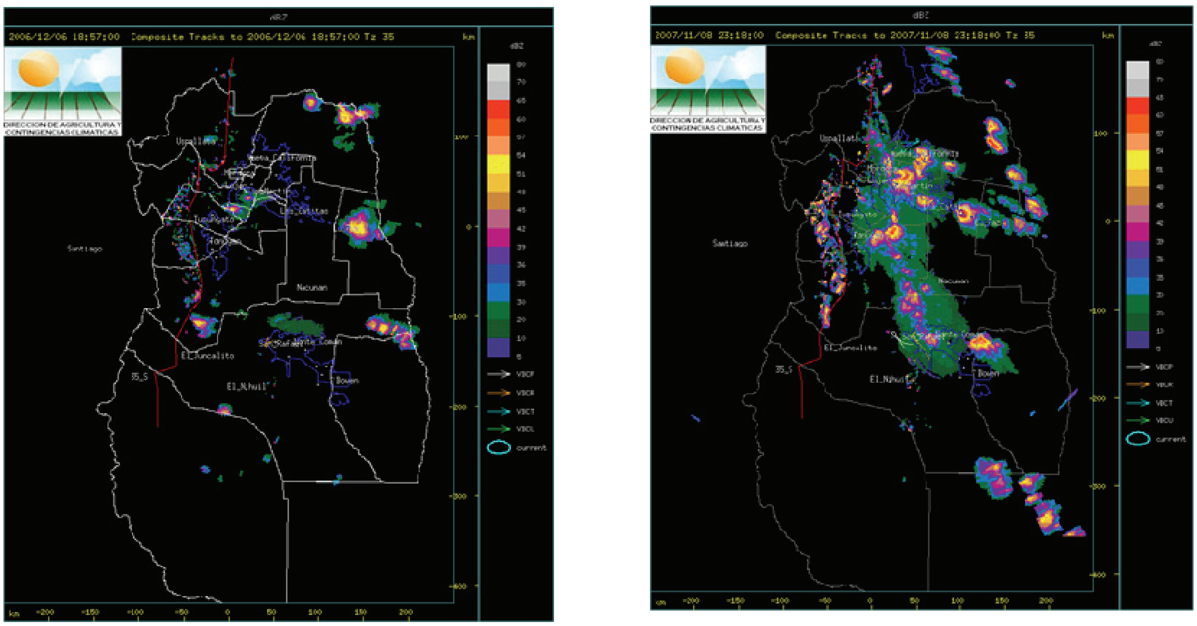

Fig. 4. (a) Unorganized multicells convective process (left); (b) Organized multicell convective process (right).

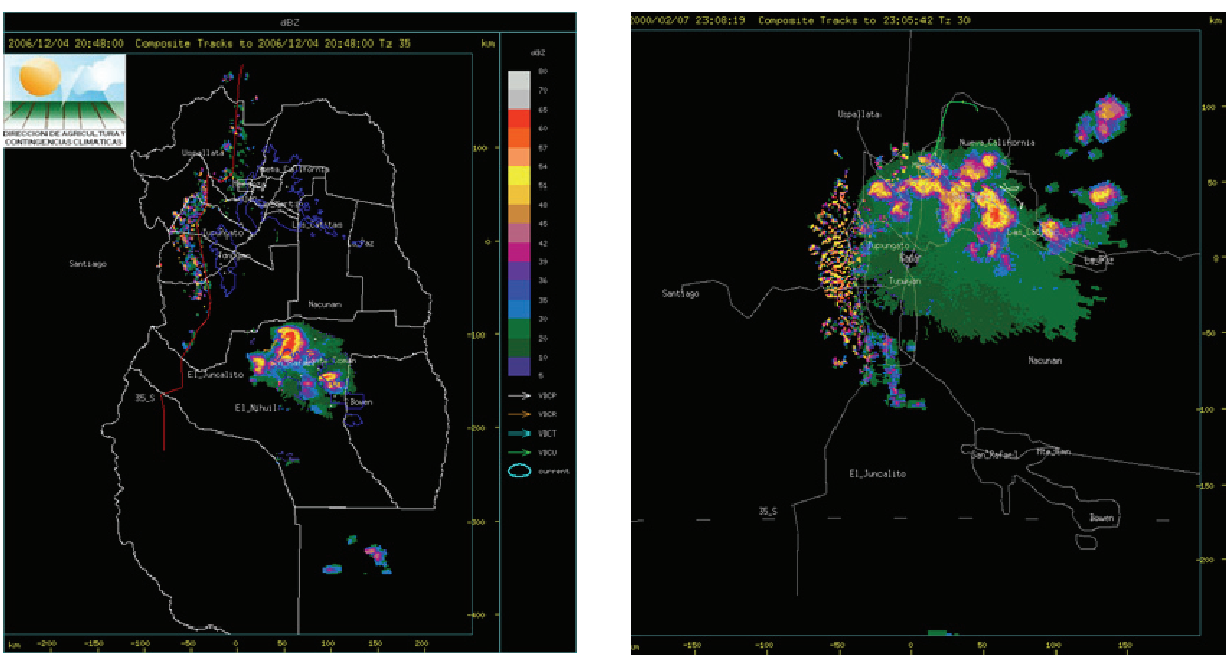

Fig. 4. (cont.)(c) Intermediate cell convective process (left), (d) Supercell convective process (right).

4.2 The natural convection and the thermal conductivity process

The natural convection equation (Zemansky, 1980) is:

$$\frac{Q}{t} = h.A.(T2 - T1) \quad (3)$$

where, the left side member is the heat over time unit flux, between two regions of the fluids that are at T_1 and T_2 temperatures; on the right side member, A is the cross section area at the heat flux direction and *h* is the natural convective coefficient which depends on the factors that follow:

1. Geometry and boundary conditions of the particular problem.
2. Sense and direction of the convection.
3. Properties of the fluid.
4. Fluid velocity that determines its movement regimen.
5. Different physical states (solid, liquid and gaseous) of the fluid; and its exchange rates.

The physical properties of the fluids depend on temperature and pressure, and the calculation of the convection coefficient *h* for each particular situation is a very complicated problem, because it must take into account all the factors described above. But, if the thermal conduction process produced from the temperature difference of the fluids is considered, equation (3) can be rearranged as follow:

$$\frac{Q}{t} = Um.A(T2 - T1) \quad (4)$$

where the total heat conduction coefficient U_m is:

$$\frac{1}{Um} = \left(\frac{1}{h1} + \frac{1}{h2} + \dots + \frac{1}{hi} + \dots + \frac{1}{hn} + \dots + \frac{x1}{k1} + \dots + \frac{xi}{ki} + \dots + \frac{xn}{kn}\right)$$

The h_i factor represents the individual convection coefficient of each different air layer through which must pass the heat flux. The x_i terms represent the thickness of these shells and the k_i are the thermal conductivity values respectively.

The term [0.012635 (2.69.T_S - T_{500})] in (2) corresponds to the temperature difference between the ground and 500 mb levels of Mendoza atmosphere. Then, we can associate with this term the temperature difference factor in equation (4). Also we can observe that the class and severity of the storm convective process depends on the vertical temperature gradient between both levels, which agrees with the above described heat flux in fluids due to the natural convection and thermal conduction. The factor that multiplies the surface temperature (T_S) is expressing that its statistical weight is higher than the 500 mb level temperature (T_{500}) on the vertical convection roll. On the other hand, this fact shows that in a storm convective process the surface temperature is more relevant than the temperature at 500 mb level. Finally, the constant value of the 0.012635 that multiplies the temperature gradient, can be assumed to be the media value of the *total heat conduction coefficient U_m* for the Mendoza atmosphere.

From the above correlation, we can observe that the class and severity of the storm convective processes do not depend on the dew point at 500 mb level (DP_{500}); but, on its surface value. This is associated with the fact that the vertical ascendant movement of the circulating air feeds the storm process carrying the water vapor from the ground to upper levels. Moreover, the class and severity of the convective process depends on the vertical temperature difference between both levels (T_S - T_{500}). This result is associated with the heat transfer by thermal conductivity and natural convection. In this way, the factor 2.69 that multiplies T_S suggests that the on surface temperature has a more important role in the convective vertical motion than the 500 mb level temperature. Then, in the storm convective process the surface temperature value is more relevant than its value at 500 mb level. Finally, if we observe the equations (2) and (4), the value 0.012635 that multiplies the temperature differences (equation 2) can be related to the U_m of the atmosphere in Mendoza. We conclude from the above results that for higher values of the temperature difference and surface dew point, more complex and severe storm convective processes in Mendoza are expected. The storm types predicted by thermodynamic calculation using the multivariate model consistently compared with storm types seen in GOES satellite images and the C and S band radar displays produced by the TITAN system.

4.3 Relevance of the water vapor

As shown in (2), the storm process class does not depend on the 500 mb level dew point value, but it does strongly depend on the surface dew point (Pérez, 2008). This result seems to be related to the fact that the storm convective process depends on the moist and the thermal available energy on the surface, in order to start the convection process, independently from the 500 mb level dew point value. It is well known that the surface dew point parameter has a threshold value of 12 °C in Mendoza. When the dew point value is lower than this threshold, it is improbable to have a severe storm present in the zone, and alternatively, when about the dewpoint is at the threshold or above, the convective process was severe for the same pressure and temperature conditions. This fact means that the water vapor on surface is the *"raw material"* that produces the storm clouds particles, and it is necessary to have a minimal amount of moisture in order to be able to trigger the deep convection process.

5. CONCLUSIONS

The previous version of DCPIM (Deep Convection Process Identification Model) index used only surface meteorology data to forecast the convective storm class in Mendoza (Argentina). But this model was not able to forecast correctly about five percent of the studied cases. In this paper an improvement to the above index was obtained by adding vertical atmospheric information. The main variables added are the temperature T_{500}, and dew point DP_{500} at the 500 mb pressure level taken from radiosonde data over Mendoza and Santiago (Chile). Orographic considerations and further theoretical analysis of the heat transfer for natural convection and thermal conductivity confirmed the relevance of including the temperature difference between these two levels. Moreover, observations showed that the class and severity of the storm convective process do not depend on the dew point at the 500 mb level (DP_{500}); but, they strongly depend on the surface dewpoint value. This is associated with the fact that vertical ascendant movement of the circulating air feeds the storm process carrying the water vapor from the ground to upper levels. Finally, through statistical analysis, we obtained the mean value for the total heat conduction coefficient U_m of the Mendoza atmosphere. The storm class predicted by the multivariate model consistently compared well with storm class based on GOES satellite image, and the C and S band radar, and its TITAN system.

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SUMMARY OF STUDIES THAT DOCUMENT THE EFFECTIVENESS OF CLOUD SEEDING FOR SNOWFALL AUGMENTATION

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Abstract. A brief summary of past research studies related to wintertime cloud seeding for snowfall augmentation has been compiled to illustrate what has been learned in those experiments that proved to be successful. The summary focuses primarily on physical studies, and on some randomized experiments that were accompanied by physical studies which verified aspects of the cloud seeding conceptual model. The important research areas covered include studies on: (1) the availability of supercooled liquid water, including its spatial and temporal distribution, (2) verifying the transport and dispersion of seeding material to clouds over target areas, (3) the microphysical changes caused by seeding with silver iodide and liquid propane, and (4) the precipitation increases that have been verified in physical studies and randomized experiments. The summary of results from past research details the specifics of the "*strong suggestions of positive seeding effects*" referred to in the 2003 report to the National Academies of Science entitled *Critical Issues in Weather Modification Research*. Although plentiful evidence regarding the effectiveness of cloud seeding is presented, it is also noted that further research on wintertime cloud seeding could provide answers to uncertainties that still exist, and also potentially benefit ongoing operational cloud seeding projects. Some recommendations for future research that take advantage of recent technological developments are presented.

1. INTRODUCTION

A report completed several years ago for the National Academies of Science (NAS) entitled "*Critical Issues in Weather Modification Research*" (NRC, 2003) concluded that there was no convincing scientific proof of the efficacy of intentional weather modification efforts. The NAS report further stated that, "*In some instances there are strong indications of induced changes, but this evidence has not been subjected to tests of significance and reproducibility*". Several responses to the NAS report (*e.g.*, Garstang *et al.,* 2004; Boe *et al.,* 2004) have pointed to many positive seeding effects (enhanced ice crystal concentrations or precipitation increases) in both summer and winter cloud seeding experiments. One of the main points of disagreement was the definition of scientific proof adopted in the NAS report, which Boe *et al.* (2004) indicated "few atmospheric problems could satisfy". The Weather Modification Association response (Boe *et al.*, 2004) provides a very detailed summary of pertinent findings related to rain enhancement, hail suppression and snowfall augmentation. The intent of this paper is to summarize only the results of well designed research projects related to seeding winter orographic cloud systems, which the NAS report admitted showed "*strong suggestions of positive seeding effects*". Numerous carefully conducted winter orographic cloud seeding experiments in the 1980s, 1990s, and early 2000s contributed much of the evidence of positive seeding effects to which the NAS report refers. In many instances the results of small-scale experiments were repeatable and in some instances the results were statistically significant. It is this evidence of positive effects that most in the field of weather modification believe validates the use of cloud seeding for practical operational snowfall enhancement projects.

What follows is a brief discussion which summarizes decades of research into the effectiveness of wintertime cloud seeding. With two exceptions, only peer-reviewed papers have been used as references. Included in the discussion is the generally accepted conceptual model for successful wintertime cloud seeding, and the findings of the most important experiments and projects that provided both physical measurements and statistical evaluations of results. The conclusion of this paper is that there has been ample evidence that wintertime cloud seeding is effective when the cloud conditions specified in the conceptual model exist. This paper also concludes and agrees with the NAS report finding that uncertain-

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ties still exist in this field, and should be rigorously studied in a broad new area of federally-supported research.

Cloud seeding programs with the purpose of increasing snowfall over mountainous terrain are based on results of research conducted over the past 40+ years, which has in large part been funded by federal agencies such as the U.S. Bureau of Reclamation and the National Oceanic and Atmospheric Administration. The research studies range from randomized statistical experiments conducted over entire drainage basins to highly detailed physical experiments conducted over the scale of individual seeding plumes from ground-based or aircraft seeding platforms. For cloud seeding programs conducted in mountainous regions of the western U.S. the following research results are the most applicable and have been used in the design of many of the ongoing operational snowfall augmentation programs in the U.S. and elsewhere.

2. CLOUD SEEDING CONCEPTUAL MODEL

As an introduction to the research results it is worthwhile to restate the generally accepted conceptual model for successful wintertime cloud seeding, which has evolved over the past 40 years, but is not substantially different now compared to its description in the design of the Bridger Range Experiment (BRE) in Montana (Super and Heimbach, 1983). As stated, the model is based on seeding by an ice nucleant such as silver iodide (AgI) which has ice-forming capability at temperatures below about -5^{o} C. The model is depicted as follows:

1) *Seeding material must be successfully and reliably produced.*
2) *Seeding material must be transported into a region of cloud that has supercooled liquid water (SLW).*
3) *Seeding material must be dispersed sufficiently in the SLW cloud, so that a significant volume is affected by the desired concentration of ice nuclei (IN) and a significant number of ice crystals (ICs) are formed.*
4) *The temperature must be low enough* (depends on seeding material used) *for substantial ice crystal formation.*
5) *ICs formed by seeding must remain in an environment suitable for growth long enough to enable them to fall into the target area.*

An ongoing randomized cloud seeding experiment in the Snowy Mountains of Australia (Huggins *et al.,* 2008) is patterned after these same basic concepts.

3. DOCUMENTING THE CLOUD SEEDING CHAIN OF EVENTS

3.1 Availability of SLW for Cloud Seeding

Before discussing experiments that have documented the steps in the conceptual model, it is important to note that numerous studies in mountainous regions of the western U.S. have examined the temporal and spatial availability of SLW and its temperature range. Successful cloud seeding depends on there being an excess of SLW in winter storms, and that the SLW exists at low enough temperatures for seeding material to be effective.

Analysis of aircraft, microwave radiometer and mountain top icing measurements have shown some consistent SLW characteristics in wintertime storms. The more important ones are as follows.

- SLW is present at some stage of nearly every winter storm (Super and Huggins, 1993; Heggli and Rauber, 1988), but also tends to exhibit considerable temporal and spatial variability (*e.g.,* Super and Huggins, 1993; Heggli and Rauber, 1988, Heggli *et al.,* 1983; Boe and Super, 1986; Rauber and Grant, 1986).
- A given storm passage may result in a number of SLW periods interspersed with other periods with no SLW. (This implies that it is generally not practical to seed only the SLW periods because of these rapid natural changes.)
- The SLW is found predominantly over the windward slope of a mountain range, and often extends considerably upwind of the physical barrier (Heggli and Rauber, 1988; Rauber *et al*., 1986).
- The SLW decreases downwind of the mountain crest, or region of maximum lift,

due to removal by precipitation and/or evaporation (Rauber *et al*., 1986; Boe and Super, 1986; Huggins, 1995).

- In the vertical, the zone of maximum SLW generally extends from somewhat below the mountain crest to less than one kilometer above the mountain crest (Heggli *et al*., 1983; Boe and Super, 1986; Huggins, 1995).

The temperature in the SLW zone varies considerably depending in large part on the height of the mountain barrier and its geographical location. This indicates, therefore, that the most appropriate seeding methodology can also vary considerably from one location to another, from storm to storm, and even within the same storm. Studies in the Rocky Mountains have shown SLW cloud bases typically in the temperature range of -2^o to -10^o C (Boe and Super, 1986, Huggins, 1995; Rauber and Grant, 1986), with aircraft measurements and radiometer-inferred estimates indicating temperatures at the top of the SLW layer are generally -10^o to -15^o C (Huggins, 1995; Rauber and Grant, 1986). A general finding was that SLW was abundant in clouds with tops warmer than about -22^o C where natural snowfall was also found to be generally very light (Rauber *et al*., 1986; Rauber and Grant, 1986). Lack of SLW was at times observed with colder cloud tops and higher natural snowfall rates, but SLW occurrence has also been observed during periods of moderate snowfall (Boe and Super, 1986). In the Sierra Nevada cloud base is commonly warmer than 0^o C and the top of the SLW layer within one kilometer of mountain top is generally -12^o C or warmer (Heggli and Rauber, 1988; Heggli *et al*., 1983).

Several studies used radiometer measurements to compute the total flux of SLW across a mountain barrier for a winter season and determined that the total SLW flux, if converted to precipitation, could increase the observed seasonal snowfall by 50-100% (Super and Huggins, 1993; Boe and Super, 1986; Super, 1994). Note that the flux estimates were based on point measurements over a three-dimensional mountain, and that only a perfect seeding methodology that could target all of the SLW all of the time (and at all temperatures) could realize this potential increase. The overall conclusion of every study of SLW availability was that significant cloud seeding potential existed in winter storms over mountainous terrain provided the proper seeding technique could be applied at the appropriate time and location.

3.2 Transport and Dispersion of Seeding Material

In studying the effects of cloud seeding it is important to be able to verify the conceptual model, or what has come to be termed the cloud seeding "chain-of-events". All or portions of the chain-of-events have been documented by research studies in the Sierra Nevada of California, in the Rocky Mountains of Montana, Colorado and Utah, and in the mountains of northern Arizona. In the initial studies of the BRE in the 1970s (Super and Heimbach, 1983; Super, 1974) steps 1-4 of the conceptual model were documented a high percentage of the time. For example, during one winter of experimentation every aircraft flight (42 passes on 13 days) detected the AgI plume from one seeding site moving toward the target area. With a combination of surface and upper air wind and temperature measurements, and documentation of seeding plume locations using an aircraft equipped with an ice nucleus counter, the authors indicated they "...*believed that the BRE has some of the most convincing evidence of successful targeting obtained in a winter orographic program*", and further stated that "*data are quite consistent with the concept that AgI* (the seeding material) *was transported rapidly up the west slope of the Bridger Range, crossed the Main Ridge and moved toward the intended Bangtail Ridge target area*". In addition, the authors presented some of the first evidence of successful cloud seeding targeting using the trace chemical analysis of snowfall for silver content. They found that "…*increased Ag concentrations* (from the seeding material) *found on Bangtail Ridge lend further support to evidence of proper targeting…*"

In the late 1980s similar techniques were used to document very consistent and successful transport and dispersion of seeding material over the Grand Mesa in Colorado (Holroyd *et al*. 1988; Super and Boe, 1988) from both ground-based and aircraft releases of silver iodide. Additional verification of successful transport and dispersion of ground-released seeding material has been documented over the Wasatch Plateau in Utah (Holroyd *et al*., 1995). These and other transport and dispersion studies during the 1980s and 1990s began to include high-resolution model simulations of plumes that were verified by observations. Additional examples include Sierra Nevada studies (Meyers *et al.,* 1995) and Arizona experiments (Bruintjes *et al*., 1995).

