DRI
Desert Research Institute

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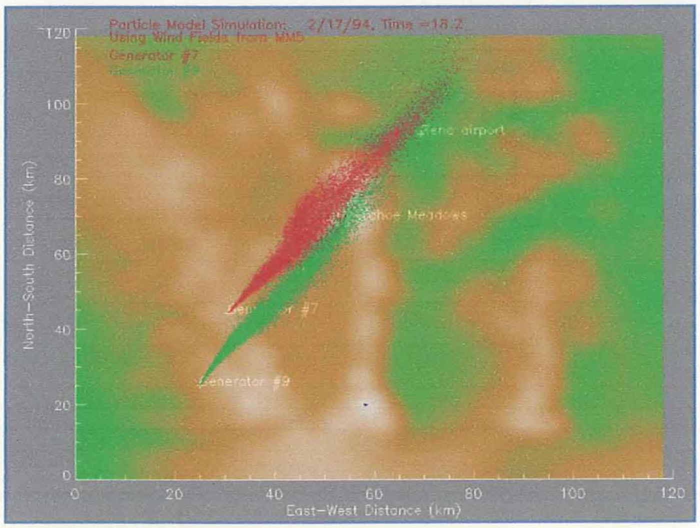
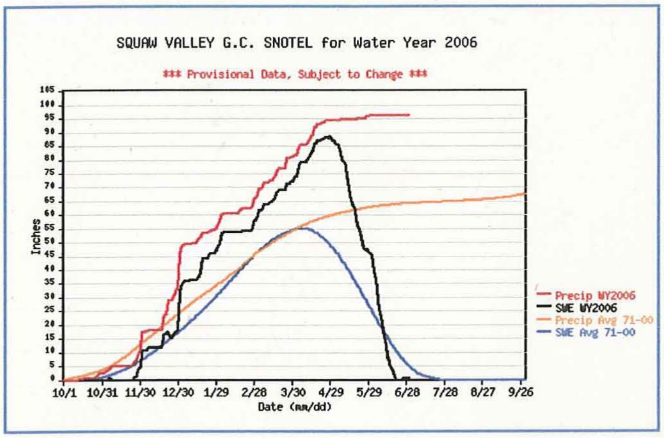
Report on the Nevada State Cloud Seeding Program

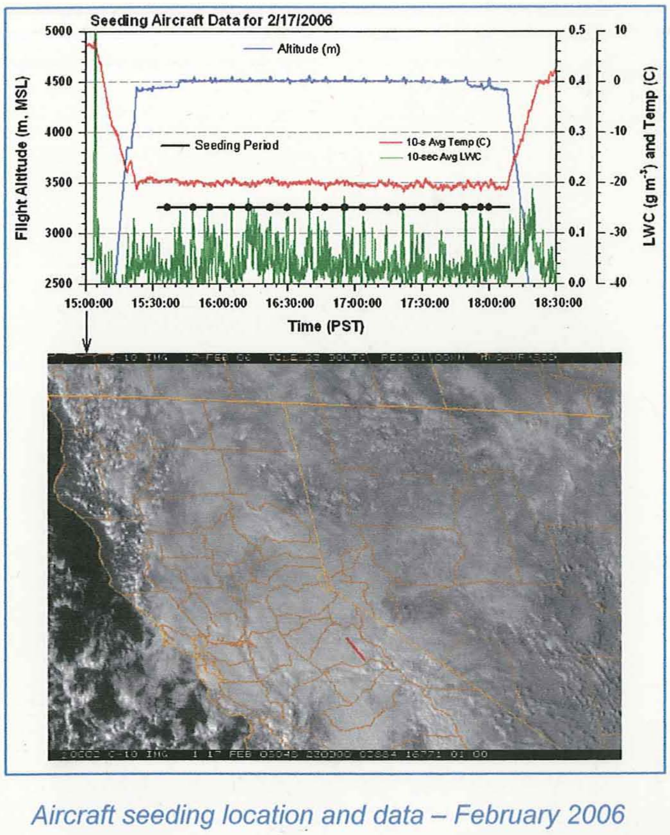


Seeding plume simulation – Tahoe Basin



Squaw Valley SNOTEL data – 2006 Water Year

Tahoe seeding site – January 2006



Aircraft seeding location and data – February 2006

ABSTRACT

The Nevada State Cloud Seeding Program completed its 22nd consecutive season of operations in five mountainous regions of Nevada and California. All regions except the Toiyabe Mountains had well above average snowpack for the second straight season. The Sierra Nevada target areas experienced a series of relatively warm and very wet storms in December that produced flooding on several streams including the Truckee River in Reno. The Walker and Carson basins, due to their higher terrain, developed snowpacks that reached 200% of average during the early winter, while the Tahoe region remained below 150%. After a midwinter lull, late winter and spring were quite wet in all the seeded basins, and all except the Toiyabe region exceeded their seeding suspension limits by 1 April. The larger than average snowpacks also led to spring and summer runoff predictions that ranged from 142% to 270%. Runoff and reservoir storage indicated that northern Nevada and California had rebounded significantly from the drought years prior to the 2005 water year. This was not the case in the Lower Colorado Basin where the drought still persists, and 2006 runoff and reservoir storage were still below average.

Cloud seeding operations were conducted from late November 2005 through early April 2006. Lengthy periods of cloud seeding suspensions were common, and due to both abnormally large snowpacks in late fall and spring, and flooding situations at the end of December and in the spring. Although storms were frequent, the suspensions resulted in a somewhat below average number of ground seeding hours. Aircraft seeding opportunities were relatively plentiful and actual seeding hours were higher in the past two seasons. Because of the lower than average number of seeding hours, snow water augmentation estimates were also somewhat lower than the average of the past 10 years. The estimated total of 54,170 acre-feet of augmented water by seeding efforts was still attained at a relatively low cost of $10.84 per acre-foot.

The states involved in the USBR Weather Damage Modification Program completed their research projects in 2006. Reports detailing the results are available through the USBR office in Denver, Colorado. A summary of results of the Nevada WDMP conducted by DRI appears as an Appendix to this report, and findings are referenced in several sections.

The 2006 water year saw a resurgence of interest in wintertime cloud seeding in the Colorado River Basin. Lower basin states, including Nevada, rely on the snowfall in the upper basin to supply the runoff to lower basin reservoirs. Several studies this past year looked again at the water augmentation potential that cloud seeding in the upper basin could provide. Relatively conservative estimates put the potential increase in flow at more than one million acre-feet annually. The seven basin states began to formulate plans aimed at increasing water supply on the Colorado River with cloud seeding being considered as one option. Several documents are provided in this report that summarize the current status of cloud seeding in the Colorado River Basin and offer recommendations on how basin states might proceed to augment seeding operations and to develop a scientific means of evaluating the results of the enhanced operations.

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Cover Photo of Tahoe Seeding Site by Tom Swafford, DRI

Summary of Activities and Results from the 2005-06 Nevada State Cloud Seeding Program

Arlen W. Huggins
Desert Research Institute
August 2006

I. Introduction and Background

The purpose of the Nevada State Cloud Seeding Program is to augment snowfall in selected mountainous regions of Nevada to increase the snowpack, the resultant spring runoff and the water supplies of municipalities, agricultural regions, recreational lakes, and environmentally threatened terminal lakes (Pyramid and Walker). The 2006 Water Year (WY2006) marked the 22nd year of continuous operation of the program for the State of Nevada by the Desert Research Institute. The Program is currently conducted in the basins of Lake Tahoe, the Truckee River, the Carson River, the Walker River, the Humboldt River, and the South Fork of the Owyhee River (Tuscarora Mountains). The Humboldt River regions include the Ruby Mountains in the Upper Humboldt and the Reese River (Toiyabe Mountains) on the Lower Humboldt. These seeding operations areas are shown in Figure 1.

Although regions that have been actively seeded by the State Program have historically been in the river basins of northern Nevada, the southern portions of the state that depend on water from the Colorado River currently have serious water supply problems that are the result of a prolonged drought over much of the Colorado River Basin. Below normal snowpacks in the mountainous regions of the Upper Colorado have resulted in drastic reductions in the levels of Lake Powell and Lake Mead. Delivery of adequate water from the Colorado River to meet the needs of Lower Basin states has become a serious problem. The complete recovery of Lakes Powell and Mead will take years to accomplish even with several normal to above normal years of snowfall in the Upper Basin. Colorado River Basin states have therefore begun to look at a variety of methods to mitigate the drought by increasing water supplies in both the Upper and Lower Basin. Programs proposed by the seven Basin States to mitigate shortages were described in a letter to then Secretary of Interior Gale Norton in February 2006. A copy of the letter is included in Appendix A.

Over the past year the DRI, through its membership in the North American Interstate Weather Modification Council (NAIWMC), has been involved in numerous discussions and the development of two white papers that pertain to snowfall augmentation as a means of increasing water supplies on the Colorado River. The executive summaries of the two white papers also appear in Appendix A. DRI and other NAIWMC members participated in a Western States Water Council Workshop on "Water Needs and Strategies for a Sustainable Future" in March 2006 in Washington, D.C., and in a workshop sponsored by the California Water Education Foundation entitled "Colorado River Basin States Weather Modification Workshop" in June 2006 in Boulder, Colorado. The results presented at the Boulder workshop has led to a cooperative program among basin states whereby active sponsorship of cloud seeding projects in the Upper Basin by Lower Basin states will begin in the winter of 2006-07.

The bulk of this 2006 report pertains to the active operations of the Nevada State Cloud Seeding Program in northern Nevada for WY2006. Snowpacks, reservoir conditions and streamflow forecasts are described, in addition to ground and aircraft seeding operations. The winter of 2005-06 provided quite a variety of weather conditions, from flooding due to warm storms in the early winter, to heavy snowfall and snowpacks that that were well above average for the second straight year. Cloud seeding operations were somewhat below average due to suspensions that were imposed due to the extremes in runoff or snowpack that were experienced at various times during the late fall, early winter and early spring. Warm storms with high freezing levels and very cold storms with high precipitation efficiencies also reduced the number of hours when seeding was potentially effective.

The benefits of the 2006 cloud seeding efforts are also summarized. The benefits are estimated based on the results of both physical and statistical experiments conducted in the Sierra Nevada and other mountainous regions of the western U. S. since the 1960's. Carefully controlled physical experiments in the 1980's showed that seeding winter storms over mountains can augment the natural precipitation rate by 0.1 to 1.0 mm per hour (Reynolds, 1988). More recent research results from projects in Utah and California (Super, 1999 and McGurty, 1999) have provided additional evidence for snowfall enhancement by cloud seeding. McGurty (1999) used physical and chemical analyses of snowfall in a California hydroelectric project basin to show evidence of an 8% seasonal increase in snowpack due to seeding. More recent research results have given credibility to earlier statistical studies which indicated seasonal precipitation increases of about 10% were possible (Reynolds, 1988). The results of a very recent randomized cloud seeding experiment conducted in Utah were published last year (Super and Heimbach, 2005), and showed a ratio in precipitation of seeded compared to nonseeded events to be 1.22 (indicative of a 22% increase due to seeding). Water augmentation estimates for WY2006 in Nevada are presented in Section IV of this report.

DRI research from as early as 1960 through 1995, funded through Bureau of Reclamation (BOR) and National Oceanic and Atmospheric Administration (NOAA) programs, added considerably to our knowledge of cloud seeding materials, the best periods of storms to seed, the methodologies for evaluating seeding programs, and quantitative estimates of snowfall augmentation. Examples of research results and additional references can be found on the Nevada State Cloud Seeding Program web page at: http://cloudseeding.dri.edu.

Between 1996 and 2001 there were no federally funded weather modification research programs, although at least $15,000,000 was being spent annually on summer and winter operational cloud seeding programs. In FY2002 a program named the Weather Damage Modification Program (WDMP) was initiated through legislative action that placed the program in the BOR, an agency with a long history of weather modification research and technology transfer. This resurgence in research funding (about $2,000,000) came about through the efforts of the state members of the NAIWMC.

Lacking funds to fully evaluate their programs the NAIWMC states sought a federally funded research program to supplement state funding which supported operations almost exclusively. In FY2003 additional money was added to the WDMP. Two summertime and three wintertime research programs were funded through the WDMP. Nevada, through DRI, conducted one of the wintertime WDMP projects, and concluded the field work in 2005. A report on the Nevada WDMP results (Huggins et al, 2006) was completed in May 2006, and a summary is given in Appendix B of this report.

The subsequent sections provide additional details about the 2006 Water Year, the water outlook for the summer and fall of 2006, the operations of the State Program during the past winter, and the estimated benefits of the Program. In addition to the WDMP summary in Appendix B, pertinent details of the WDMP research are also provided in various sections of the report where they are applicable. Changes to operations for the 2006-07 season are noted in Section VI. Appendices C and D describe project operational and suspension criteria, DRI staff member duties, the project facilities at the Stead Airport and the annual project work cycle.

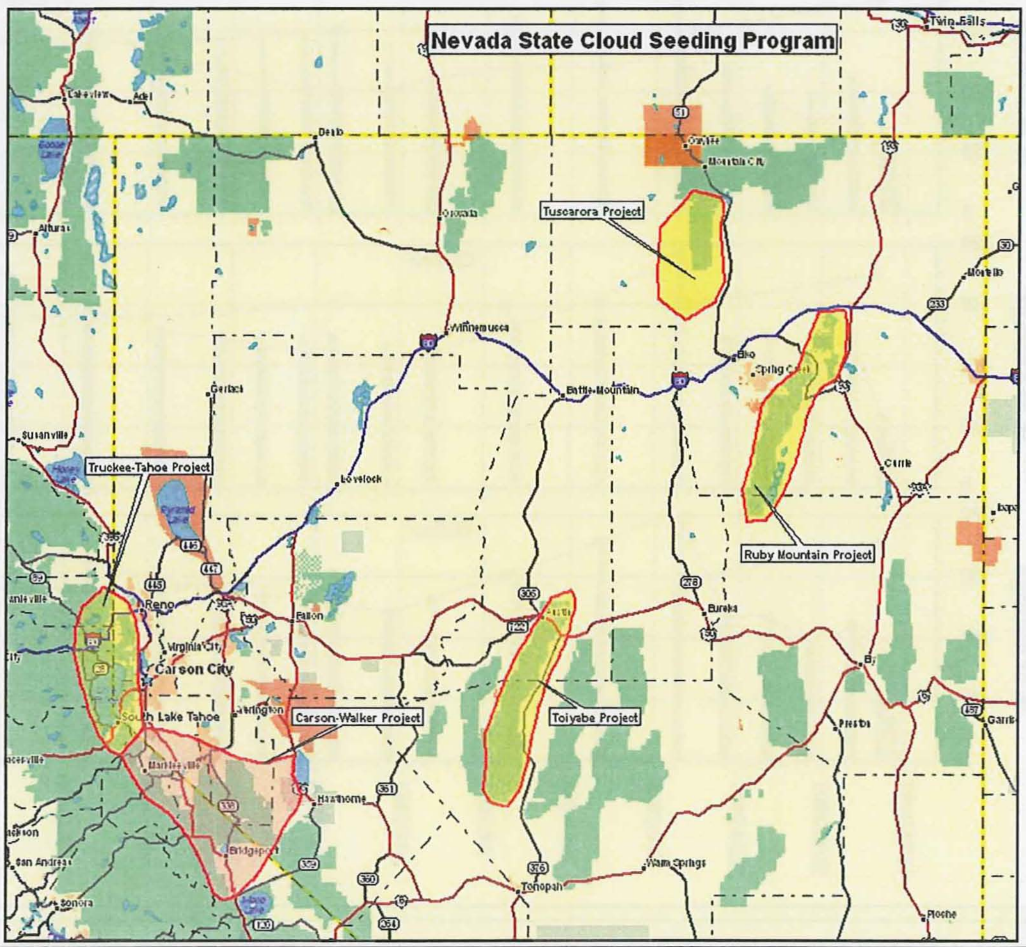

Figure 1. Map showing portions of northern Nevada and eastern California that contain the Nevada State Cloud Seeding Program target areas. Yellow shaded regions show the Truckee-Tahoe, Tuscarora, Toiyabe and Ruby Mountain target areas. Red-shaded region is the Walker-Carson target area.

II. Summary of the 2006 Water Year

A. Precipitation and Snowpack Conditions

Figures 2 and 3 show precipitation and snow water equivalent (SWE) percentages of normal for the seven basins seeded by the Nevada State Program from the end of November 2005 through April 2006. All data were taken from Natural Resource Conservation Service

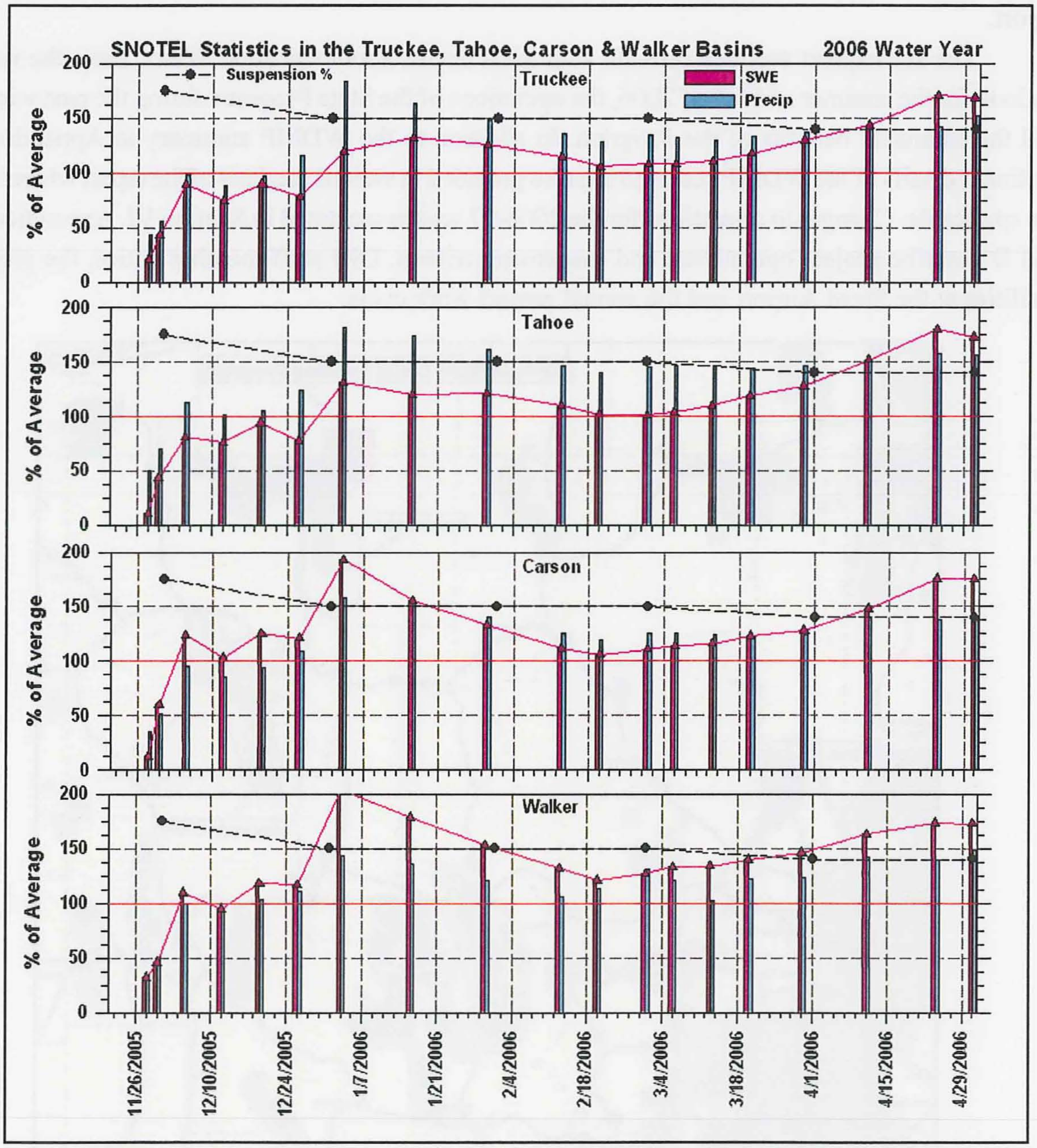

Figure 2. Graphs showing the temporal trend in percent of average snow water equivalent (SWE) and precipitation in the four Sierra Nevada basins targeted by the Nevada State Cloud Seeding Program during WY2006. Dashed lines show snowpack suspension levels for curtailment of cloud seeding operations.

(NRCS) SNOTEL reports. Figure 2 shows that storms in December and early January produced precipitation that brought the seasonal amounts in the Tahoe-Truckee region to about 180% of average by the beginning of 2006. These storms had relatively high snow levels and therefore the SWE percentage did not rise nearly as steeply. The large jump in precipitation percentage at the end of December occurred with a series of storms that produced flooding on the Truckee River in Reno. Over the same period, the bottom two panels of Fig. 2 show that more of the precipitation fell as snow in the Walker and Carson target areas where the mountains are significantly higher. Note that the SWE trend experienced the greater increase in these basins. This resulted in seeding suspension due to excess snowpack in the Walker-Carson; while the cutoff limit was never reached for Tahoe-Truckee (seeding was suspended in the Tahoe region when there was flooding potential).

SWE percentages in the Sierra Nevada remained steady or declined between early January and mid-February, with the Walker-Carson area showing a very steady decline that allowed the resumption of cloud seeding by mid- to late January. From the beginning of March through the end of April SWE percentages steadily increased, resulting in the suspension of seeding beginning about 1 April and continuing through the end of the active winter season.

The pattern of precipitation and snowfall depicted in Figure 3 for the central and northeastern Nevada basins was somewhat different from the Sierra Nevada, particularly in the Owyhee and Lower Humboldt regions. The trends through early January were similar, but the percentages never approached suspension limits as in the Sierra Nevada. In January and February, while SWE percentages declined in the Sierra Nevada, they increased steadily in the Owyhee area. The SWE trend in the Lower and Upper Humboldt resembled that of the Tahoe area, but the Lower Humboldt SWE percentages stayed below 100% until about the first week of March when all basin percentages were moving upward. The Toiyabe Mountains (bottom panel of Fig. 3) were an anomaly for most of the winter. They were not affected by the large early season storms in the Sierra Nevada, nor were they influenced by the pattern that increased the Owyhee snowfall in February. Only the late season storms produced an upward trend in SWE that matched the pattern of the other basins.

