P1.12 SUMMARY OF TRACE CHEMICAL AND PHYSICAL MEASUREMENTS OF SNOWFALL IN TWO NEVADA CLOUD SEEDING TARGET AREAS

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1. INTRODUCTION AND BACKGROUND

For nearly two decades chemical tracer techniques have been used to aid in the evaluation of wintertime snowfall augmentation projects. The basis for the success of these techniques is that unique chemical species released into the atmosphere as part of cloud seeding operations can be quantified in snowfall to evaluate targeting, ice nucleation versus scavenging processes, and potentially to quantify changes in precipitation due to the release of ice nucleating aerosols. Warburton et al. (1995a, 1995b) summarized trace chemical analysis from two projects in the Sierra Nevada, using the presence of silver from the ice nucleating agent to assess temporal and spatial targeting efficiency. These authors also described a dual-tracer technique which used the ratio of silver (Ag) to a non-ice nucleating tracer (Indium) to differentiate between the processes of nucleation and scavenging. Chai et al. (1993) used the spatial distribution of silver-indium ratios to suggest the specific ice nucleation mechanism at work in the Pacific Gas and Electric Lake Almanor Project in the northern Sierra Nevada.

Researchers continue to refine these trace chemical techniques in attempts to quantify the snowfall due to cloud seeding activities. McGurty (1999) reported on an evaluation that used an apparently detectable difference in snow densities between seeded samples (higher density) and unseeded samples to estimate the amount of water added to the snowpack by seeding operations. This same evaluation also used a third tracer (Cesium) to determine the targeting effectiveness of aircraft seeding versus ground-based seeding.

The tracer techniques for evaluating targeting effectiveness and verifying ice nucleation processes in target areas have been used successfully now in several projects with similar results. However, the method of quantifying snowfall increases using a correlation between snow density and silver concentration requires further investigation. Snow density is a very difficult quantity to measure. In a snowpack it can change quite rapidly in days or even hours. The segmented profiler method of determining snow density was used in the works cited above, and was used in the study described here. Part of the task was to determine if a silver-density relationship could be found in two Nevada cloud seeding project areas.

In the winter of 2003-04 the Desert Research Institute (DRI) conducted research as part of the U. S. Bureau of Reclamation Weather Damage Modification Program (WDMP) to evaluate the impacts of wintertime cloud seeding on the snowfall and streamflow in a watershed. One of the research tasks was aimed at using a trace chemical method to evaluate targeting efficiency in two areas seeded in Nevada's operational cloud seeding program. In addition, physical measurements of snow mass and density were made and compared to silver concentration to determine if a silver-density relationship, such as that used by McGurty (1999), could by found and used to quantify seeding effects in the Nevada target areas.

2. DESCRIPTION OF THE WDMP SNOW CHEMISTRY EXPERIMENT

The chemical and physical measurements of snowfall were made in conjunction with the Nevada Cloud Seeding Program. Much of the work described here relates to samples collected in the Walker River Basin. Figure 1 shows the area of the study with instrument locations, snow sampling sites, cloud seeding generator sites and seeding aircraft flight tracks. Huggins et al. (2004) describes a mesoscale modeling study centered on this region for a February 2004 storm. Snow samples

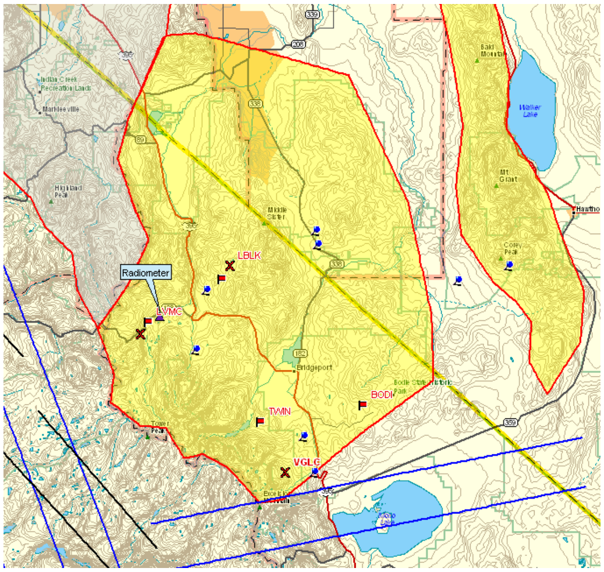

Figure 1. Map showing Walker Basin cloud seeding target area (yellow), seeding generator (blue pins), SNOTEL (X), snow sampling (red flags) and radiometer sites. Blue and black lines are aircraft seeding tracks.