3.3 Microphysical Effects (Formaiton, Growth and Fallout of Ice Crystals

Measurements which verified the initiation, growth and fallout of ice crystals were included in many of the experiments involved with tracking silver iodide seeding plumes. Some of the first evidence of this type was documented in the BRE (Super and Heimbach, 1988). For clouds containing SLW it was found that ice particle concentrations were significantly enhanced and estimates of precipitation in seeded regions exceeded natural clouds by factors of two or more. No decreases in precipitation were found in seeded cloud regions. The best evidence of seeding was found in cloud regions colder than -9^{o} C with cloud tops generally warmer than -20^{o} C.

Similar experiments over the Grand Mesa of Colorado also verified plume transport over the intended target and ice crystal enhancement of at least 10 times the natural background in the seeded zones of both aircraft and ground-released plumes (Super and Boe, 1988). The Grand Mesa experiments included measurements of precipitation rate increases at the surface that were typically many times greater than unseeded periods. Additional links-in-the-chain evidence exists for a number of ground seeding experiments from the Wasatch Plateau of central Utah. Seeding plume locations, ice particle enhancement, and precipitation increases within seeding plumes were carefully documented in four papers (Holroyd *et al.,* 1995; Super and Holroyd, 1997; Huggins, 2007; Holroyd *et al*., 1998). As in the BRE the best results from AgI seeding came from the colder cases (Super, 1999). Further evidence of the evolution of ice particles in seeding plumes released by aircraft was provided by cloud seeding experiments over the Sierra Nevada of California (Deshler *et al.,* 1990) and in a unique experiment conducted over the Mogollon Rim in Arizona (Reinking *et al*., 1999), where analysis of data collected by circularly-polarized radar during chaff releases, and aircraft measurements of cloud characteristics, revealed the formation and evolution of ice particles from seeding within a naturally precipitating cloud.

3.4 Evidence of Precipitation Increases

Randomized experiments are considered the "gold standard" of experimental evaluations and are necessary to supply the "proof" referred to in the NAS report (NRC, 2003). Statistical analyses of weather modification experiments, where natural variability can be 100 times the expected seeding signal, are also greatly improved by the use of covariates (*e.g.* Mielke *et al.,* 1981; Gabriel, 1999; Gabriel, 2002). The best covariates are precipitation measurements in control areas upwind or crosswind of a target area. This covariate approach was applied to the BRE data sets and the results from statistical evaluations matched very well with what was learned in the physical studies. Two seasons of a randomized seeding experiment produced results that showed significant differences between seeded and unseeded populations of events (Super and Heimbach, 1983). The main findings were: a) Seeding increased snowfall in the intended target and sometimes downwind, when the ridge top (~2595 m) temperature was less than -9^{o} C; b) The seeding increase was found for the entire 100 days which met this criterion over two seasons, as well as when each season was analyzed separately; c) Positive seeding effects were suggested in the target and in the valley downwind of the target, also mainly for the colder cases; d) A seeding effect of about +15% was also found just a few kilometers from the seeding sites, and; e) Double ratios of target and control gage precipitation suggested seasonal increases of ~15% on seeded days, but increases as great as +50% were indicated when only the colder days were included in the analysis (a finding in close agreement with the microphysical observations).

Some of the best physical evidence of seeding-induced precipitation increases came from the many experiments conducted over the Wasatch Plateau where both silver iodide seeding and liquid propane seeding methods were tested (Super, 1999). Individual experiments revealed precipitation rate increases in seeding plumes of a few hundredths of a millimeter (estimated from imaging probe data) to more than one millimeter per hour (Holroyd et al., 1995; Super and Holroyd, 1997; Huggins, 2007; Holroyd et al., 1998). The careful and repeatable documentation of seeding plume transport and dispersion, and microphysical effects, led to the design of a randomized experiment using liquid propane in this same region of Utah. The use of propane was thought preferable to AgI because of the high frequency of time SLW was found to occur over the Wasatch Plateau at temperatures too high (> -5^{o} C) for ice formation by AgI (Huggins, 1995; Super, 1994: Super, 1999). As in the BRE a target-control analysis was also applied in the Utah study (Super and Heimbach, 2005). The results of this 1-season experiment were statistically significant and indicated that seeded periods produced about 20% more precipitation than unseeded periods (Super and Heimbach, 2005).

Other statistical evaluations of wintertime cloud seeding have produced similar results, but none are nearly as well documented by physical observations as was the BRE. Another randomized experiment was conducted by the Pacific Gas and Electric (PG&E) Company in a region near Lake Almanor in the northern Sierra Nevada (Mooney and Lunn, 1969). A statistically significant result came from a cold-westerly storm stratification where a 32% increase in precipitation was indicated for seeded cases. Trace chemical evaluations of snowfall in the Lake Almanor project area (Warburton et al., 1995a, and 1995b) have since helped substantiate the statistical indications. A common finding from the projects referenced here is that the most pronounced seeding effect occurred in relatively cold and shallow orographic clouds. Evidence indicated that precipitation can be increased by 50% or more in these storm periods, which can result in seasonal increases of snowfall by the ~10% augmentation that is quoted in capability statement of the American Meteorological Society (Amer. Meteor. Soc., 1998).

4. AN INCREASINGLY POPULAR EVALUATION TECHNIQUE: TRACE CHEMISTRY ANALYSIS

Additional research on wintertime cloud seeding over the past 20 years has produced some very promising techniques for evaluating seeding effects over basin-sized areas. As shown in the BRE (Super and Heimbach, 1983) the trace chemical analysis of snowfall can be used to verify targeting. The technique has now been used on numerous projects to determine: (1) if seeding material has reached the target area; (2) how it is spatially distributed over the target; (3) how it is temporally distributed throughout a storm; and (4) whether the seeding material arrived at the target as a result of ice nucleation by the seeding material (Warburton *et al*., 1995a, 1995b, Chai et al., 1993; Warburton *et al*., 1996). This technique is currently being used in a randomized seeding project in Australia (Snowy Precipitation Enhancement Research Project, Huggins *et al*., 2008) where ultra-trace chemical measurements have been used to identify seeded and unseeded experimental units even before the randomization pattern has been revealed. One operational program in the Sierra Nevada used this trace chemical technique to show that cloud seeding operations produced a seasonal 8% increase in the snowpack over a specific watershed (McGurty, 1999). Such results from physical and trace chemical analyses compare well with earlier randomized experiments such as that of PG&E (Mooney and Lunn, 1969) which showed similar increases in the northern Sierra Nevada.

5. CONCLUSIONS AND RECOMMENDATIONS

The studies and experiments summarized in this paper represent millions of dollars worth of research effort conducted over many decades by meteorologists, physical scientists, and statisticians. These studies led to a well defined cloud seeding conceptual model that was verified in numerous case studies, and also documented the potential impact of cloud seeding, the cloud conditions needed for successful snowfall augmentation, and the chain-of-events in effective cloud seeding. I believe this combined evidence shows more than the "suggestion of positive effects" noted in the NAS report. It is also worth noting that many of the studies referenced here, that documented both microphysical changes and precipitation enhancement by cloud seeding, were not included in the NAS report. Including these results might have affected the overall conclusions of the report.

Innovative techniques for evaluations of seeding experiments have been developed, and new ones are still needed to prove cloud seeding effectiveness and to refine cloud seeding programs. The World Meteorological Organization's policy statement indicates that "*glaciogenic seeding of clouds formed by air flowing over mountains offers the best prospects for increasing precipitation in an economically-viable manner*". This is a suitable, and somewhat conservative, summary of the work that has been done to date. It also apparent that recent advances in atmospheric modeling, remote sensing, and laboratory techniques can assist with advances in cloud seeding research and ultimately in seeding operations. The main recommendation of the NAS report that a "*coordinated national research program*" is needed to apply the new technologies to key uncertainties in weather modification is an appropriate goal for the weather modification community.

Recommendations for evaluations of current operational seeding programs and for future research in snowfall augmentation should include, but need not be limited to, the following:

- Evaluate new or existing operational seeding projects (which have not done so) to document the initial steps of the conceptual model to ensure seeding in the SLW zone is actually occurring. The following techniques can be used.
    - ◊ Trace chemical analysis of snowfall in the target area.
    - ◊ Transport and dispersion studies using modeling, plume tracking, etc.
    - ◊ Air flow, temperature and SLW measurements over the project area.
- Continued testing of silver iodide and liquid propane seeding methods.
    - ◊ Conduct relatively small-scale randomized experiments, which have been done on only a very limited basis in the past 20 years.
    - ◊ Use accepted statistical techniques with the randomized studies to analyze the magnitude of seeding effects. Use predictor variables to strengthen the statistical analyses and reduce the number of experiments needed to obtain significant results.
    - ◊ Support any statistical study with observations sufficient to enable understanding of the physical processes.
- Test current, or develop new satellite and ground-based remote sensing techniques to detect cloud seeding potential and monitor seeding induced changes in clouds.
- Use the newest high resolution atmospheric models to predict seeding plume transport and dispersion. However, verification by observations is essential.
- Develop explicit microphysical modules for cloud models to predict microphysical and precipitation seeding effects. Verify with observations.
- Refine techniques, such as the trace chemical analysis of snowfall, to evaluate new or ongoing wintertime seeding projects over drainage basin-sized areas.
- Study the impact of air pollution on winter clouds and precipitation.

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TEXAS WEATHER MODIFICATION OPERATIONS IN 2008

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Abstract. The State of Texas completed another year of successful weather modification operations in 2008. During this season, a total of seven projects were operational in Texas conducting rain enhancement and, in one project, hail suppression operations. Operationally, some projects experienced a below average year flight-wise due to the emergence of a drought that began in the fall of 2007. As well, some clouds exhibited tropical characteristics that resulted in less than desirable seeding by glaciogenic materials. Most parts of the state were dry, with the exception of a few spots in northern and far southern Texas. This paper will serve as an update for the Texas projects in 2008, offering a comprehensive summary of each of the operational projects in the state. Additionally, this paper will provide an analysis of the Texas projects conducted by Active Influence and Scientific Management.

1. INTRODUCTION

Weather modification activities continued in 2008 over six target areas spread across parts of Texas. These operational areas cover 29.9 million acres of a total 172 million acres in the state of Texas. For the most part, flight activity was below average. The reason for the below average flight activity was due to the abundance of tropical moisture resulting in cloud structures that were not best suited for glaciogenic seeding.

For the 2008 season, seven projects were operational: Panhandle Groundwater Conservation District's (PGCD) precipitation enhancement project in White Deer, Seeding Operations and Atmospheric Research (SOAR) in Plains, Trans-Pecos Weather Modification Association (TPWMA) in Pecos, West Texas Weather Modification Association (WTWMA) in San Angelo, Southwest Texas Rain Enhancement Association (SWTREA) in both Carrizo Springs and Pleasanton, South Texas Weather Modification Association (STWMA) in Pleasanton, and the Edwards Aquifer Authority's (EAA) precipitation enhancement project. The EAA project is operated by the STWMA and the SWTREA. A map showing the location of all the projects is presented in Figure 1.

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2. TEXAS WEATHER IN 2008

2008 and 2007 were very different years in terms of the overall weather pattern. In 2007, the state experienced a very wet pattern that persisted through most of the summer months. 2008 contrasted with 2007, as most of the state fell into drought conditions. However, there was an exception to this drier pattern in 2008, as portions of the Texas coast throughout the summer and into fall were affected by tropical cyclones. Almost all areas of the state emerged back into drought conditions except for a few locations. Areas that escaped drought for the most part during 2008 were the lower Rio Grande Valley, parts of the Panhandle, some locations in the Pecos River Valley, and spots in east Texas. Most parts of the state received 75% or less of the average annual rainfall. In some of the most drought stricken areas, only 25-50% of the average annual rainfall occurred. Drought conditions can be traced back to the fall of 2007.

Two hurricanes and one tropical storm affected the state of Texas during the summer months. Hurricane Dolly made landfall near Brownsville in late July as a Category 2 storm, providing very heavy rainfall to portions of the Rio Grande Valley. Early in August, Tropical Storm Edouard made landfall in southeastern Texas as a strong tropical storm. Finally, Hurricane Ike made landfall at Galveston in mid-September as a strong Category 2 storm. Figure 2 illustrates the radar-derived yearly rainfall for Texas.

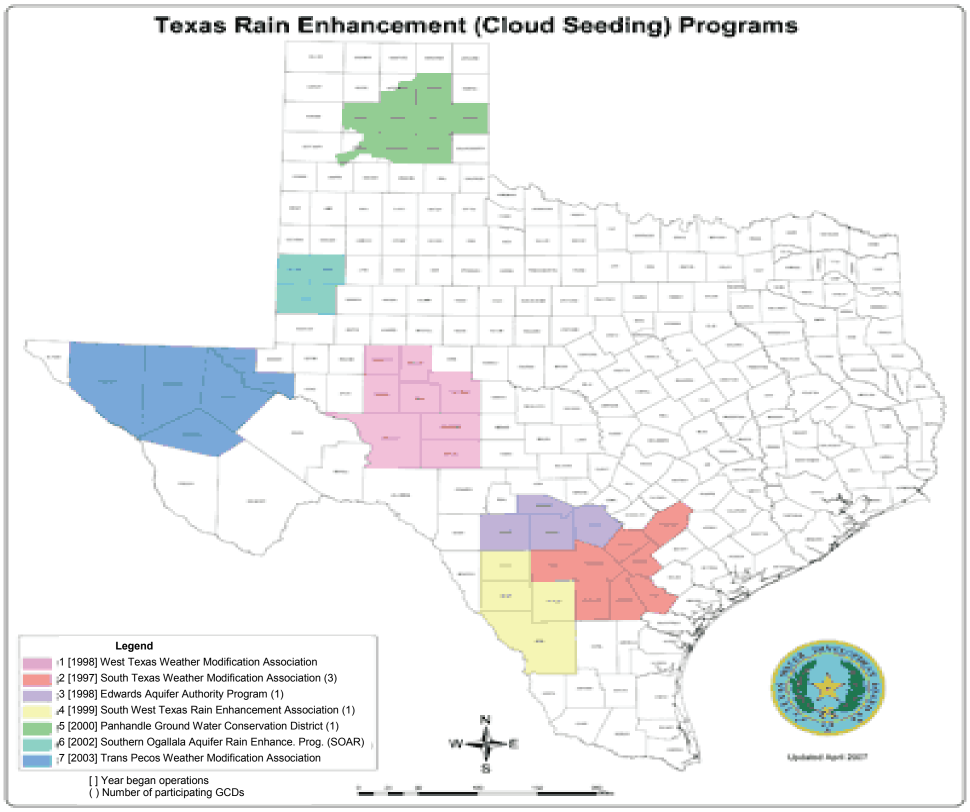

Fig. 1. Locations of Weather Modification Programs in Texas in 2008

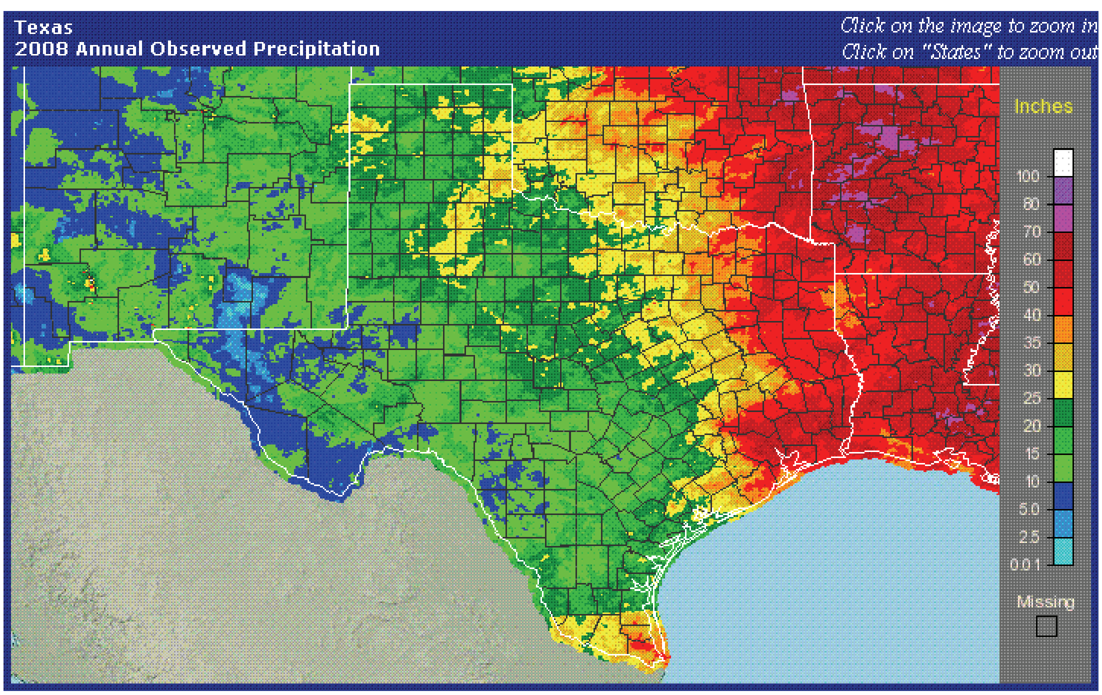

Fig. 2. Radar-derived yearly precipitation for Texas in 2008. Image courtesy of NWS Precipitation Analysis website, http://www.srh.noaa.gov/rfcshare/precip_analysis_new.php .

3. PROJECT SUMMARIES

3.1 Panhandle Groundwater Conservation District (PGCD)

The conclusion of the Panhandle Groundwater Conservation District's 2008 Precipitation Enhancement Program marked the ninth year of cloud seeding in the Texas Panhandle. This season began with the first mission on April 23rd and concluded on September 5th with the last mission. Typically, the season runs from April 15th until September 30th; however, if suitable opportunities are present before the 15th the season will commence.

The 2008 seeding season contained 23 days with seeding events, which consisted of 26 seeding missions and six reconnaissance missions. This season had the least amount of seeding days since 2000 which had only 22 days of seeding. This year we seeded 15 less days and 33 fewer clouds than in 2007, which can be attributed to very few seeding opportunities through the summer. Each month contributed its own factor for fewer seeding conditions.

During April, the Texas Panhandle experienced many cold fronts, warm fronts, trough passages and dry lines; however, the missing ingredient for convection was moisture. May was characterized by stratus clouds with little to no convection, and concluded with a few dry line events that the National Weather Service (NWS) issued severe thunderstorm warnings on. In the beginning of June much of the precipitation favored the eastern Texas Panhandle; however, at the end of June the pattern changed. During most days precipitation formed off the mountains with a trough and upper-level shortwave being the focus for initiation. This activity moved southeast across the western counties in the Texas Panhandle. All of the seeding missions were cut short due to NWS severe thunderstorm warnings. July was dominated by high pressure, but the weather that did occur was due to normal summer daytime heating with the combination of some mid-level dynamics to create scattered afternoon thunderstorms. All of the weather systems that moved through the area during August were dominated by slow-moving, heavy rainfall thunderstorms. Therefore, some seeding missions were ended due to flash flood warnings issued by the NWS. All of the rain in September occurred on or before the 12th due to three cold fronts and a stationary front, and the rest of the month was characterized by high pressure. In combination with the monthly changes in weather patterns, we also saw more continental clouds this year that consisted of smaller than normal volumes of supercooled water, which also affected our seeding results.

Table 1 shows the number of seeding and reconnaissance missions, flares used, and time flown during the 2008 seeding season.

Table 1: Weather Modification in PGCD in 2008

Month	Seeding Flights	Recon Flights	Hours Flown (H:M)	Flares Used
April	1	1	3:44	8
May	3	2	8:30	21
June	5	1	13:10	54
July	6	0	16:55	53
August	10	2	23:55	95
September	1	0	1:45	7
Totals	26	6	67:59	238

3.2 Seeding Operations and Atmospheric Research (SOAR)

Cloud seeding operations in the SOAR project area were not as busy as in 2007. Overall for the year, 20 days saw clouds being seeded within the tri-county area. In May, the eastern parts of the target area saw above normal rainfall while the western areas were drier than normal. Cloud seeding occurred on three days during the month with two additional days of reconnaissance flights. Wetter than normal weather was experienced in June; this happened to be the busiest month of the season. Eleven days of cloud seeding were recorded with an additional four days where reconnaissance flights took place. Drier weather resulting from high pressure parked over the area in July yielded only two days where seedable clouds were treated, and a further two days of reconnaissance flights. August, like May, saw variable rainfall across the target area with the central third seeing above normal rains while the northern and southern areas were drier. Two days during the month offered clouds that were treated, with one reconnaissance day. September ended up being the last month of operations for the SOAR project, with two days of seeding taking place. It was also a wet month for all but the far northwestern corner of the target area, mainly attributed to a very wet period at mid-month when a flow of tropical moisture across western Texas resulted in a train of very heavy rains. For the entire season, 58 ejectable and 53 burn-in-place flares were used, totaling 3280g of AgI.