The basin to basin differences shown in Figs. 2 and 3 are not particularly unusual. Winter precipitation patterns over Nevada have often shown above normal trends in one area and below normal in another. When the general circulation pattern has mainly westerly air flow (termed zonal flow) coming into California, storms coming directly from the mid-Pacific region tend to produce heavy snowfall in the Sierra Nevada, and less in northern and central Nevada. When a slight (pressure) ridge exists over California, storms tend to move into Washington and Oregon, and then drop southeast across the northern corner of Nevada. This pattern can produce significant precipitation in the Owyhee and Humboldt Basins, and relatively little in the Sierra Nevada. Weather systems that move south along the California coast, then west across southern California frequently bring moisture into the southern Sierra Nevada and the ranges of central Nevada (like the Toiyabes). The early season deficit in SWE over central Nevada can be

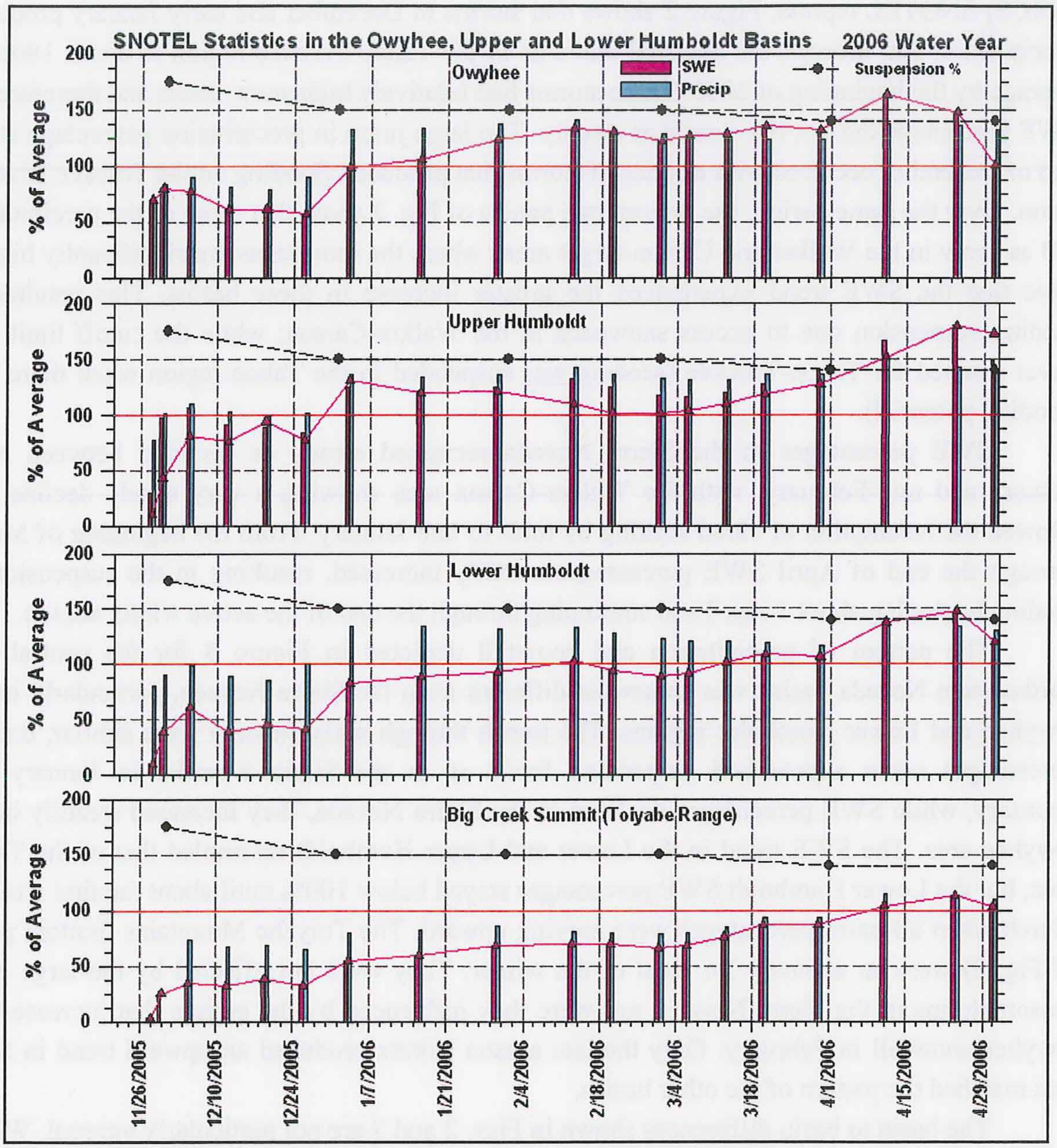

Figure 3. As in Fig. 2, except showing SWE and precipitation percentages for central and northeastern Nevada basins. Bottom panel shows data from a single SNOTEL site in the Toiyabe Mountains.

attributed to weather patterns that favored either the Sierra Nevada region or extreme northern Nevada, while the late winter patterns eventually brought precipitation into central Nevada.

Figures 4 – 8 provide examples of the accumulation of SWE and precipitation at specific SNOTEL sites in each of the five regions seeded by the Nevada Cloud Seeding Program for WY2006. Figure 4 shows data from Squaw Valley at 8200 feet in the Tahoe Basin (location shown in Fig. 9). The period from the end of October to about 1 January produced nearly 50 inches of precipitation. Much of this fell as rain as evidenced by the precipitation trace exceeding

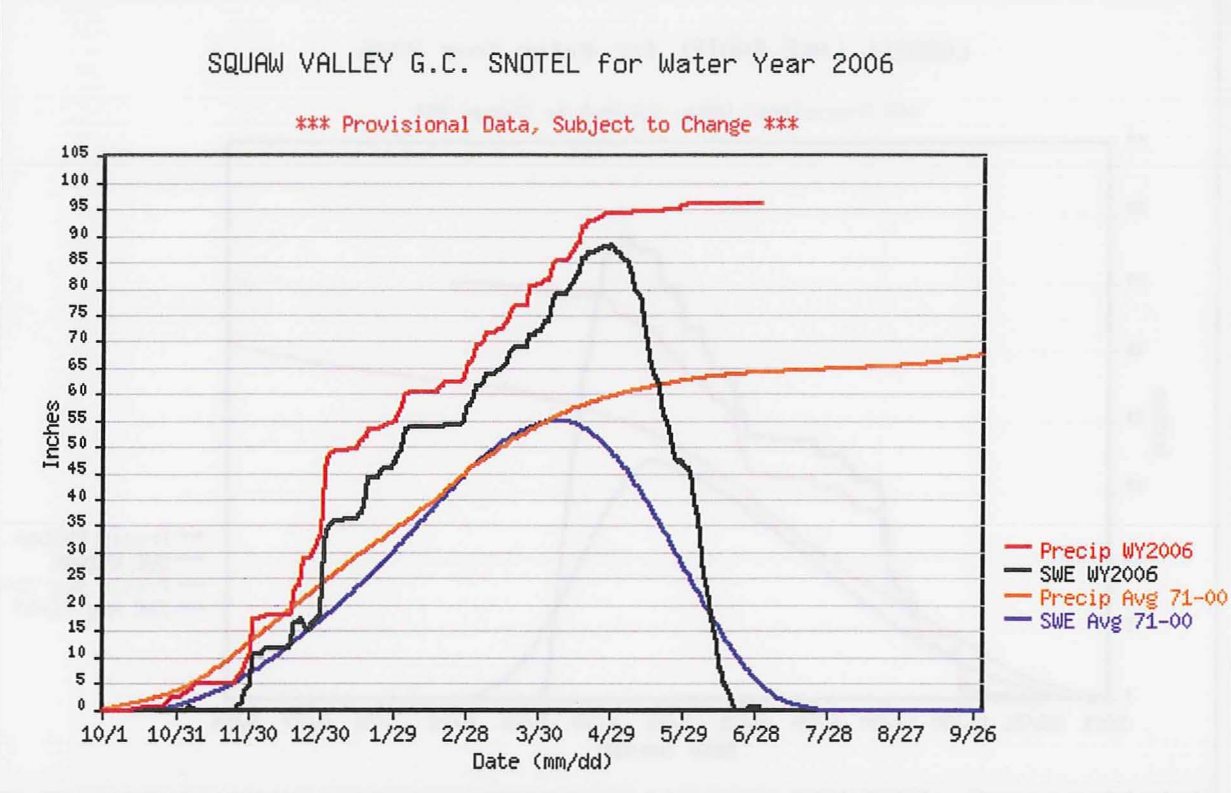

Figure 4. SNOTEL data from Squaw Valley in the Tahoe Basin. SWE and precipitation trends are shown together with averages based on data from 1971 to 2000. Graph was obtained from the NRCS web site (http://www.wcc.nrcs.usda.gov/snow/).

the SWE trace by about 20 inches at the beginning of January. Most of this difference came about during storms at the end of December that resulted in flooding on the Truckee River. Because of the warm nature of these early storms only two cloud seeding events took place in the Tahoe region prior to January 2006. Although there were a few relatively dry periods, SWE and precipitation remained well above average throughout the winter season. SWE continued to accumulate for nearly a month after the average peak in SWE near 1 April. The SWE peak of about 88 inches was 33 inches (160%) above the average maximum of 55 inches at Squaw Valley. The most active month of cloud seeding in the Tahoe Basin was January when SWE remained below suspension levels.

Figure 5 shows data from a high elevation SNOTEL site in the Walker Basin. At Lobdell Lake at 9200 ft on the downwind side of the main Sierra Nevada crest (location shown in Fig. 10) SWE equaled or exceeded precipitation accumulation, except for one period in November. Note that SWE will often be greater than precipitation due to capping of the precipitation gauge, or to under-catch due to wind conditions. This was in contrast to Squaw Valley in the Tahoe Basin, which is 1000 feet lower than Lobdell. The fact that precipitation fell as snow, even during the warm storms on late January, resulted in SWE at Lobdell and other Walker SNOTEL sites exceeding the Nevada Cloud Seeding Program suspension criterion of about 160% in late

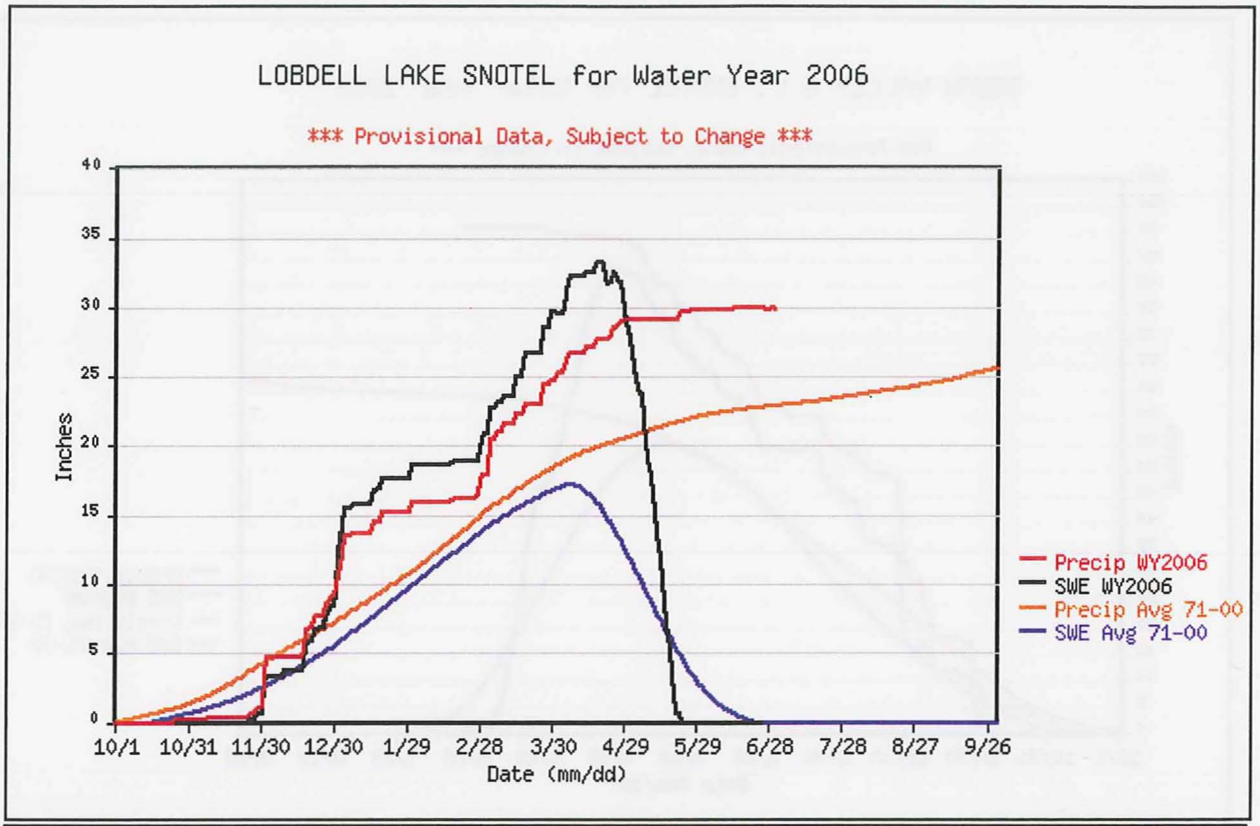

Figure 5. SNOTEL data from Lobdell Lake in the Walker Basin. SWE and precipitation trends are shown together with averages based on data from 1971 to 2000. Graph was obtained from the NRCS web site (http://www.wcc.nrcs.usda.gov/snow/).

December. After a relatively dry period in January and February, during which SWE fell below the suspension level, SWE again increased steadily through the end of April, ending at about 33 inches (about 194% of the average maximum at Lobdell Lake). The snow melt at Lobdell was also delayed about two weeks compared to the average near 1 April. March was the most active month of cloud seeding in the Walker and Carson Basins, but seeding was curtailed completely near the 1st of April when SWE levels again exceeded suspension criteria.

In the northernmost target area, the Owyhee Basin, the Jack Creek Upper SNOTEL (Fig. 6) showed a somewhat different SWE and precipitation pattern than that seen in the Sierra Nevada. The very large Sierra Nevada storm in late December did not produce nearly as much precipitation in northeast Nevada, although precipitation did exceed SWE at Jack Creek, indicating it was also a warm event. January was the most productive month for SWE accumulation at Jack Creek. The SWE trace after February 1st tended to follow the average slope, with the maximum SWE of about 27.5 inches occurring near the time of the average peak in mid-April. The SWE maximum was about 131% of the average maximum. Snowmelt at this relatively low elevation site (7254 feet) occurred rapidly after 1 May. Although SWE was above average after about 1 February, the suspension level was not exceeded until 1 April, so cloud seeding activity until then was only limited by specific storm conditions (temperature, winds,

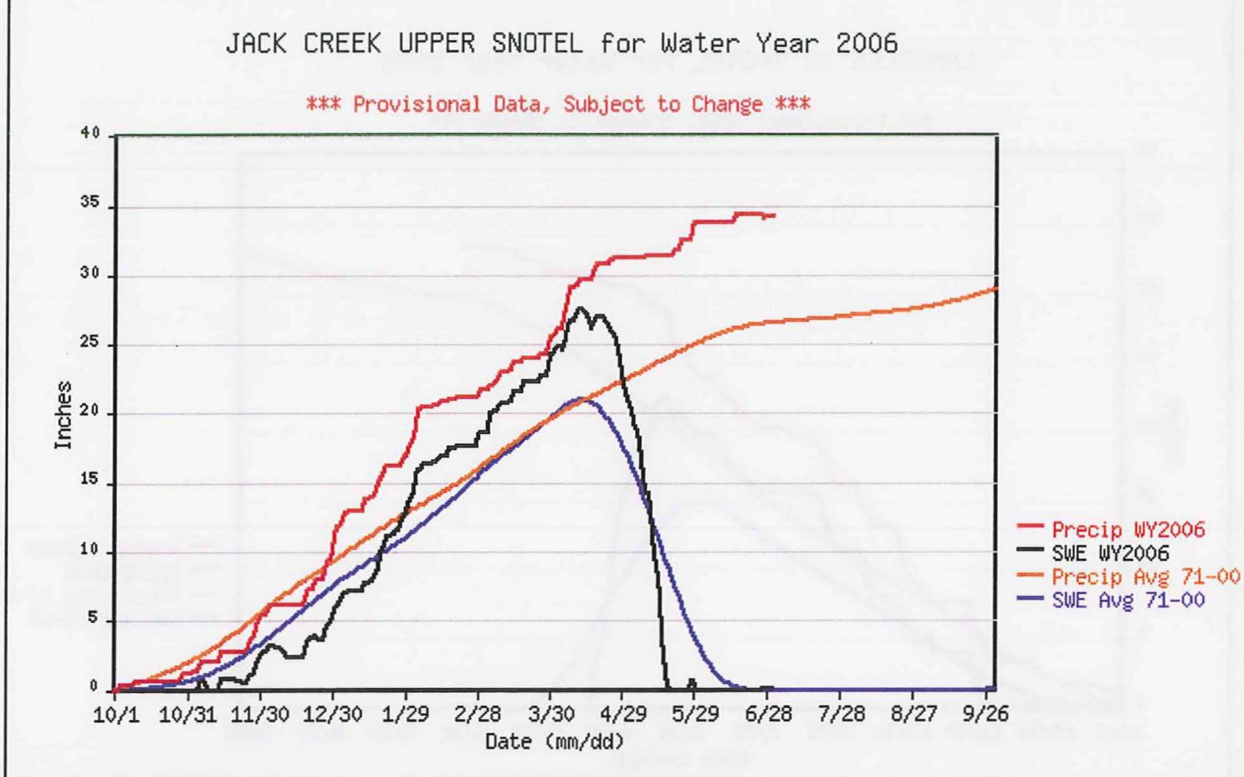

Figure 6. SNOTEL data from Jack Creek Upper in the Owyhee Basin. SWE and precipitation trends are shown together with averages based on data from 1971 to 2000. Graph was obtained from the NRCS web site (http://www.wcc.nrcs.usda.gov/snow/).

etc.). Seeding was curtailed for the season on 1 April.

The SWE pattern at the Lamoille #3 SNOTEL (7700 ft) in the Ruby Mountains (Fig. 7) was similar to that of Jack Creek Upper. Due to early warm storms the precipitation accumulation exceeded SWE throughout the season. The SWE accumulation crossed the average curve about a month earlier than at Jack Creek, primarily due to a large storm in late November that did not melt away as it did at Jack Creek. The Lamoille site had above average SWE until mid-April and reached its SWE maximum of about 22.5 inches (7.5 inches above average) somewhat later than normal (early April compared to late March). Lamoille lost its snowpack in early May, about a week sooner than Jack Creek. As in the Owyhee, the Ruby Mountain SWE exceeded Program suspension criteria on about the 1st of April, so cloud seeding was suspended in the Upper Humboldt at that point.

Finally, the SNOTEL data from Big Creek Summit in the Toiyabe Mountains of central Nevada is shown in Fig. 8. The SWE pattern at Big Creek was markedly different from other sites through February. After the 1st of March Big Creek accumulated SWE at a rate similar to northern Nevada sites; however the large increase in SWE near 1 April was not reflected in the Lamoille SWE trace. After staying at below normal SWE for nearly the entire winter season, SWE at Big Creek finally reached 100% during the first week of April. Frequently this is not the

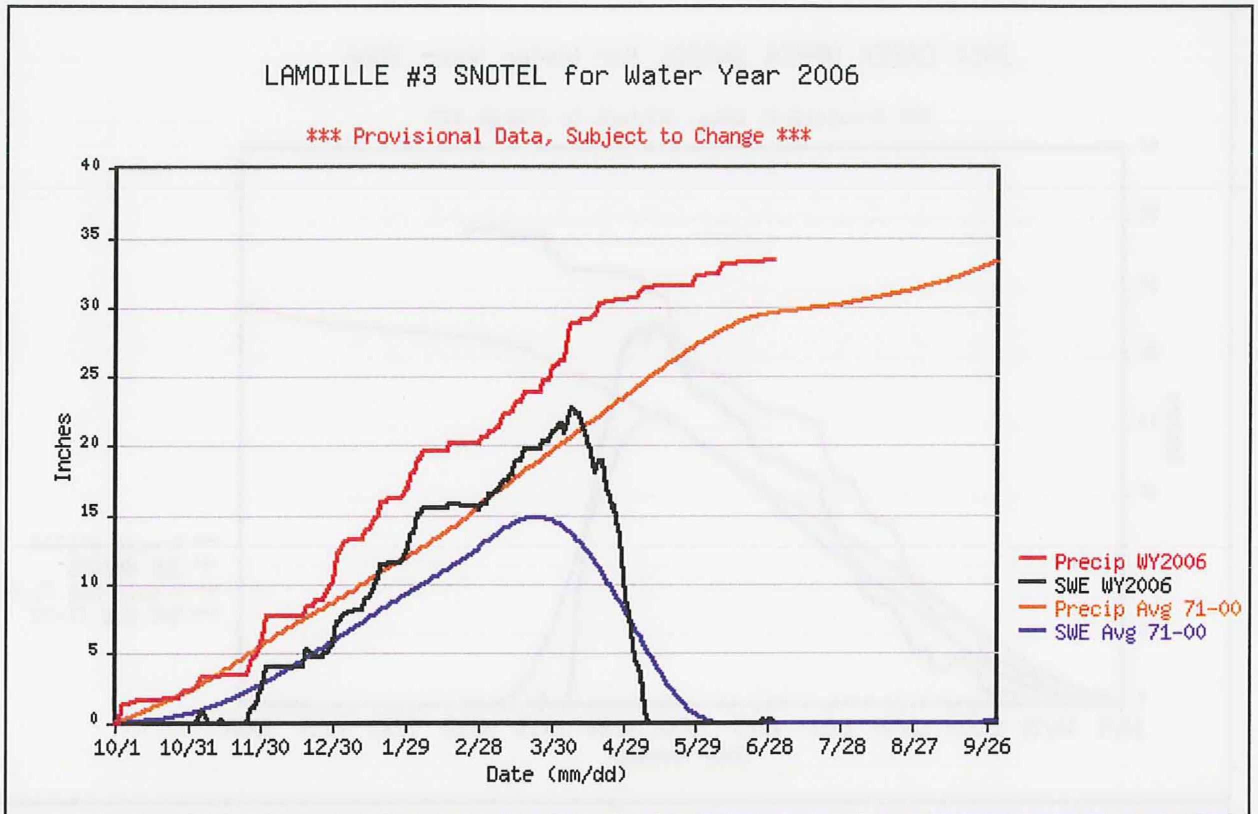

Figure 7. SNOTEL data from Lamoille #3 in the Upper Humboldt Basin. SWE and precipitation trends are shown together with averages based on data from 1971 to 2000. Graph was obtained from the NRCS web site (http://www.wcc.nrcs.usda.gov/snow/).

case. Big Creek exceeded its average maximum SWE of 20 inches by about 2 inches. Snowmelt began about two weeks later than normal, but was complete by about the third week in May, which was somewhat sooner than normal.

B. Water Storage and Streamflow Forecasts

The NRCS Nevada Basin Outlook Report for 1 May 2006 indicated that reservoir storage in northern Nevada and eastern California was well above storage levels of one year ago, and also well above average. Reservoirs on the Truckee River were at 139% of average, compared to 86% in 2005 and 93% in 2004. Lake Tahoe storage finally rebounded from the effects of several dry seasons, and stood at 138% of average, significantly up from 24% and 30% of average on 1 May of the prior two years. The lake level was at 6227.52 ft on 30 April, well up from 6223.81 ft last year and a level of 6224.01 ft in 2004. Tahoe was holding 550,500 acre-feet of storage water on 30 April, compared to about 98,300 acre-feet at the same time in 2004 and 122,600 in 2003. The average storage on 1 May is 403,000 acre-ft. The predicted rise in the lake from 1 May to the summer maximum was 1.53 feet. As of 1 August 2006 Lake level was 6228.84, or 1.32 ft above the 30 April level and just 0.26 ft below capacity. This indicates that the past winter with its early heavy rainfall and runoff and well above average snowpack has erased the storage shortage of prior years.

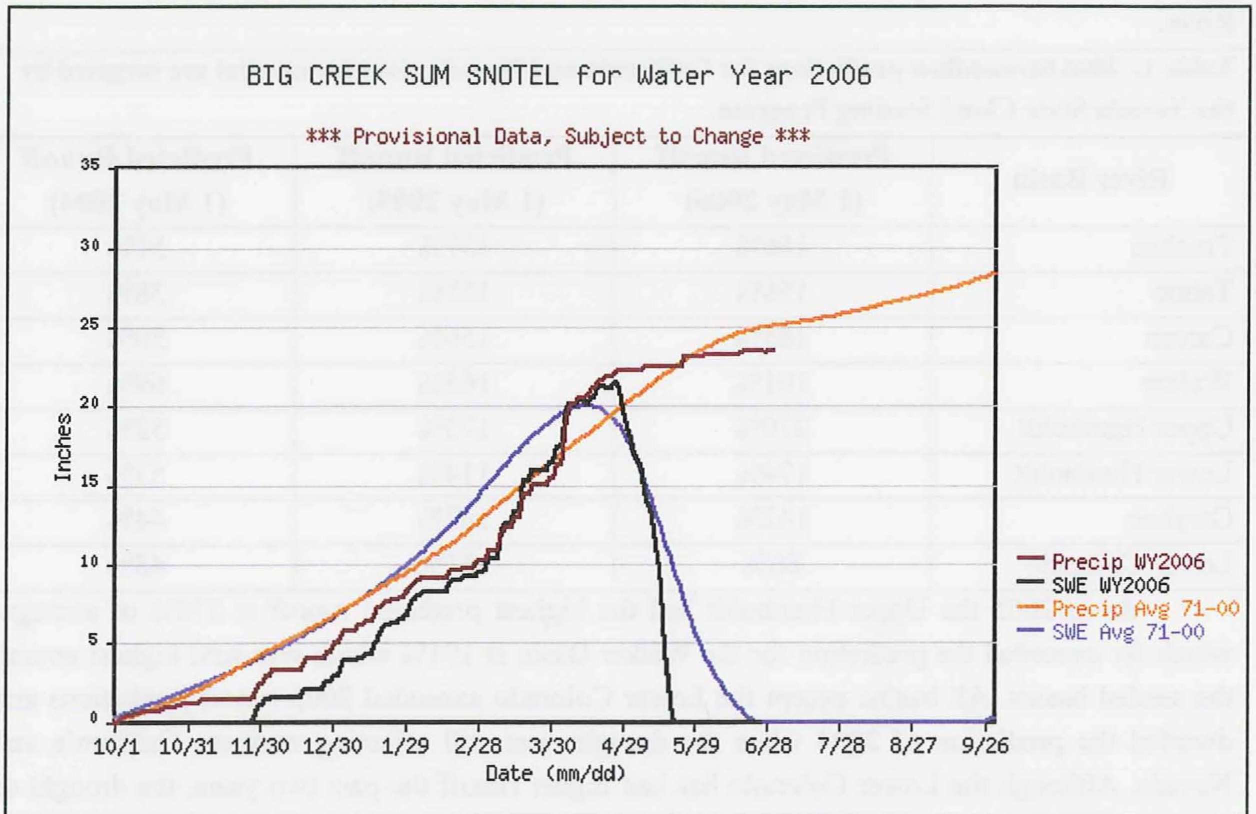

Figure 8. SNOTEL data from Big Creek Summit in the Lower Humboldt Basin. SWE and precipitation trends are shown together with averages based on data from 1971 to 2000. Graph was obtained from the NRCS web site (http://www.wcc.nrcs.usda.gov/snow/).