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from that period are among those described in this study.

2.1 Cloud Seeding Operations

As noted in Fig. 1 eight ground-based seeding generators were used in the Walker Basin. Wind and temperature criteria were used by the Nevada Program to determine what generators, or what seeding flight track, were used during a particular storm period. The cloud seeding agent used was a fast-functioning silver chloroiodide aerosol with a small amount of sodium chloride, similar to ones described by Feng and Finnegan (1989). Ground-based seeding operations were conducted from November 2003 through April 2004. Aircraft seeding was conducted between late December 2003 and late February 2004.

As part of past operational seeding programs, some trace chemical analysis of snow samples was done in the Walker Basin. In a given season only one or two sites were sampled, so overall targeting effectiveness could not be evaluated. Results were also quite varied, with some profiles containing a high percentage of relatively high silver concentrations (> 20 PPT), and other profiles having nearly all samples with silver < 4-6 PPT. In the past several years the number of seeding generators has been increased from three to the current eight. The 2003-04 snow sampling at four sites on multiple occasions presented the opportunity to evaluate targeting effectiveness more comprehensively. Near the end of the aircraft seeding operations period, a silver iodide - cesium iodide mixture was used. The flights with this mixture took place in the Tahoe Basin, but some snow profile data from this period will be presented.

2.2 Snow Sampling and Analysis Methods

The method for collecting snow samples was similar to that described by Warburton et al. (1995a). Snow boards were set in place at eight sites in the Tahoe-Truckee and Walker drainage basins. Figure 1 shows the locations of these sampling sites and other instrumentation used on the project in the Walker Basin.

A 1-meter long segmented acrylic profiling device was used to collect snow samples. Samples were collected at the sites when an adequate amount of snow had fallen from one or more storms. The profile was partitioned into ~2-cm deep segments using polycarbonate dividers that fit into grooves along the sides of the profiler. The profiler cross-sectional area was ~200 cm^2, making the volume of each segment ~400 cm^3.

The profiler segments were unloaded in the field into clean polyethylene bags, labeled, and kept frozen while being transported to the DRI trace chemistry laboratory. In the lab the samples were weighed and prepared for analysis using a high resolution inductively-coupled plasma mass spectrometer (HR-ICP-MS). The DRI HR-ICP-MS is capable of detecting some elements in the PPQ range (10^{-15} g g^{-1}). The elements of interest in the seeding target area were Ag, Cs, and In, which are typically present in the PPT range (10^{-12} g g^{-1}). Although In was not used in the 2003-04 season, it is often used as a tracer in seeding experiments, so background values were of interest. In addition, Al and Rb were analyzed as examples of earth crustal elements to identify parts of the snowpack that might have been contaminated by upwind dust sources.

Once the trace chemical analysis was completed the chemistry data were combined with the mass measurements. The computed snow water equivalent (SWE) depth from each profile segment was then used to determine the density (SWE depth/segment depth) of each snow segment. Knowing the time between sampling site visits and the total integrated SWE in a profile, a temporal history of each profile can be estimated using data from collocated or nearby recording precipitation gauges. In the Walker Basin several SNOTEL sites were used for this purpose (see Fig. 1). Once correlated with a SNOTEL record, snow profile segments can then be associated with specific storm periods and seeding events. An example will be given in the results.