3.3 Trans-Pecos Weather Modification Association (TPWMA)

The TPWMA's cloud seeding program, under guidance from SOAR, continued in 2008 with their sixth year of operations. The past year was comparable to 2007, with 17 seeding days recorded versus 21 in 2007. The program's first day of seeding occurred in June, where a total of four seeding days were recorded along with an additional four days of reconnaissance flights. The regular occurrence of orographic convection to the lee of the Davis Mountains resulted in a zone of above normal rains over the far eastern target area. This pattern continued into July, with more widespread above normal rains along and to the east of the Davis Mountains. July was the busiest month of the season for Trans-Pecos, with seven seeding days and four reconnaissance days. The presence of tropical moisture helped with the orographic convection, with some enhancement late in the month by the remains of Hurricane Dolly. August, with four days of seeding and three days of reconnaissance, was drier than normal for all but the far eastern portions of Jeff Davis County. September saw a return to above normal rainfall to the lee of the Davis Mountains, primarily resulting from the mid-month intrusion of deep tropical moisture from the Pacific. Despite this, only one day of seeding took place along with three reconnaissance days. October saw the final seeding mission of the year. Overall, 106 burn-in-place flares were used for seeding, amounting to 4240g of AgI.

3.4 West Texas Weather Modification Association (WTWMA)

2008 West Texas seeding operations started on March 17th and ended on September 24th with 38 operational days. Three days were classified as experimental due to the limited moisture or suppressed vertical structure which hindered sufficient inflow. 77 clouds were seeded with 1,431 flares during 57 flights. Eight reconnaissance flights were flown while making an attempt to find seedable clouds on marginal days and pilots flew 150 flight hours.

Changes to the data format created some problems with the Thunderstorm, Identification, Tracking, Analysis, and Nowcasting (TITAN) software used in the Texas project. The National Weather Service Offices installed a new software package called Build-10 with super-resolution capabilities. The software update required manipulation to the Local Data Manager (LDM). The LDM data stream is what TITAN uses to receive and process radar data. One day (June 13) was completely lost while the new code was written. Weather Decision Technologies (WDT) worked hard to provide the new data stream through the month of June. New issues continued to crop up through the summer associated with the change. Several instances of lost radar hindered operations at various times.

2008 was a rather dry year. The annual rainfall, 19.00 inches, at San Angelo was below normal by 1.91 inches. Record rainfall at the San Angelo Regional airport on September 8th and several days in August where Mathis Field received plentiful rains does not show accurately the amount of rainfall seen by the majority of the target area. August was the most active this season with 15 operational days. Precipitation and percent of normal maps show that much of Texas was well below normal except for March which had mainly one rain event. Another event occurring in September west of the Pecos River and over western Crockett County was also noteworthy.

Table 2: Weather Modification and average rainfall in WTWMA in 2008

Month	Days	Flares	Rainfall (Avg.) In inches
March	1	27	2.43
April	2	90	0.64
May	4	95	0.65
June	7	267	2.24
July	7	253	0.43
August	15	707	3.37
September	2	17	2.47
Total	38	1456	12.23

Table 3: Comparison of operational data analysis from 2002-2008 in WTWMA

	Seeded Clouds	Opera-tional Days	Flares	Increase Million ac-f	Annual Rainfall
2002	285	47	3024	0.78	14.41
2003	265	50	3184	0.76	19.76
2004	109	46	1140	1.35	30.48
2005	133	39	1524	1.26	20.4
2006	157	53	1810	1.7	17.65
2007	95	46	1166	1.19	32.05
2008	78	38	1420	1.18	19.00

3.5 Southwest Texas Rain Enhancement Association (SWTREA)

The 2008 operational season for the Southwest Texas Rain Enhancement Association was one that could be termed as a “flip-flop” season. 2008 marked the tenth operational season for the SWTREA. The season was below normal flight-wise but much more active than 2007. Most of the spring months were very slow and not until later in the summer, during July and August, did operations peak. Usually, operations peak in May and in September with the two precipitation maxima that occur over south Texas. May was about normal precipitation-wise but not operationally. As well, September turned out to be very slow compared to normal. The wettest month of the operational season was August, with a total of sixteen seeding flights on eleven seeding days. September saw a drop in flight activity, as did October when activity usually drops off. The spring months over the southwest Texas area were active in terms of severe weather, with a total of six hail suppression flights taking place in May and April.

The project’s first flight usually takes place in March but this year did not take place until the beginning of April due to lack of convection across the area. A recurring problem during the 2008 operational season involved the quality of clouds that were observed. On a number of occasions, convection present in the target area was characterized by low tops, warm rain processes, and weak echo returns. This was the case mostly during the summer months and greatly impacted operations as seen in Table 4.

There was a stark contrast in rainfall over the target area from north to south. While the northern parts of the target area received very little rainfall during the summer months, southern parts of the target area saw heavy rainfall. August was an especially wet month for the two southern counties, LaSalle and Webb, as a series of upper level lows were situated over southwest Texas and eastern Mexico. These same counties also received ample rainfall from Hurricane Dolly, which moved across the lower Rio Grande Valley in July.

Operationally, there was an addition of a new pilot that served both the SWTREA target area and the SWTMA target area. The STWMA is the eastern border of the SWTREA project, so this only increased operational efficiency in south Texas. As well, the project experienced data

Table 4. Weather Modification in SWTREA in 2008

Month	AgI used	Number of flights	Rain Enhancement	Hail Suppression
April	5360	5	1	4
May	5760	5	3	2
June	4600	6	6	0
July	4760	7	7	0
August	9160	16	16	0
September	5080	5	5	0
October	560	1	1	0
Totals	35400	47	41	6

issues during the summer months due to the Build-10 upgrade that the National Weather Service made operational in all radars around the state.

3.6 South Texas Weather Modification Association (STWMA)

2008 marked STWMA's twelfth year of cloud seeding operations in south-central Texas and the seventh year of operations for the Edwards Aquifer Authority's (EAA) tri-county area. While the year as a whole was dry, there were a few months where above normal rainfall fell within the target area, notably July and August, the heart of the seeding season. March was also wet for some parts of central Atascosa County, but this was attributed to a supercell thunderstorm that dropped nearly four inches of rain. The remaining months were quite dry across the STWMA target area, with far northern parts of the area classified as being in exceptional drought by year's end. Overall, 104 clouds were seeded over a total of 41 days in 2008, almost twice as many days as in 2007.

The season's first seeding flight took place on March 18th, the only day of seeding during the month. A storm system with impressive dynamics moved across the state, generating a line of convection over the eastern counties. This was the first flight for our new pilot, Matt Pope, who trained throughout the year with Craig Funke. This was the only day of seeding in March. Given the past history, one can expect a day with seedable clouds in March about every third year. April gave the STWMA no seeding missions as much of the area received only 25-50% of their normal rainfall. May was much drier than normal, with eastern areas only receiving 10-25% of their normal rainfall. This was not good, as May is typically one of, if not the wettest month of the year. Only two days saw cloud seeding take place, both of which occurred during the latter half of the month. In both cases the seeded convection appeared to do quite well, continuing past sunset while other untreated convection dissipated. The dry pattern continued into June, with all of the target area receiving less than 50% of the average monthly rainfall and many areas receiving less than 5%! Oddly enough, this was one of the busiest months of the year, with nine days of cloud seeding taking place. The vast majority of clouds in June, however, were small and short-lived. One exception was on June 20th, when a seeded cloud in the eastern target area tracked southwestward into the southern target area with an average rainfall of 1-1.5 inches along the track. July brought welcome rains to the area, with all but far western Bandera County receiving above normal rains, a good chunk of which fell on the 23rd-24th when a weakening Hurricane Dolly impacted the area. Eight days saw cloud seeding take place in July, the majority of which occurred during the first week. The wet pattern continued into August, with much of the area seeing well above normal rainfall, although there were a few locations that missed out and received below-normal rains. The month was quite active, with 16 days of cloud seeding recorded. Four days in September saw cloud seeding take place, near the start of the month and also towards the end. September, unfortunately, saw a return to very dry conditions despite the presence of tropical moisture. Hurricane Ike impacted the area as it made landfall at Galveston on the 13th, but instead of bringing us rains, the circulation around Ike brought scorching heat, with many locations in the target area topping out between 100-105°F. Our final day of seeding took place on October 14th, the only day of the month that operations took place.

3.7 Edwards Aquifer Authority (EAA)

The South Texas Weather Modification Association and the Southwest Texas Rain Enhancement Association participate in a precipitation enhancement program over a small portion of the Edwards Aquifer located in south-central Texas. Both the above mentioned projects have been seeding in the EAA target area for the last seven years. For 2008, a total of twenty-two seeding flights were flown in the EAA target area.

In 2007 at the request of the EAA, the STWMA began a multi-year experiment within the EAA target area counties of Bandera, Bexar and Medina where randomized seeding would take place. 2008 provided even less randomization opportunities than 2007, with one randomized case overall, and that was in the SWTREA target area. The primary problem stemmed from potential candidates being too close to larger clouds, which did not satisfy the existing protocol. The upcoming season in 2009 will hopefully bring many more opportunities for the experiment to continue.

4. 2008 STATE EVALUATION BY ACTIVE INFLUENCE AND SCIENTIFIC MANAGEMENT

Since 2000, Active Influence and Scientific Management (AISM) has been performing a yearly analysis of all seeded clouds in the state of Texas. Individual analyses of each project are also conducted. The analysis involves looking at a seeded cloud as identified by the TITAN software which uses WSR-88D data from radars covering the various target areas in the state. WSR-88D data has been ingested into TITAN since 2004. The evolution of the identified seeded cloud is then compared to the evolution of a control cloud that best matches the seeded cloud in its early life. Several factors are compared between seeded and control clouds such as lifetime, area, volume and precipitation mass. Each cloud is put into one of the three categories and is either classified as a small cloud, large cloud, or a type B cloud depending on its lifetime and size. Small clouds are those defined as clouds with radar-derived precipitation mass values less than 10,000 kilotons. Large clouds are those with precipitation masses greater than 10,000 kton. Type B clouds are those clouds, large or small, that were not seeded until they were at least an hour old as seen on radar. In this section we will look at the results of all seeded small clouds. Note that this analysis does not include data from both the SOAR and TPWMA projects.

Table 5 shows the results of the AISM analysis of all seeded small clouds in the state of Texas. Bold values in parentheses are modeled values, whereas **η** is defined as the quotient of Precipitation Mass divided by Cloud Mass, and is interpreted as efficiency. A total of 618 flares were used in this sub-sample with an excellent timing (88%) for an effective dose near 80 ice-nuclei per litre, which might have reached slightly higher levels in some individual cells. An increase of 121% in precipitation mass together with an increase of 51% in cloud mass illustrates that the seeded clouds grew at expenses of the environmental moisture (they are open systems) and used only a fraction of this moisture for their own maintenance. The increases in lifetime (48%), area (44%), volume (51%), volume above 6 km (64%) and precipitation flux (53%) are notable. There are slight increases in maximum reflectivity (1%) and in top height (2%). The seeded sub-sample seemed 45% more efficient than the control sub-sample. Results are evaluated as excellent for this sub-sample.

An increase of 121% in precipitation mass for a control value of 1124.2 kton in 119 cases means:

$$
\begin{aligned}
\Delta_1 &= 119 \times 1.21 \times 1124.2 \text{ kton} \\
&= 161{,}874 \text{ kton} \\
&= 131{,}279 \text{ ac-ft}
\end{aligned}
$$

Large clouds that were seeded in Texas produced an additional **1,760,470 ac-ft** of water, and Type B clouds that were seeded in Texas produced an additional **463,850 ac-ft** of water as determined by the AISM analysis. The apparent total water produced by all seeded clouds in Texas was **2,355,599 ac-ft** in 2008 (Ruiz-Columbié 2008).

The AISM analysis results are comparable to results from research that has been conducted in the state of Texas in the past. Most notably of which was an evaluation of the Texas Cloud Seeding Programs for Seeding Effect during a 2002-2006 time period (Woodley and Rosenfeld 2007).

For many people, the increases in precipitation mass of over one million acre-feet is rather incomprehensible. Annually, a single person consumes 265 gallons (.008 acre-feet) of water. Household water uses on average is 50-100 tons which is equivalent to .445 and .885 acre-feet respectively. Additionally, water used to irrigate crops for making clothing and the food we eat is estimated at 1500-2000 tons or 13.27-17.70 acre -feet (Pearce 2007). Collectively, a single person uses on average 18.6 acre-feet each year. In the State of Texas, the cost of water ranges greatly from $300-$1,200 but for the purposes of this explanation we will use an average value of $750 per acre-foot. Using these values, the cost of water per person is $13,950 per year. The average state-wide budget for weather modification operations is $1.6million. AISM estimated the total increases in precipitation at 2,355,599 ac-ft in 2008 yielding a cost of one acre-foot of water at $1.47.

Table 5. Seeded Sample versus Control Sample (119 couples, averages)

Variable	Seeded Sample	Control Sample	Simple Ratio	Increases (%)
Lifetime	65 min	40 min	1.63	63 **(48)**
Area	88.0 km^2	57.8 km^2	1.52	52 **(44)**
Volume	253.2 km^3	157.0 km^3	1.61	61 **(51)**
Top Height	7.9 km	7.6 km	1.05	5 **(2)**
Max dBZ	50.7	49.3	1.03	3 **(1)**
Top Ht of max dBZ	4.3 km	4.3 km	1.00	0 **(0)**
Volume above 6 km	25.1 km^3	12.7 km^3	1.98	98 **(64)**
Precip Flux	695.6m^3/s	415.8 m^3/s	1.67	67 **(53)**
Precip Mass	3150.6 kton	1124.2 kton	2.80	180 **(121)**
Cloud Mass	223.5 kton	131.7 kton	1.70	70 **(51)**
η	14.6	9.0	1.62	62 **(45)**

5. SUMMARY

During the 2008 season, many clouds were seeded in the state of Texas. Six of the seven projects in the state saw a below-average number of flights as drought conditions affected a majority of Texas. Some locations in southwest Texas and the Panhandle did receive substantial rains for parts of 2008 but overall, drought was the story for the year. AISM's annual analysis concluded that even that the majority of seeded clouds were in the small category, all cloud seeded cloud categories yielded increases in precipitation mass, with almost 2.5 million acre-feet of water produced in the state's target and surrounding operational areas.

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DESIGN AND EVALUATION OF HYGROSCOPIC SEEDING OPERATIONS IN ANDHRA PRADESH, INDIA

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Abstract. Hygroscopic seeding operations were carried out in twelve districts of Andhra Pradesh, India from 2003 to 2008. The operations were carried out in both the southwest and northeast monsoon periods for a period from June to November. These operations were carried out with the help of two C-band radars and two pressurized aircraft. The present paper attempts to summarize the results of the operations being carried out and also evaluate these results. Statistical methods are used to estimate the percentage increase in the rainfall that could have occurred due to seeding operations. In the present context, regression equations, double ratio method, impact coefficient, target control and downwind comparisons are used to arrive at the percentage increase in rain mass over this region. A total of 2200 seeding sorties were carried out and this study presents the summary of 1600 sorties which were analyzed using various statistical software packages.

1. INTRODUCTION

Cloud seeding operations have been undertaken in 12 Rain Shadow Area Districts (RSAD) in the state of Andhra Pradesh, India for the years 2003 to 2008. The operations were carried out with the help of two radars and two pressurized aircraft for an average of 120 days every year. These operations are essentially carried out in the monsoon period, typically June to November covering both the Southwest Monsoon and Northeast Monsoon seasons. Evaluation of weather modification programs is difficult because no two clouds or even two storm systems are exactly the same, and one cannot simply compare the seeded and unseeded clouds and then observe the differences. Evaluations on a cloud or storm basis are possible using several methods like statistical–double ratio method, regression analysis, impact coefficient method, radar-based cloud comparison, target control method, and chemical analysis of seeded and unseeded rain water analysis (Changnon and Lambright, 1990; ASCE, 2004). Radar reflectivity data can be used to estimate precipitation, especially during warm-season programs when most of the precipitation is in liquid form at lower levels. Such estimates are derived from empirical relationships between radar reflectivity, Z, and rainfall rate, R, termed Z-R relationships. Once the Z-R relationships are accomplished for a particular storm, the radar can be used to estimate precipitation, providing estimates of total rainfall amount over the area covered by the radar (Super and Huggins, 1993; Woodley *et al*., 1994). Evaluation statistics comprising differences between seeded and unseeded variables are increasingly helpful (Bigg, 1997; Super and Huggins, 1993; Reisin *et al.*, 1996; Kopp, and Orville, 1994; Orville and Kopp, 1990; Krauss *et al*. 1987; Stith *et al*., 1990; and Takeda and Kuba, 1982) in estimating the effectiveness of the seeding operations. Enhancement of rainfall intensity, duration, and spatial correlation can help in detecting and assessing seeding effects (Rosenfeld and Woodley, 1993; Silverman, 2001; Gabriel, 2002; Ben-Zvi and Fanar, 1997). Some experiments (e.g. South Africa and Mexico) used estimates of the quartiles to determine if cloud seeding produced significant differences (Mather *et al*., 1997; Bruintjes *et al*., 1999 Cooper *et al*., 1997). However, quartile estimates have undesirable properties when used on small samples, especially when the distribution of the samples is asymmetric or skewed. A few types of ratio statistics were devised in the course of other experiments (Silverman and Sukarnajaneset, 2000; Gabriel, 2002). Use of a standard statistical measure that is able to “cope” with small samples and skewed measurements, the Wilcoxon-Mann Whitney test, is recommended for the confirmatory phase on weather modification experiments (Gabriel, 1999).

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This paper aims to highlight some of the work undertaken in Andhra Pradesh, India. An attempt has been made to evaluate the cloud seeding operations by using various methods of analysis like linear regression equations, target control, impact coefficient and quartile analysis methods.

2. DESIGN AND METHODOLOGY

Two radars were located in areas identified according to the need for coverage over preselected districts and the main factors taken into site selection were need of the area, services available and terrain. Each location provided the best possible efficient coverage for the state. TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) developed in South Africa (Dixon and Wiener, 1993) is used to track storms on each volume scan. For each volume scan, parameters, such as storm height, volume, mass, etc., are estimated for each storm, and the time history of these constitutes a description of their life cycle. The definition of a "cell" for storm tracking purposes on the TITAN was defined as a radar echo of 20 dBZ or greater, with an echoing volume greater than 12 km^3 above the 3000 ft MSL height. Rain gauges are used to measure the ground truth rainfall recorded during the seeding operations. This measurement is taken every 24 hrs. The rainwater collected in these raingauges was analyzed for its chemical constituents.

Figure 1 shows the study area in which the operations were carried out. The area is administratively divided into districts which are sub-divided into blocks called "mandals". The ground truth for rainfall data and chemical analysis was carried out at the mandal level. The study was carried out in 12 districts viz. Ananthapur, Chittoor, Kadapa, Kurnool, Medak, Mahaboobnagar, Prakasham, Guntur, Nalgonda, Karimnagar, Nellore and Ranga Reddy. These districts are classed under RSAD as they receive an average rainfall of less then 1000mm per annum. Figure 2 shows the total number of rain gauge stations in these districts along with the normal rainfall data, which is calculated over a period of 30 years by the Indian Meteorological Department (IMD).