Reservoir storage in the Carson Basin rose to 105% compared to 68% last year. Storage on the Walker River was at 117% of average, up from the 74% noted in 2005 and 59% in 2004. With the well above average runoff predicted for the Walker Basin, the elevation change for Walker Lake to its high point this summer should exceed three feet.

As in 2005 the Lower Humboldt Basin showed a considerable gain in reservoir storage with Rye Patch Reservoir going over capacity and holding 172% of average on 1 May, compared to 55% last year. In central Nevada the May to July streamflow forecast of 13,000 acre-ft for the Reese River at Ione, Nevada is about 206% of the long-term average of 6,300 acre-ft. In the Owyhee Basin in northeastern Nevada the storage in Wild Horse Reservoir was 140% of the 1 May average, compared to 56% last year.

NRCS streamflow predictions for all river basins currently part of the Nevada State Cloud Seeding Program are shown in Table 1, for the period from 1 May through the end of the runoff season. Also shown is the prediction for the Lower Colorado Basin. The larger than normal snowpacks in all basins (except the Lower Colorado), the late season storms (producing up to 283% of average precipitation in April) and the cool weather that delayed the snowmelt, have led to well above average runoff predictions for the spring and summer. The large runoff produced spring flooding on nearly all the streams in northeast Nevada including the Humboldt River.

Table 1. 2006 Streamflow predictions for California and Nevada river basins that are targeted by the Nevada State Cloud Seeding Program.

River Basin	Predicted Runoff (1 May 2006)	Predicted Runoff (1 May 2005)	Predicted Runoff (1 May 2004)
Truckee	156%	137%	51%
Tahoe	156%	155%	38%
Carson	185%	156%	50%
Walker	191%	165%	69%
Upper Humboldt	270%	173%	52%
Lower Humboldt	174%	114%	53%
Owyhee	142%	107%	44%
Lower Colorado	86%	111%	48%

As in 2005 the Upper Humboldt had the highest predicted runoff at 270% of average, which far exceeded the prediction for the Walker Basin at 191% which was next highest among the seeded basins. All basins except the Lower Colorado exceeded 2005 runoff predictions and dwarfed the prediction of 2004 when the drought was still affecting northern California and Nevada. Although the Lower Colorado has had higher runoff the past two years, the drought of the past several years is ongoing in the portions of the Southwest and water storage on the Lower Colorado has yet to recover significantly. Reservoir storage on the Lower Colorado was 71% of average on 1 May, somewhat lower that 2005 when storage was 77% of average.

III. Summary of Nevada State Cloud Seeding Operations in WY2006

The WY2006 cloud seeding season began with twenty remotely controlled ground generators operating in the five main project areas of the State Program (Fig. 1). One older generator was refurbished, and one new generator was fabricated. The installation of a new generator at the Kirkwood Ski Area, to target the southern portion of the Tahoe Basin and the Carson Basin, was accomplished in September 2005. Seeding in the Tahoe-Truckee region was conducted with four ground generators (Fig. 9) and in the Walker Basin with eight ground-based generators (Fig. 10). One of the two Walker Basin generators near the Sweetwater Mountains was seriously vandalized early in the season and was not operated after November 2005. This site is being abandoned and a reconstructed generator will be relocated to a more secure site. A seeding aircraft (Cessna 340) was used from late December 2005 through early April 2006 to augment the seeding in the Tahoe, Truckee, Walker and Carson Basins. As in 2004 and 2005, aircraft operations were conducted through a subcontract with Weather Modification, Inc. (WMI), a company in Fargo, ND that specializes in airborne cloud seeding operations.

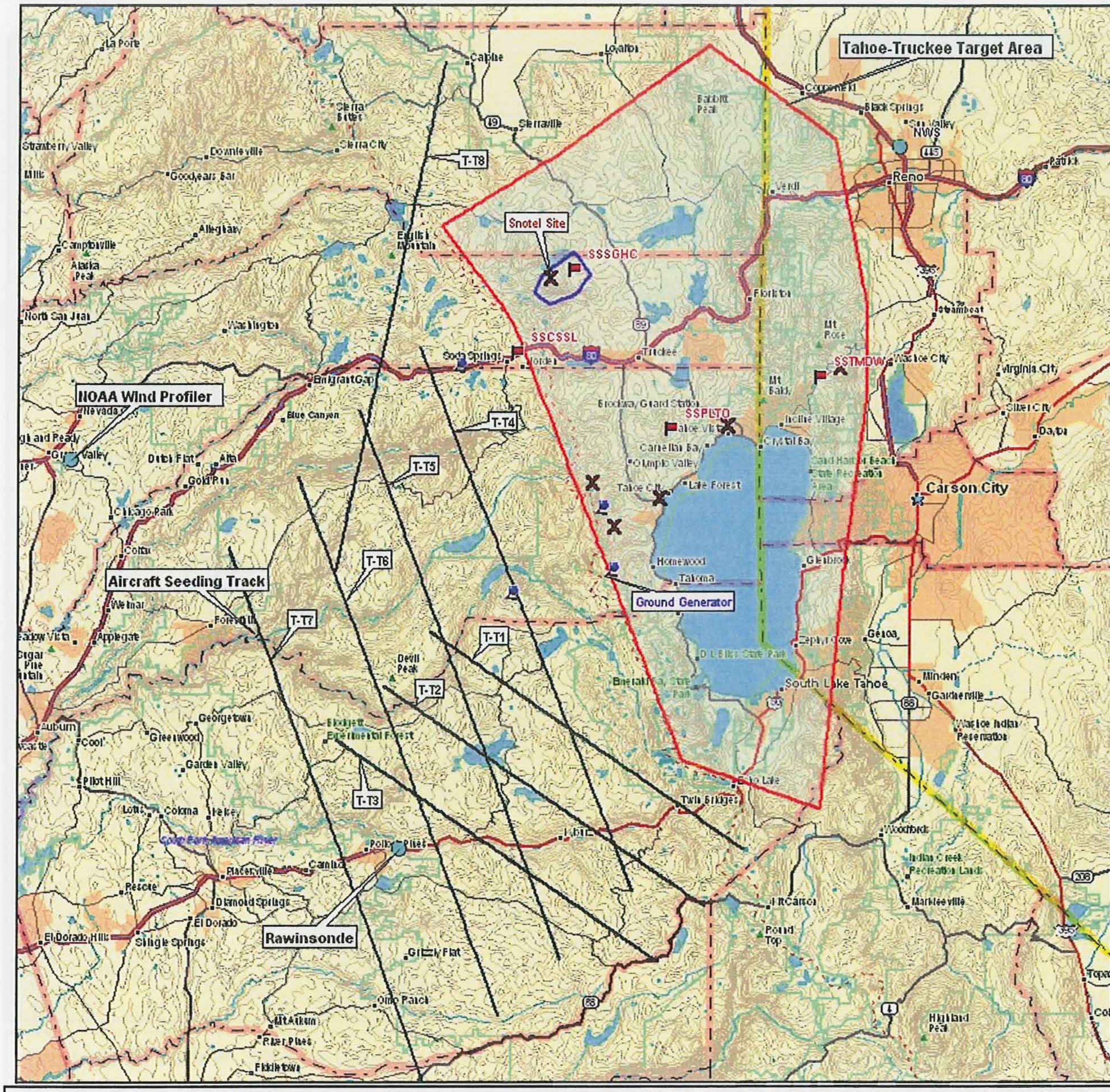

Figure 9. Gray shaded area represents the Tahoe-Truckee cloud seeding target area. Ground seeding generator sites, seeding aircraft flight tracks, and SNOTEL sites are as indicated by map labels. Red flags show snow-sampling sites used in 2005. Cyan-colored circles indicate vertical wind profiler and upper air sounding sites.

In central and northeast Nevada, one ground generator was operated in the Toiyabe Mountains (Fig. 12), two were operated in the Owyhee or Tuscarora area (Fig. 11) and four were operated upwind of the Ruby Mountains (Fig. 11).

The periods when seeding operations were suspended due to flooding hazards and above average snowpacks were much longer than any since the flooding episode of 1997. In the Walker and Carson Basins seeding suspensions due to project snowpack criteria (see Fig. 2) lasted a little

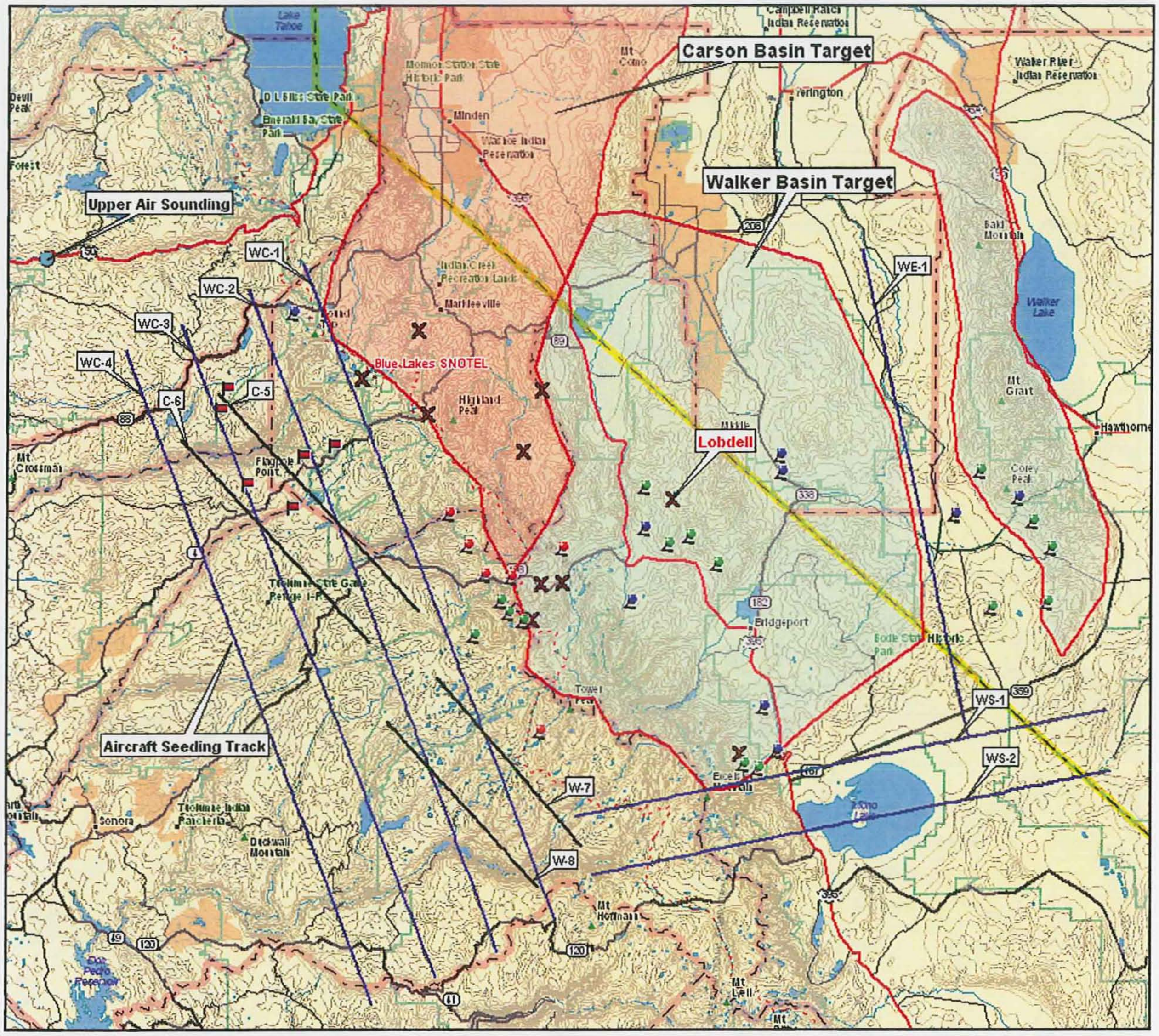

Figure 10. Map showing a portion of the Carson Basin (red shading) and the Walker Basin (gray shading) cloud seeding target areas. WY2006 ground-based cloud seeding generators are shown by blue pins. Seeding generators operated by the Pacific Gas and Electric Company are shown as red flags. Red and green pins represent potential new seeding sites for the Walker and Carson. SNOTEL sites are red X's. The Lobdell Lake SNOTEL site is labeled (data in Fig. 5). Cyan circle is an upper air sounding site.

over a month in December 2005 and January 2006. At the end of the season another month of potential seeding was lost as snowpack levels again exceeded suspension criteria. Figure 2 indicates the Tahoe-Truckee area never exceed snowpack limits in December and January, but warm storms and flooding potential prompted seeding curtailment for about two weeks in late December and early January. All the basins exceeded the snowpack limit in April 2006, and spring flooding would also have curtailed operations in May, had suitable storms been encountered. In addition to suspensions, seeding was significantly limited in December due to seeding criteria not being met. Only two ground seeding operations were conducted in the Walker-Carson and Tahoe-Truckee areas in December even though large and very lengthy storms occurred in that month. Ground seeding was limited mainly because cloud temperatures were too warm for seeding with silver iodide.

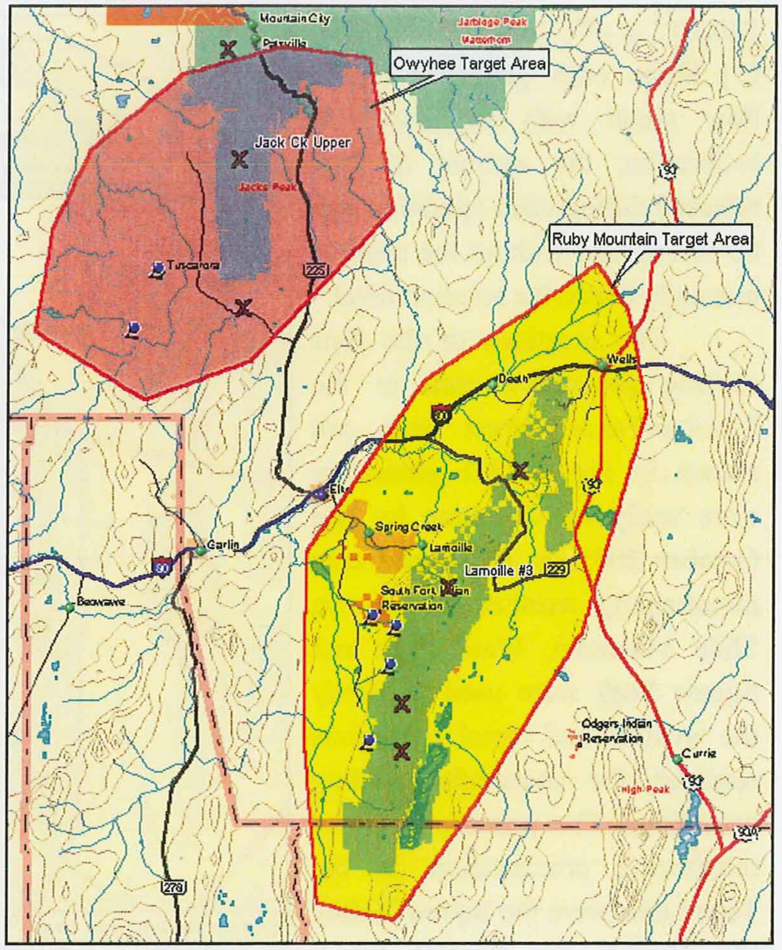

Figure 11. Map showing a portion of northeast Nevada with the Owyhee Basin (Tuscarora) and Upper Humboldt Basin (Ruby Mountain) cloud seeding target areas. Blue pins show ground seeding sites and red X's show SNOTEL sites.

A. Ground-based Generator Seeding Operations

For the 2006 water year both aircraft and ground-based solution-burning generators used a mixture of silver iodide (AgI), a small amount of sodium iodide (NaI) and para-dichlorobenzene ($C_6H_4Cl_2$) dissolved in acetone. This solution, when sprayed as a mist into a propane flame and burned, produces a smoke of very small ice nucleating particles ($\leq$ 0.1 micrometer in size) that can produce ice crystals by a condensation-freezing mechanism (a small water drop forms, then freezes) when particles are released in conditions saturated with respect to water at temperatures $\leq$-5° C. Ground generators are positioned at relatively high altitude to maximize the chances of AgI particles encountering these conditions. In a saturated environment these nuclei also create ice crystals very rapidly. This is a very favorable characteristic in nearly all of the regions seeded in the State Program, where the distances from the generators to targets are relatively short, and therefore a limited amount of time is available for ice crystals to grow and fall out over the intended targets.

The ground generators' seeding solution tanks are pressurized with nitrogen and calibrated with an inline flow meter to produce a solution flow rate of about 0.4 gallons per hour. Using a 2% by weight concentration of AgI, this flow rate corresponds to a silver iodide release rate of 24.7 grams per hour. [Calibration tests on the Nevada seeding solution in a cloud chamber at Colorado State University showed that the yield in ice nuclei per gram of AgI ranged from

1.0×10^{12} at -6°C to 5.0×10^{14} at -12° C.] Since each generator has a flow meter with an individual calibration, the amount of AgI released during each operation can be determined without the need to manually check the solution level.

The locations of the four seeding generators used in the Truckee-Tahoe target area are shown in Fig. 9. All generators were ready for operation by late October 2005. In the Tahoe area mountaintop weather stations on Slide Mountain, Ward Peak and Squaw Peak were used to verify the weather and cloud conditions required for successful seeding operations. The primary sites for monitoring precipitation in the Tahoe area were the Squaw Valley Ski Resort, the Central Sierra Snow Lab and the Sagehen Creek Experiment Lab (outlined in blue in Fig. 9). Table 2 summarizes ground seeding operations conducted in the six separate areas of the Nevada State Program for WY2006. In the Walker-Carson region the Wassuk Mountains have been treated as a separate target area. In the Tahoe-Truckee region there were 26 seeding operations, three more than conducted in WY2005. Both of the past two seasons have had fewer operations than is typical of a season when seeding suspensions are rare. Seeding hours (886) were slightly greater than during WY2005, but the amount of AgI released (19,617 g) was roughly the same. The average duration of each seeding operation was 12.2 hours, also nearly the same as last season.

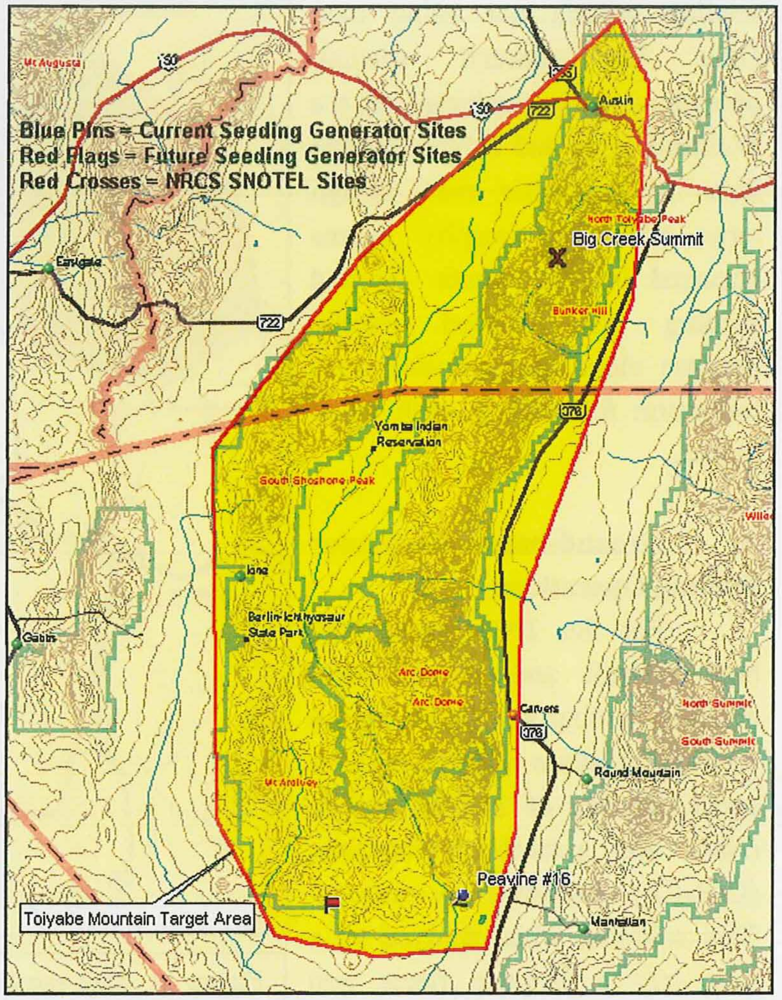

Figure 12. Map showing a portion of central Nevada and the Lower Humboldt Basin (Toiyabe Mountain) cloud seeding target area. Blue pin shows the current ground seeding site and the red flag indicates a second potential site. Red X is the Big Creek Summit SNOTEL site (Fig. 8).

The generator efficiency noted in Table 2 is the ratio of actual hours of operation compared to the total number of hours that generators could have been operated between the requested start and end times. In the Tahoe Basin the generator efficiency of 70% was about the same as last year. The Tahoe area continues to be the most problematic to maintain due to the difficulty of gaining access to the remotely sited generators after heavy snowfall and when breaks between weather systems are short. The two generators that are hardest to access have been outfitted with dual operating systems, but at times both systems have failed. Such was the case for one generator in WY2006. One side of the dual system failed completely in February, and the second system had intermittent problems, one that caused 10 missed operations during a very stormy sequence in March. This one generator accounted for more than half of the missed hours in the Tahoe network.

Table 2. Summary of ground-based seeding operations in the Nevada State Cloud Seeding Program during WY2006.