3. RESULTS FROM THE WALKER BASIN

3.1 Storm Periods and Snowfall

Data from three SNOTEL sites in the Walker Basin are shown in Fig. 2 for the period from 8 December 2003 to 7 March 2004. The SNOTEL locations are shown in Fig. 1. The top panel shows the dates on which snow profiles were collected on boards at the LBLK, TWIN and BODI sampling sites. The bottom panel shows similar times for the LVMC sampling site. The LBLK and BODI sites had only one profile taken due either to difficultly gaining access to the site (as with LBLK), or lack of snow (as with BODI on 1/6/04).

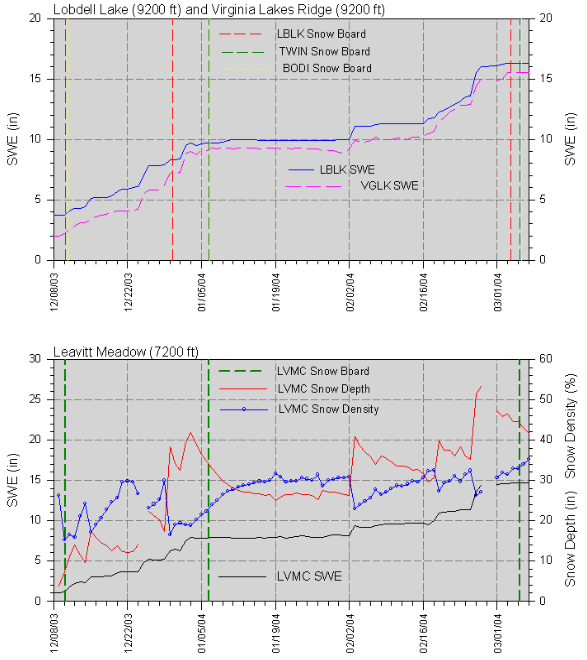

Figure 2. Time history of SWE from Lobdell Lake and Virginia Lakes SNOTEL sites (top) and SWE, snow depth and snow density at the Leavitt Meadow SNOTEL bottom. Dates of snow sampling board placement and profile collection are shown by vertical dashed lines.

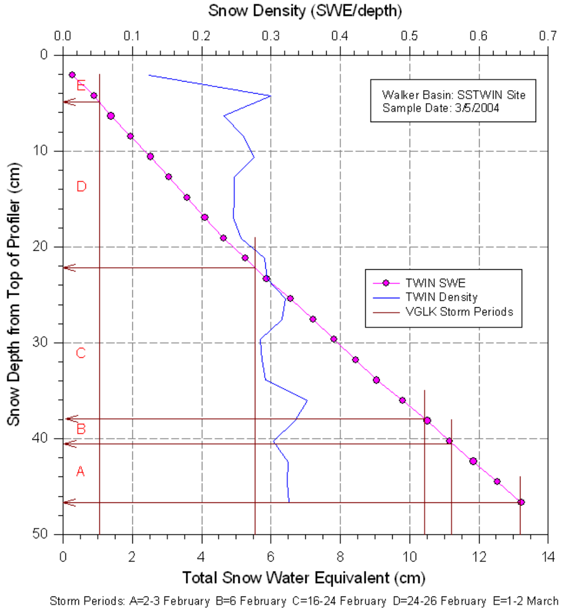

Figure 3. Plot of total SWE and snow density versus depth on the TWIN snow profile taken 5 March 2004. Vertical red lines mark storm periods defined by VGLK SNOTEL data. Horizontal red lines show the storm periods by profile snow depth.