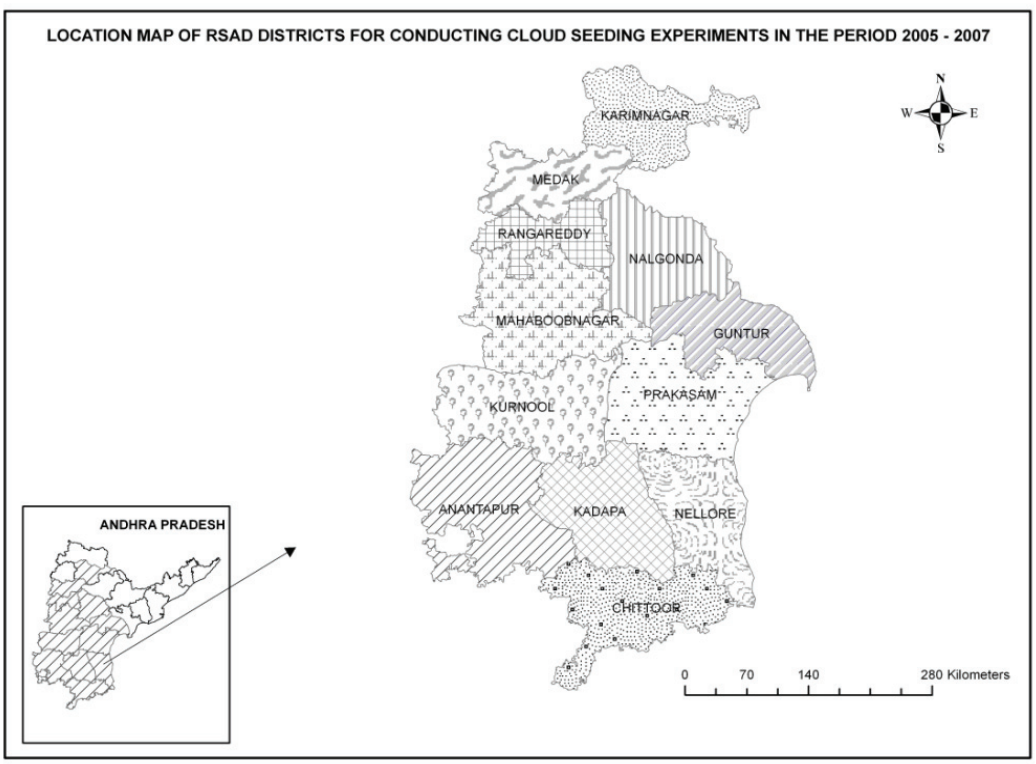

Fig. 1. The study area - 12 Rain Shadow Districts of Andhra Pradesh.

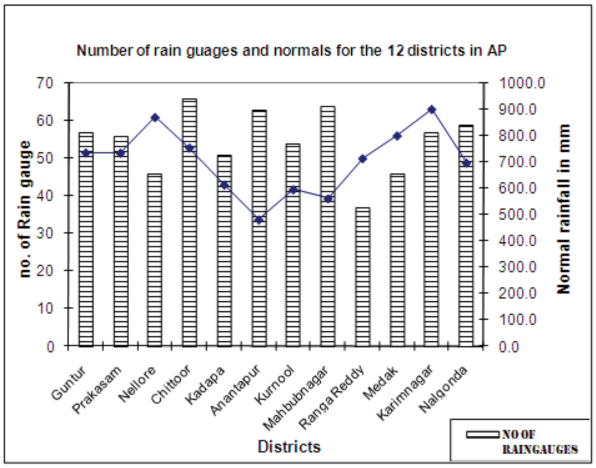

Fig. 2: Rainfall and Rain gauge details in the study area.

The operations were essentially carried out using hygroscopic flares with a typical chemical composition of 65% oxidizing agent (Potassium per chlorate), 18% organic binder, 2% magnesium, 15% calcium chloride that acts as the cloud condensation nuclei. The average particle size after burning was 5 to 10 micros. Once a cloud is seeded it takes 4 seconds for flare to ignite, the time aircraft moves 0.3 km (aircraft speed 250 km/hour). It takes 4 minutes for the hygroscopic flare to burn, during which the aircraft travels a flight path of 16.7 km. For cloud to respond to seeding material, it takes 8 to 13 min with a flight path of 33.3 to 54.2 km (mean value 43.7 km). Sometimes cloud response to seeding material takes more time. Assuming the aircraft is moving in a straight path, aircraft might have traveled 60.7 km from the ignition time. The buffer zone (zone of influence) is the area surrounding the operational area over which suitable clouds are seeded before they moved. The width of the buffer zone depends on the maximum speed at which the storm clouds are expected to move. The area is calculated as reaction time (h) * speed with which cloud moves (km/h) = km. Based on this it was found that the average reaction time varied from 30 to 40 mins and the wind speed during the season was on average 30 to 40 km/hr. A 40-km zone of influence from the point of seeding was drawn using ARC GIS software and the rainfall in this zone was estimated from the rainfall recorded in the rain gauge located at each mandal. The VIL values are normalized by the corresponding values of cloud depth and the derived liquid. The formula used to calculate LWC (g/cubic meter) is = (VIL kg/m^2) / (cloud depth km). The precipitation mass is calculated as: Precipitation mass (ton) = Precipitation flux (cum per sec) * cloud lifetimes (sec).

Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration (10 years). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites are selected in an area meteorologically similar to the target, but one that would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period as that of the proposed or previous seeding. The target and control sets of data for the unseeded seasons are used to develop a linear regression equation that estimates the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control areas. This allows a comparison between the predicted target area natural precipitation and that actually occurred during the seeded period to determine if there are any differences potentially caused by cloud seeding activities.

The historical 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 in district wise. The values of the average control area precipitation (*x* observed), the observed target area precipitation (*y* observed), the calculated target area precipitation (*y* calculated), the ratio of *y* observed to y calculated, and the difference between *y* observed and calculated values. This equation is then modified and months predicts the amount of target area precipitation used during the seeded period to estimate what the target area precipitation should have been based on that observed in the control area. This is the target area actual expected precipitation. Seeded cells were compared with similar, non-seeded cells that could have been seeded. Storms were called seeded if they were seeded at any time during their lifetime. Areas under similar meteorological conditions were grouped into regions. For this study two regions were identified – Rayalaseema Region and Telangana Region.

3. RESULTS AND DISCUSSION

The linear regression equations were developed based on the 30 years of historical data set available. This equation was used to estimate the target area average precipitation. A comparison was then made between the actual target area precipitation and after seeded estimation during the same time and region. Figure 3 shows that calculated estimated rainfall and that observed during the season. Sufficient data sets were not available for all the 12 districts hence only 9 districts were estimated using this method. The result indicated the average total expected estimated precipitation was 66 mm but the actual seeded observed rainfall was 118 mm, which is a 44% increase of the expected value.

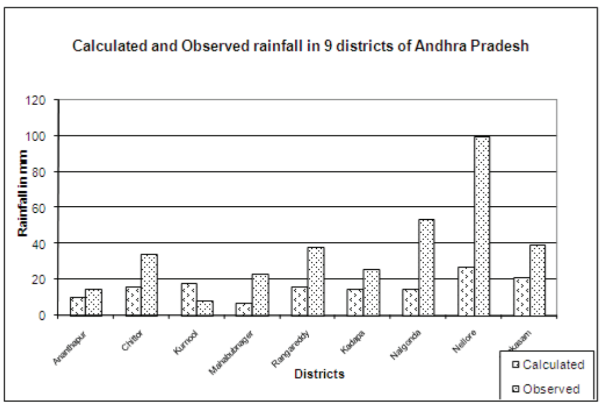

Fig. 3: Calculated and observed rainfall in 9 districts of Andhra Pradesh.

Generally, the closer the target and control areas are in terms of elevation and topography, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable in the seeded years. An equation indicating perfect correlation would have an r value of 1.0. In the present study the correlation values varied from a minimum of 0.67 for Anantapur district to a maximum of 0.88 for Nalgonda district.

To further substantiate the results obtained by the regression equation, various other evaluation techniques were also used. One of these was to study the effects of seeding rain gauges by categorizing into target, control, and downwind regions for selected seeding districts. The downwind regions were determined by the mean storm flow on days seeded from years 2004 to 2008. For each district, a wind flow was determined where the majority of days seeded originated. The control regions were selected by determining areas not affected by seeding and upwind to the target and downwind regions. Precipitation amounts were calculated for each region. All the gauges in the regions for that wind regime were averaged to get the mean daily rainfall for that region. At the end of the month and season means for the region were calculated. A percentage difference was calculated between the target regions and their corresponding control regions. Climatological rainfall amount for the region was calculated. A ratio between the target and the control regions and between the downwind and control regions was also calculated. A percent difference was calculated between the target regions and their corresponding control regions and downwind regions. Figure 4 shows the percentage difference between the control region, target region and the downwind region. The Region 1 (Rayalaseema Region) target mean rainfall was 18% greater than the control mean total rainfall amount. However, for Region 2 (Telangana Region) the target region rainfall was only 8% more than the control region but the downwind region received 6% less than the control region.

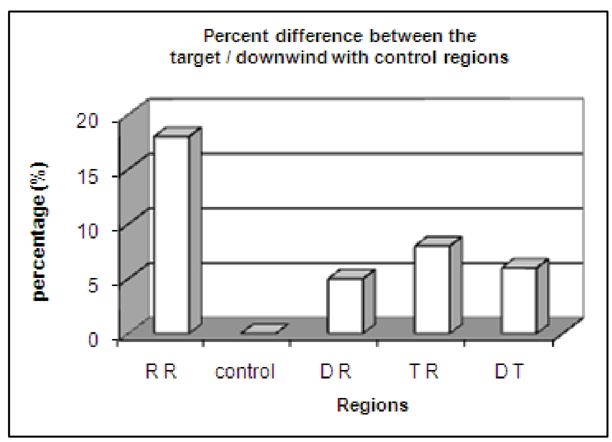

Fig. 4: Percentage difference between the target, downwind and control regions.
RR – Rayalaseema Target Region; DR – Downwind Rayalaseema Region, TR – Telangana Target Region, DT – downwind Telangana Region.

Impact coefficient

The assessment presented here is based on the findings and report by Sen O, S. Incecik and E. Omay, (1993). Double Ratio method was used to assess impact of the cloud seeding on the local rainfall. Impact Coefficient is defined by the equation IC = (S / NS) / (H/K); where, I.C = Impact coefficient (decrease or increase of rainfall); S = Total rainfall in the target area during seeding period; NS = Total rainfall in the control area during seeding period; H = 10 years of total rainfall in the targeted area; K = 10 years of total rainfall in the control area. Table 1 shows the percentage change that is observed for two districts, Anantapur and Nalgonda, where the operations were carried out extensively during the years 2004-2008. When IC exceeds 1.0, increase in rainfall may be attributed to cloud seeding activities in these areas. If I.C. equals 1, there is no change in rainfall as a result of the cloud seeding applied.

Separation of clouds data

In an attempt to further find methods of estimation of the impact of seeding in the state of Andhra Pradesh, India data sets from the radar were evaluated and the results are presented below (Table 2).

The data of all eleven parameters of the seeded clouds available from the TITAN was segregated depending on its time of residence in the atmosphere after they have been seeded. Earlier studies have indicated that four classifications can be made based on the residence time viz. clouds whose life is less than 20 minutes after they have been seeded; clouds whose life is in between 20 to 40 minutes after they have been seeded; clouds whose life is in between 40 to 60 minutes after they have been seeded; clouds whose life is greater than 60 minutes after they have been seeded. In this study the first type whose lifetime is less than 20 min is not considered.

Clouds were divided into three basic types based on the areas Type A (small seeded clouds), Type B (seeded clouds) and Type C (large seeded clouds). In the operations carried out in the study area approximately 2200 seeding sorties were carried out, randomly 1600 (72%) samples cases have been selected and analyzed.

Quartile analysis

The database of 1600 storm couples was developed. A quartile analysis of these groups was done and the results of the upper quartile (75% of data below the line and 25% above the line) are presented in Fig. 5a and 5b. The results

Table 1. Calculation of Impact Coefficient for two districts in Andhra Pradesh

Target / Control	**S / NS**	**H / K**	**(S / NS) / (H/K)**	**% Change**
Anantapur / Kadapa	0.90	0.75	1.22	22
Anantapur / Kurnool	1.18	0.81	1.47	47
Anantapur / Chittoor	0.73	0.54	1.34	34
Nalgonda / Ranga Reddy	1.04	0.85	1.22	22
Nalgonda / Medak	1.88	0.83	2.27	127
Nalgonda / Mahaboobnagar	1.39	1.07	1.30	30

Table 2. Number of cases examined in each type of cloud

S.No	Type of cloud	Life time of clouds (min)	Couples analyzed
1	A type	20 to 40	433
2	B Type	40 to 60	960
3	C Type	more than 60	207
	Total		**1600**

showed that the mean rain mass for the seeded storms was significantly larger than for the control. The maximum variation was for Group B type of clouds. The means of the total radar estimated rain mass between 40 to 60 mins after the seeding decision were 212 kilo tons for the seeded storms and 98 kilotons for the non seeded storms. The estimated seeding effect was 335%.

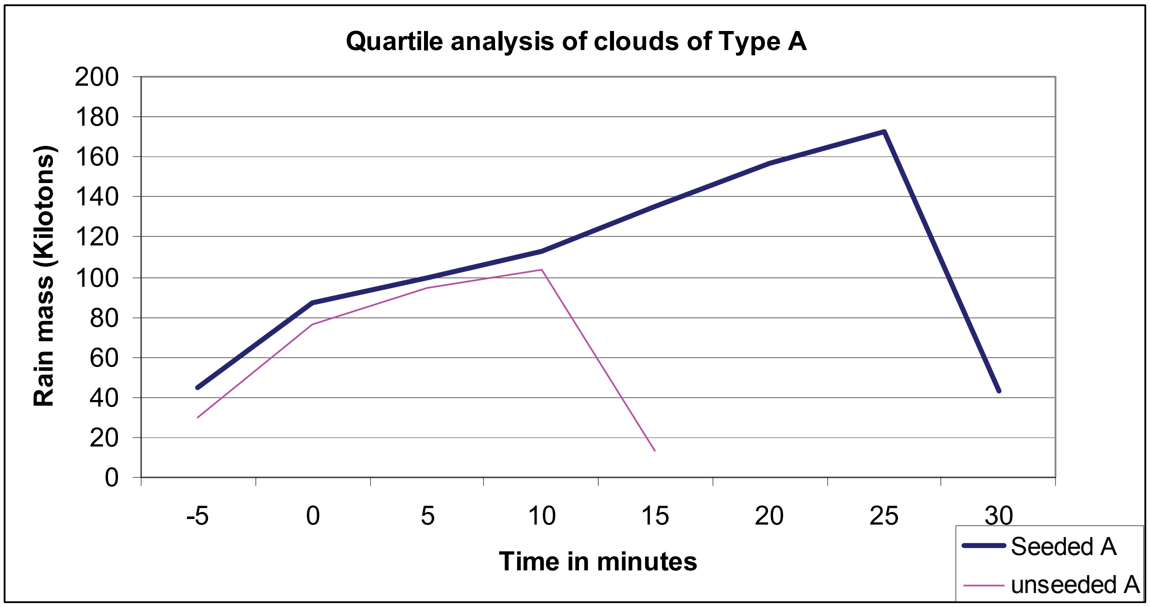

Fig. 5a: Quartile analysis for the selected groups of seeded and unseeded clouds.

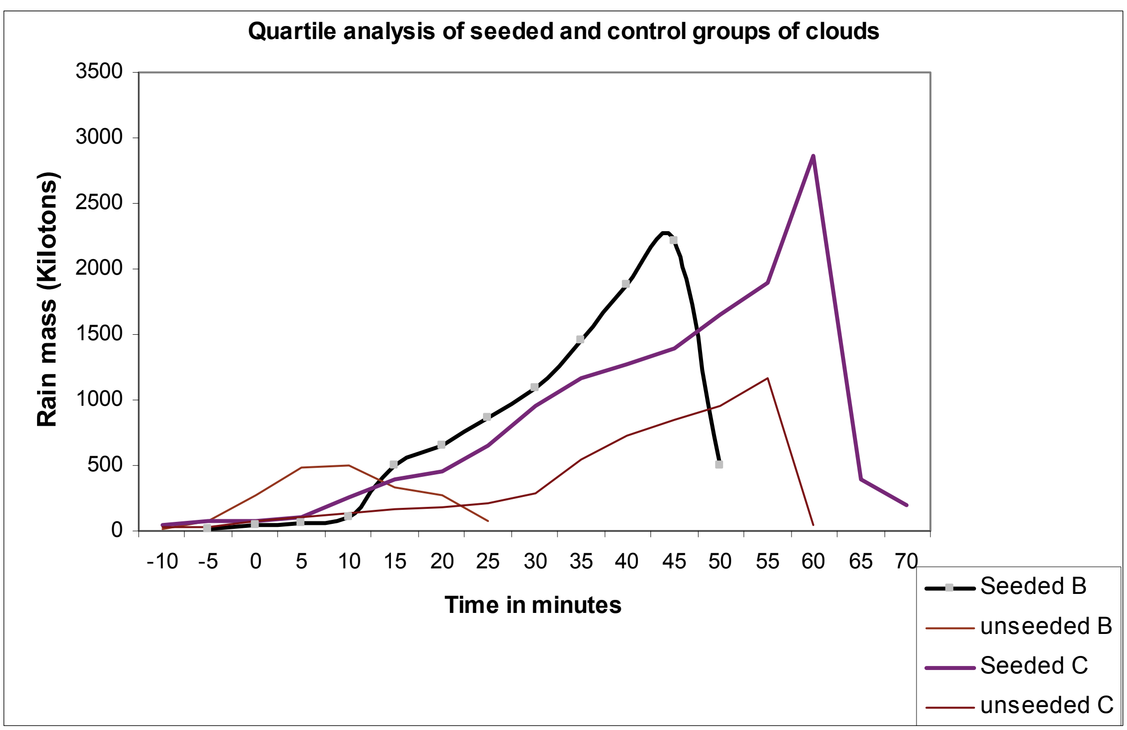

Fig. 5b: Quartile analysis for the selected groups of seeded and unseeded clouds.

Table 3 shows the results from the classic TITAN evaluation for the seeded clouds for which proper control clouds were obtained.

Table 3. Seeded samples versus control samples (couples, averages)

Variable	Seeded sample (S)			Control sample (C)			Simple ratio (S/C)			Increase (%)		
Cloud type	A	B	C	A	B	C	A	B	C	A	B	C
Life time [min]	35	46	126	30	28	64	1.16	1.64	1.97	16	64	97
Area [km²]	51.26	161.04	159.27	31.75	67.46	120.93	1.61	2.39	1.32	61	139	32
Volume[km²]	228.46	872.70	741.62	103.12	319.53	484.86	2.21	2.73	1.53	121	173	53
Cloud Top [km]	7.86	10.11	8.5	5.54	8.06	7.8	1.41	1.25	1.08	41	25	8
VIL [kg/m²]	5.01	25.64	8.65	2.78	6.16	10.52	1.80	4.16	0.8	80	316	20
Thickness(T) [kms]	6.16	9.41	7.11	4.01	6.66	6.54	1.53	1.41	1.09	53	41	9
LWC=VIL/T [g/m³]	0.8	2.72	1.2	0.78	0.9	1.6	1.02	3.0	0.75	02	200	25
Prec. Flux [m²/sec]	82.26	801.79	378.72	57.93	221.9	303.33	1.41	3.61	1.25	41	261	25
Prec. Mass [Ktons]	172.7	2210	2863.1	104.2	507.38	1164.78	1.66	4.35	2.46	66	335	146
Cloud Mass[Ktons]	76.4	546.87	319.86	56.75	123.93	234.4	1.34	4.41	1.36	34	341	36
Efficiency (E)	2.26	4.04	8.95	1.83	4.0	4.96	1.23	1.01	1.80	23	10	80
Rain = P mass/area [mm]	3.36	13.7	17.97	3.28	7.52	9.63	1.02	1.82	1.87	02	82	87
Rain rate = [s/200]**0.625[mm/hr]	15.22	65.2	26.76	12.84	21.71	27.58	1.18	3.0	0.97	18	200	03

In Type B an increase in 335% of the precipitation mass together with an increase of percentage in cloud mass illustrates that the seeded clouds grew at the expense of the environmental moisture and used only a fraction of the moisture for their own maintenance. Notable increase in lifetime, volume, precipitation flux was observed. The increase of percentage in precipitation mass for a control value of kton in various case means would indicate that the Δ can be calculated as Δ_i (Kilotons) = no. of cases * % increase in precipitation mass * precipitation mass of control value. The details of the Δ for each case is given in Table 4. The total Δ_i for the period from 2004 to 2008 is **2011566** Kilotons.

4. CONCLUSIONS

Hygroscopic cloud seeding operations carried out in Andhra Pradesh India for the last 5 years are studied on a case to case base using various statistical methods. The measurements included radar based analysis and ground truth measurement of rainfall. The districts chosen for the study are predominantly rain shadow areas, i.e. areas which receive less than 1000 mm of season rainfall. Regression equations developed for the districts in this study indicate that on an average 44% increase has occurred in the study area. The correlations between the control and target areas vary from a minimum of 0.67% at Anantapur to a maximum of 0.88% for Nalgonda district.

Table 4. Increase in the Δ values for the various clouds during the period 2004-2008.