Location	No. of Events	Date of First Event	Date of Last Event	Total Seeding Hours	Total Possible Hours	Generator Efficiency (%)	Total AgI Released (grams)	Avg. AgI Release Rate (grams/hr)
Tahoe-Truckee	26	25-Nov-05	1-Apr-06	885.9	1270.3	70	19,617	22.14
Walker-Carson	23	28-Nov-05	20-Mar-06	853.2	977.2	87	23,470	27.51
Wassuk Mtns.	5	15-Feb-06	20-Mar-06	100.9	110.6	91	2,522	25.00
Owyhee	15	28-Nov-05	1-Apr-06	252.7	309.4	82	6,874	27.20
Ruby Mtns.	20	26-Nov-05	1-Apr-06	786.6	902.5	87	19,121	24.31
Toiyabe Mtns.	14	18-Dec-05	5-Apr-06	162.2	162.2	100	3,934	24.26
Totals/Avgs.	103	25-Nov-05	5-Apr-06	3041.5	3732.2	81	75,538	24.84
Avg. Ops Period = 10.59 hrs								

Walker and Carson area generator locations are shown in Fig. 10. Even with the lengthy seeding suspensions in the Walker and Carson areas, the 23 seeding periods were five more than in WY2005. The 853 seeding hours represented a 33% increase compared to the previous year. The difference was not only due to the increase in events, but also the increase in generator efficiency, from 69% to 87%, and the addition of the Kirkwood generator in the Carson Basin which, due to its upwind location, tended to encounter seedable weather conditions more frequently than the bulk of the Walker Basin generators that are downwind of the main Sierra Nevada crest. The lack of suitable weather conditions for seeding led to a sharp decrease in the number of seeding events in the Wassuk Mountains in WY2006, only five compared to 12 in WY2005. This resulted in a drop in seeding hours from 229 to 101.

In northeast Nevada the Ruby Mountains were seeded 20 times compared to 22 in WY2005. The Ruby Mountain target and generator sites are shown in Fig. 11. Several more events would likely have been added in April 2006 if seeding had not been suspended when the snowpack exceeded the project criteria. Seeding hours also dropped from 922 in WY2005 to 787 this year. Since generator efficiency and the length of seeding events was about the same both years, the decline in hours was almost entirely due to the fewer number of events this past season. The Owyhee region (see Fig. 11) had an even larger drop in seeding events and hours, with 15 events this year compared to 24 in WY2005, and 253 seeding hours compared to 475 in

WY2005. The fewer events were due to the suspension in April, but also because many storms in the early part of the winter did not meet the project's seeding criteria.

The Toiyabe target (see Fig. 12) had below average snowpack conditions for almost the entire winter and therefore was not affected by suspension criteria. For this reason seeding events and hours were considerably higher than in WY2005. There were three more events and seeding hours increased from 57 in WY2005 to 162 in WY2006.

For the entire 2006 water year ground seeding hours totaled 3,041, only slightly below the WY2005 total of 3,106. Both of the past two seasons had well above average snow conditions and, although seeding opportunities were as plentiful as previous dry winters, seeding suspensions led to fewer seeding hours per season compared to the 10-year average for the Nevada State Program of about 3,500 hours. Seeding generator efficiency was up slightly this year compared to last, and was again close to the long term average efficiency of slightly over 80%.

B. Aircraft Seeding Operations

To supplement ground seeding operations in the Sierra Nevada target areas a subcontract for a seeding aircraft was negotiated with Weather Modification, Inc. (WMI) of Fargo, North Dakota. WMI has now provided the seeding aircraft to the Nevada Program the past four seasons. The aircraft used each year has been a twin-engine Cessna 340 (Fig. 13). This past season the aircraft became available in late December 2005 and was operated for the program through the first week of April 2006. One logistical change this past year was to have the aircraft based in Sacramento rather than Reno. The advantages were: 1) fewer problems with wind conditions for takeoff and landing; 2) shorter flight time to the target areas; 3) no problem with snowfall at the lower altitude airport (see Fig. 13); and 4) having a better chance of doing fog seeding for the Reno airport, since fog at Reno would prevent that operation.

Aircraft seeding equipment included two wing-mounted solution-burning generators (Fig. 13). Each generator carries about 7 gallons of solution. Compressed air is used to force the solution through a spray nozzle into the burn chamber at the rear of the generator. The atomized solution is directly ignited and burned at a rate of up to 150 grams of AgI per hour per generator (300 grams per hour if both units are used simultaneously). The aircraft also carried two racks for end-burning, or BIP flares, that were mounted at the back of each wing and used in the event that one or more of the solution-burners failed to operate, the burners ran out of solution during a flight, or a high cloud liquid water content warranted a higher seeding rate. Each flare rack holds 12 flares with the firing control directed from the cockpit. A single flare burns a pyrotechnic compound containing AgI for a period of 5 minutes, releasing about 30 grams of AgI per minute (1800 grams per hour). This seeding rate is about six times higher than that of the solution-burners. For the liquid water concentrations encountered in most wintertime clouds the solution-burners are considered adequate, so the end-burning flares are used less frequently.

Figure 13. WMI Cessna 340 cloud seeding aircraft at the Reno Airport. Right photo was taken in 2005 after a heavy snowfall in Reno. AgI solution-burning generators are visible below each wing tip in both photos.

The aircraft was equipped with a temperature sensor, an instrument for measuring the amount of supercooled liquid water in clouds, and a GPS receiver for determining position. WMI provided flight track data, as well as the temperature and liquid water data for each seeding operation. The flight data also contained event markers to show when solution-burners were operated and when flares were ignited. These data can be correlated with other weather data, such as radar or satellite images, for a more complete assessment of the cloud conditions in which seeding occurred.

Based upon the time required for AgI to produce ice particles, and for these particles to grow and fall out on the eastern side of the Sierra Nevada, a group of flight tracks were constructed that account for a variety of wind speeds and directions. These predetermined flight tracks are shown on the Tahoe-Truckee and Walker-Carson target maps in Figs. 9 and 10. Upper level winds were assessed using forecast model predictions, upper level sounding data, and, when available, the data from a NOAA wind profiler positioned on the western slope of the Sierra Nevada. Wind profiler and sounding locations are also shown in Figs. 9 and 10. Once a seeding flight was initiated the pilots periodically estimated flight level winds, and changed to a more appropriate seeding track if necessary.

Table 3 summarizes the aircraft seeding flights conducted for the Nevada Program in the Tahoe-Truckee region and Table 4 shows similar data for the Walker-Carson target area. The large disparity in the number of flights was mainly due to the lengthy periods of seeding suspension in the Walker Basin. The Walker-Carson area had six seeding flights that included about 19 hours of seeding using solution-generator hours and four BIP flares. The Tahoe area was seeded on 21 flights with a total of nearly 71 solution-burning generator hours and 26 BIP flares. The total of seeding hours was more than double the number of hours seeded in WY2005, and indicated that suitable seeding conditions were encountered much more frequently in WY2006 since the flight hours were roughly the same in both years.

Table 3. Summary of WY2006 aircraft seeding flights for the Nevada State Cloud Seeding Program in the Tahoe-Truckee target area. [Flight tracks correspond to flight track labels in Fig.9]

Date	Engine Time (hours) for:			Total Engine Time	Flight Track	No. of BIP Flares	Burner Time (hh:mm)		AgI Released (grams)
	Seed	Recon	Other				Left	Right	
12/23/05			1.52	1.52	-	0	0:00	0:00	0.00
12/27/05	3.08			4.60	TT6-7	5	0:00	2:08	1027.33
01/11/06	3.82			8.42	TT5-6	1	2:39	2:12	780.50
01/14/06	2.45			10.87	TT2-3	0	1:24	1:24	364.00
01/17/06			1.07	11.93	-	0	0:00	0:00	0.00
01/18/06	2.60			14.53	TT5-6	3	1:34	0:00	653.67
01/23/06			0.58	15.12	-	0	0:00	0:00	0.00
01/28/06	2.08			17.20	TT-6	1	0:40	0:40	323.33
01/28/06	1.15			18.35	TT-6	0	0:09	0:09	39.00
01/30/06	1.98			20.33	TT6-7	0	1:53	1:53	489.67
02/01/06			0.83	21.17	-	0	0:00	0:00	0.00
02/04/06	2.50			23.67	TT-6	4	1:34	1:34	1007.33
02/10/06			1.00	24.67	-	0	0:00	0:00	0.00
02/10/06			0.80	25.47	-	0	0:00	0:00	0.00
02/12/06			0.38	25.85	-	0	0:00	0:00	0.00
02/28/06	3.22			29.07	TT5-6	6	2:21	2:13	1493.67
03/02/06	3.20			32.27	TT2-3	2	0:50	2:12	694.33
03/02/06	3.58			35.85	TT-6	0	2:37	2:30	665.17
03/06/06	2.95			38.80	TT-5	0	0:00	2:06	273.00
03/07/06	3.35			42.15	TT5-6	0	2:25	2:13	602.33
03/14/06	3.30			45.45	TT-6	0	2:30	2:26	641.33
03/16/06	3.52			48.97	TT5-6	0	2:32	2:27	647.83
03/20/06	3.22			52.18	TT5-6	0	2:11	2:11	567.67
03/20/06	0.55			52.73	TT-5	0	0:10	0:11	43.33
03/25/06	2.68			55.42	TT6-7	4	1:53	1:53	1089.67
03/27/06	3.00			58.42	TT-3	0	2:03	2:03	533.00
03/30/06	3.00			61.42	TT-3	0	2:18	2:05	569.83
03/31/06	3.62			65.03	TT-3	0	2:36	2:10	619.67
Totals	58.85	0.00	6.18	65.03		26	34:19	36:39	13125.67
							Burner AgI Total (gm)		9225.67
							BIP AgI Total (gm)		3900.00

Seeding material is released at a much higher rate with the aircraft compared to ground generators, primarily because of the need to fill a much larger volume with an adequate number ice nucleating particles. The total amount of AgI released by the aircraft over the Tahoe target was 13,126 grams, which was about 67% of what was released from four ground generators in 886 hours of seeding. In the Walker target 2,936 grams of AgI were dispensed by aircraft. This was 12.5% of the amount released in 954 hours of ground seeding using eight generators. In addition to seeding suspensions, the timing of seedable conditions over the Sierra Nevada also favored aircraft flights in the Tahoe region. It is frequently the case that the shallower clouds (lower cloud tops) that are most conducive to seeding cannot be penetrated using the flight tracks for the Walker Basin which must be flown at altitudes 2000-4000 feet higher than Tahoe seeding tracks due to terrain avoidance issues. In several instances in WY2006 this resulted in a shift to Tahoe seeding tracks when the aircraft could not get low enough to seed clouds upwind of the Walker-Carson target. Based on the amount of seeding material released, the single aircraft augmented the seeding operations in the Tahoe-Truckee and Walker-Carson targets by about 35%. This is significantly higher than the percentage of the budget that was allocated to aircraft operations.

Table 4. Summary of WY2006 aircraft seeding flights for the Nevada State Cloud Seeding Program in the Walker-Carson target area. [Flight tracks correspond to flight track labels in Fig. 10.]

Date	Engine Time (hours) for:			Total Engine Time	Flight Track	No. of BIP Flares	Burner Time (hh:mm)		AgI Released (grams)
	Seed	Recon	Other				Left	Right	
12/28/05	3.27			3.27	WC-3	0	2:04	2:04	537.33
02/15/06	2.90			6.17	WC-2	4	1:10	1:37	961.83
02/17/06	3.73			9.90	W-8	0	2:37	2:28	660.83
03/06/06	3.28			13.18	W-8	0	1:59	1:59	515.67
03/11/06	1.20			14.38	C-5	0	0:09	0:09	39.00
03/20/06	1.33			15.72	WC-3	0	0:51	0:51	221.00
Totals	15.72	0.00	0.00	15.72		4	8:50	9:08	2935.67
						Burner AgI Total (gm)			2335.67
						BIP AgI Total (gm)			600.00

C. Assessment of Weather Conditions during Cloud Seeding Operations

Appendix C lists the various weather data sources that are used to assess weather conditions for the Nevada State Program. The most commonly used products are available on the internet and can be accessed through the State Seeding Program web page: http://cloudseeding.dri.edu/Weather/Weather.html. These products include weather maps, NEXRAD radar images, satellite images, upper air soundings, regional surface weather data, weather forecasts, and much more. This past season the State Seeding Program operated remote weather stations at four generator sites; two in the Walker-Carson target area, one in the Tuscarora area, and one in the Ruby Mountain target area. The data from these weather stations are accessed by cellular telephone modem. The Tahoe area also has several mountaintop weather sites that can also be accessed either from the Internet or by telephone modem. The Nevada Program obtains upper air sounding data from a site on the western slope of the Sierra Nevada (see Figs. 9 and 10) that is operated by the Sacramento Municipal Utilities District (SMUD).

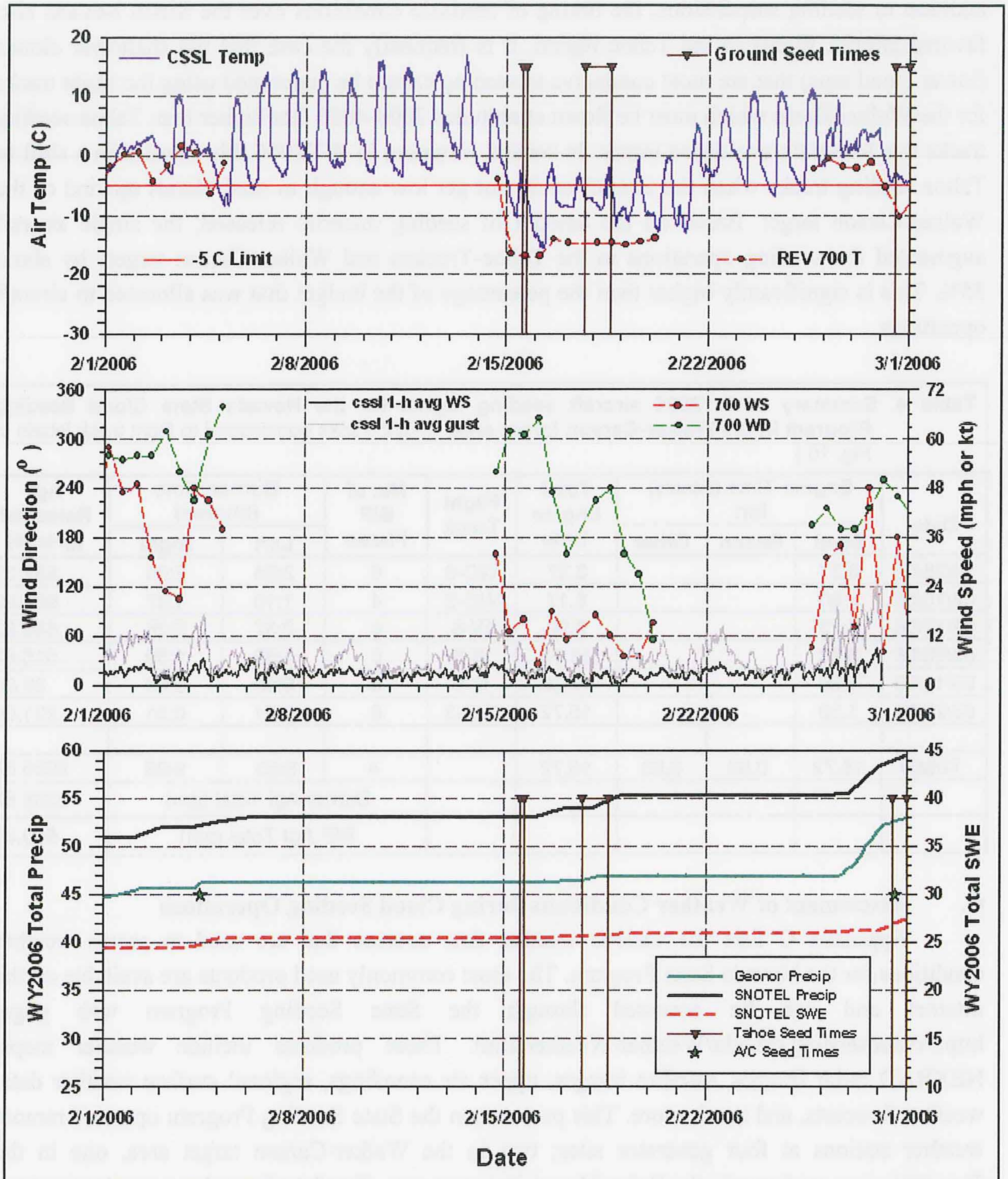

Figure 14. Meteorological data and cloud seeding periods for the Tahoe-Truckee region during February 2006. Top Panel: Surface air temperature at CSSL (see Fig. 9) and 700 mb temperatures from Reno NWS soundings. -5° C is shown by a red line. Ground seeding periods are shown by dark red vertical lines. Middle Panel: Wind data from CSSL and Reno soundings. Bottom Panel: WY2006 SWE and precipitation accumulation from the CSSL SNOTEL site and precipitation accumulation from a Geonor precipitation gauge. Ground seeding periods are shown by dark red vertical lines and aircraft seeding times are shown by green stars.

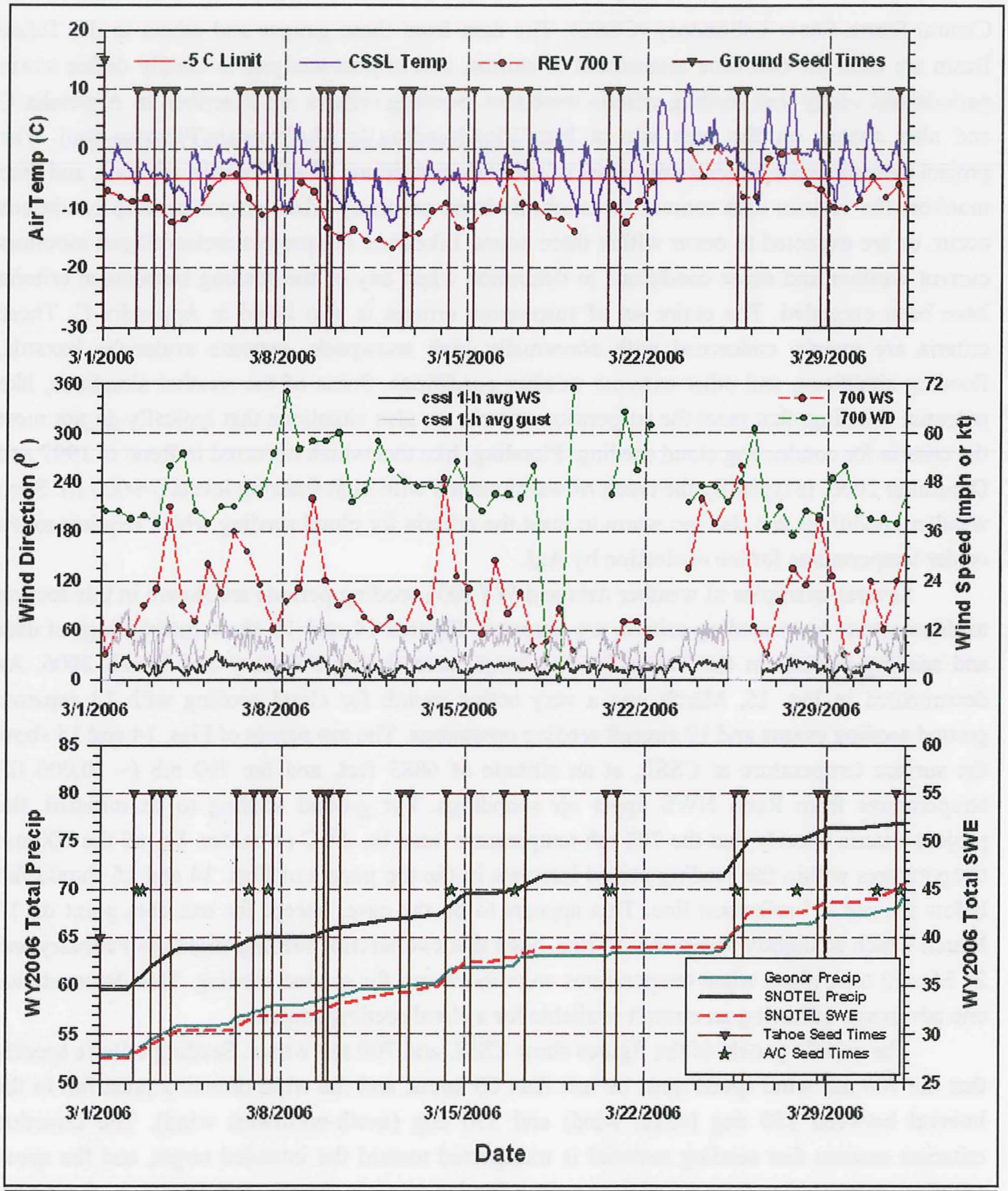

Figure 15. As in Fig. 14, except showing data and seeding periods for the Tahoe-Truckee target region for March 2006.

DRI has also added two special high resolution precipitation gauges to the Tahoe region, one in the Truckee Basin (Sagehen Creek) and one at a site just west of Donner Summit at the

Central Sierra Snow Laboratory (CSSL). The data from these gauges and others in the Tahoe Basin are used for real time assessment of storms, and in post-analysis to clearly define storm periods and verify that seeding criteria were met. Seeding criteria are described in Appendix C and also appear on the web site at http://cloudseeding.dri.edu/Program/Program.html. The project meteorologist forecasts the onset of seedable conditions 24-48 hours in advance, and then monitors the various data sources to determine more precisely when proper seeding conditions occur, or are expected to occur within three hours. Likewise, the project meteorologist monitors current weather and snow conditions to determine when any of the seeding suspension criteria have been exceeded. The entire set of suspension criteria is also listed in Appendix C. These criteria are mainly concerned with abnormally high snowpack, extreme avalanche hazards, flooding situations, and other extreme weather conditions. Some of the weather situations, like potential flooding, that meet the suspension criteria are also situations that typically do not meet the criteria for conducting cloud seeding. Flooding, like that which occurred in Reno in 1997 and December 2006, is typically the result of warm storms with high freezing levels (>9000 ft). Such weather conditions are also too warm to meet the criteria for cloud seeding which requires much colder temperatures for ice nucleation by AgI.

Several examples of weather data and WY2006 seeding periods are shown in this section to demonstrate how seeding criteria are assessed. Figures 14 and 15 show meteorological data and seeding periods in the Tahoe-Truckee target area during February and March 2006. As documented in Fig. 15, March was a very active month for cloud seeding with 13 separate ground seeding events and 12 aircraft seeding operations. The top panels of Figs. 14 and 15 show the surface temperature at CSSL, at an altitude of 6883 feet, and the 700 mb (~ 10,000 ft.) temperatures from Reno NWS upper air soundings. For ground seeding to be initiated, the project criteria specify that the 700 mb temperature must be -5° C or colder. So, all the 700 mb temperatures within the seeding period intervals in the top panels of Figs. 14 and 15 should fall below the red -5° reference line. This appears to be the case, except for one data point on 16 March which is slightly above the -5° line. Note that two aircraft seeding flights (4 February and 27 March) took place when temperatures were too warm for ground seeding. This demonstrates one advantage of having an aircraft available for a cloud seeding project.