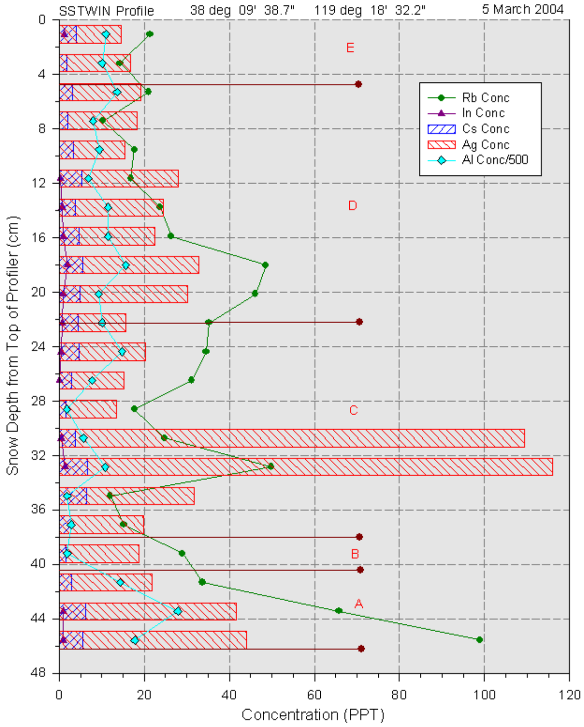

Figure 4. Concentrations of trace chemical elements versus depth in the TWIN snow profile of 5 March 2004. Storm periods A - E from Fig. 3 are shown between dark red horizontal lines.

Figure 2 provides the information on storm periods that can be correlated with the snow board profiles. The LVMC SWE and snow depth data in the bottom of Fig. 2 also give an indication of how quickly snow density changes following a storm. Density is shown in the plot as an average of the entire profile, however specific periods can be analyzed in more detail. For the 2-3 February storm SWE increased 1.2 in and snow depth increased 14.5 in, giving a density of 0.083. In two days the new snow had compressed to 8 in, giving a density of 0.15, or nearly twice the density of the fresh snowfall. Other storms, like that of 25 February, show how density can vary between storms. In this case an increase of 3 inches in SWE and 17.5 inches in snow depth gave a density of 0.17, also nearly twice the 2 February snow density. Such variability in natural snowfall make density changes related to cloud seeding quite difficult to verify.

3.2 Snow Profile Data

Data from the TWIN profile collected on 5 March are shown in Figs. 3 and 4. Figure 3 shows cumulative SWE computed from the masses of the individual 2-cm segments and the snow density variation with depth. From the VGLK SWE record in Fig. 2 the five storm periods that contributed to the TWIN snow profile can be identified. Note that nearly a month passed before snow fell on the TWIN board placed on 6 January. The VGLC SNOTEL recorded about 17 cm of SWE from 6 January through 5 March, while the TWIN profile contained about 13 cm. The proportional contribution of each storm period was determined from the VGLK record and the storm periods on the TWIN profile were estimated as in Fig. 3.

Figure 4 shows the trace chemical analysis for the TWIN profile. Each storm period except E was seeded by aircraft, ground generators, or both. The lengthy period C had four ground seeding operations totaling 57 hours, and two aircraft operations. Storm A had 24 hours of ground seeding and two aircraft operations. The profile suggests silver from the seeding was incorporated into the snowfall at TWIN a relatively high percentage of the time. All measured silver concentrations are higher than what was previously considered the background concentration in the Sierra Nevada (~4 PPT), in fact there are no values < 10 PPT.

Some peaks in Ag and Cs are associated with peaks in crustal tracer concentrations, suggesting some portion of the enhancement may be due to sources other than cloud seeding. The highest peaks in Al and Rb were at the bottom of the profile where the snow board had been exposed for a long period between storms, increasing the chance for dust contamination. Although Cs concentrations are quite low (Cs was not used in seeding here), Cs was weakly correlated with Al (R^2 = 0.21). Similar correlations of Cs with Al were found in several other profiles in both the Walker and Tahoe Basins. Silver was generally not well correlated with Al or Rb. Indium, on the other hand, was generally barely detectable in the profiles of both regions.

A summary of Walker Basin profile data is given in Table 1. Data from the beginning of the winter were only available at TWIN and LVMC. The remaining samples will markedly increase the sample size. Snow characteristics were similar, except at BODI which had higher snow density, possibly due to its lower elevation and potentially warmer temperature. TWIN and LVMC had much higher values of Al, which could account for the higher levels of the other elements compared to BODI and LBLK. The January data led to the higher overall averages at TWIN and LVMC, since the March data was much more consistent across all sites.