S. No	Type of cloud	Control Prec. Mass	% increase	Δ **(Kilo tons)**
1	Type A	104	65	29270
2	Type B	507	335	1630512
3	Type C	1164	146	351784
	Total			**2011566**

The analysis using the target-control and downwind methods shows that in the Rayalaseema target region 18% more rainfall than the control and downwind regions could be achieved. Similarly in the Telangana region 8% increase was calculated. The calculations of impact coefficient for Anantapur and Nalgonda districts show a considerable percent change. 1600 couples were analyzed for the comparison between seeded and non seeded clouds. Three classes were studied. Type A showed a 65% increase, Type B a 335% increase and Type C 146% increase in precipitation mass that results in an increase of Δ by 2011566 kilotons.

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ATMOSPHERIC DC CORONA EFFECT IONIZATION AS A POTENTIAL TOOL FOR AEROSOL DEPOSITION: AN EXPERIMENT

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Abstract. High concentrations of ions produced by cosmic rays have an effect on the fair weather electric field which may produce significant and observable changes in local aerosol population properties. Cosmic ray ions may lower nucleation barriers promoting charged nanoparticle growth into the Aitken range and even beyond 100 nm to become cloud condensation nuclei. A twofold assumption was made. On one hand, it was hypothesized that artificially generated direct current corona effect ions would become attached to existing aerosols and these charged aerosols would be far more effective than neutral aerosols in growing via condensation, coagulation and collision which would consequently enhance the deposition rate. On the other hand, the ions may behave as catalyzers of cloud microphysical processes if they reach the cloud bases. This paper evaluates the results obtained in an experiment designed to verify the enounced hypothesis. An ionization station was installed about 8 miles south of downtown Laredo, Texas, in order to measure the impact of unipolar, corona effect ionization on aerosol population and some meteorological phenomena. The station was operated from October, 2005 through August, 2007. Real time airborne spectrometer measurements were obtained and meteorological data were recorded. Data analyzed since the conclusion of the Laredo experiment produced no evidence to support the assumption that ionization had an impact on precipitation, but the hypothesis that ionization does produce gravitational deposition of atmospheric particles was supported by the airborne measurements performed.

1. INTRODUCTION

Man has been fascinated by atmospheric electricity. From the "King of Olympus and Ruler of the Gods", Zeus, God of Sky, Lightning and Thunder, to his Roman counterpart, Jupiter, to the middle age pagan Gods of Lightning, the Nordic God Thor. More recently and crossing the bridge from paganism to science we find perhaps the most talented and accomplished individual of his time inventing the lightning rod after learning how to fly a kite with a heavy metal key attached to it. In the waning days of the nineteenth century, CTR Wilson ran experiments in his cloud chamber and found negative ions to become active at supersaturation rates of 4 and positive ions required a saturation rate of 6 (Wilson, 1897) among many other experiments using his invention.

More recently and more to the point of ionization, in the mid to late 1950's Bernard Vonnegut and C.B. Moore applied ionization technology and conducted experiments that produced unipolar corona effect (CE) ions using a power supply feeding high voltage to a long, thin wire electrically isolated from ground. They used a direct current, high voltage power supply consisting of a step-up transformer and a vacuum tube half wave rectifier to provide pulse energy of either polarity to a thin wire antenna. The wire antenna itself was "T" shaped and the total wire length was about 9 miles. Power was fed in the form of corona discharge pulses 60 times a second. These pulses peaked at about 50KV and the current driven was about 1×10^{-3} amp. They were able to detect ions as far as 7 miles away from the ionization station and observed changes in the potential gradient and space charge concentration in ground based as well as airborne measurements (Vonnegut *et al.,* 1962).

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2. GALACTIC COSMIC RAYS, AND ALTERNATING AND DIRECT CURRENT IONIZATION

Recent work linking cosmic ray ionization to aerosol behavior led us to believe that corona effect DC ionization might play a substantial role in aerosol deposition. This work is described in the paper submitted by the authors to the American Meteorological Society in January of 2005 (Kauffman and Ruiz-Columbié, 2005).

Although most ions generated by cosmic rays will be lost because of ion-ion recombination, the few remaining ions will catalyze the nucleation of ultrafine, stable particles (<1-2 nm) by condensation. Most of them will feed larger existing particles (aerosols) thus increasing particle size and catalyzing the process of cloud condensation nuclei (CCN) formation. Some will be scavenged by cloud droplets, contributing to the cleansing effect of depositing small particles (pollutants) on the ground. A fraction of the ultrafine condensation nuclei will again condense and coagulate to form critical embryos (2-5 nm) and a fraction of the former will again coagulate and condense to form cloud condensation nuclei (~100nm). Charged aerosols are more effective in inducing condensation than uncharged ones because polar molecules have an enhanced rate of condensation. Calculations show that this growth rate is greater by a factor of at least 2, and, since a 5 nm particle's coagulation loss rate is $1/20^{th}$ that of a 1 nm particle, it is an important factor in determining the early survival rate of aerosol (Harrison and Carslaw, 2003).

Aerosols charged by galactic cosmic ray (GCR) ions are far more effective than neutral aerosols in growing via collision. The collision efficiency of a charged aerosol-droplet is increased by thirty-fold for aerosol carrying large (>50) elementary charges (Tinsley and Yu, 2002).

Corona effect is the only method that will produce unipolar ions at a high enough concentration to be useful for aerosol charging (Hinds, 1999). It is probable that unipolar corona effect ions produced by direct current generators will add to and enhance the catalyzing effects that cosmic ray ions produce, including lowering nucleation barriers, increasing the scavenging rate in clouds and, most importantly, stimulating charged particle growth. Since all direct current generated ions will have the same polarity, very few ions will be lost to ion-ion recombination. That means that almost all these small ions are lost only by ion-aerosol combination and ion-droplet attachment in clouds.

Alternating current corona effect ionization produced by high voltage, high power, electrical distribution lines has been linked to polluted aerosol deposition. This type of ionization may improve conductivity in the lower atmosphere by cleaning pollutants which are barriers to the Earth's natural current flow. Alternating current corona effect ionization has been directly correlated to deposition of polluted particles. The model developed by Fews *et al.* (1999) "predicts a two to three-fold increase in deposition of aerosols on spherical surfaces mimicking the human head under high voltage power lines. Experimental measurements using detectors mounted on grounded metal spheres showed an enhanced deposition of both ^{218}Po and ^{214}Po aerosols. The measurements recorded enhanced ^{218}Po and ^{214}Po deposition under 400 kV power lines of 1.96 ±0.15 to 2.86 ±0.32.Enhanced ^{214}Po deposition on 275 kV lines was 1.43 ±0.07".

3. PHYSICAL CONSIDERATIONS ON DC CORONA DISCHARGE

In the vicinity of a corona discharge, the air flow should be considered an electro-hydrodynamic flow in which parameters such as electric and magnetic field intensities, charge distribution, fluid dynamics, and mass and heat transfers play important roles. The Maxwell and Navier-Stokes equations provide the proper background for the solutions, but the problem in general is so complex that it becomes intractable. In the case of a corona generated by a wire under DC high voltage in an open circuit, an electrostatic first approximation for the electric field intensity can be made since electrical currents are negligible. Collisions among charged particles created by the corona (primarily electrons but later other ions) take place thus complicating the process.

In this approximation, the electric potential V is then governed by the Poisson's equation:

$$\nabla \bullet \nabla V = -\frac{\rho_q}{\varepsilon_0} \quad (1)$$

where ρ_q is the space charge density and ε_0 is the dielectric permittivity of air (≈ $8.85\times10^{-12}\,Fm^{-1}$). The electric potential V is associated with the electric field intensity vector by equation 2:

$$\vec{E} = -\nabla V \quad (2)$$

The electric current density is given then by equation 3:

$$\vec{J} = \mu_E \vec{E} \rho_q + \vec{V} \rho_q - D \nabla \rho_q \qquad (3)$$

where μ_E is the air ion mobility, $\vec{V}$ is the airflow velocity vector and D is the diffusivity coefficient.

In turn, $\vec{V}$ is described by the Navier-Stokes equation (4):

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \bullet \nabla \vec{V} = -\frac{\nabla p}{\rho_{air}} + \nu \nabla \bullet \nabla \vec{V} - \frac{\rho_q}{\rho_{air}} \nabla \vec{V} \qquad (4)$$

The intrinsic complexity associated with this set of equations lead to numerical modeling. However, here a scaling approach might allow us to estimate the value of the space charge density ρ_q .

From the continuity equation (charge conservation)

$$\nabla \bullet \vec{J} + \frac{\partial \rho_q}{\partial t} = 0 \qquad (5)$$

mathematical manipulations lead to equation 6 (Zhao and Adamiak, 2005):

$$|\nabla \rho_q || \nabla V | \approx \frac{\rho_q^2}{\varepsilon_0} \qquad (6)$$

In cylindrical coordinates this expression becomes

$$\frac{\partial \rho_q}{\partial r} \frac{\partial V}{\partial r} \approx \frac{\rho_q^2}{\varepsilon_0} \qquad (7)$$

Through scale analysis (scaling) one can estimate the magnitude of the terms. For equation 7:

$$\frac{\rho_q}{r} \frac{V}{r} \approx \frac{\rho_q^2}{\varepsilon_0} \qquad (8)$$

Therefore:

$$\rho_q \approx \varepsilon_0 \frac{V}{r^2} \qquad (9)$$

Equation 9 shows an approximated linear relationship between voltage and space charge density. For a voltage of about 70 kV, the space charge density at a distance of 1 m away from the wire results in

$$\begin{aligned} \rho_q &\approx 8.85 \times 10^{-12} \times 7 \times 10^4 Cm^{-3} \\ &\approx 6.2 \times 10^{-8} Cm^{-3} \\ &\approx 3.875 \times 10^{-8} em^{-3} \end{aligned}$$

In the atmospheric boundary layer (ABL) natural ionization is produced by a combination of cosmic rays and radiative gases emanating from the soil. By modeling, Hoppel *et al*., 1986, predicted space charge density of the order of 3×10^9 em^{-3}. In the vicinity of a 70 kV corona discharge the space charge density is about one order of magnitude higher than the value generated by natural resources.

Of course this is an electrostatic approximation and the real world is a hydrodynamic model. Measurements made in the experiment described below detected the influence of high space charge densities at considerable distances from the source of the DC corona generator. The development of a hydrodynamic model for space charge densities using the Maxwell and Navier-Stokes equations, a model supporting the field measurement data, is left for future efforts.

4. CONCEPTUAL MODEL

The conceptual model describes the operation of natural (galactic cosmic ray produced) and anthropogenic direct current CE ionization operating in parallel. Galactic cosmic ray ionization is greater in the upper levels of the atmosphere and only a very small fraction of cosmic rays reach the lower levels of the troposphere. The model is represented in Fig. 1.

In both cases, cosmic ray or corona ions, will quickly (<1s) form ion clusters that have the stability and lifetime to allow them to either attach or grow by condensation and coagulation into stable charged clusters. This will happen in a time-span of a few minutes. In either case the net effect of ionization will be to charge pre-existing aerosols or to form new charged aerosols. Aerosols have lifetimes measured in hours and sometimes days, depending on a wide array of variables.

The illustration in Fig. 2 depicts the conceptual model of microphysical interplay comparing neutral and charged aerosols. Charged molecules

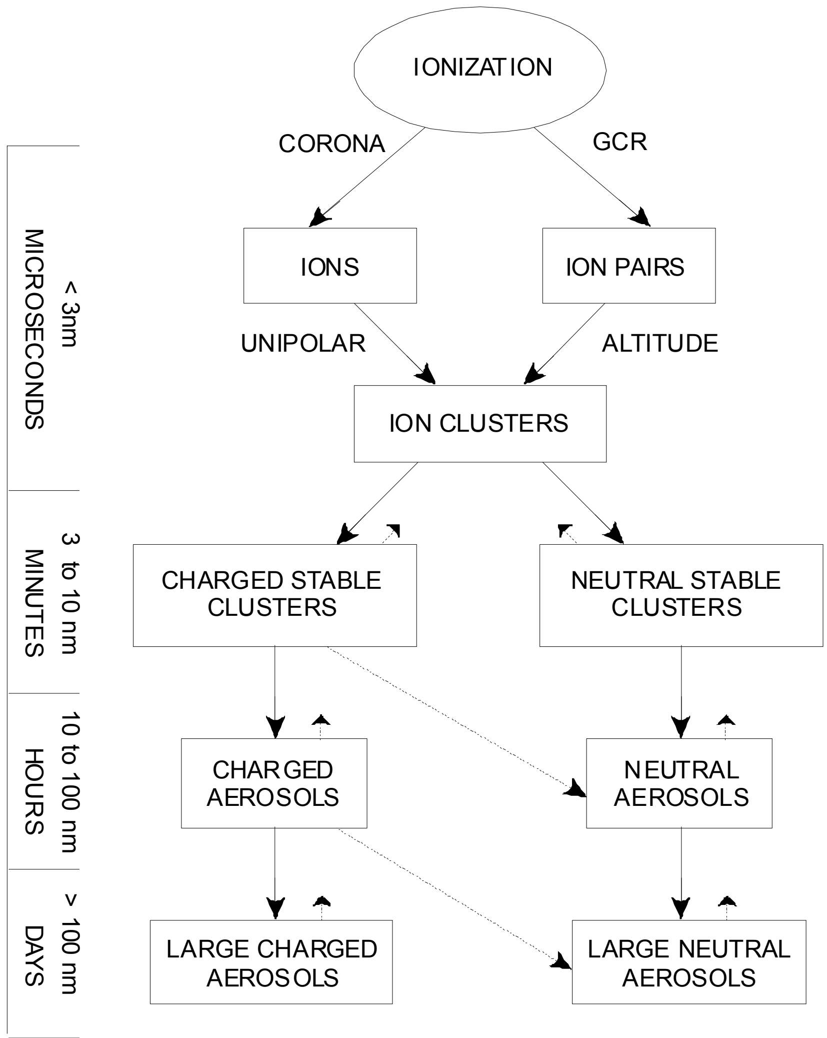

Fig. 1. Block Diagram, Conceptual Model of GCR and DC Corona Ionization

are gray, neutral molecules are white and water molecules are charcoal gray.

For illustration purposes, the model starts with a single aerosol. If there is no charge in the atmosphere, the nucleation process produces new aerosols, however, if ionization is present, the nucleation barriers are lowered, resulting in a larger number of new aerosols. At this point all aerosols are nanoparticles (<10 nm). Within a short period of time neutral aerosols will grow into the Aitken range (10 to 80 nm) and one of the growth mechanisms will be condensation of water vapor. Charged aerosols will grow more aggressively and, if the charge in the aerosols is produced by CE ions, which are more hygroscopic than cosmic ray ions, the condensation growth will be further accelerated. Aerosol growth is also produced by collision and coagulation. Again, in the case of ionized aerosols this growth will be more aggressive. As aerosols become further charged, mirror image charges will be induced in surrounding aerosols to insure collision. The final result is that larger particles are formed under charged atmospheric conditions. Larger particles are made up of orders of magnitude more aerosols than smaller ones. A 100 nm particle CCN is composed of 10^3 nanoparticles, each with a diameter of about 10 nm. The result is that, even though a larger number of nanoparticles are nucleated under charged conditions, the overall particle population is decreased because of two reasons: First, many of the smaller particles have coalesced into larger ones; and second, some of the larger particles are continuously being deposed to ground due mainly to gravitational attraction.

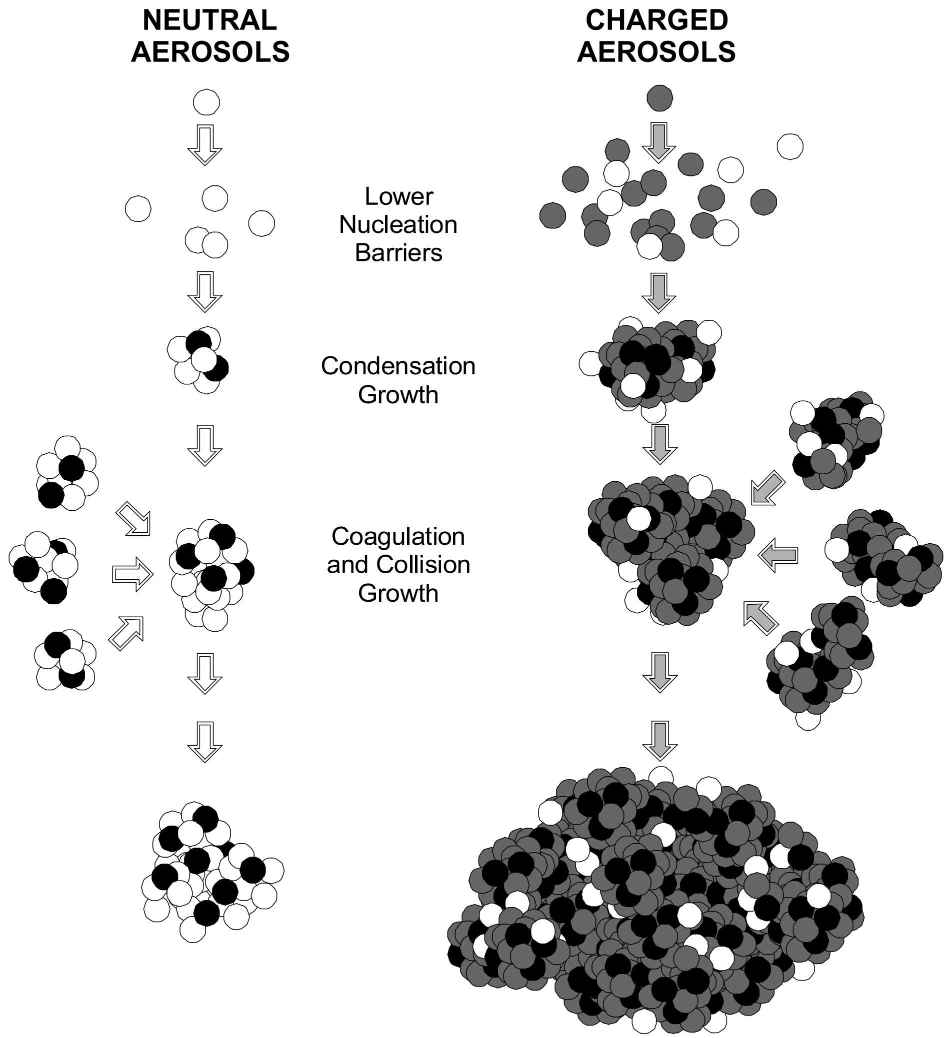

Fig. 2. Illustration of Aerosol Growth, Conceptual Model

5. LAREDO – THE EXPERIMENT

5.1 Preliminary Considerations

The primary objective of this experiment was to measure the impact of the ionization station on precipitation. A secondary goal was to measure any effect attributable to ionization on temperature and the third objective was to observe aerosol size distribution as a tool to provide some insight into ionization plume characteristics.

Particle growth processes induced and aided by corona effect ionization were expected to essentially be the same as for particles ionized by cosmic rays, with the added advantage of unipolarity and thus the avoidance of ion-ion recombination. These growth processes might include condensation, coagulation, coalescence, collision, taking some of the ultrafine (1 – 2 nm) particles to the Aitken range, some of these to the CCN (~100 nm) range, a few of these to the micron level range, possibly resulting in deposition to ground and a few others possibly forming cloud droplets and, ultimately, raindrops.

Precipitation and temperature data along the path of prevailing winds, approximately South to North, would be recorded. There would be two stages for comparing recorded data: One stage would include historical data provided by NOAA, which included precipitation and temperature information from the year 1947 onward. The other stage would be to compare data in a target operational point, Laredo International Airport, with a “control;” or witness point, Cotulla Airport.

The historical precipitation and temperature data provided a framework for predicting rainfall at the target point based on actual rainfall at the witness point and then performing statistical analysis to determine, within a certain level of confidence, whether the actual data was within the limits of natural variation (no ionization effect) or whether it exceeded these limits (due to ionization effect).

Airborne spectrometer data would also be collected to determine particle size distribution in order to determine the range of effectiveness of the ionization plume and to gain insight into the level of ground deposition induced.

5.2 <u>General Description</u>

An ionization station was installed on a farm located off Mangana Hein Road, approximately 8 miles south of downtown Laredo and about 2 miles east of the Mexican border. The official duration of the project was one year, although the experiment was extended another 10 months in order to capture additional data.

The ionization station was comprised of a support structure, a central tower and peripheral towers, which allowed a very long, thin wire antenna to be suspended. The antenna was electrically isolated from the support elements. The antenna was fed by a very high voltage, direct current generator, which was computer controlled to allow for remote operation of the ionization station. The design of the antenna is proprietary and a patent is pending. The antenna design is perhaps the biggest difference between the Vonnegut-Moore antenna (a “T” shaped thin wire with a total wire length of 9 miles) and the antenna used in this experiment, which only had slightly more than 1.5 miles of thin wire, in spite of which the ionization effects were present several tens of miles away. A schematic diagram of the antenna appears in Fig. 3.