The middle panels of the figures show CSSL and 700 mb winds. Seeding criteria specify that the 700 mb wind speed must be less than 60 knots, and the wind direction must fall in the interval between 180 deg (south wind) and 330 deg (north-northwest wind). The direction criterion ensures that seeding material is transported toward the intended target, and the speed criterion ensures that there is adequate time for ice particle growth and fallout in the target. Figures 14 and 15 indicate that the wind criteria were also satisfied for all February and March seeding events. The bottom panels of Figs. 14 and 15 show data from a high resolution precipitation gauge (Geonor-type with a vibrating wire sensor) and the CSSL SNOTEL instrument (part of the NRCS network). The Geonor gauge provides better temporal resolution, and also better depth resolution in the lighter precipitation events, compared to the SNOTEL

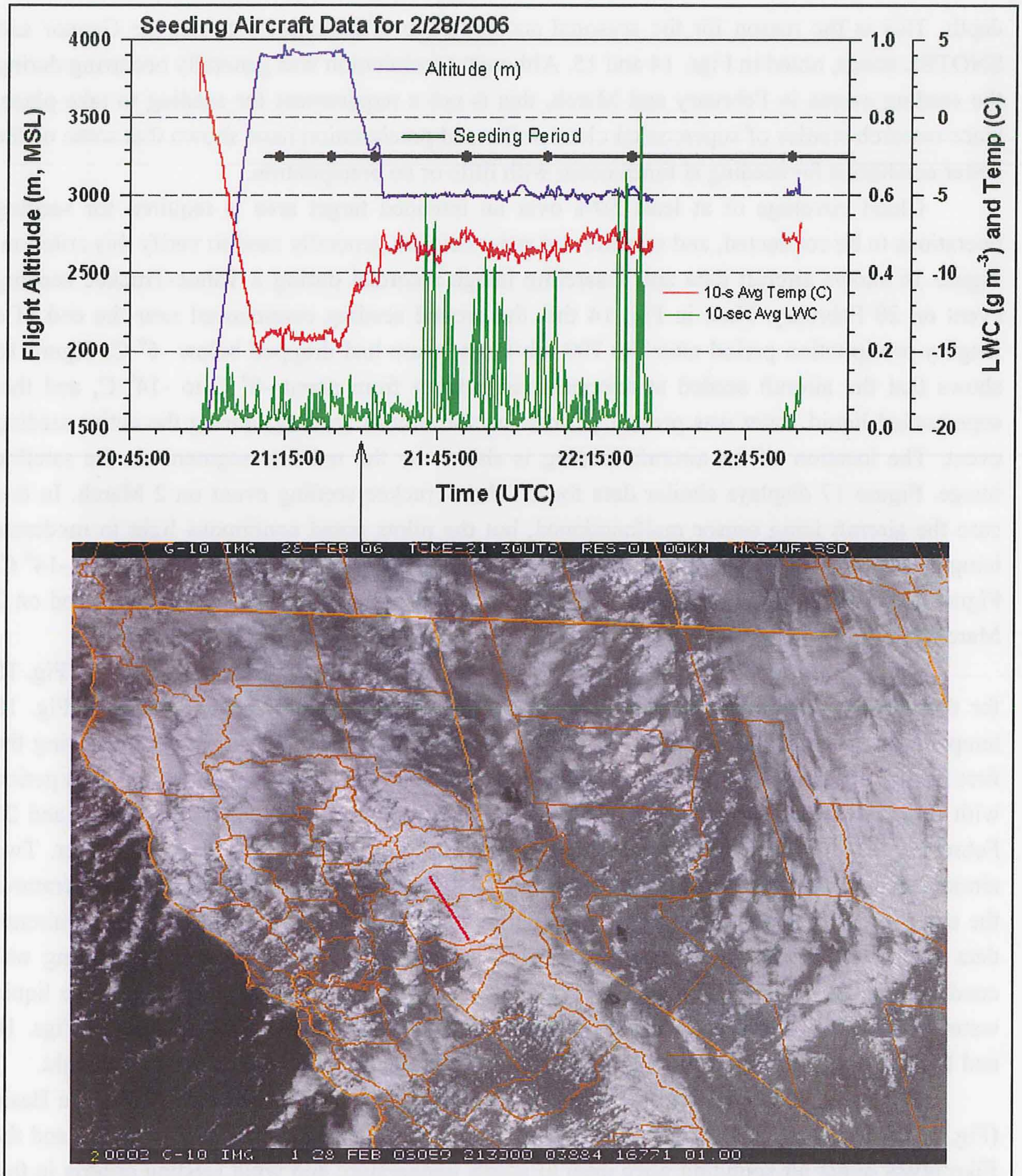

Figure 16. Aircraft data collected during a cloud seeding event on 28 February 2006 (top) and a visible satellite image recorded about 20 minutes after seeding began (bottom). Aircraft data include the flight altitude, air temperature and cloud liquid water content. The seeding period is shown by the black line in the top panel. The seeding location is shown by the red line segment on the satellite image.

instruments. However, in heavy snowfall events, the Geonor tends to underestimate precipitation depth. This is the reason for the seasonal accumulation differences, between the Geonor and SNOTEL traces, noted in Figs. 14 and 15. Although precipitation was generally occurring during the seeding events in February and March, this is not a requirement for seeding to take place, since research studies of supercooled cloud water and precipitation have shown that some of the better conditions for seeding at times occur with little or no precipitation.

Cloud coverage of at least 50% over an intended target area is required for seeding operations to be conducted, and satellite and radar data are generally used to verify this criterion. Figure 16 shows aircraft data and a satellite image recorded during a Tahoe-Truckee seeding event on 28 February. Note in Fig. 14 that the ground seeding commenced near the end of a lengthy precipitation period after the 700 mb temperature had dropped below -5° C. Figure 16 shows that the aircraft seeded at temperatures ranging from about -8° C to -14° C, and that supercooled liquid water was present (a criterion for aircraft seeding) during the entire seeding event. The location of the aircraft seeding is shown by the red line segment on the satellite image. Figure 17 displays similar data for a Tahoe-Truckee seeding event on 2 March. In this case the aircraft icing sensor malfunctioned, but the pilots noted continuous light to moderate icing on the airframe of the Cessna 340 at seeding temperatures that ranged from -12° to -14° C. Figure 15 indicates that conditions for ground seeding were also met for a lengthy period on 2 March.

Seeding periods, SNOTEL and sounding data from February 2006 are shown in Fig. 18 for the Walker Basin. The Lobdell Lake SNOTEL location is shown in Fig. 10. In Fig. 18 temperature and precipitation data are all shown in the top panel. A lack of storms during the first half of the month resulted in the corresponding lack of seeding events. A very cold period with a few weak storms resulted in three ground seeding events between 15 February and 20 February. Note that the 700 mb temperatures during this period were -15° C or colder. Two aircraft seeding flights were also conducted during this period, and despite the cold temperatures the aircraft still detected supercooled liquid at the seeding altitude. Figure 19 shows the aircraft data and a visible satellite image recorded during the 17 February event. The seeding was conducted at -20° C, which was likely very near the tops of the clouds on this day. The liquid water contents were markedly less than those recorded in the much warmer events in Figs. 16 and 17, but were relatively continuous and satisfied the seeding criteria throughout the flight.

Figure 20 shows seeding periods and meteorological data relative to the Owyhee Basin (Fig. 11) for January 2006. The Jacks Creek Upper SNOTEL site in the Owyhee Basin and the Elko NWS upper air sounding were used to assess temperature and wind seeding criteria in this region. Images from the Elko NWS NEXRAD radar and satellite images are used to assess cloud cover. Figure 21 shows similar data for the Ruby Mountain region using Lamoille #3 as the representative SNOTEL site (Fig. 11). Two seeding periods in the Owyhee region and one in the Ruby Mountain region had accompanying 700 mb temperatures that were 1-2° warmer than specified by the project seeding temperature criterion. This happens at times when seeding is initiated based on a forecast, and the expected trend in temperature does not occur.

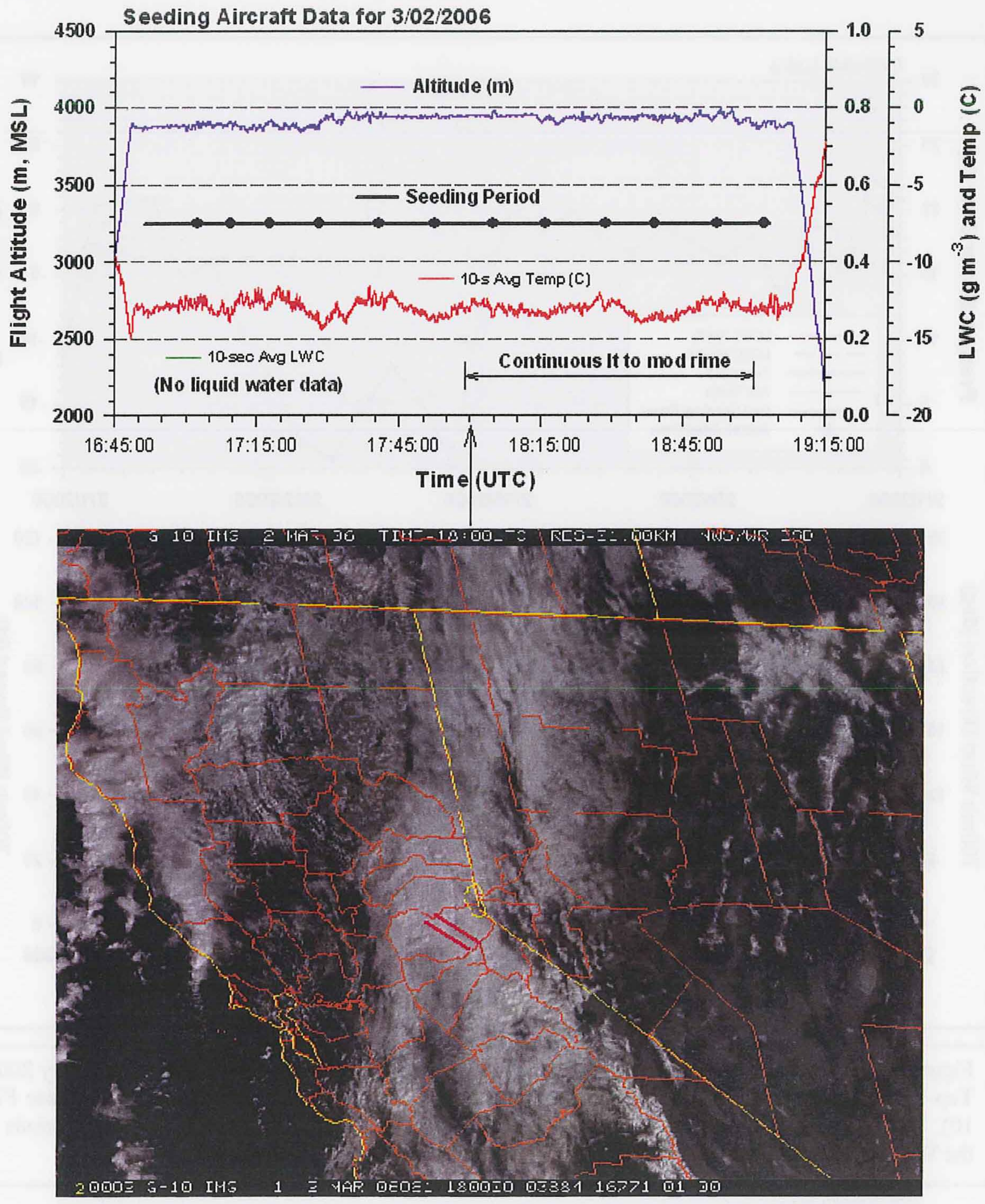

Figure 17. As in Fig. 16, except showing aircraft data and a visible satellite image for an aircraft seeding flight on 2 March 2006. The seeding flight tracks used are shown by the red line segments on the satellite image. The satellite image (see black arrow) was taken about midway through the flight.

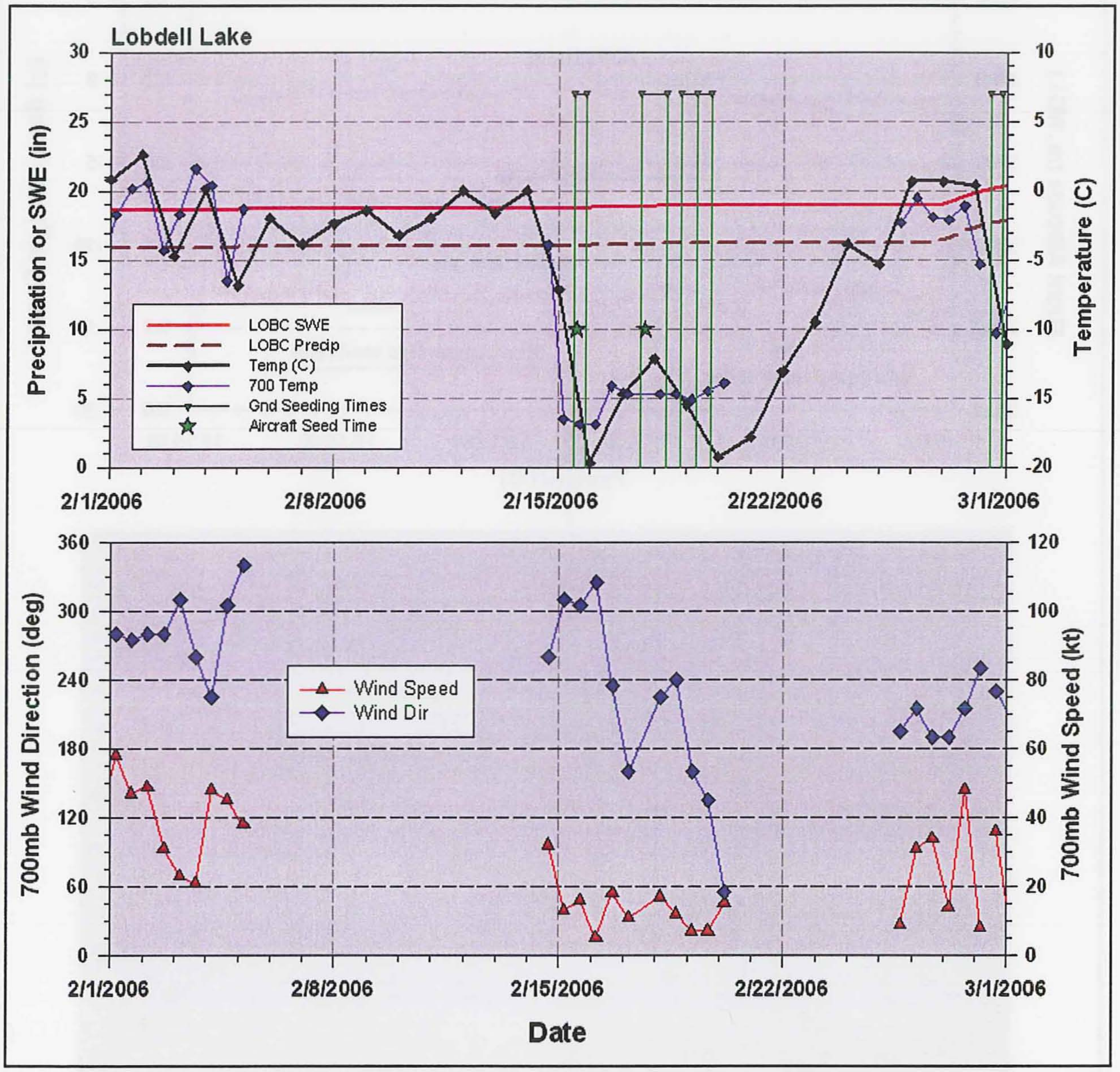

Figure 18. Meteorological data and cloud seeding periods for the Walker Basin during February 2006. Top Panel: SWE, precipitation and temperature data from the Lobdell Lake SNOTEL site (see Fig. 10). 700 mb temperatures from the Reno NWS sounding, and ground and aircraft seeding periods in the Walker Basin. Bottom Panel: 700 mb wind data from the Reno NWS sounding.

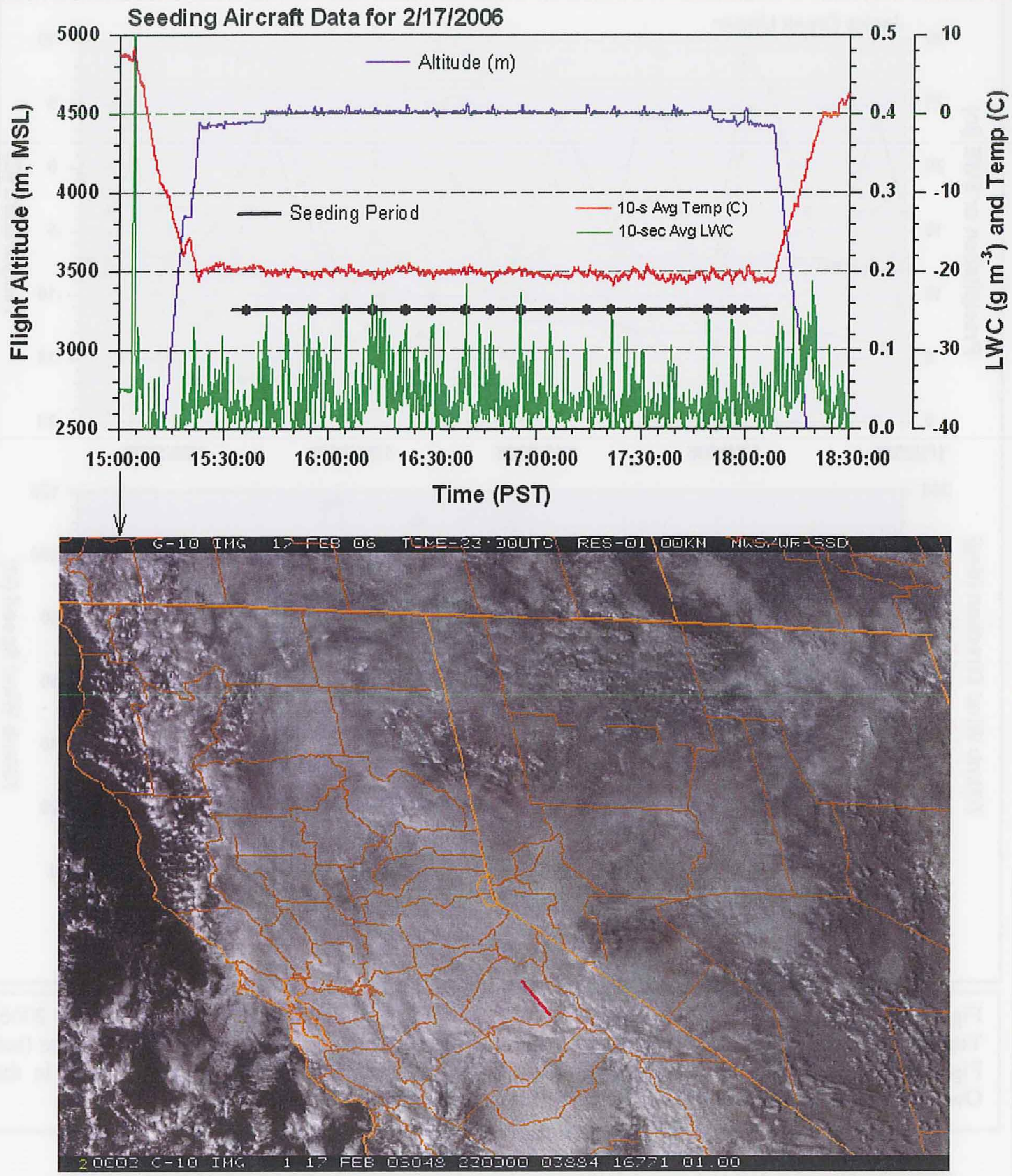

Figure 19. As in Fig. 16, except showing aircraft data and a visible satellite image recorded during an aircraft seeding flight for the Walker Basin on 17 February 2006. Satellite image was taken just prior to the start of seeding (see black arrow) on the flight track shown by the red line segment on the satellite image.

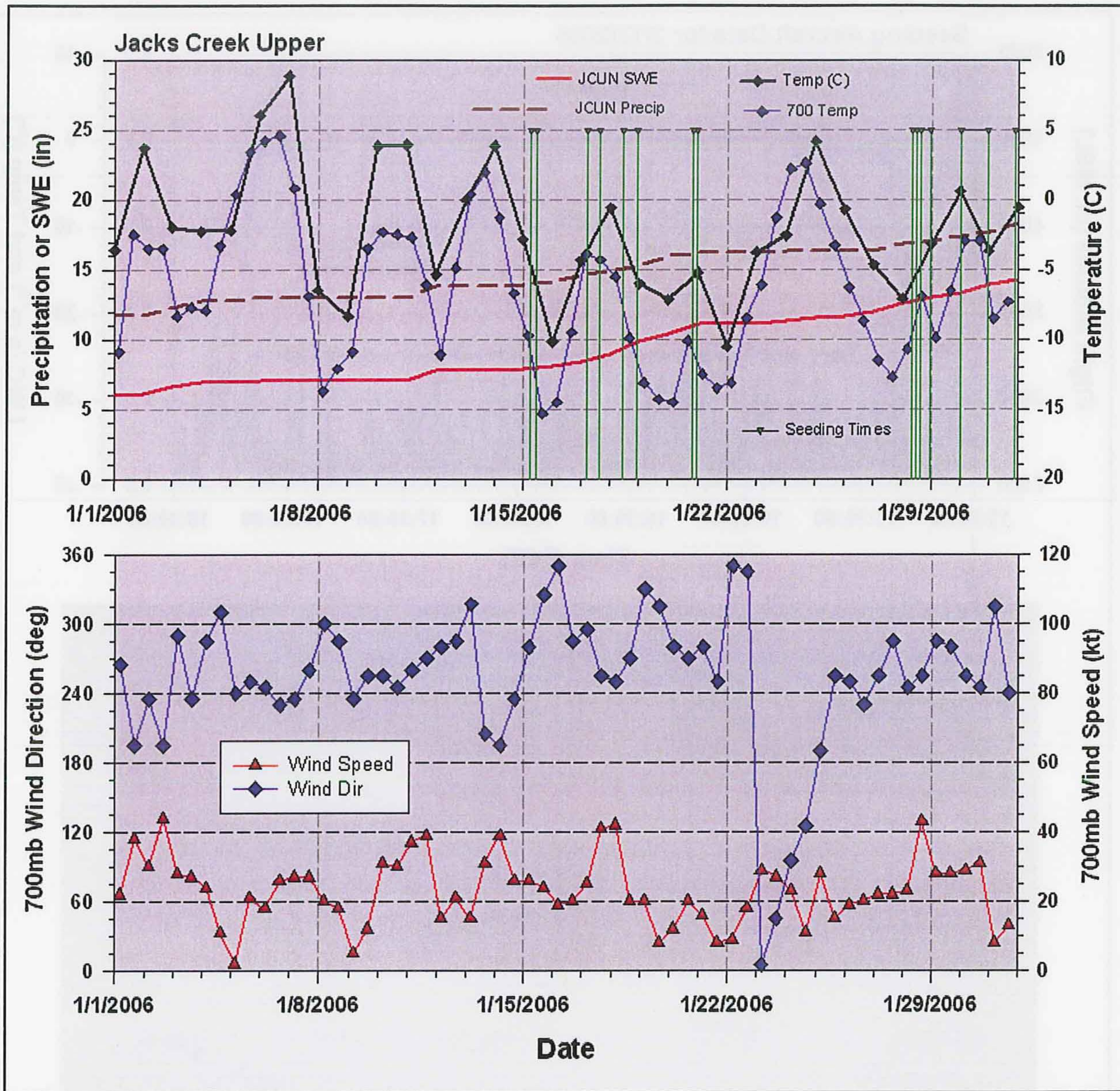

Figure 20. Meteorological data and cloud seeding periods for the Owyhee Basin during January 2006. Top Panel: SWE, precipitation and temperature data from the Jacks Creek Upper SNOTEL site (see Fig. 11). 700 mb temperatures from the Elko NWS sounding and ground seeding periods in the Owyhee Basin. Bottom Panel: 700 mb wind data from the Elko NWS sounding.