Table 1. Average values of snow profile samples from the Walker Basin (6 January to 5 March period).

	TWIN	LVMC	BODI	LBLK
Samples	37	44	13	19
Mass g	117.0	102.9	145.2	107.3
Density	0.28	0.23	0.34	0.21
Al/500 PPT	24.5	47.6	10.7	4.3
Ag PPT	33.8	62.4	28.7	18.9
In PPT	3.53	7.24	0.15	1.05
Cs PPT	6.07	4.69	4.1	2.6
Rb PPT	31.5	30.0	48.8	28.7

The highest site in the interior of the Walker Basin (LBLK) had the lowest average Ag concentration, and this may reflect somewhat poorer targeting from seeding operations. The Ag means fell within the range of values (13.9 - 121.0 PPT) reported by McGurty (1999) in an evaluation of a Southern California Edison seeding project in the San Joaquin watershed of the southern Sierra Nevada. Unlike the McGurty (1999) study, the analysis of this set of Walker Basin samples has shown no obvious snow density differences between seeded and unseeded samples.

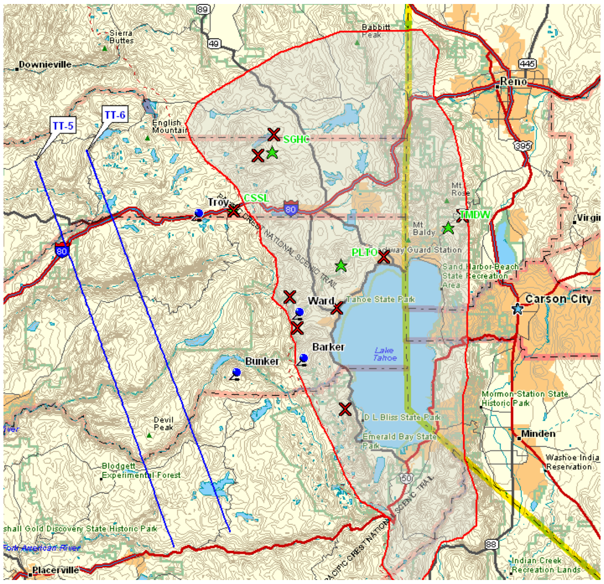

Figure 5. Map showing Tahoe area cloud seeding target area (gray shading) with ground seeding sites (blue pins), snow sampling sites (green stars), SNOTEL sites (red Xs) and aircraft seeding tracks (blue lines).

4. RESULTS FROM THE TAHOE-TRUCKEE AREA

Snow samples in the Tahoe area were collected and analyzed in the same manner as the Walker samples. The four sites used for sampling are shown in Fig. 5. Table 2 gives average values from samples collected in the Tahoe region between 17 December 2003 and 26 March 2004. About 10% of the entire trace chemistry data set are not represented in the Table 2 averages and masses and densities from two sites have not been analyzed. The crustal tracer, Al, had higher average concentrations in the Tahoe area compared to the Walker by a factor of ~2.5. This might account for the somewhat higher averages of the other elements, particularly Cs which showed a much higher correlation with Al in the Tahoe region. In several Tahoe profiles the correlation coefficient (R^2) for Al and Cs was greater than 0.5.

Table 2. Average values of snow profile samples from the Tahoe-Truckee area (12 Dec 2003-26 Mar 2004).

	TMDW	PLTO	CSSL	SGHC
Samples	94	69	39	37
Mass g	116.4	119.7	–	–
Density	0.29	0.30	–	–
Al/500 ppt	22.6	36.5	14.4	11.0
Ag ppt	89.4	36.2	12.6	16.3
In ppt	2.79	4.42	0.65	0.19
Cs ppt	2.34	3.29	5.99	2.85
Rb ppt	–	–	–	25.7

On 25 March 2004 the AgI-CsI seeding mixture was put into one Tahoe-area ground generator (Troy in Fig. 5). The site is due west and only a few miles from the CSSL snow sampling site. Samples were collected at CSSL on 26 March after a seeding event on 25 March, and on 22 April after seeding a single storm event on 21 April. Both CSSL profiles had Cs concentrations at much higher levels than any previous profile. The six samples collected 22 April had an average Ag concentration of 25.6 PPT and an average Cs concentration of 34.0 PPT (not part of Table 2 data), by far the highest Cs amounts found in any other samples. The two storms seeded with the Cs mixture from the aircraft produced no identifiable signature in the Tahoe samples.