Other differences with the Vonnegut-Moore experiment are that their power source provided power pulses at a rate of 60 s^{-1} at 20-50 kV and about 1 mA, whereas the power source used for this experiment provided direct current, continuous power in the range of 70 to 110 kV at 1 to 2 mA. Additionally, the operation for the Laredo experiment was controlled remotely by computer.

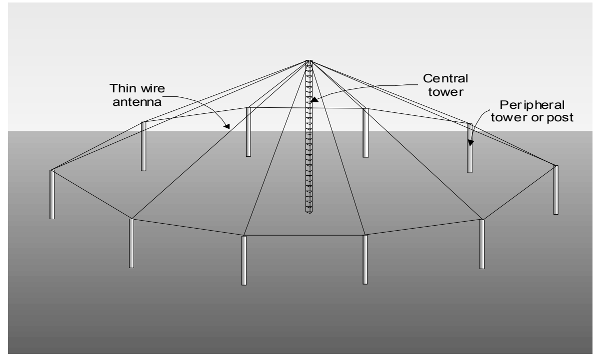

Fig. 3. Antenna Schematic

Operational and historical precipitation and temperature data was provided by the National Oceanic and Atmospheric Administration (NOAA). Aerosol size distribution data was recorded using a pair of optical spectrometers manufactured by Grimm Technologies (Model number 1109 and 1107). The selection of these spectrometers was based primarily on the real time, optical capabilities of measuring aerosol counts and the adaptability for mounting the instrument on an airplane. The spectrometer’s 31 channel aerosol size selectivity was, at this stage of our work, only of secondary importance. The spectrometers were mounted on the wingtips of a Piper Comanche 260B and the spectrometers were calibrated for the optimum cruise speed of the aircraft and the isokynetic air intake of each spectrometer was adjusted for precisely that speed. See Fig. 4.

Since the main focus of the experiment was to evaluate the precipitation enhancement capability of the ionization station, all flight data was recorded between 2,000 and 3,500 feet, at the approximate base of rainfall producing stratus, stratocumulus and nimbostratus clouds.

Fig. 4. Piper Comanche 260B, Equipped with Two Wingtip Mounted Spectrometers

The map in Fig. 5 shows the approximate location of the ionization station, the operational point (LRD – Laredo International Airport), the witness point (Cotulla), the prevailing wind direction during the summer and the preliminary expectation of the coverage of the ionization plume.

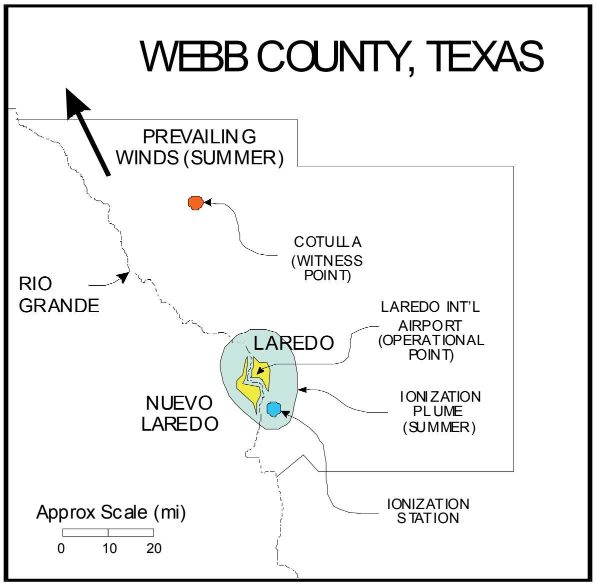

Fig. 5. Ionization Station Map

5.3 <u>Data: Precipitation</u>

Precipitation data were recorded during the experiment for the operational point, Laredo, and the control, or witness point, Cotulla. Rain gage values of precipitation, provided by NOAA, for the Hydroyear 1947-1997 (defined as the 12 months between Oct 1 and Sep 30 of the next year) at Cotulla and Laredo were used to obtain an evaluation of the apparent impact of the ionization station. The analysis also included a detailed description using some percentiles of the precipitation distributions in both areas. This methodology allowed us to classify every month during the aforementioned period as very dry, dry, normal, wet and very wet (Ruiz-Columbié *et al.*, 2006).

The average precipitation in Laredo for the hydroyears 1947 to 1997 is 19.96. The historical precipitation percentiles for Laredo are provided in Tables 1a & 1b.

Table 1a. *Percentile Boundaries, Laredo*

13.86 in (20th percentile)
16.43 in (40th percentile)
21.15 in (60th percentile)
24.89 in (80th percentile)

Table 1b. *Historical Precipitation Levels – Laredo*

Very Dry	(precip < 13.86 in)
Dry	(13.87 < precip < 16.43 in.)
Normal	(16.44 < precip < 20.04 in.)
Wet	(20.05 < precip < 21.15 in.)Very
Wet	(21.16 < precip < 24.89 in.)

Precipitation for Laredo during the experiment's hydroyear (defined for this project as Oct 1, 2005 through Sep 30, 2006) was 14.88, which categorizes it as "Dry".

The average precipitation in Cotulla for the hydroyears 1947 to 1997 is 20.68. The historical precipitation percentiles for Cotulla are:

Table 2a. *Percentile Boundaries, Cotulla*

16.27 in (20th Percentile)
18.84 in (40th Percentile)
20.69 in (60th Percentile)
24.38 in (80th Percentile)

Table 2b. *Historical Precipitation Levels – Cotulla*

Very Dry	(precip < 16.27 in)
Dry	(16.28 < precip > 18.84 in.)
Normal	(18.85 < precip > 20.68 in.)
Wet	(20.69 < precip > 24.38 in.)
Very Wet	(24.39 < precip > 28.28 in.)

Precipitation for Cotulla during the experiment for the hydroyear was 24.53, which qualifies the year as "Wet". The regression analysis offered the following results: The linear correlation coefficient r = 0.71 indicates good correlation. Based on Cotulla's actual precipitation of 24.53 inches for the hydroyear of the experiment, the expected precipitation level for Laredo was 21.55. The equation used is:

$$\text{Laredo Expected Prec.} = 0.70 \times \text{Cotulla Actual Prec.} + 4.38 = 0.70 \times 24.53 + 4.38 = 21.55 \quad (1)$$

The actual precipitation was 14.88, which is 6.67 inches below the expected level. The Working Hotelling amplitude (at the 95% confidence level) is 1.52 (Working and Hotelling, 1929) which means that the precipitation decrease is significant.

The above analysis clearly shows that precipitation in Laredo for the hydroyear Oct 05 through Sep 06 was not enhanced. It was, in fact, significantly below the historically predicted level. The annual report to the TDLR also states that the choice of Cotulla as a witness point was a mistake and that it was strongly suspected that Cotulla was well within the influence zone of the ionization station.

5.4 <u>Data: Aerosol Size Distribution - General</u>

The basic flight plan used was designed to attempt to capture data both in the operational as well as the control (witness) areas by flying over the longest axis of the ionization plume. It is shown in the map in Fig. 6.

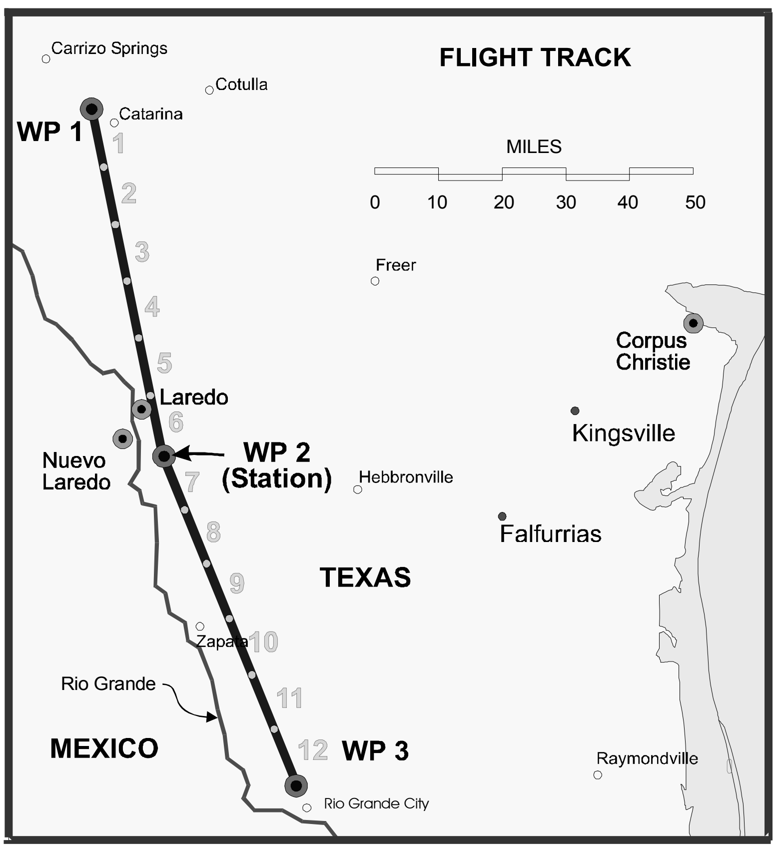

Fig. 6. Measurement Flight Plan

The aircraft starts its measurement run at Waypoint 1, West of Cotulla, proceeds to Waypoint 2, which is the location of the ionization station, then on to Waypoint 3, close to Rio Grande City. Airspeed and altitude are maintained by the airplane's autopilot in order to stay within limits required by the spectrometer's isokynetic air intake. The total length of the flight path is about 120 miles.

Each spectrometer is designed to measure atmospheric particles in 31 channels ranging from 250 nm to 32 microns. Readings are taken every 6 seconds and the data are presented as number of aerosols per liter. In order to simplify viewing and analyzing the data, the particle sizes were reduced from 32 channels to 4: Small (0.0 to 0.280 μm), Medium (0.281 to 0.350μm), Large (0.351 to 0.800 μm) and Giant (0.801 to 32.000 μm). This allows viewing 4 graphs instead of 31. Further simplification resulted from dividing the flight path into 12 flight zones, each one about 10 miles long, and the recorded data were averaged for each flight path, thus reducing the number of data points from around 700 to 12.

All measurement flights were analyzed, verifying a number of parameters, among them, flight recorder data including coordinates, altitude and groundspeed, cloud formations observed by the pilot during flight. Background conditions were also analyzed, including 24 hour backward wind trajectories at waypoints 1, 2 and 3 NOAA HYSPLIT Model (Draxler and Rolph, 2003), atmospheric background, including NAAPS (Navy Aerosol Analysis and Prediction System) images for optical depth and sulfate, dust and smoke concentrations. Also, any unusual conditions encountered during flight were reported by the pilot to rule out anomalies such as vehicular or cattle traffic which might impact the measurements. An example of typical HYSPLIT Model backward wind trajectories (BWT) appears in Fig. 7, which shows the BWT for Waypoints 1, 2 and 3.

An example of the NAAPS background is provided in Fig. 8.

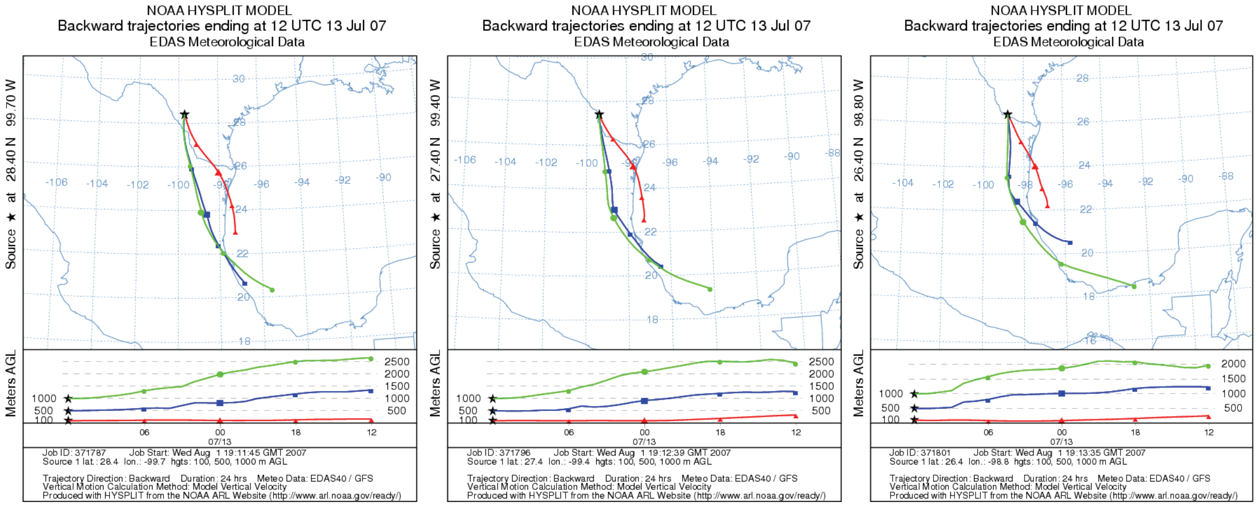

Fig. 7. HYSPLIT Model Backward Wind Trajectories, 07/13/2007, WP 1, WP 2 and WP 3

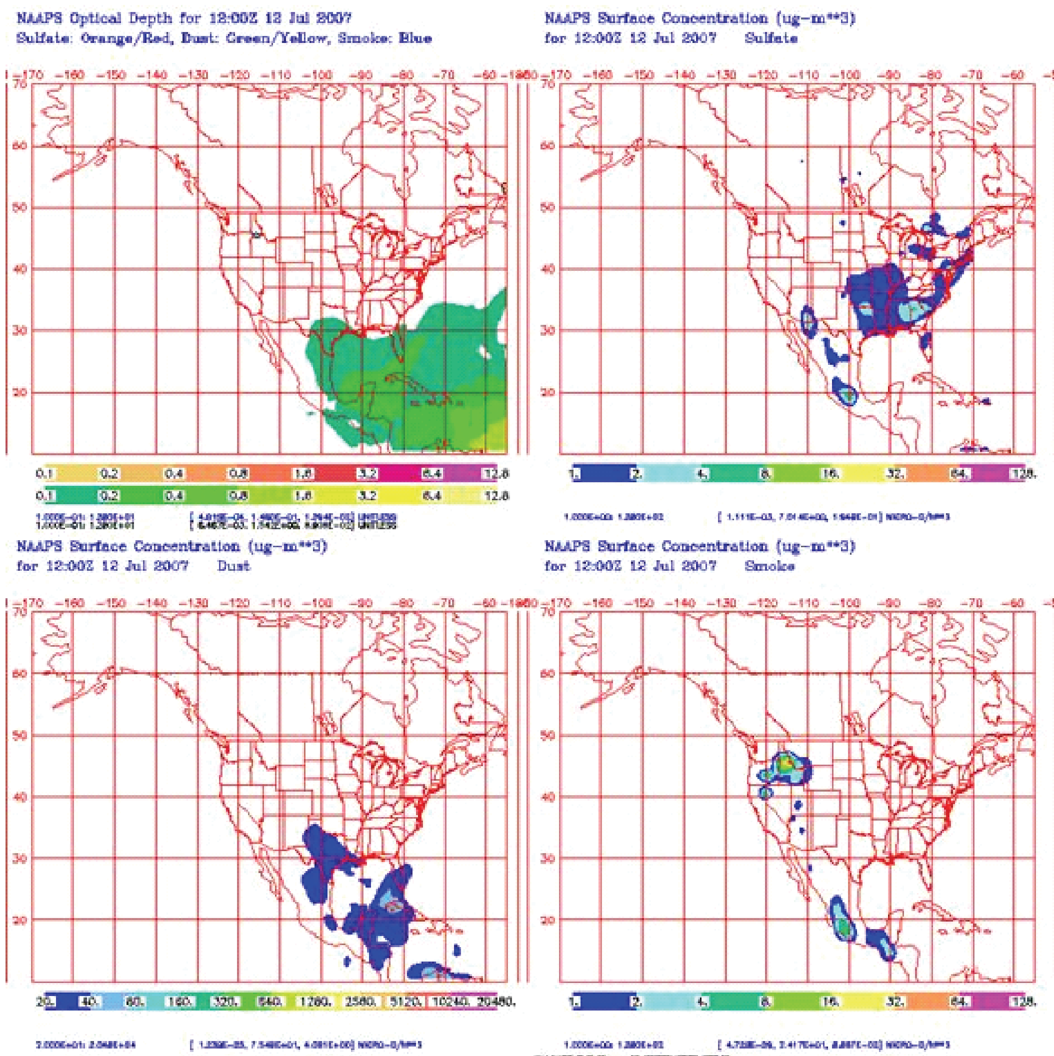

Fig. 8. NAAPS Background Information, April 14, 2006, 12:00 Z

There were a total of three sets of measurement flights performed: One set, called "Zero Operation" when the ionization station is turned off, another set called "Positive Operation" with the station operating on positive polarity, and, a third set called "Negative Operation" where the station was operating on negative polarity.

Data was further simplified in order to allow graphic analysis. Because of the very large variability in atmospheric conditions from day to day and because it was necessary to compare flights performed in different dates, all data was normalized so that the maximum particle count reading for each flight was forced to a value of 1.00 (or 100%). Further, the four particle size ranges was reduced to one in order to analyze the relative total number of atmospheric particles along the measurement flight path in a simple and straightforward fashion.

In order to switch from operational or non-operational state a period of transition to achieve steady state conditions was required. It was estimated that to go from an operational state (either positive or negative) to a non-operational state it would take about 20 hours at a constant wind speed of 3m x s^{-1} to travel 200 km (about 120 miles) provided there was no change in wind direction (Time = (100 x 1000) / 3 = 66,000 seconds = 66,000 / 3,600 = 18.3 hours. If wind speed and direction change it would take longer to "sweep" the ionized air away. Similarly, for non ionized air to charge the ionized aerosols must be transported by the wind, but an additional time period is required for aerosols to grow to a point where aerosol deposition reaches a steady state value. For purposes of this experiment, it was deemed that a period of transition of about 96 hours would be enough to achieve substantially steady state conditions when switching from one operational state to another.

The historical (1947 to 1998) prevailing wind direction in Laredo for the months of February through September is SSE, approximately 155^o. Due to some difficulties pointed out by our pilot, the flight plan was designed slightly off the prevailing wind vector at approximately 160^o for flight zones 12 through 7 and 170^o for flight zones 6 through 1.

All flights were performed during the months of February through August. All flights were scheduled during the morning hours to avoid, where possible, measurements after convection had started in earnest. The overall predominant wind direction for all flight days was from the ESE (approximately 125^o), which means that the flights did not cut the ionization plume along it's predicted major axis, although the directional difference did allow the flights to measure along much of the length of the plume.

5.5 <u>Data: Aerosol Size Distribution – Non Operational</u>

Because maritime atmosphere is less polluted than continental atmosphere, the expectation was that the total number of particles in suspension would increase as the aircraft went further inland and would decrease as the aircraft approached the coast.

As can be seen from the previous Alpha Flight Plan map in Fig. 6, the aircraft is closer to the coast at WP 3 (Flight Zone 12) than it is at WP1 (Flight Zone 1). In fact, WP 3 is about 60 miles closer to the Gulf coast than WP 1. Therefore, for the case where the ionization station is turned off (non-operational), the expected total number of particles at Flight Zone 12 should be lower than at Flight Zone 1. In order to test this hypothesis, normalized data was used to compare flights performed on different days. The goal was to see how the total number of aerosols increase or decrease along the flight path.

The average normalized data of all six non-operational flights is depicted in the chart in Fig. 9.

Fig. 9 shows the average aerosol counts (pink line) average plus one standard deviation (brown line) and average minus one standard deviation (blue line). It is obvious that aerosol counts vary greatly for natural, non operational atmospheric conditions and so the standard deviations are quite large. Fig 9 also shows a linear trendline, its equation and a good correlation of 0.82. The trendline clearly supports the hypothesis that aerosol counts increase as the atmosphere becomes more continental and less maritime. The rate of increase in aerosol counts is about 3.4% for every ten miles traveled along the flight path described in Fig. 6.