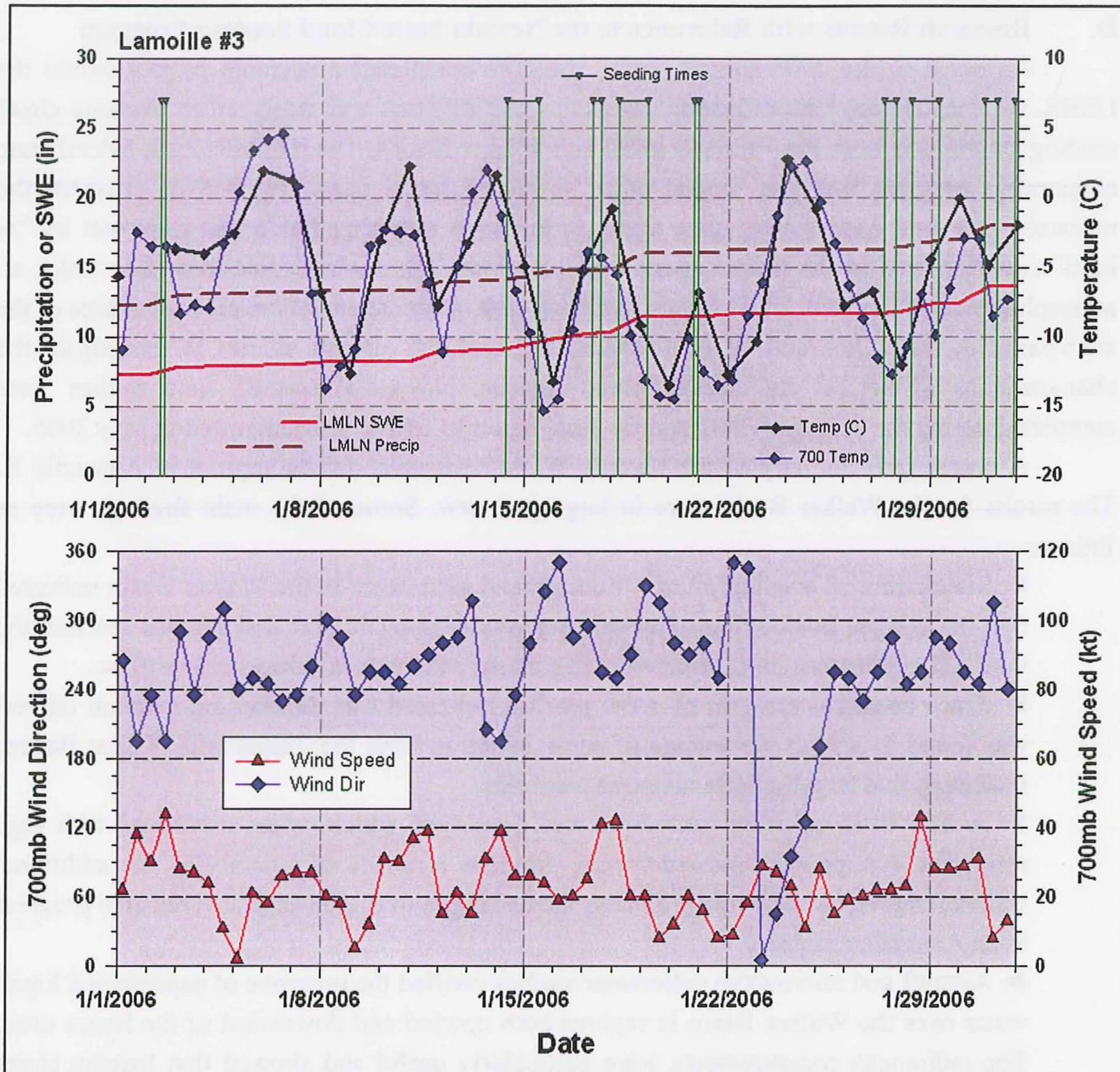

Figure 21. Meteorological data and cloud seeding periods for the Ruby Mountains (Upper Humboldt Basin) during January 2006. Top Panel: SWE, precipitation and temperature data from the Lamoille #3 SNOTEL site (see Fig. 11). 700 mb temperatures from the Elko NWS sounding and ground seeding periods in the Ruby Mountains. Bottom Panel: 700 mb wind data from the Elko NWS sounding.

D. Research Results with Relevance to the Nevada State Cloud Seeding Program

As noted in the 2005 annual report, the DRI completed a research project within the USBR Weather Damage Modification Program (WDMP) that was designed to evaluate cloud seeding activities in both the Tahoe-Truckee and Walker Basins. The WDMP was a federal-state cooperative program that was funded on a 50/50 cost share basis. The USBR provided the research funds and participating state agencies provided matching funds that were met by "in kind" costs incurred in the states' operational programs. The research had four main tasks; an atmospheric modeling task, a hydrologic modeling task, physical and chemical evaluations of the snowpacks in the Tahoe and Walker Basins, and research aircraft studies to investigate the characteristics of natural and seeded cloud regions. Nevada's research field studies were completed during the spring of 2005 and the final report to USBR was submitted in May 2006.

A condensed summary of the Nevada WDMP research results appears in Appendix B. The results for the Walker Basin were in large part new. Some of the main findings were as follows:

- ► Simulations of seeding plumes from ground generators in the Walker Basin indicated that the current positioning of generators was reasonable and that plumes reached the intended target areas most effectively in southerly to south-southwesterly airflow.
- ► Trace chemical analysis of snow profiles indicated that the seeding material (silver) was found in a high percentage of snow layers in both the Tahoe and Walker Basins, indicating that targeting effectiveness was high.
- ► A new snow profiling technique was developed which, when combined with high resolution precipitation measurements, provides a means of quantifying the additional snowfall due to cloud seeding. Testing the technique over a basin-wide area is in progress in an Australian project.
- ► Aircraft and microwave radiometer studies verified the presence of supercooled liquid water over the Walker Basin in regions both upwind and downwind of the Sierra crest. The radiometer measurements were particularly useful and showed that lengthy storm periods with seeding opportunity existed over the Walker Basin.
- ► Aircraft studies were quite valuable in verifying model results, and in a few cases also detected ice particle concentrations and types that were consistent with earlier documented case studies of seeding effects in the Sierra Nevada.
- ► A hydrologic model was successfully set up for the Walker Basin and used to estimate runoff from simulated snowfall enhancement in five specific regions of the basin. For WY2004 the bulk of the enhanced snowfall was predicted to result in additional streamflow.

An evaluation of a wintertime cloud seeding project conducted for Idaho Power in the Payette Basin of southern Idaho was completed by DRI scientists. The evaluation was based on the dual-trace chemical technique developed at DRI and reported on by Chai et al. (1993) and by

McGurty (1999) for projects in the Sierra Nevada of California. The McGurty study used a relationship between snow density and silver concentration to estimate snow water increases due to seeding. The Idaho trace chemical analyses produced results that were similar to those of McGurty (1999), although for a relatively small number of snow samples. The newer trace chemical and high resolution gauge method of evaluation continues to be tested in an Australian project in the Snowy Mountains. One season produced quite good and consistent results, while a second season plagued by rain-on-snow events produced very poor results. The technique depends heavily on there being a high correlation between the gauge-measured precipitation for a storm, and the integrated amount of snow water in a coincident snow profile for the same storm period. Therefore the technique has a better chance of success in high mountainous regions where rain events are rare. The Sierra Nevada target areas above 8000 ft are much better suited to this evaluation method than the Australian mountains which have little area above 6500 ft.

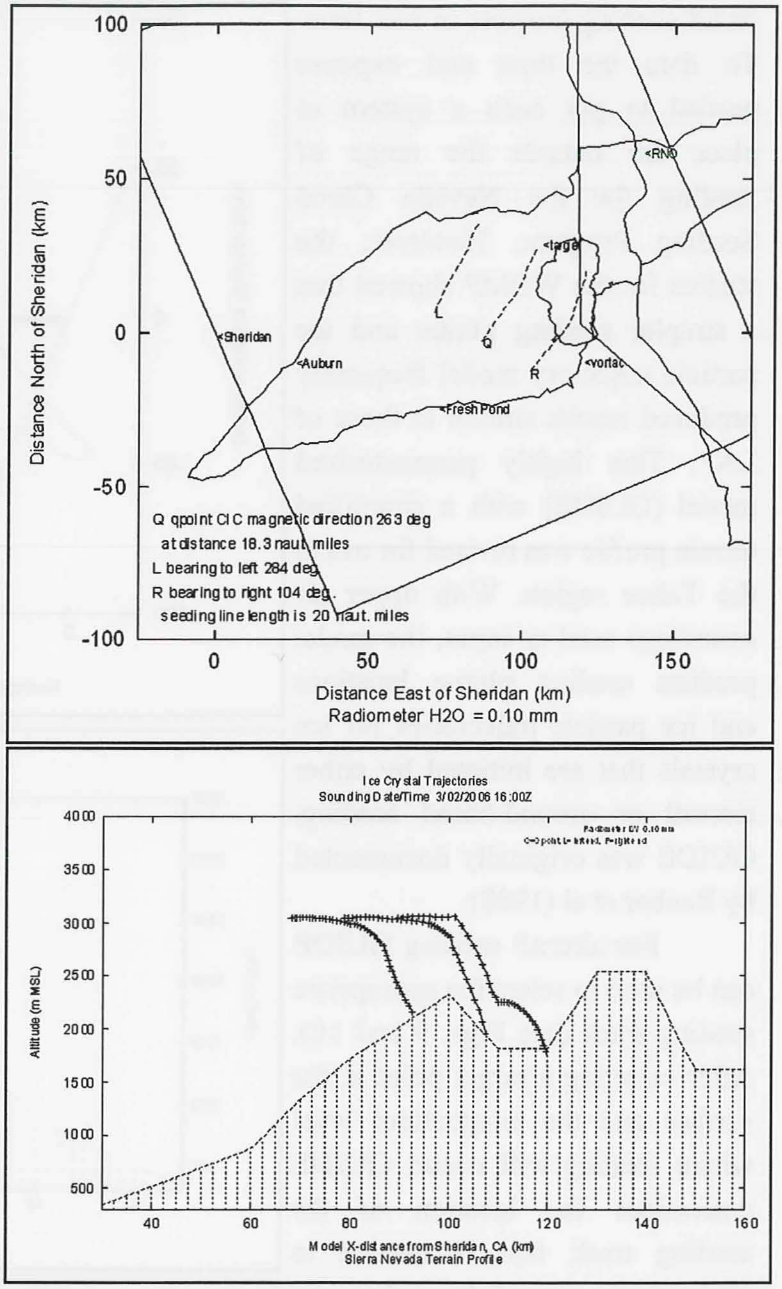

Figure 22. GUIDE model predictions for aircraft seeding using a sounding from 3/2/06 at 1600 GMT. Top: GUIDE predicted seed line represented by points L, Q and R. Dashed lines are the predicted paths of ice crystals formed on the seeding line. Bottom: Vertical terrain profile from GUIDE showing crystal fallout trajectories from the seeding line end points.

The high resolution atmospheric modeling studies conducted as part of the WDMP are of importance to operational cloud seeding programs. The seeding plume dispersion predicted by DRI's Lagrangian particle dispersion model (LAP) are quite realistic and would be of great benefit if they were available to cloud seeding projects in real time. To date the time and expense needed to put such a system in place are outside the range of funding for the Nevada Cloud Seeding Program. However, the studies for the WDMP showed that a simpler seeding plume and ice particle trajectory model frequently produced results similar to those of LAP. This highly parameterized model (GUIDE) with a simplified terrain profile was revised for use in the Tahoe region. With upper air soundings used as input, the model predicts seeding plume locations and ice particle trajectories for ice crystals that are initiated by either aircraft or ground-based seeding. GUIDE was originally documented by Rauber et al (1988).

For aircraft seeding GUIDE can be used to select the appropriate seeding track (see Figs. 9 and 10). After selecting a target point at the surface and the temperature level where seeding will occur, GUIDE determines the location of the seeding track that is needed to allow an ice crystal formed on the seeding line to fall on the target. Figure 22 shows the results of running GUIDE for a storm event on 2 March 2006 using a sounding taken by SMUD at Fresh Pond. The predicted location of the seeding line in the top panel of Fig. 22 is quite close to the line chosen for the actual seeding event on this day (see Fig. 17). The bottom panel of Figure 22 shows the ice

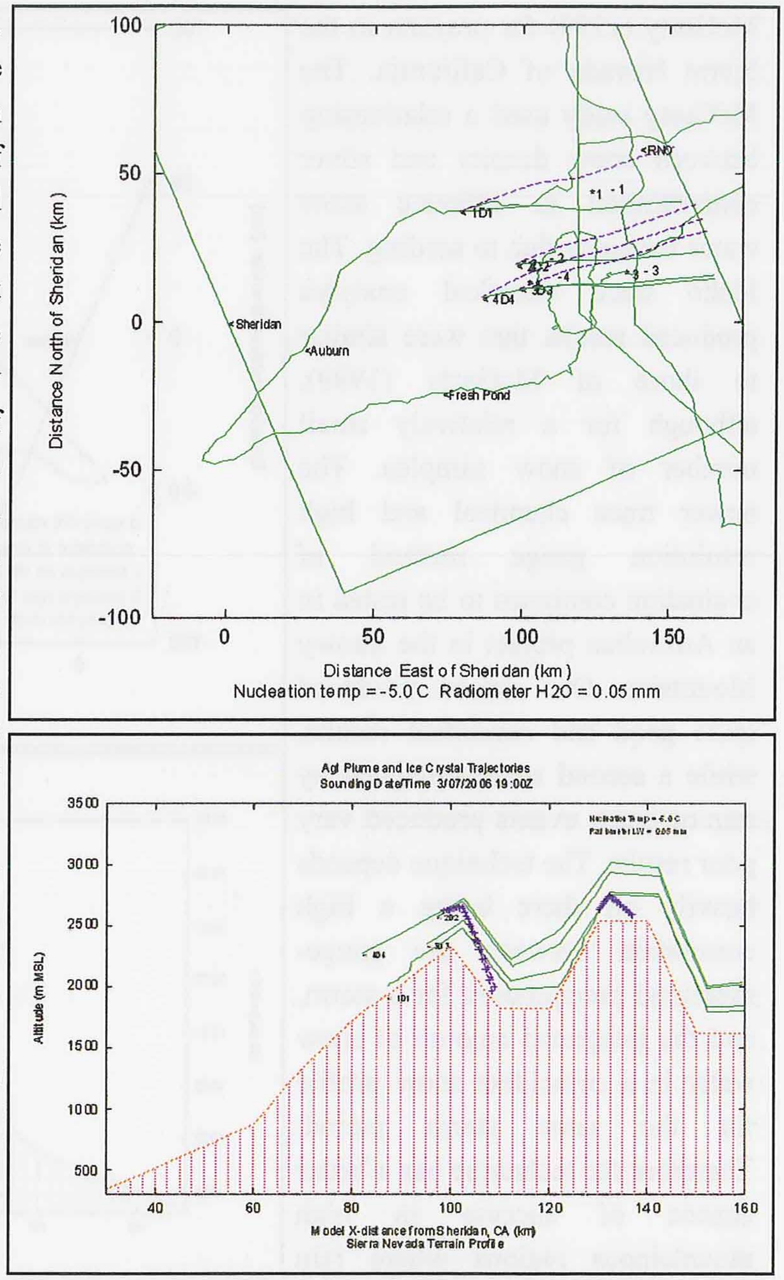

Figure 23. GUIDE model predictions for ground seeding using input from a sounding on 3/7/06 at 1900 GMT. Top: Seeding plume boundaries (dashed line is left edge and solid green line is right edge) from the four DRI Tahoe ground-based generators. Numbers correspond to locations where an ice crystal is predicted to form (asterisk) and where it reaches the surface (minus sign). Bottom: GUIDE terrain profile with the midpoints of seeding plume trajectories (green lines) and ice crystal trajectories (+'s). The model terrain is assumed to be the same in the north-south direction.

crystal trajectories predicted from the middle and end points of the seeding line. The crystal emanating from the center of the line (marked Q in Fig. 22) is the one that is predicted to fall on the selected target point (Mt Pluto just north of Lake Tahoe). For the upcoming winter GUIDE will be used with both forecast soundings and actual soundings to help in the selection of track locations for the seeding aircraft.

Figure 23 illustrates the use of GUIDE for ground seeding events. The top panel of Fig. 23 shows the horizontal spread of plumes from DRI's four Tahoe seeding generators for a storm on 7 March 2006. A SMUD sounding was again used as input for the model. The numbers 1, 2, 3 and 4 in Fig. 23 show both the points where ice crystals were predicted to form (asterisk) and the points where the same crystals were predicted to reach the surface (minus sign). The bottom panel of Fig. 23 shows the same seeding plumes and crystal trajectories, but in a vertical profile. In this panel the lines show the predicted locations of just the midpoints of the seeding plumes, and the +'s represent ice crystal trajectories. Here two plumes produced crystal fallout in the Tahoe Basin and two produced fallout on the Carson Range east of Tahoe. The terrain profile is a smoothed average of the terrain for this portion of the Sierra Nevada, so individual generators, which are often on the highest local terrain features, can be above the smoothed profile. For ground-based seeding, GUIDE can be used to evaluate project seeding criteria, since it integrates winds and temperature structure in its predictions, and also to determine which generators to operate in a specific storm situation.

IV. Estimate of Benefits from the Nevada State Cloud Seeding Program in WY2006

The meteorological and snow chemistry measurements currently taken by the Nevada State Cloud Seeding Program only permit a partial assessment of the effectiveness of the seeding operations. Quantitative estimates of seeding effects from operational projects are still difficult to routinely obtain. This is due to the non-random nature of the seeding, and because there is often no good unseeded control area with which to compare snowfall from treated areas. This is particularly true of the Tahoe-Truckee and Walker-Carson regions where upwind seeding projects in California frequently affect these Nevada Program target areas. Without additional outside funding, the expense involved in conducting a comprehensive assessment based on very detailed precipitation and snow chemistry measurements is also prohibitive. Until the newer assessment methods are validated, we will continue to rely on results of past research and operational projects to estimate the impact of seeding in the Nevada State Program. Examples of research results that summarize snowfall enhancement are given in Reynolds (1988) for numerous regions of the mountainous West, Super (1999) for central Utah, and McGurty (1999) for a Southern California Edison project in the central Sierra. Also, Super and Heimbach (2005) evaluated a randomized cloud seeding experiment in Utah that used liquid propane (nucleates ice crystals by cooling as the liquid is released into a cloud) as the seeding agent. The results showed (with less than a 5% chance of error) that seeded periods at the primary target gauge produced 22% more SWE than unseeded periods. An estimate, based on all seedable periods, indicated an

8% increase in precipitation could have been produced in a 3.5 month season.

For ground-based seeding with AgI, an average documented precipitation rate increase of 0.25 mm h^{-1} (see Reynolds, 1988) is applied to periods of generator operation in all of the Nevada State Program target areas. Total generator operational hours are used to determine the AgI release rate and the expected precipitation increase over a constant downwind area of 35 square miles (per generator). This area is based on the typical horizontal spread of a seeding plume, the average transport speed of the seeding material, and the average time needed for ice crystals to grow large enough to fall to the ground.

Not every seeding operation is conducted during the best conditions for producing seeding effects, so the total seeding effect estimate is then adjusted by a seedability factor (SF) which is roughly the fraction of the total hours of seeding during which seeding criteria were satisfied. For each operational area SF is determined by comparing seeding periods to meteorological data like that displayed in Figs. 15 - 21. Then, for the augmented water calculation, the total time of generator operation is multiplied by the average constant precipitation rate increase of 0.25 mm h^{-1}. This product is then multiplied by the estimated area of effect (35 sq. mi.), and then by SF, the seedability factor. The variation in SF across the five target regions was relatively small. The Tahoe and Walker areas both had an SF's computed to be 0.80. For WY2006 the project areas with less validation data were also assigned a value of 0.80. The final augmented water volume estimates were then converted to units of acre-feet (AF). Table 5 summarizes the results for seeding operations by project area and for all areas combined.

The computation of effects from aircraft seeding was treated somewhat differently. Documented precipitation rate increases from aerial seeding have been found to be somewhat higher than from ground seeding. This is mainly because the seeding is done at higher altitude, and the ice crystals created have a longer time to grow and accumulate mass as they descend to the surface. Reynolds (1988) reported a range of rate increases from aerial seeding between 0.2 and 0.6 mm h^{-1}, with a typical duration of effect from a single seeding line being only about 10 min at ground level. With a surface wind of 10 knots, the average width of a seeding effect would be about 3.1 km. The distance covered by a seeding aircraft in an hour is about 277.8 km.

Using these values an estimate of the volume of precipitation produced by one hour of aircraft seeding, or one gram of seeding material can be made as follows:

Total area covered per hour = 277.8 km x 3.1 km = 861.2 km^2/hour

Volume of water per hour = 861.2 km^2 x 10^6 m^2/km^2 x 0.0004 m = 344,480 m^3/hour

Acre-feet (AF) of water per hour = 344,480 m^3 ÷ 1234.4 m^3/AF = 279.1 AF/hour

Average release rate of seeding material = 245.0 grams/hour

Volume of water per gram of seeding material = 1.14 AF/gram.

This average seeding effect was used to estimate the volume of snow water produced by aircraft seeding. The documented cloud liquid water conditions were used to determine a seedability factor (SF) for each flight, where SF = 1.0 was assigned to flights with moderate icing, SF = 0.75 for light-moderate icing, SF = 0.50 for light icing, and SF = 0.10 for sporadic light icing. Since the pilot did not seed unless some icing was detected, the poorest conditions were eliminated from consideration in the augmentation estimates. A weighted average SF was computed by summing the product of SF times the AgI mass released for all flights, then dividing by the total AgI released. The total water volume estimate was then adjusted by the average SF value.

Table 5. Nevada State Cloud Seeding Program Water Augmentation and Cost Estimates for WY2006. SF is the seedability factor explained in the text.

Project Area	Seeding Method	AgI Released (grams)	Avg SF	Water Augmentation (acre-feet)	Average Cost (per AF)
Tahoe-Truckee	Ground	19,617	0.800	13,222	
	Aircraft	13,126	0.490	7,332	
	All Types	**32,743**		**20,554**	
Walker-Carson	Ground	25,992	0.800	14,242	
	Aircraft	2,936	0.430	1,439	
	All Types	**28,928**		**15,681**	
Ruby Mountains	Ground	**19,121**	0.800	**11,742**	
Owyhee	Ground	**6,874**	0.800	**3,772**	
Toiyabe	Ground	**3,934**	0.800	**2,421**	
Totals		**91,600**		**54,170**	**$10.84**
Average cost is based on a WY2006 project expenditure of $587,475					

The aircraft snow water augmentation estimates for the Tahoe-Truckee and Walker-Carson are also shown in Table 5. For WY2006 aircraft seeding conditions, as indicated by the computed SF, were similar over the two targets. The amount of AgI released over Tahoe was about 4½ times the Walker amount, and as noted previously the Tahoe region had about four times as many flight hours as the Walker region. This past winter this difference was mostly due the lengthy seeding suspension periods in the Walker, but was also due to the better liquid water (icing) conditions generally being found in the Tahoe region where the lower terrain allows the aircraft to be flown 2000-3000 feet lower where liquid water concentration are generally higher.

Table 6. Summary of cloud seeding by the Nevada State Cloud Seeding Program for Water Years 1997-2006.

	Water Year									
Catchments	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Tahoe-Truckee										
Aircraft Hours	0	0	3	0	0	19	33	36	28	54
Ground Hours	198	854	391	581	590	986	1872	1141	820	886
Total Hours	198	854	394	581	590	1005	1905	1177	848	940
Walker-Carson										
Aircraft Hours	0	45	28	22	0	51	57	37	15	14
Ground Hours	56	505	373	825	1044	641	1114	1048	833	954
Total Hours	56	550	401	847	1044	692	1171	1085	848	968
Ruby Mts.										
Aircraft Hours	0	0	0	0	0	0	0	0	0	0
Ground Hours	968	1865	1024	1638	1586	891	1142	816	922	903
Total Hours	968	1865	1024	1638	1586	891	1142	816	922	903
Owyhee Basin										
Aircraft Hours	0	0	0	0	0	0	0	0	0	0
Ground Hours	134	621	421	643	540	553	499	352	475	253
Total Hours	134	621	421	643	540	553	499	352	475	253
Toiyabe Mts.										
Aircraft Hours	0	0	10	0	0	0	0	0	0	0
Ground Hours	4	259	24	219	173	141	130	80	57	162
Total Hours	4	259	34	219	173	141	130	80	57	162
Total Hours	1,360	4,149	2,274	3,928	3,933	3,282	4,847	3,437	3,107	3,226
Est. Water Augmentation (acre-feet)	14,671	84,098	49,240	82,765	79,490	79,085	86,418	64,012	58,593	54,170
Water Cost (per acre-foot)	$19.06	$8.50	$10.76	$6.69	$6.11	$6.61	$6.10	$8.16	$9.44	$10.84
10-Year Annual Average of Seeding Hours: 3,354 hours										
10-Year Annual Average of Estimated Water Augmentation: 65,254 acre-ft										
10-Year Annual Average of Estimated Water Cost from Cloud Seeding: $9.23 per acre-foot										

Using the assumptions described in the preceding paragraphs, Table 5 indicates that the total water produced by seeding in WY2006 was 54,170 acre-feet, and the estimated cost of this water was $10.84 per acre-foot. If SF had been determined to be as low as 50%, the cost would still have been only about $12 per acre-foot. For comparison with previous years, data from this season and the preceding nine seasons are shown in Table 6. Total seeding hours for the current year were slightly below the ten-year average, and the WY2006 water augmentation estimates were about 17% below average. It is interesting to note that the beginning and ending years in Table 6 were both years with significant floods, and both had a decrease in seeding due to suspensions. This led to the two highest water costs over the ten year period. However, it should be noted that the seedability factor has only been applied to water estimates of the past five years. Prior to 2002 SF was assumed to be 1.0 for both aircraft and ground seeding operations. Reducing water augmentation estimates by a factor of about 0.80 in Water Years before 2002 would result in earlier augmentation totals being similar to, or even lower than that estimated for the current season (and water costs correspondingly somewhat higher).