5. SUMMARY AND CONCLUSIONS

As part of the USBR Weather Damage Modification Program the Desert Research Institute conducted a trace chemical evaluation of the Nevada operational cloud seeding program in the Tahoe-Truckee Basin and the Walker River Basin. In the area of winter snowfall augmentation quantifying the effects of seeding over large drainage basin-sized areas remains an important problem. Trace chemical evaluation techniques have shown promise in this area, but a specific, and practical, method of using the physical and chemical characteristics of snowfall for evaluation has yet to be validated.

The research project was designed to: 1) evaluate targeting effectiveness from ground and aircraft seeding by analyzing snow samples from the seeding target areas for the presence of the main element (Ag) in the cloud seeding aerosol; 2) attempt to differentiate between seeding methods through the use and detection of a second tracer element (Cs); and 3) examine the density of snowpack samples to determine if density was correlated with the concentration of the seeding aerosol.

The method of collecting snow samples was similar to the technique used and previously documented by DRI researchers in past studies. The trace chemical analysis was performed on a state of the art HR-ICP-MS capable of detection at the 10^{-15} g g^{-1} level. The improved detection limit, the capability of this HR-ICP-MS to analyze up to 10 elements in one analysis run, and the automation for running multiple samples has markedly improved this aspect of the methodology.

Regarding the targeting effectiveness portion of the study, enhanced concentrations of silver were found in a high percentage of samples from both target areas. The percentage and average silver concentration at the eight selected sampling sites were considerably higher than that found in Tahoe area sites examined in the 1980's and 1990's. This apparent increase in targeting effectiveness could be due to a number of improvements that have occurred in the Nevada cloud seeding program over the past 10-20 years. These include use of a more reliable and efficient remotely-controlled cloud seeding generator, use of a more effective and fast-functioning cloud seeding aerosol, and some repositioning of seeding generator sites based on plume dispersion studies. The targeting success in the Walker Basin is also very likely related to the increase in the number of generators over the past 10 years from two to eight.

The use of Cs as a second tracer to evaluate the targeting effectiveness of aircraft and ground-based seeding was only marginally successful. The aircraft only flew two missions with an AgI-CsI mixture in the Tahoe region, and no obvious chemical signature was noted in the Tahoe samples taken following those seeding events. The trace chemical analysis did reveal a correlation between Cs and the crustal tracer Al, suggesting that Cs may be enhanced by contaminants (dust) from other upwind sources. It should be noted that the higher Cs values found when no seeding with Cs was occurring were still relatively low, generally less than 7-8 PPT. Two ground seeding events that used a Cs tracer produced what appeared to be very high Cs signatures at the closest sampling site. These enhanced Cs values were a factor of 10 or more higher than samples analyzed before Cs was being used. Cesium or some other tracer can still be a valuable tool used to differentiate between seeding methods or between adjacent project areas.

Finally, the technique that makes use of a difference in snow density between seeded and unseeded samples was not verified in this research. The typical finding was that density increased with depth in a profile regardless of silver concentration. Obviously this is more likely to occur when the snowpack has aged, but SNOTEL observations show that the density change with snow compaction can occur quite rapidly following a snowfall. The measurement of density itself remains a serious problem. Most techniques, including the profiler used in this work, can alter the density of the snow being sampled. This is particularly true of very light fresh snow. The best determination of density is probably one done in near real time, by measuring snow water content and snow depth over very short time intervals. Future studies in this area should combine the real time measurement with subsequent profiles at the same location to determine if the relationship between physical and chemical properties of the snow is preserved in the profile.

6. REFERENCES

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