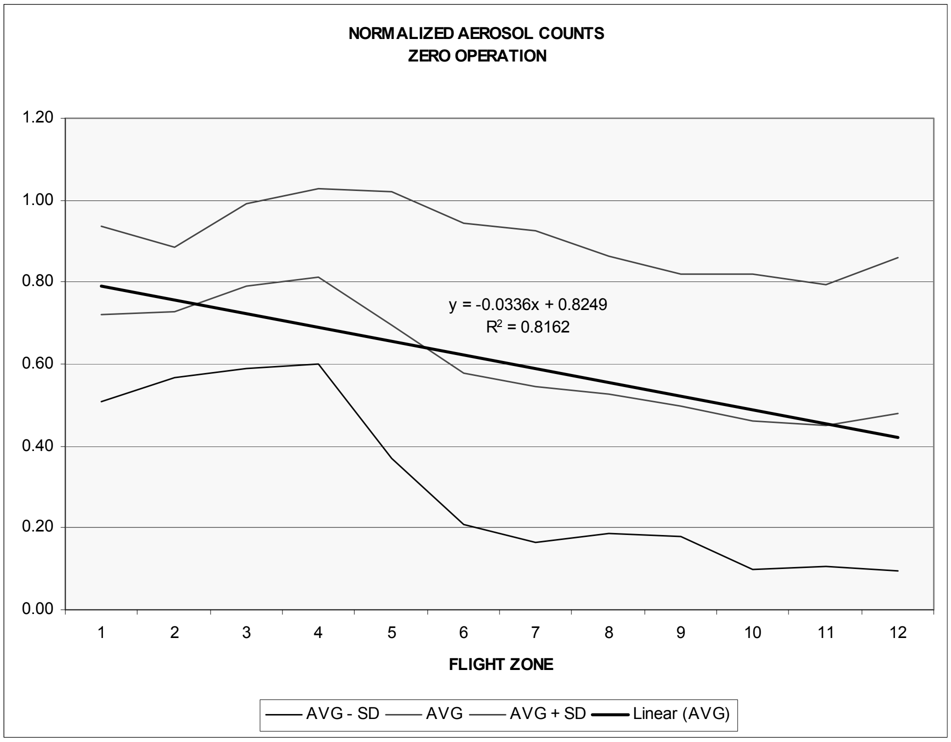

Fig. 9. Average Normalized Flight Measurement Data – Non Operational

5.6 Data: Aerosol Size Distribution – Operational Negative

When operating the station it was logical to assume that in either mode of operation, positive or negative, the number of aerosols measured in Flight Zone 1 would be less than the ones measured in Flight Zone 1 for non-operational conditions. This is because ionized aerosols grow more aggressively than electrically neutral ones. Part of this growth is by coagulation, which should substantially lower the number of smaller aerosols. Larger aerosols would also be more likely to depose to ground over a period of time due to gravity. The normalized data recorded for the four flights for negative operation are shown in Fig. 10. It is clear that there is a significant reduction in the number of aerosols measured in Flight Zone 1. Furthermore, the slope of the linear trendline went from negative under non-operational conditions to positive under negative operation. Additionally, it appears that standard deviations are smaller and perhaps growing smaller even as the flight zone numbers decrease, which are the areas where ionization is producing larger effects.

5.7 Data: Aerosol Size Distribution – Operational Positive

When analyzing positive operation, one would expect results to be similar to negative operation, since what is most important in either mode of operation is that all CE ions are unipolar. The normalized data for the eight flight segments measuring aerosol counts during positive operation are shown in Fig. 11.

As shown in Fig 11, the decrease in the number of measured aerosols from Flight Zone 12 to Flight Zone 1 is larger than for negative operation. In both negative and positive polarity there is deposition of aerosols caused by the aggressive growth of charged aerosols which increases gravitational attraction and, consequently, their downward vertical velocity. However, during negative operation, negatively charged aerosols are repelled by the negatively charged ground, whereas under positive operation, positively charged aerosols are attracted to ground. Thus, in the case of negative operation deposition is the result of gravity less electrical repulsion, whereas in positive operation, deposition is the result of gravity plus electrical attraction.

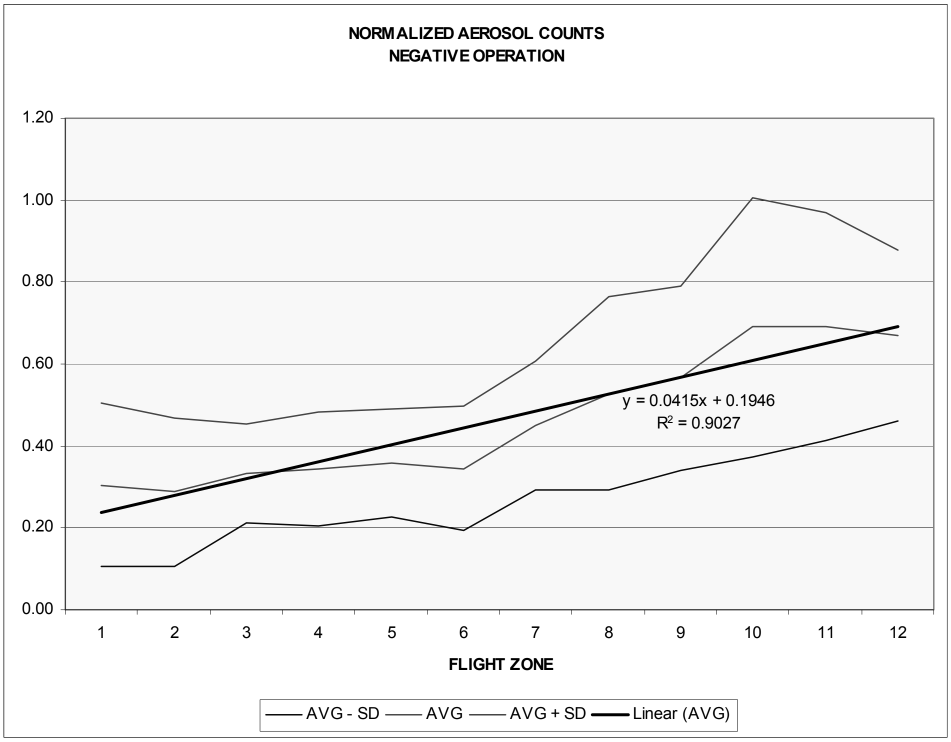

Fig. 10. Average Normalized Flight Measurement Data – Operational, Negative

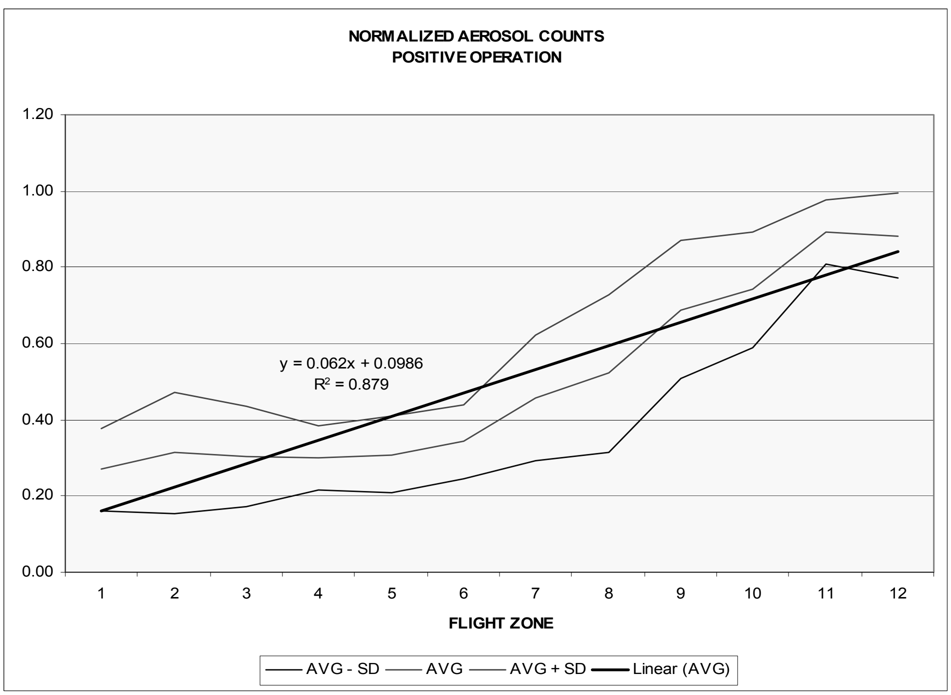

Fig. 11. Average Normalized Flight Measurement Data – Operational, Positive

5.8 Data: Aerosol Size Distribution – Flights Extended to the Gulf Coast

Additional flights were also performed extending the flight to the Gulf Coast after completing the normal Flight Zone 1 thru 12 track. This added flight zones 13 to 19 heading straight East from flight zone 12 and flight zone 20 heading North from flight zone 19. Two of the flights were under non operational conditions and one was operational. The flight track is depicted in Fig 12.

Flight data for segments 1 through 12 of these flights have been included in the previously described analysis, but looking at all 20 flight zones may prove interesting.

The non operational flight data for flights with an extension to the Gulf Coast are charted in Fig 13.

It would appear that the number of aerosols does, in fact, increase as the air becomes less maritime and more continental. There is an increase of about 70% in the number of aerosols measured in Flight Zone 1 from the number measured in Flight Zone 12.

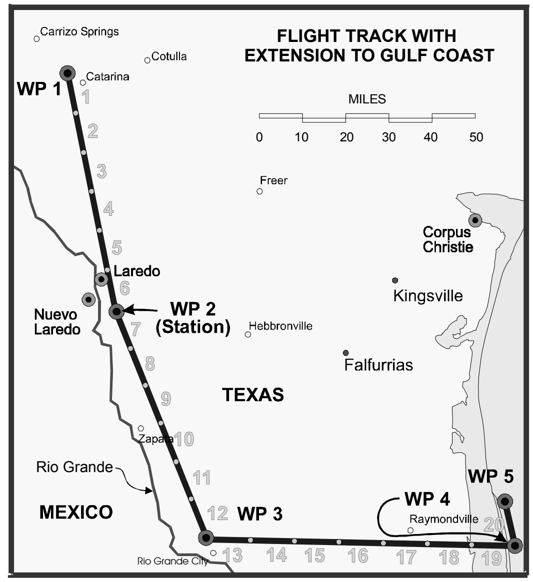

Fig. 12. Flight Track with Gulf Coast Extension

Another flight with a Gulf Coast extension was performed when the station was operational with positive voltage. The results are shown on Fig 14.

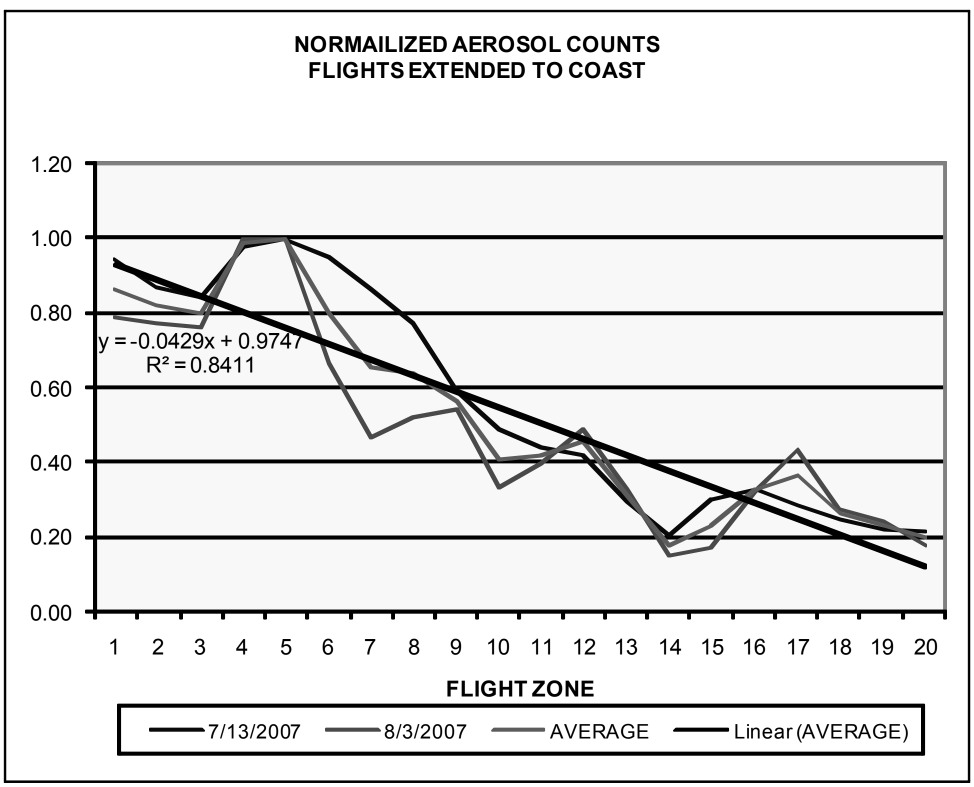

Fig. 13. Normalized Aerosol Counts – Flights extended to the Coast- Zero Voltage

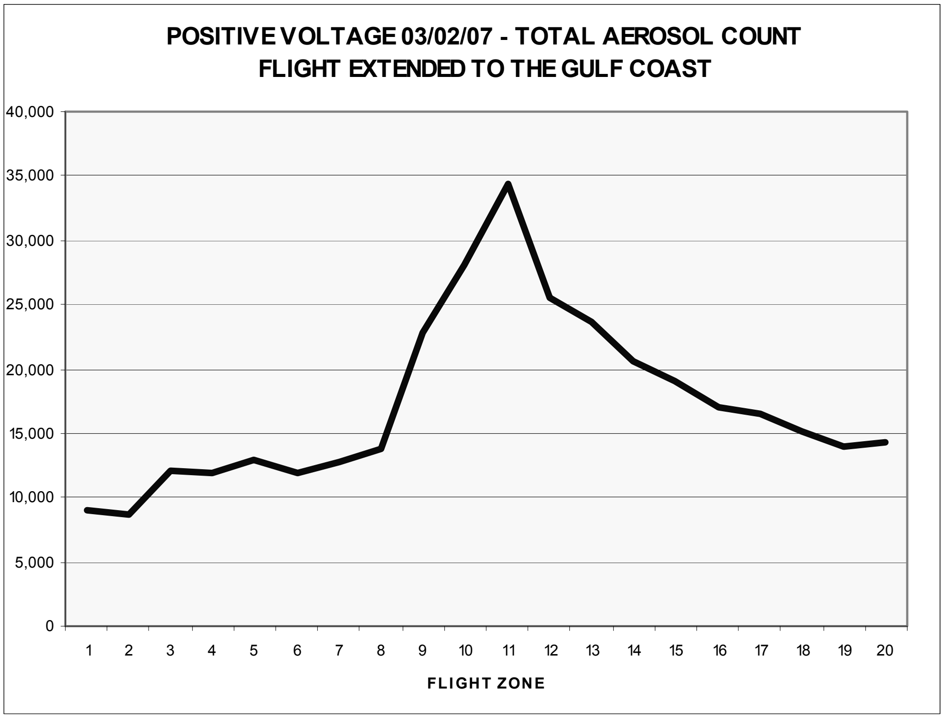

Fig. 14. Flight extended to Coast – Positive Voltage

The graphic indicates that there are two distinct patterns: The first one, going from Flight Zone 1 to Flight Zone 11, shows that aerosol counts are increasing. This is due to the effect of ionization. The second pattern, going from Flight Zone 12 to Flight Zone 20, shows decreasing aerosol counts, substantiating the hypothesis that maritime air is cleaner (less aerosols) than continental air.

5.9 Data: Aerosol Size Distribution – Operational vs. Non Operational

In order to visualize the effect of the ionization station on aerosol counts, a final data manipulation was performed. The normalized data for all three operational states at Waypoint 3, the start of Flight Zone 12, was forced to equal 1.0 and then all the rest of the normalized data for each Flight Zone was plotted, based on the common Waypoint 3 starting point. Waypoint 3 is clearly well outside the area of influence of the ionization station so that the readings at that waypoint would be the same, whether the station was operating or not.

Another simplification was made in that operational data for positive and negative operation were combined so that a comparison of "Operational vs. Non Operational" conditions can be made in a straightforward manner. The result is shown in Fig. 15.

It seems clear that ionization does not truly start to influence aerosol populations beyond zone 10, so that the area of ionization influence appears to be from Flight Zone 1 through Flight Zone 9, a distance of approximately 90 miles.

It is interesting to observe that the "bandwidth" between plus and minus one standard deviation for non operational conditions is much wider than the corresponding operational bandwidth. Although the bandwidth is tighter the closer we come to Flight Zone 1, at Flight Zone 12, where there is, presumably, no ionization effect, the bandwidth is still tighter for operational conditions than for non operational conditions.

The efficiency of ionization in aerosol reduction can be calculated by obtaining the ratio of Operational and Non-Operational normalized aerosol counts for each flight zone and subtracting 1. The results can be read as the efficiency of the Operational Mode in increasing (positive efficiency number) or decreasing (negative efficiency number) aerosol counts in the corresponding Flight Zone. The results are reflected in Table 2.

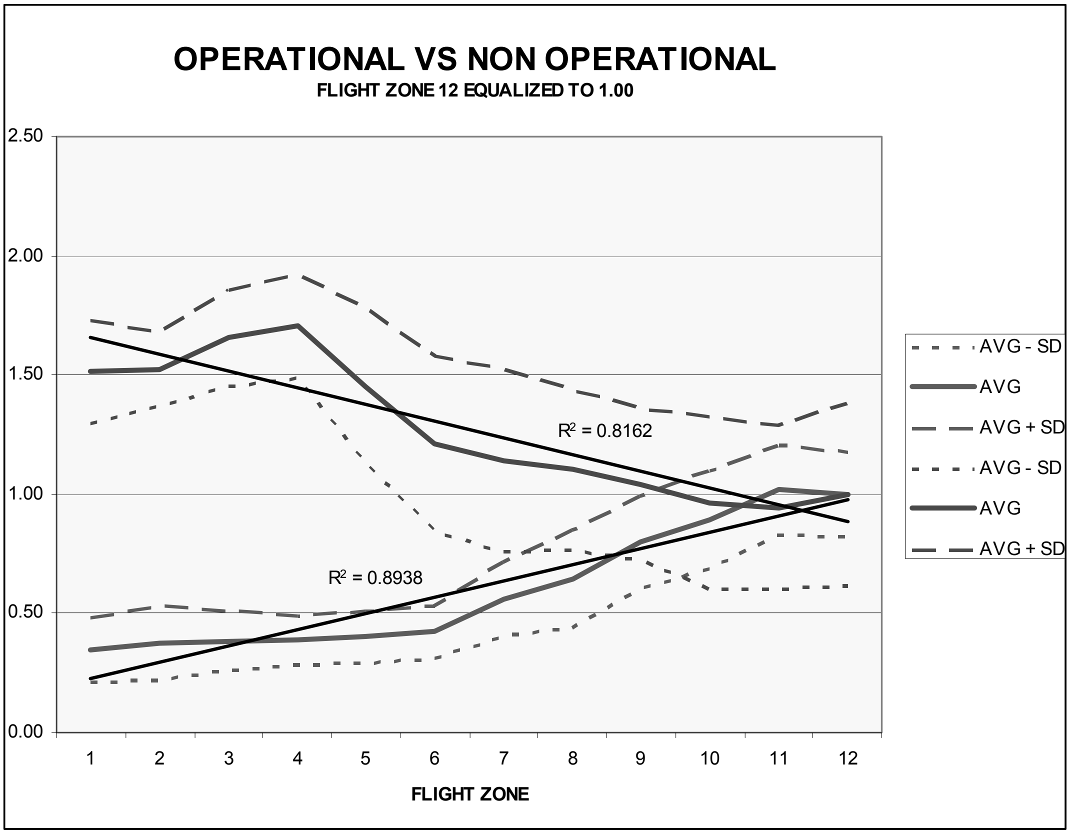

Fig 15. Average Normalized Flight Measurement Data Comparison of Non Operational and Operational Modes

Table 2. Operational Ionization Efficiency

ZONE	OPER AVG	NON OP AVG	RATIO OP TO NON OP	EFFIC'Y PCT
1	0.35	1.51	0.23	-77%
2	0.38	1.52	0.25	-75%
3	0.39	1.65	0.23	-77%
4	0.39	1.70	0.23	-77%
5	0.40	1.45	0.28	-72%
6	0.42	1.21	0.35	-65%
7	0.56	1.14	0.49	-51%
8	0.65	1.10	0.59	-41%
9	0.80	1.04	0.76	-24%
10	0.89	0.96	0.93	-7%
11	1.02	0.94	1.08	8%
12	1.00	1.00	1.00	0%

An approach can be made toward the interpretation of Fig. 15 by assuming a normal distribution and using a Fermi question approach to examine the probabilities of occurrence of the events recorded (Morrison, 1963). To do this we need to determine how far away the Non Operational mean is from the Operational mean, in units of standard deviation. The equation that is used for this is:

$$\text{Op Mean} = \text{Non Op Mean} - Z \times \text{Non Op Std Dev} \quad (1)$$

From eq (1), multiplying both sides by -1:

Z = Distance between Op and Non Op Means = (Non Op Mean – Op Mean) / Non Op Std Dev

The results are displayed in Table 3.