V. Developments with Implications to Northern and Southern Nevada Water Issues

Several organizations in the western U.S. began developing plans for sustaining or augmenting water supplies in the West that included the use of snowpack augmentation technology. Much of the focus of this planning was the Colorado River Basin. Two detailed White Papers documenting cloud seeding theory, methodology and potential in the Colorado River Basin were developed. [These papers can be viewed on the North American Interstate Weather Modification website at: http://www.naiwmc.org/NAIWMC/news.html] The initial paper was developed by Tom Ryan of the Metropolitan Water District of Southern California (reviewed and edited by A. Huggins at DRI), and the second by North American Weather Consultants (NAWC) in Utah. The second of these papers was funded by the 7-Basin States organization. A third paper from the USBR (Hunter, 2006) also looked at the potential for water augmentation by cloud seeding in the Upper Colorado River Basin. The NAWC and USBR papers both indicated that the potential for additional water (to the Lower Basin) through cloud seeding was in excess of one million acre-feet. This is indeed a significant amount, particularly when considering that Nevada's share of Colorado River water is 300,000 acre-ft. These papers are careful to point out that this is potential augmentation. The current cloud seeding operations in the Upper Basin affect only a fraction of the mountainous regions that would need to be seeded to realize this potential.

Weather modification has also been discussed this past year by the Western States Water Council as one of the strategies for increasing water supplies. Their recommendations appear in a recent report by the Western Governors Association entitled, "Water Needs and Strategies for a Sustainable Future". A link to this report can also be found on the NAIWMC website noted above. The interest generated by the various reports and papers, and by discussions held during a workshop on weather modification (relative to the Colorado River Basin) conducted in Boulder, Colorado in June 2006, has led to further planning regarding cloud seeding among the 7-Basin states. In the short term Colorado, Utah and Wyoming will receive funding from lower basin states for the purpose of augmenting selected operational seeding programs in the upper basin. For the longer term a 5-year plan is being prepared to 1) initiate additional cloud seeding operations in the upper basin, and 2) to develop a robust method of evaluating the results of the cloud seeding in the upper basin. The DRI has always felt that these two components should be done coincidently and has frequently piggy-backed research and operations in the Nevada target areas, as was the case with the recent WDMP, and previously with the NOAA Atmospheric Modification Program and the USBR Project Skywater.

Since the WDMP ended in 2005, no federal agency has initiated any new programs in weather modification research despite the recommendations of the National Academy of Sciences Report (NAS, 2003). However, there are still two bills in Congress (S 517 and HR 2995) that propose the formation of a national weather modification advisory board and the development of federally-funded research programs. NOAA would likely be the agency to organize the research program. The congressional bills, subcommittee testimony on the Senate bill and supporting resolutions by various state agencies can be found on the NAIWMC website at: http://www.naiwmc.org/NAIWMC/news.html. The federal research proposed by the bills offers the best opportunity to address key scientific issues in weather modification, to continue evaluations of ongoing state programs, and also to provide the means to scientifically assess the effectiveness of the new or augmented programs being considered in the Colorado River Basin.

VI. Additions and Changes Planned for the 2006-2007 Nevada State Cloud Seeding Program

The cloud seeding operations planned for the winter of 2006-2007 will be much the same as this past year. The Ruby Mountain, Owyhee and Toiyabe ground seeding networks will have the same number of generators, with two sites in the Rubies getting refurbished units. The generator fabricated this past year will be installed in the Tahoe network at a site considerably south of the current four generators, bringing the Tahoe network up to five generators. Two Tahoe sites will also get generators with refurbished solution tanks and tubing. The Walker-Carson network will be basically the same with one new ground site being selected to replace one of the Sweetwater sites that was abandoned this past winter.

Operations will be conducted under the same guidelines and seeding criteria, however the newly revised GUIDE model will begin to be used to help assess seeding conditions for both ground-based and aircraft operations in the Tahoe Basin. Aircraft operations are planned for the Walker-Carson and Tahoe-Truckee target areas, with about the same number of flight hours as in prior years.

The program director will continue to work with state agencies in the Colorado River Basin as planning evolves for additional cloud seeding operations (and evaluations of the augmented operations) in the Upper Basin.

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APPENDIX A

Weather Modification White Paper (Ryan, 2005)
Winter Cloud Seeding White Paper (Griffith and Solak, 2006)
Seven Basin States Letter to Secretary of Interior (2005)

WEATHER MODIFICATION FOR PRECIPITATION AUGMENTATION AND ITS POTENTIAL USEFULNESS TO THE COLORADO RIVER BASIN STATES

October 2005

Tom Ryan, Metropolitan Water District of Southern California

Technical Reviewers

Joe Busto, Colorado Water Conservation Board,
Vice-Chairman North American Interstate Weather Modification Council

Arlen W. Huggins, Desert Research Institute, Nevada,
Chairman North American Interstate Weather Modification Council

Steven M. Hunter, U.S. Bureau of Reclamation, Denver

Executive Summary

This paper provides a brief background of weather modification, information on existing programs and current issues, and provides recommendations for the Colorado River Basin States (Basin States) involvement or support of precipitation management through weather modification efforts.

The purpose of winter cloud seeding to increase snowfall in mountainous areas is to increase runoff for hydroelectricity and water supplies for downstream areas. Increases in precipitation can improve soil moisture, stream flows, and reservoir levels. More water storage in reservoirs can allow for increased power generation, irrigation, and municipal and industrial use. Recreation, water quality, salinity reduction, fisheries, forest health, sensitive species, ranching, and tourism can all benefit from additional runoff.

Members of weather modification organizations, public agencies, and private sector companies believe that cloud seeding has reached the point that a well designed and managed program with a proper design component can be implemented to produce cost-effective water resources benefits. More research on the specific cause and effect relationship between cloud seeding and additional water on the ground should be conducted as well. Any proposed operational cloud seeding program should include a strong evaluation component.

It is estimated that cloud seeding six major runoff-producing areas within the Colorado River Basin could produce between 1.1 and 1.8 million acre-feet (maf) in the Upper Basin (approximately 10% of the average annual stream flow) and an additional 830,000 acre-feet in the Lower and adjacent basins. Of the total, it has been estimated that approximately 1.7 maf would be available to reduce deficits and meet new demands.

Although there is wide discussion regarding the effectiveness of weather modification since it began in the 1940s, proponents of ongoing projects believe programs in Utah have resulted in precipitation increases between 7 and 20%, at costs of less that $20 per acre-foot, which compares favorably with traditional water resources projects. The programs currently in operation in Colorado and Utah demonstrate the success of weather modification (WxMod) activities there. Ski areas, water authorities, and agricultural users are the most common project sponsors.

There are several good reasons for the Basin States to continue its research on this topic. One of the most important is the 2000-2004 Colorado River drought, which is a normal part of the climate of the arid Western United States and Colorado River Basin. Others are a general trend toward reduction in snowpack, increased water demands, as well as the growing concern about reductions in precipitation due to inadvertent anthropogenic modification to weather (air pollution). Factors to consider in deciding how to proceed are that: new projects take 1-3 years to plan; planning is relatively inexpensive; there is a real need for research and project funding; these projects are very cost-effective, and there are existing programs with data that can be leveraged.

This paper recommends:

- further investigation continue as to the availability of WxMod projects in which the Basin States can participate, particularly those focusing on the Upper Basin States of Colorado and Utah;
- legislation continue to be monitored, and attempts to influence legislators be considered;
- an implementation plan be developed with next steps, including a schedule, costs, and deliverables for a feasibility study to increase winter precipitation that would include both operational and evaluation components;
- the Basin States enlist either the U.S. Bureau of Reclamation (Reclamation) and/or the National Oceanic and Atmospheric Administration as the lead federal agency in the development of a coordinated national research program, and that this program should piggy-back research onto existing and proposed operational programs like Reclamation's Weather Damage Modification Program;
- cost-share with Reclamation in an objective impartial evaluation of existing operational programs, and;
- for an interim period while the feasibility study is being prepared, expand ongoing operational programs by adding generators and by operating the programs for an expanded period of time each year.

The additional precipitation can help the Basin States potentially increase water supply in the Colorado River basin, and assist in reducing shortages, or reservoir storage recovery. WxMod should be a standard tool, similar to implementing conservation measures or storing and withdrawing water in groundwater basins for water resources managers to meet demands and assure reliability.

White Paper prepared by Don Griffith and Mark Solak of North American Weather Consultants, Inc., Salt Lake City, UT for the Upper Colorado River Commission (March 2006)

THE POTENTIAL USE OF WINTER CLOUD SEEDING PROGRAMS TO AUGMENT THE FLOW OF THE COLORADO RIVER

EXECUTIVE SUMMARY

Recent drought conditions and the associated drop in Lake Powell storage has generated renewed interest in means that might be used to better manage the water supplies for the seven basin states that share water from the Colorado River system through the 1922 compact. Means of augmenting the flows of the Colorado are also being examined. One technique that has been frequently mentioned is that of weather modification or "cloud seeding" as it is more commonly known. The Upper Colorado River Commission contracted for the preparation of this White Paper. The goals of this paper were to consider the status of the weather modification field and how cloud seeding could potentially be used to augment streamflows in the Colorado River region.

The potential for use of cloud seeding to increase the amounts of naturally occurring precipitation dates back to some early discoveries and experiments, first conducted in the laboratory and then in the atmosphere, in the late 1940's. Early enthusiasm for such applications led to the conduct of a number of research and operational programs during the 1950's. Some of this early enthusiasm diminished due to difficulties in detecting the effects of seeding on precipitation. In a sense, the potential of cloud seeding was oversold during this period. Additional research and operations were conducted with more realistic expectations beginning in the 1960's and continuing to the present time. Some skepticism remains regarding the effectiveness of cloud seeding, although several professional societies now state that winter time precipitation in mountainous areas can be increased on the order of 10%. Compelling evidence exists for the positive effects of cloud seeding in augmenting water supplies in the west, although proof in the strict scientific sense is elusive.

Several operational winter cloud seeding programs have been conducted in the Sierra Nevada Mountains of California dating back to the early and mid-1950's in a couple of cases and the early to mid 1960's in several other cases. Winter cloud seeding programs have also been operated for a number of years in portions of Colorado, Utah, and Wyoming. For example, programs in Utah date back to 1974. Estimations of the effects on precipitation commonly indicate seasonal increases of the order of 5% to 15%.

This paper identifies areas within the Colorado River Basin where a) new <u>operational</u> winter cloud seeding programs could be developed and b) existing programs enhanced through additional funding to provide additional runoff in the Colorado River system. These activities

would include new or expanded programs in the States of Arizona, Colorado, Utah and Wyoming. Streamflow that contributes to Colorado River flows in these areas is primarily generated via melting snow from the higher elevation areas of these states, thus the recommendation for the focus on winter time programs.

A distinction is made between operational programs and research programs. Operational programs are conducted to achieve a specific objective or objectives; in this case, increases in streamflow in the Colorado River Basin. Cloud seeding research programs are conducted to advance knowledge; perhaps to gain a better understanding of how cloud seeding works or to demonstrate the effectiveness of a new seeding approach. Research programs are inherently more costly than operational programs. Research activities could be superimposed on some of the operational programs, as has been done in programs such as the Bureau of Reclamation's Weather Damage Modification Program that is currently active and the earlier National Oceanic and Atmospheric Administration's Atmospheric Modification Program conducted in the 1980's and 1990's. Additional federal funds would be needed to perform such "piggyback" programs, if desired.

The anticipated effects from well designed and conducted operational seeding programs range from 5-15% increases in precipitation. Streamflow model simulations performed by the National Weather Service, River Forecast Center located in Salt Lake City, Utah for the Upper Basin States of Colorado, Utah and Wyoming predict increases of 650,500 acre feet of April through December runoff into Lake Powell during an average year resulting from the conduct of new cloud seeding programs assuming a 10% increase in October through March precipitation. Similar projections for existing operational seeding program areas indicate an estimated average increase of 576,504 acre feet of October through March runoff into Lake Powell in an average year, assuming a 10% increase in precipitation. The total from new and existing areas would be 1,227,004 acre feet. Obviously, the same percentage increases in precipitation in wet years would produce higher amounts of runoff and lower amounts in dry years. Seeding suspensions in very wet winters would limit the expected total increase from such winters. Ample storage would typically be available in the tributary and especially the main stem reservoirs such as Lake Powell to contain any amounts of expected increases in runoff even from wet and very wet winters. It is estimated that an additional 154,000 acre feet of annual runoff could be generated from new seeding programs in the lower Colorado River Basin of Arizona. **The total estimated average potential would therefore be 1,381,004 acre feet.** Some of this potential is currently being realized through the conduct of existing programs in Colorado and Utah, but no attempt has been made in this study to quantify the amount of runoff being generated by these programs. Means of augmenting some of these existing programs are contained in this study. No attempt was made in this study to quantify the additional streamflow that might be generated through such augmentation of existing programs. In a sense, these latter two issues are offsetting; some increases in streamflow from existing programs are currently being realized which would lower the estimated increases whereas enhancements of existing programs operations would increase these estimates.

A preliminary estimate of the costs associated with developing new operational programs and augmenting existing ones for the four states on an annual basis is $6,965,000. Design studies for each of the new potential operational areas are advisable in order to customize cloud seeding activities for specific areas. The above estimated costs include a reservation of 15% of the total funds for evaluations of the effectiveness of the cloud seeding in the new operational areas. Both statistical studies and physical measurements (e.g., detection of silver in snow that could be attributed to the seeding agent, silver iodide) could be performed. **The approximate cost of the estimated additional water which could be produced through cloud seeding is estimated to average $ 5.00 /acre foot.** Estimates of the value of the additional water could be used to assess the benefit/cost aspect of the proposed projects.

An attractive aspect of cloud seeding programs is that they can be implemented and, if needed, terminated comparatively quickly, since they generally do not involve the development of large permanent infrastructure. Further, operations can readily be suspended during very wet periods and restarted when appropriate.

No significant negative environmental impacts are anticipated from the conduct of such programs, based upon the findings from a number of large scale office and field environmental programs funded by the Denver offices of the Bureau of Reclamation. Several of the field programs have been conducted in the winter environments of California, Colorado, Utah and Wyoming.

When objective assessments of various water resource management and supply options are conducted in similar situations, the weather modification option typically emerges as a most attractive avenue. It appears that this is true for the Colorado River system. This White Paper describes various aspects of the winter cloud seeding option in some detail including a list of recommendations in Section 18.

Recommendations shown in the text are also listed here.

- New operational winter cloud seeding programs should be established in suitable areas in the states of Arizona, Colorado, Utah and Wyoming that are currently not part of active operational programs. This will enhance runoff into the Colorado River Basin. The term "operational" is used to denote programs whose primary goal is to produce additional precipitation. In other words, these programs would not be research oriented, although some research activities might be "piggybacked" on some of these programs should additional Federal or state funding become available. There is precedent for this approach in earlier "piggyback" research activities being added to operational programs in Colorado, Nevada and Utah through Federal funding.
- The development of new programs should follow the existing regulations that are concerned with weather modification activities within each State in which the program is to be conducted. All four states (Arizona, Colorado, Utah and Wyoming) have such regulations.
- Design studies should be conducted to guide the development of potential projects in new areas. Such studies will allow a customized approach to the development of each new program, taking into consideration area-specific factors such as climatology, topography, presence and frequency of seedable conditions, and seeding targeting and social considerations. The State of Wyoming, through their Water Resources Development

Commission, has recently adopted this approach in their consideration of new programs in the Wind River, Sierra Madre, Medicine Bow, Salt and Wyoming Mountain Ranges.

- Existing operational programs within the Upper Colorado River Basin could be potentially enhanced. Means of enhancing these effects should be coordinated by the existing program sponsors and operators. Modifications might include additional seeding equipment, different types of seeding equipment (e.g. aircraft in addition to ground seeding and/or remotely controlled ground generators), and longer operational periods if the full seasonal window of seeding opportunity is not currently being seeded.
- Approximately 10-15% of the budget to conduct new programs should be devoted to evaluations of the effectiveness of the new programs. Two general types of evaluations should be considered; statistical (e.g. historical target/control analyses) and physical (e.g. chemical analysis of snow to detect the presence of silver associated with the release of the silver iodide seeding agent). Additional evaluations of existing programs are not proposed since the program sponsors and/or operators are currently performing their own evaluations.
- Additional simulations of impacts of assumed seeding increases on streamflow should be performed. Such simulation work should be a part of any design studies conducted for potential new seeding areas.
- It is recommended that a multi-year research program be conducted to determine the effectiveness of propane seeding in generating increases in precipitation over large scale areas the size of typical *operational* winter programs. It is recommended that the funding for this research program be obtained from federal sources and consequently the costs of conducting such a research program are not included in the cost estimates contained in Section 15.
- It is recommended that the Seven Basin States support any Congressional Bills that relate to the development of a "coordinated national weather modification research program" such as that proposed in HR 2995 and S 517.
- The Upper Basin States should develop cooperative agreements that feature the development of a "basin-wide water augmentation via cloud seeding program."
- Representatives of the Seven Basin States should consider convening an ad hoc committee to develop the scope of a short-term (3 year) program to augment and fund some of the existing operations and develop and fund some of the potential new programs.
- Representatives of the Seven Basin States should consider beginning discussions regarding cost-sharing and administration of new programs and augmentation of existing programs.

Seven Basin States Letter to Secretary of Interior Norton (2005)
[Cloud seeding mentioned as one option to augment water supply]

The States of Arizona, California, Colorado, Nevada,
New Mexico, Utah and Wyoming
Governor's Representatives on Colorado River Operations

August 25, 2005

Honorable Gale A. Norton, Secretary
Department of the Interior
1849 C. Street, NW
Washington, D.C. 20240

Re: Development of Management Strategies to Address Operations of Lake Powell and Lake Mead under Low Reservoir Conditions

Dear Secretary Norton:

This letter responds to your May 2, 2005, letter to the Governors of the Seven Colorado River Basin States (basin states) in which you announced your intent to undertake a process to develop Lower Basin shortage guidelines and to explore management options for the operation of Lakes Powell and Mead. The Bureau of Reclamation published a notice on June 19, 2005, in the Federal Register announcing its intent to solicit comments and hold public meetings on the development of management strategies for Lakes Powell and Mead, including Lower Basin shortage guidelines, under low reservoir conditions.

For more than a year, the basin states Governors' representatives, the Bureau of Reclamation, and others have engaged in discussions on a variety of potential management options to address the system-wide drought in the Colorado River Basin. Recently, the basin states agreed that management strategies should be designed to delay the onset and minimize the extent and duration of shortages in the Lower Basin. The states agreed that management strategies should maximize the protection afforded to the Upper Basin by Lake Powell against possible calls upon the Upper Basin to curtail uses. The states agreed that shortage guidelines should be premised upon proportionate sharing of shortages by Mexico pursuant to the Mexican Treaty.

The basin states are in the process of developing and evaluating alternatives for coordinated reservoir management and Lower Basin shortage strategies to address the above objectives. In addition, the basin states are exploring a larger, more comprehensive management arrangement. This arrangement would avoid political and legal confrontation over the meaning of fundamental aspects of the Law of the River; supplement the supply of Colorado River water; develop acceptable interim shortage guidelines for the Lower Basin; and realize a common goal to implement management strategies that might allow more efficient, flexible, responsive and reliable operation of the system reservoirs for the benefit of the states of both the Upper and Lower Basin. The states regard such an arrangement as important to the continued development and use of the Colorado River resource in both the Upper and Lower Basins. The Secretary should recognize that the coordinated management and shortage strategy outlined in this letter is recommended only on the condition that the other aspects of that more comprehensive management arrangement can be finally agreed upon and implemented by the states and the Secretary.

The states propose that any reservoir operational strategy developed by the Secretary be explicitly limited to an interim period. The interim operations should be tied to the implementation of additional measures that will accomplish the dual objectives of supplementing the supply of the Colorado River, and operating the existing infrastructure in the system more efficiently. The elements set forth in this letter are interrelated, and represent an integrated strategy for managing the Colorado River into the future. Therefore, all of the elements of this strategy will need to be implemented. In addition, practical resolution of differences among the basin states regarding mainstream and tributary development will be required. The states' strategy consists of three elements.

Coordinated Reservoir Management and Lower Basin Shortage Strategies

The states are discussing ways to utilize the water surface elevations or volumetric contents of both Lake Mead and Lake Powell to determine the beginning and end of a Lower Basin shortage condition. The strategy could incorporate various water management components including: tiered releases from Glen Canyon Dam; content balancing; alternative release schedules; continued operations under Section 602(a); other equalization strategies; and storage (banking) of water in Lake Mead. All of these operational components are currently being studied under the assumption that the Lower Basin shortage strategy would be two-tiered, the first tier protecting a Lake Mead water surface elevation of 1,050 feet, and the second tier assuring maintenance of a Lake Mead water surface elevation of 1,000 feet.

There may be additional reservoir water surface elevations identified to help achieve the management objectives prior to the actual declaration of a shortage. The quantities of reductions in demand are still being analyzed. After consultation with water users and completion of the analyses, the basin states will recommend conditions under which the Secretary may declare that insufficient water will be available for release from Lake Mead to satisfy 7.5 maf of consumptive use from the mainstream in the Lower Basin, and a delivery of 1.5 maf to Mexico. The basin states will also recommend reductions in deliveries that can be reasonably managed by the states and water users during the interim period. A plan to manage the shortage condition and to allocate reductions among water users within the Lower Basin will be developed and recommended to the Secretary. Acceptance of the recommendations is an essential condition for the success of an integrated strategy for the operation of the Colorado River.

The coordinated operational policies and procedures for the storage of water in and release of water from Lakes Mead and Powell may apply during a defined interim period consistent with the Interim Surplus Guidelines (until 2016, or as the ISG might be modified and extended), or for so long thereafter as may be necessary to achieve selected target elevations in Lakes Powell and Mead. Power and recreational impacts of such operations will be coordinated, but water supply operations will remain the first priority of coordinated operations.

Shortages to Mexico under the 1944 Treaty would be shared proportionately with those incurred by the Lower Basin states, as shortages may be imposed under the shortage guidelines. The states anticipate that shortages to both Mexico and the Lower Basin will be reduced proportionately with the implementation of the coordinated operation strategy.

Because such coordinated operations may alter the volume of water delivered from Lake Powell from that under existing operations during times of low reservoir conditions, the states are evaluating the effects that coordinated reservoir management may have on the recently adopted Interim Surplus Guidelines, as well as considering whether to agree that during the interim period they will not raise issues of the meaning, interpretation or enforcement of the Colorado River Compact, the 1968 Colorado River Basin Project Act, or other aspects of the Law of the River concerning any obligation of the Upper Basin to meet any requirement at Lee Ferry. The states are considering whether agreement not to raise Law of the River issues will continue to the end of the interim period, or longer.

System Efficiency and Management

The basin states will work with the Department of the Interior to analyze and implement a program of tamarisk eradication throughout the basin. The states believe such a program may yield multiple benefits to the environment and water supply of the basin.

The basin states will work with the Department of the Interior to develop a prioritized list of specific measures that will result in the more efficient management of the River in the Lower Basin. Initial priorities for implementation will include development of All-American Canal Drop 2 storage, evacuating accumulated sediments behind Laguna Dam, development of Wellton-Mohawk regulatory storage, and full utilization of Senator Wash Reservoir. Additionally, the states are discussing measures to better coordinate daily system operations and water orders of contractors in the Lower Basin to prevent the loss of water. It will be necessary for the Department to take all necessary actions to account for and replace water that has been released to Mexico through the bypass drain since 2004, and continue to implement measures that minimize the over-deliveries of water to Mexico. It will also be necessary for the Department to aggressively pursue elimination of unauthorized uses of Colorado River water in the Lower Basin.