Table 3 shows that Flight Zones 10, 11 and 12 are naturally occurring events, while zones 1 through 8 are probably not. It is also evident that zones 1 through 5 are more than 3 standard deviations apart. Flight Zone 9 is the transition point.

6. CONCLUSION

A number of direct and indirect references have been made to recent publications which point out the ever more widely accepted postulate that ionization contributes to more aggressive aerosol growth. Growth that is accomplished not by one or two but by all growth mechanisms observed to date, including condensation, coagulation, coalescence, scavenging and collision/aggregation. The data charted in Fig. 10. provide an additional pebble on the road to understanding aerosol properties by showing that it is probable that aerosol growth leads to a reduction of aerosol counts because smaller aerosols are “feeding” larger, charged, aggressively growing aerosols and these larger aerosols will likely enhance gravitational deposition, which is recorded in proxy data as an overall reduction in the number of aerosols in the atmosphere surrounding an ionization station, preferentially upwind of the station.

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Table 3. Probability of Natural Occurrence of Figure 15 Results

FLIGHT ZONE	NON OP STD DEV	NON OP MEAN	OP'L MEAN	Z NUM OF STD DEVS	PROB'Y OF OCCUR
1	0.21	1.51	0.34	5.57	0.00
2	0.15	1.52	0.37	7.67	0.00
3	0.20	1.65	0.38	6.35	0.00
4	0.21	1.70	0.38	6.29	0.00
5	0.32	1.45	0.40	3.28	0.00
6	0.36	1.20	0.42	2.17	0.02
7	0.38	1.14	0.56	1.53	0.06
8	0.33	1.10	0.64	1.39	0.09
9	0.31	1.04	0.79	0.81	0.22
10	0.36	0.96	0.89	0.19	0.42
11	0.34	0.94	1.01	-0.21	0.59
12	0.38	1.00	1.00	0.00	0.50

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COMMENTS ON SILVERMAN'S EVALUATION OF THE KERN RIVER PROGRAM

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I am skeptical about Silverman's (2008) approach of taking point estimates of a seeding effect (in this case, from the Kern River program) at face value, as in the interpretation of his Fig.1, and viewing a variation in those estimates with increasing length of record as an indication of a time trend in the seeding effect. A point estimate is just that: An estimate. There is a 10% chance that the "true value" of the effect does not even lay within the 90% confidence interval. I question whether small variations of the point estimate, within a confidence interval that does not substantially narrow with increasing sample size (no plot of the variation of the confidence intervals appears in Silverman 2008, but see Fig. 3 of Silverman 2007 for an example), indicate anything other than simple statistical variations of the point estimate.

(a) Problems with the Point Estimates

Examination of some of the data and Silverman's results provides a suggestion of the kind of problems that can occur with taking the point estimates at face value. The term *flow* as used herein designates the annual "Full Natural Flow" (FNF) values calculated from data obtained from the California Data Exchange Center (CDEC) as employed in Silverman's analysis. These comments consider values of the flow at three stations: The Kern River below Isabella (KRI), the primary target station in Silverman (2008) and representing runoff from an upper drainage area of 2407 mi^2; the Kern River at Bakersfield (KRB), a second downriver target station incorporating an additional lower drainage area of 333 mi^2; and (later) Success Dam (SCC), the control station showing the strongest correlation with the flow at KRI.

Table 1 shows some of the relevant mean flow values from the KRI and KRB stations. The "difference" column shows the increment contributed by the lower drainage area. Values in the bottom row were calculated by taking the point estimates at face value and dividing the mean-seeded-flow values by the appropriate factor; *e.g.* for KRI 762,467/1.122 = 679,561.

The values in the last column of the table raise an interesting question. The mean flow at both target stations was higher during the seeded years, but the increment contributed by the lower drainage area was actually *lower* during those years. This suggests that the seeding may have *decreased* the contribution from the lower drainage area. A possible explanation for this would be that the seeding effects moved the precipitation higher up the terrain, but that does not seem compatible with any seeding conceptual model that involves accelerated development of precipitation. Moreover, according to the last row in the table taking the point estimates at face value would exacerbate the problem by suggesting that

Table 1: Summary of key flow information for Kern River program

Variable	Units	KRB	KRI	Difference
Mean flow in 22 historical years	AF	707,677	656,571	51,106
Mean flow in 28 seeded years	AF	794,488	762,467	32,021
Point estimate of seeding effect	%	+8.4	+12.2	--
Estimate of mean flow in 28 seeded years in absence of seeding	AF	732,922	679,561	53,362

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the increment from the lower drainage should have increased by 4% in the absence of seeding (in contrast to the observed 37% decrease).

A more likely interpretation is that the point estimates should *not* be taken at face value. This does not negate the statistical evidence of a positive seeding effect, but it does appear that the two point estimates are incompatible. One or the other, and perhaps both, probably misrepresent the true seeding effect. They nevertheless stand as the best estimates available pending accumulation of further data. But any time trend in those estimates as data are accumulated should not be viewed as a definitive indication of a time variation in the seeding effect.

(b) Evidence of Seeding Effect Mainly in High-flow Years

Sifting through the data revealed another interesting aspect that warrants further study. As noted above, the mean flows at the two target stations were higher during the seeded years. Moreover, the frequency of high flows (> 10^6 AF) at both stations increased from about 18% (4 of 22) during the historical years to 32% (9 of 28) in the seeded years. Yet the *median* flow at both stations was actually substantially *lower* during the seeded years. The mean flow at the SCC control station was also higher during the seeded years, and the median flow decreased only slightly. This suggests that the positive effects of the seeding were mainly realized during high-flow years.

Figure 1 compares cumulative frequency distributions of the flows at KRI for the two sets of years; the values have been normalized by dividing by the respective median values. The plot highlights a distinct shift in the seeded years toward higher relative values in flows greater than the median. A similar plot of the SCC control station flow values in Fig. 2 shows little difference between the historical and seeded years, except for a couple of extreme cases, suggesting that this shift is a feature of the seeded flows.

The only hypothesis to account for this observation that comes readily to mind is that the seeding effect may not be a simple multiplicative factor. In any case, the observed behavior seems at least as worthy of further investigation as Silverman's hypothesis about temporal variations in the seeding effects.

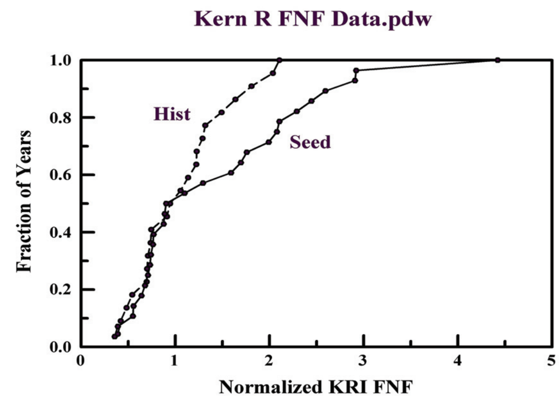

Fig. 1: Cumulative frequency distributions of flow at KRI target station; Hist denotes historical years and Seed denotes seeded years. Flow values normalized by dividing by the median value for the period.

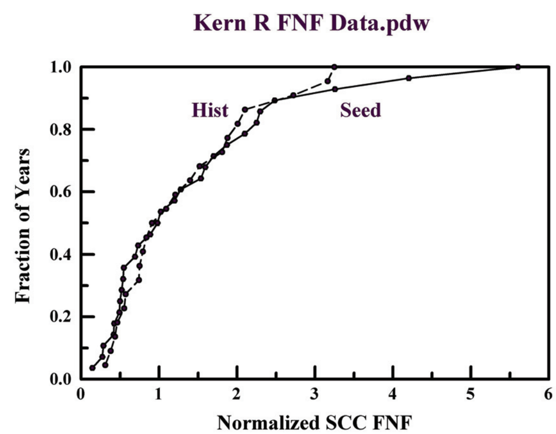

Fig. 2: Cumulative frequency distributions of flow at SCC control station; Hist denotes historical years and Seed denotes seeded years. Flow values normalized by dividing by the median value for the period.

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REPLY TO PAUL SMITH'S COMMENT

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Smith stated that he is skeptical about taking point estimates of the seeding effect literally. That is a valid concern. They should not be taken literally. After all, point estimates are statistical estimates with an inherent degree of uncertainty that is quantified by the standard error of estimate. A point estimate with its standard error of estimate is generally used in null hypothesis testing to infer if there is any effect at all. The best estimate of the strength of a seeding effect is given by its confidence interval because it infers a range within which the true effect lies at the specified level of confidence. That is why I emphasized the use of confidence intervals in the Kern program evaluation using a 90% level of confidence.

Any attempt to use point estimates literally will undoubtedly lead to problems in reconciling the numbers generated from them since they don't take into account the uncertainty in the point estimates. In addition, it should be noted that the point estimates are obtained from the regression ratio that is empirically adjusted for bias due to the non-randomization of the seeding operations. The main purpose of the bias adjustment is to obtain confidence intervals that are statistically comparable to those obtained through re-randomization analysis. As such, it is not possible to generate an internally consistent set of streamflow estimates by taking the point estimates literally.

The important thing to note from Smith's Table 1 is that the ratio of the estimated average target streamflow during the operational period in the absence of seeding (row 4) to the average target streamflow during the historical period (row 1) is greater than one, and that is qualitatively correct. This factor is taken into account in a more quantitatively accurate way by the regression ratio, enabling it to produce the most precise estimate of the seeding effect.

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Smith stated that he is skeptical about viewing a variation in point estimates of the seeding effect with increasing length of record as an indication of the time trend in the seeding effect and points out that there was no plot of the variation of the confidence interval for the 3 Kern targets in Silverman (2008). Taking the second point first, I hasten to point out that 90 percent confidence limits were not shown for clarity of presentation only. For each of the targets the 90 percent confidence limit lines follow the pattern of their point value plot and narrow with time, albeit relatively little, as the standard error of estimate decreases with increasing sample size.

As for Smith's first point, Smith does not provide any theoretical or empirical basis for his skepticism. On this point, we have a difference in scientific opinion. I believe that a significant, multi-year change in the slope of the plot of the cumulative year seeding effect and its confidence limits with time is indicative of a possible change in one or more of the factors that determine seeding effectiveness, such as the quantity/quality of seeding opportunities and/or the seeding procedures. It signals a change in events that is worthy of further investigation. The interpretation of the plot of the cumulative year seeding effect and its confidence limits with time is similar in concept to the interpretation of a double-mass curve. In the evaluation of cloud seeding based on streamflow, for example, the cumulative target (seeded) runoff is plotted against the cumulative control (non-seeded) runoff. A break in slope is assumed to be change in the mean of the target series and the ratio of the slopes is an estimate of the multiplicative change in that mean (see, e.g., NAWC, 1978).

I became convinced of the value of this statistical tool (plot of the cumulative year seeding effect and its confidence limits with time) when I applied it to the evaluation of the Pitman Creek target in the San Joaquin Basin operational cloud seeding program which was done to compare and pool the results from the Kern, King River and San Joaquin seeding programs (Silverman, 2008).

The time evolution plot for Pitman Creek (PIT) showed a significant increase in the slope starting in 1975 (see Fig. 1). It was found that it was consistent with the introduction of aircraft seeding as a supplement to the ongoing ground-based seeding. It is likely that the addition of aircraft seeding to the ongoing ground-based seeding was the cause of the dramatic increase in seeding effectiveness. With the addition of the supplemental aircraft seeding, a statistically significant seeding effect became evident.

Smith presents data that he suggests indicates the seeding effect occurs mainly in high-flow years. If true this is an important finding; therefore, I agree that the observed behavior is worthy of further investigation. In fact, I believe that follow-up physical studies prompted by both expected and unexpected statistical and physical findings are warranted since they will help establish the physical plausibility of the statistical results and they will provide insights on how to improve the seeding operations.

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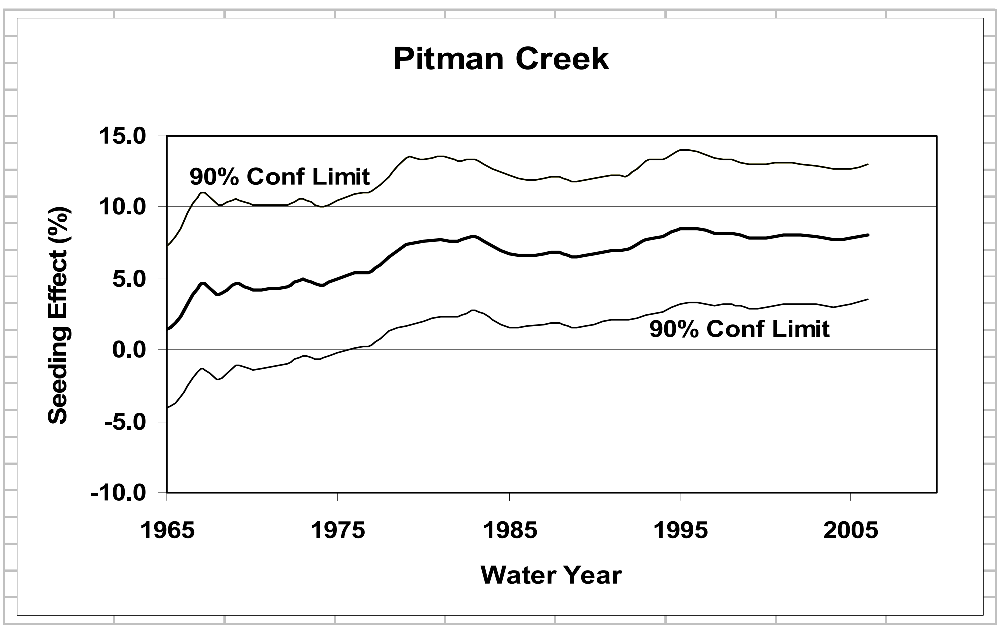

Fig. 1. The proportional seeding effect for PIT, $\delta(\%) = 100*(RR_A-1)$ where RR_A is the bias-adjusted Regression Ratio, as a function of the cumulative number of seeded years. Also shown are the 90% confidence limits. The seeding effect calculated for each seeded water year is the value that would have been obtained if the evaluation were done for all seeded years up to and including that water year.

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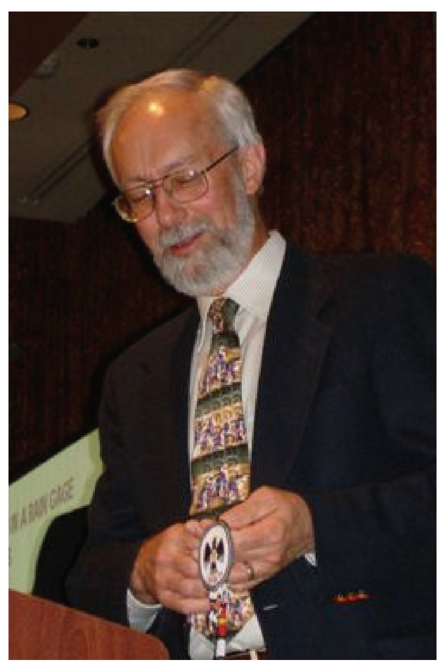

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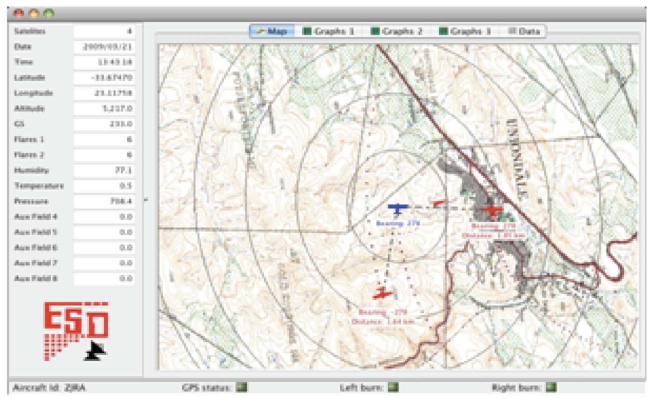

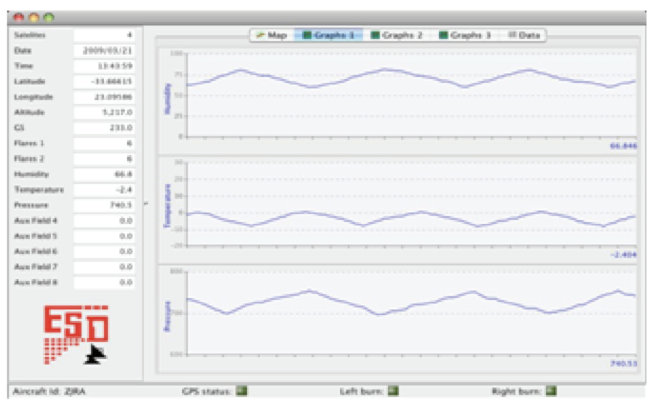

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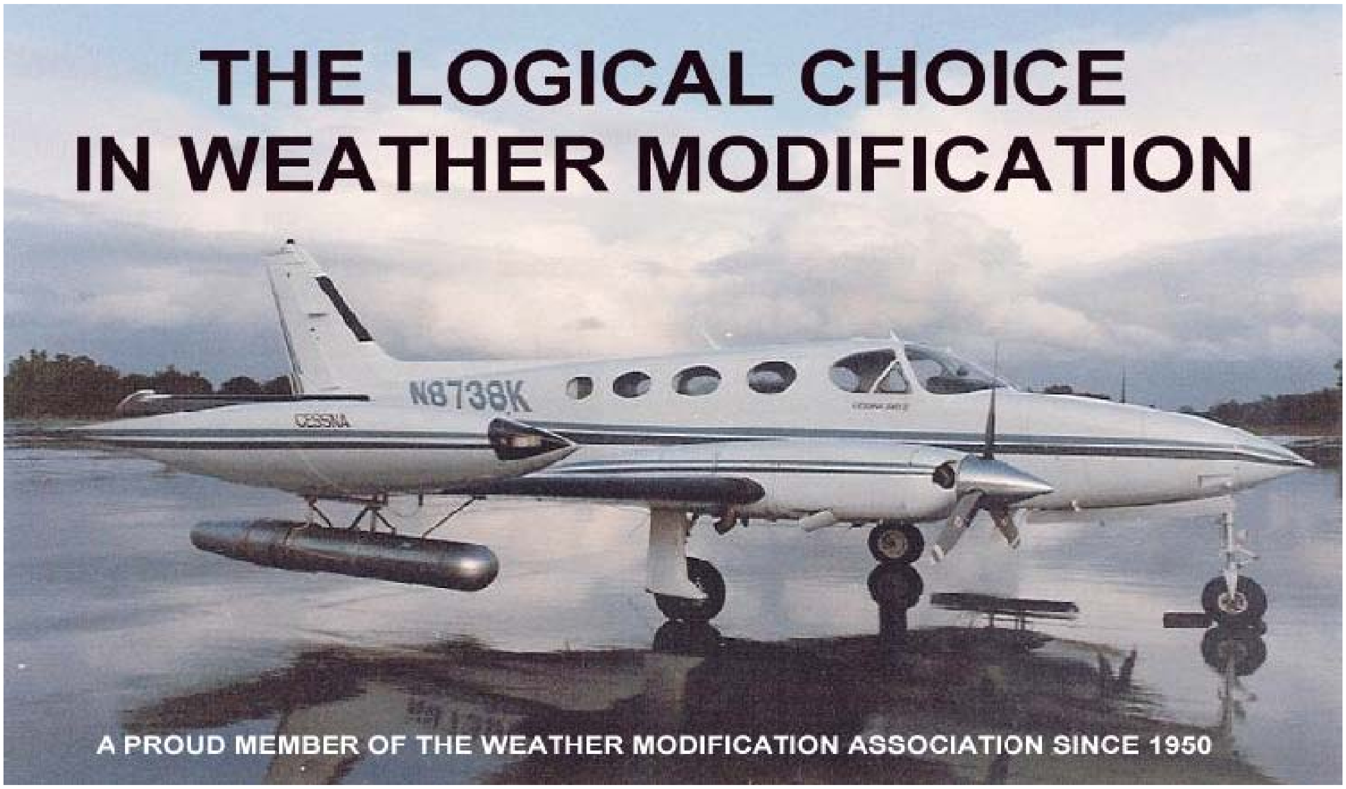

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