Augmentation of Supply

The basin states will work with the Department of the Interior to implement a precipitation management (cloud seeding) program in the basin (both Upper and Lower). Any additional water generated to the Colorado River system will be considered system water. No entity or state will have any claim to any additional supply developed by precipitation management.

The basin states will work with the Department of the Interior to analyze the technological feasibility of desalination, and issues such as siting, environmental impacts and the potential to exchange desalinated water into the Colorado River system.

The states are discussing programs under which states may provide, and get the benefit of, individual supply augmentation including desalination; ground water developed and conveyed to add to the Colorado River system; tributary water that has been consumptively used for irrigation that is retired to permit its flow into the Colorado River; temporary consumptive use of additional water from Lake Mead; and wastewater that is generated by the direct use of any water and that is permitted to flow into the Colorado River. The basin states will work with the Secretary to explore additional methods of augmentation. It will be necessary for the Secretary to develop and implement regulations to allow the use of mainstream Colorado River water by forbearance, replacement or exchange.

The basin states representatives recommend that the Secretary adopt interim guidelines, concurred to by the states, for the implementation of the Long Range Operating Criteria (LROC) under low reservoir conditions in Lakes Mead and Powell, together with interim shortage guidelines in the Lower Basin. If at the end of the interim period changes to the LROC are warranted, then the Secretary may consider such changes.

Finally, the basin states recognize that the concepts discussed in this letter raise potentially significant legal and political issues. The basin states look forward to working with you and the Department in analyzing and addressing these issues.

[Signatures on Following Page]

APPENDIX B

Summary Section from the Final Report of the Nevada Weather Damage Modification Program submitted to U. S. Bureau of Reclamation in May 2006 (Authored by Arlen Huggins, Desert Research Institute)

VI. Summary and Conclusions

VI A. WDMP Modeling Summary

The WDMP mesoscale and plume dispersion modeling study included three case studies, two from the Tahoe region and one from the Walker Basin. The initial case looked at simulated plume dispersion from generator sites from the SMUD project, positioned to target the Upper American River Basin upwind of the Nevada Tahoe and Truckee target areas. The study focused on a 48-hour storm period that produced a relatively typical trough and cold frontal passage over northern California and Nevada. The storm produced heavy snowfall in the Tahoe Basin. The plume dispersion simulation indicated that SMUD generator plumes crossed the Nevada project areas in all boundary layer wind directions from south-southwest through west. For periods when liquid water and temperature conditions were appropriate, the AgI from SMUD generators was very likely to have produced a seeding impact in the Nevada project areas. AgI concentrations might not have always been sufficient to markedly increase precipitation, but the seeding operations would very likely have increased the Ag concentrations in the Tahoe and Truckee snowpacks to levels above the natural background. This finding complicates the evaluation of Nevada project areas based upon trace chemical techniques, particularly when only Ag is used as a tracer for targeting evaluations. It would be advisable to use a second tracer in Nevada generators to differentiate between seeding effects contributed by the two projects.

A second Tahoe case study focused on an event seeded by aircraft and ground generators during the Sierra Cooperative Pilot Project (18-19 December 1986), and reported on by Deshler et al. (1990) and Reynolds et al. (1989). Plume dispersion from DRI generators that were included in the SCPP randomized ground seeding experiments was simulated using LAP with MM5 wind fields for this period. The LAP results closely matched results from the simple SCPP targeting model that was run using SCPP soundings as input. LAP plumes from the initial SCPP experiment indicated that DRI generator plumes would have gone well to the north of Lake Tahoe, possibly north of the entire Nevada project area. LAP plumes from a second experiment also moved generally south to north, but would have been more likely to impact the Truckee Basin north of Tahoe. SCPP trace chemistry results from samples collected throughout the Tahoe and Truckee targets following these experiments verified that Ag was found only in the northernmost regions of the Tahoe-Truckee target. This study and an earlier modeling study by Huggins et al. (1998) revealed that, with one exception, the current network of Nevada ground generators was producing seeding plumes that consistently passed over the intended target area.

The one generator that typically produced a plume that passed to the north of the Tahoe target was removed in 2004. The locations of specific LAP plumes were also consistent with locations of snow profiles that contained enhanced levels of Ag (noted in Section II).

The third MM5 and LAP modeling study (2-3 February 2004) was centered on the Walker Basin to the south of Lake Tahoe. This was the first high resolution modeling study in this area and the first to simulate seeding plumes over mountainous regions downwind of the main Sierra Nevada crest. Some MM5 variables were able to be verified by WDMP measurements. The temporal trend in MM5 water vapor agreed well with microwave radiometer water vapor depth above the Walker Basin. MM5 cloud water amounts were similar to radiometer measurements, but the duration of cloud liquid over the downwind region was underestimated. MM5 precipitation estimates were very good in timing and amounts compared to measurements near the Sierra crest, but were significantly less than the observed precipitation downwind of the crest. MM5 cloud water predictions upwind of the crest matched aircraft measurements, but the extent of cloud water downwind was also underestimated.

LAP ground generator plume predictions were not verified by atmospheric measurements, but Ag from the seeding agent was found in segmented snow profiles that corresponded to the portion of the snowpack that was produced by the 2-3 February storm. LAP plumes revealed the very turbulent nature of the air motion in the downwind regime, and indicated that mountain-induced waves would at times aid in the vertical dispersion of seeding material. There was, however, no strong indication that plumes would interact with clouds formed by the waves consistently enough to produce a seeding effect. The main finding, based on LAP results, was that the ground plumes were much more likely to be transported onto clouds over the downwind target ranges in southerly to south-southwesterly air flow. Further work to verify plume locations would still be useful for this region.

Finally, the LAP model was adapted to produce the first plume predictions for a moving aircraft seeding platform. The initial method produced a stationary line source from which seeding particles moved continuously downwind. However, the final version produced a more realistic simulation of a moving point source, with the point moving at the speed of the aircraft and releasing particles in numbers proportional to the actual release rate of a solution-burning generator.

Real time versions of LAP have been developed for air pollution studies in the coastal regions of California. These versions, which are initialized from real time MM5 runs, could prove to be quite useful in future cloud seeding operations and research activities. For a complete evaluation of seeding potential, however, the plume dispersion predictions still need to be incorporated with ice nucleation, ice particle growth and fallout parameterizations.

VI B. WDMP Snow Chemistry Summary

The Nevada WDMP snow chemistry study involved the analysis of snow samples from partitioned snow profiles collected in the Tahoe-Truckee and Walker Basins during Water Years

2004 and 2005. Snow samples were analyzed at the DRI Ultra Trace Chemistry Laboratory using a state of the art Inductively-Coupled Plasma Mass Spectrometer (ICPMS). This instrument is capable of detecting some elements in the PPQ (10^{-15} g g^{-1}) range of concentration. The elements of interest for the Nevada Cloud Seeding Program were silver (Ag), indium (In), cesium (Cs), aluminum (Al) and rubidium (Rb). Ag is the main element in seeding materials used in the Nevada program. In, although not used in WY04 and WY05, has been used in seeding experiments as an inert tracer, and its background concentration in the Nevada project areas was of interest. Cs was used as a tracer in the aircraft seeding solution in WY04, and incorporated into aircraft seeding flares in WY05. Al and Rb are elements common in the earth's crust and their concentrations were analyzed to give an indication of contamination of snow samples by sources other than cloud seeding operations.

Snow profiles were collected using the DRI-Profiler 1 in WY04 and a new DRI-Profiler II in WY05. Details of the sampling methods used with both profilers were given in Section II. The snow chemistry study was designed to evaluate the effectiveness of cloud seeding targeting in the two basins, to provide a data set for verification of plume dispersion modeling studies, and to attempt to verify a correlation between snow density and Ag concentration that has been used in other cloud seeding projects to quantify the impacts of seeding on snowfall. The analysis of Cs was also used to attempt to distinguish aircraft seeding effects from ground seeding effects, since the ground-based generators contained no Cs.

Specific results from the WDMP trace chemistry study are as follows:

1) The frequency of samples from four sites in the Tahoe Basin in WY04, with Ag $\geq$10 PPT, was very high (> 70%) and indicated targeting from seeding operations was routinely accomplished. One sampling site in the Truckee Basin north of Tahoe had a much lower frequency of occurrence (~30%) of enhanced Ag. The Tahoe results were better than earlier studies in this region, and indicate that the overall efficiency of ground generators in this region has improved. The difference in targeting effectiveness between the Tahoe and Truckee regions was in agreement with plume modeling studies from past work, and with results in Section I.
2) A method of partitioning snow profiles into storm periods, using nearby time-resolved SWE measurements from SNOTEL sites, was used successfully to determine which specific seeding operations contributed to the enhanced Ag concentrations in the profiles. This technique was used in both the Tahoe and Walker Basins.
3) Case studies from the Tahoe area revealed a relatively high correlation (R^2 as high as 0.6) between Cs and either Al or Rb, suggesting that Cs can be deposited in the snow by sources other than cloud seeding. This makes the use of Cs as a cloud seeding tracer somewhat less desirable than earlier studies had indicated. It also points to the need to analyze samples for crustal tracers in order to distinguish between seeding effects and results produced by dust contamination. No similar correlation was found between Ag and the crustal tracers.

4) Targeting effectiveness results for the Walker Basin in WY04 were similar to those in the Tahoe Basin, showing very high percentages of enhanced Ag concentrations at the four sampling sites used. Relatively high correlations between Cs and Al were also found at several of the Walker sites, with the highest having an R^2 of 0.83. As in the Tahoe Basin Ag was not well correlated with the crustal tracers.
5) A correlation between Ag concentration and snow sample density was not verified from the WDMP data collected in either basin in WY04. This was primarily due to the length of time between profile collections that allowed the snowpack to compact considerably, and likely resulted in the loss of any subtle density changes that might have been due to seeding effects. For quantitative evaluation of the impacts of seeding on snowfall, snow profiles and density measurements must be taken very soon after the snow has occurred. The development of a real time snow sampling instrument would be of great benefit to evaluations of this type.
6) A new snow profiler (DRI-Profiler II) was successfully developed and tested in the Tahoe Basin in WY05. This new profiler provides an improved method of sampling snow. Compared to Profiler I, there is less maintenance, less chance of contaminating samples, a redundancy in the two-dimensional grid that would have required two complete profiles with the old method, and it is much easier to clean.
7) The overall frequency of occurrence of samples with enhanced Ag was less in the WY05 sampling period with 35-52% of samples containing Ag ≥10 PPT. This might reflect the fact that the new profilers were less likely to be contaminated, or it might also indicate that the percentage of seeded periods was different between the two seasons. However, when the historical background of 4 PPT was used, the percent of "seeded" samples was still more than three times the frequency documented by studies in the 1980's.
8) Two profiles taken from the Tahoe Basin in WY05 showed clear evidence of aircraft seeding (with Cs incorporated in flares) effects, with enhanced Cs and Ag found in similar snow layers, without the presence of enhanced crustal tracers.

The snow chemistry results from WY04 and WY05 again showed the strength of using this method in evaluating the effectiveness of seeding operations, in this case mainly targeting, but the use of combined data from other surface-based instruments should lead to a means of quantitative evaluation. A technique similar to that of Warburton et al. (1995a) that employs high resolution precipitation measurements and a dual tracer (Ag and In) is currently being tested as a means of estimating the amount of additional snowfall that seeding produces.

VI C. Summary of WDMP Measurements of Supercooled Liquid Water

The main focus of this study was to collect a set of radiometric measurements of SLW in the Walker Basin. These measurements were used for model verification, as noted in Section I, and provided the first long term documentation of SLW in the Walker Basin, in a region slightly downwind of the Sierra Nevada crest. These measurements had important implications for the Nevada State Cloud Seeding Program, where the existence of SLW beyond the crest is necessary if a cloud seeding effect is to be expected in the interior of the Walker Basin. The radiometer was operated in a zenith-pointing mode from November 2003 to April 2004. Details of the data collection are provided in Section III.

Radiometer measurements were compared to SLW measurements taken by the Nevada cloud seeding aircraft and by the WDMP research aircraft for several operations over the Walker Basin. Five case studies indicated that SLW water was generally detected by the radiometer when one or both aircraft documented SLW upwind of the Sierra crest. One case on 2 February 2004 showed reasonable agreement in the magnitudes of SLW (when radiometer depths were normalized to a 1-km thick layer) at times when the research aircraft flew in close proximity to the radiometer. In this case both instruments also indicated that MM5-modeled cloud water was underestimated in the downwind region.

The seasonal radiometer data indicated that 55-90% of the storm period (times when precipitation was recorded in the basin) hours in December through March of WY04 had radiometer liquid water above the threshold of detection of the instrument. When comparing the hours of ground seeding events to these same liquid water periods, it was found that the percentage of seeding hours to liquid hours ranged from 0 to 64%. March contributed the 0% since it was a very dry month with almost no storms, and one seeding opportunity near the beginning of the month was missed. The main reason for other liquid periods not being seeded was that the -5° C level was determined to be too high for ground seeding operations.

The radiometric measurements indicated that lengthy seeding opportunities existed over the Walker Basin, and in general the Nevada Program took advantage of these opportunities. With the general lack of meteorological data in the Walker Basin, an unattended radiometer that gathers data continuously would be of great benefit to the operational seeding program. The 2004 data also indicated that many more hours of seeding (as many as 50% more) could have been accomplished if a seeding agent such as liquid propane, which is an effective ice nucleant at temperatures as warm as -2° C, was used as a seeding agent.

VI D. Summary of the WDMP Hydrologic Modeling Study

The original plan for the hydrologic modeling study was to set up a modeling system for two basins, one in the Tahoe area and another in the Walker. Although the Tahoe region sub-basin was set up for the model, only the Walker Basin setup was used for sensitivity tests related to the impact of cloud seeding. The focus on the Walker was justified, in part, by the recent intense focus on Walker Basin water issues, in particular the declining level of the terminal Walker Lake. Numerous studies have been underway to determine how to increase the flow to Walker Lake, and augmented cloud seeding has been proposed as one option. In order to determine the impact of cloud seeding, a method is needed to assess how much additional runoff might be expected from cloud seeding efforts, and thus this modeling effort was undertaken.

The USGS Precipitation-Runoff Modeling System (PRMS) was chosen for the study. The entire Walker Basin was subdivided into Hydrologic Response Units (HRU) for the purpose of the study, and the impact of cloud seeding was simulated by increasing the SWE in specific HRU where the impact of the Nevada Cloud Seeding Program was expected. In some instances the impacts were verified by the presence of the cloud seeding chemical in the snowpack, as discussed in Section II. So, although the additional quantity of SWE could not be verified, the targeting of by seeding operations was verified.

The details of the modeling setup are given in Section IV. Two case studies were run for the 2004 Water Year, one a non-seeded condition and the other based on a 10% increase in precipitation in five specific cloud seeding target areas. The results indicated that the additional precipitation resulted in increases in evaporation and runoff from the target areas, but did not significantly impact soil moisture and groundwater. The fraction of the added precipitation that went into streamflow ranged from 49% to 89% among the five different targets. There is a relatively large uncertainty in the specific amount of runoff to be expected. It is felt, however, that the modeling gives water managers in the basin a better understanding of how the different target areas will respond to additional precipitation, both volume and timing of additional runoff. Future work will focus on quantifying the impacts of cloud seeding through trace chemistry studies, and additional hydrologic model sensitivity tests.

VI E. Summary of WDMP Research Aircraft Studies

The WDMP research aircraft studies were designed to characterize the natural cloud environment in which seeding was conducted, to document the characteristics of ice particles in seeded cloud regions and to supply verification data for modeling studies. The first and third objectives were accomplished, but the second objective was only marginally accomplished due to the lack of data needed to verify seeding plume locations. The ice nucleus counter that was intended to provide this verification data was never successfully operated on the research aircraft. Terrain avoidance restrictions also prevented sampling within ground seeding plumes, so only aircraft seeding events were studied.

Five aircraft seeding operations were studied in some detail. In each case the seeding aircraft flew predetermined flight tracks upwind of the intended target, and the research aircraft flew upwind-downwind tracks orthogonal to the seeding tracks. A method of projecting seeding lines downwind at the estimated speed and direction of the wind at flight level was used to predict when the research aircraft crossed a seeded region. The details of the analysis method are discussed in Section V. The interception of seeding lines by the research aircraft was also complicated by flight restrictions placed on the seeding and research aircraft by Air Traffic Control, and by the fact that seeding was done in a region of generally rising air, but that particle development and fallout was likely to have occurred in downward moving air to the east of the Sierra Nevada crest. Exactly where a region of seeded ice particles crossed the flight level of the research aircraft was likely different in each experiment, and put a large uncertainty on the identification of seeding signatures.

All five case studies were conducted in conditions that appeared to be conducive to seeding with an AgI nucleant. SLW was typically persistent along the seeding track, and present in concentrations at times greater than 0.3 g m^{-3}. Airframe icing was frequently observed by the pilots and the seeding aircraft at times had to descend to deice. Expect for the final case all operations took place at temperatures $\leq$-8° C. In one case the research aircraft documented SLW concentrations up to 0.6 g m^{-3} at -15° C, where the cloud droplets were in concentrations < 70 cm^{-3} and where the mean volume diameter exceeded 20 μm. Other cases were also found to have relatively large cloud drop sizes, and this finding indicates that the condensation-freezing nucleant used in the Nevada Cloud Seeding Program is appropriate. The meteorological condition leading to these large droplet situations was often found to be associated with cloud development in the relatively warm region ahead of a large cold frontal band. A fetch of cloud well ahead of the frontal band often extended from off the California coast to the Sierra Nevada, suggesting a long period of time was available for droplet growth. The 2, 16 and 18 February cases provided examples of this situation.

From the five cases and many predicted interceptions of seeding lines, only a few interceptions showed ice particle data that resembled classic seeding signatures, such as large increases in ice particle concentrations compared to surrounding natural cloud regions and particle images that showed relatively uniform sizes and shapes within the seeded region. The 26 February case provided one of the better examples where one line was apparently intercepted multiple times and exhibited signals consistent with ice produced by seeding in each instance.

The aircraft cases clearly showed the need to verify the locations of the aerosol seeding plumes either by using an independent gas tracer, or by using an ice nucleus counter. It was also found that the flight plan needed to document seeding effects in the region downwind of a mountain barrier is much more complicated than one needed in just an upwind situation. The rugged terrain in the Walker Basin is particularly difficult to fly in and low level passes of downwind valleys are just not feasible in IFR conditions. It is unlikely that any suitable flight plan can be used to document seeding effects from ground seeding operations. Mountain top measurements and trace chemical evaluations may be the only way to verify seeding effects in this location.

APPENDIX C

NEVADA STATE CLOUD SEEDING PROGRAM
Operational Guidelines and Safety Restrictions

In the event of any emergency which affects public welfare in the region of any seeding operations being carried on by the Nevada State Cloud Seeding Program, the seeding operations in that region will be suspended until the emergency conditions are no longer a threat to the public. Seeding suspensions are generally expected to occur due to one or more of the following conditions:

A) When an extreme avalanche danger exists as determined by the U.S. Forest Service.

B) When the National Weather Service (NWS) forecasts a warm winter storm (freezing level >8000 ft.) with the possibility of considerable rain at the higher elevations which might lead to local flooding.

C) When the Project Meteorologist determines that potential flood conditions may exist in or around any of the project areas, the National Weather Service Flood Forecast Services at Reno or Sacramento will be consulted about the possibility of any of the following warnings or forecasts being in effect.

1. Flash flood warnings by the NWS.
2. Forecasts of excessive runoff issued by the CA/NV River Forecast Center, including such forecasts for rivers on the adjoining west slope of the Sierra Nevada.
3. Quantitative precipitation forecasts issued by the NWS that would produce excessive runoff in or around the project area.

In addition to the above, if any of the following conditions or forecasts exist; seeding operations may be suspended, at the discretion of the Project Meteorologist, in and around the areas of concern:

A) When the wind speed is 60 knots or more for over 30 minutes at the 700 mb level (~10,000 ft). For monitoring purposes in the western part of Nevada, the winds measured at Slide Mountain (9,650 ft) are considered equivalent to the 700 mb level winds. The Reno and Elko upper air soundings can also be used to monitor this criterion, as can the Doppler winds from the Reno and Elko NEXRAD radars.

B) When wind directions lie outside of the range between 180 and 330 degrees during ground-based seeding operations on the west side of the Sierra Nevada crest. The winds measured at Slide Mountain or Ward Peak (8,480 ft), and the upper air soundings and NEXRAD Doppler winds from Reno and Elko can be used to monitor wind direction.

C) When the water content of the snowpack in the target area, as measured at existing snow courses or SNOTEL sites, exceeds the accumulation envelope defined by the following percentages to date of long-term averages on the same date. NRCS SNOTEL data and reports are used to monitor snowpacks.:

December 1...175%	February 1...150%	April 1...140%
January 1.....150%	March 1....150%	May 1....140%

Intermediate limits shall be derived by linear interpolation between the percentages given above.

D) During major holidays such as Thanksgiving, Christmas, New Year's Day, and President's Day, in areas and times of heavy traffic on Highways 50 and 80, over the Sierra Nevada.

Created: 8/27/1990
Revised: 8/23/2006

NEVADA STATE WEATHER MODIFICATION PROGRAM
Weather Monitoring Facilities and Procedures

The Nevada State Cloud Seeding Program is operated from the Desert Research Institute Division of Atmospheric Sciences, located in the Northern Nevada Science Center (NNSC), Reno, Nevada. The project has 24-hour access to a broad base of National Weather Service (NWS) weather data through UNIDATA, a program managed by the University Corporation for Atmospheric Research (UCAR). The data are received by the Western Regional Climate Center (WRCC) at DRI and are available through the WRCC web site: http://www.wrcc.dri.edu.

In addition to the above NWS data products (supplied through UNIDATA and other sources), the data from remote weather stations on Slide Mountain, Ward Peak, the Squaw Valley and Alpine Meadows Ski Resorts, on Conway Summit, and at a sites near the Ruby Mountains, Tuscarora, NV, and the Wassuk Mountains are continuously available through the Internet or telephone modem at the NNSC. Data from the Bureau of Land Management RAWS network, the Natural Resource Conservation Service SNOTEL network, and from a local NWS hydro-meteorological network are available through the WRCC on a near real time basis. The Nevada State Cloud Seeding Program maintains its own web page with the bulk of these weather data links at the following address.

http://cloudseeding.dri.edu/Weather/Weather.html

The Nevada State Cloud Seeding meteorologist also confers directly with the National Weather Service forecasters and National Forest Service staff when flood or avalanche potential exists in any of the project areas. [See Operational and Safety Guidelines.]

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Revised: 8/26/2005

NEVADA STATE WEATHER MODIFICATION PROGRAM

Cloud Seeding Operations Criteria

The following weather and cloud conditions should exist to initiate or continue cloud seeding operations in any one of the operational areas of the Nevada State Program. Operations can also be initiated based on a 0-3 h forecast of these conditions existing in any of the three operational areas. Seeding suspension criteria will always override seeding operations criteria.

1. Cloudiness of sufficient areal extent to cover at least 50% of the intended target area. Verification is by means of GOES visible or infrared satellite images and NEXRAD radar images.
2. Clouds of sufficient depth, with cloud bases at least as low as the highest mountain peaks, to provide the potential for precipitation over the target areas. Verification of these conditions can be obtained by one or more of the following:
    a) NWS hourly reports of cloud conditions and precipitation at, but not limited to, the following sites: MMH, BLU, TRK, TVL, RNO, and EKO.
    b) Visual observations and/or reports of cloud conditions by the project meteorologist, other project staff, or contacts in any of the project areas.
    c) Observation of precipitation from any automatic recording gauge whose data are telemetered by telephone modem or the Internet to DRI. The DRI has access to many such gages in the Sierra Nevada and other mountain ranges throughout Nevada.
    d) WSR-88D (NEXRAD) radar images obtained from Sacramento, Reno or Elko NWS radar sites.
3. Wind directions that are conducive to transporting seeding material over the target areas. This criterion will vary by area as follows:
    a) Truckee-Tahoe area: Wind direction at 700 mb, as measured by the Reno NWS soundings (or soundings launched by the Sacramento Municipal Utilities District "SMUD" from Fresh Pond, Calif.), or estimated by weather stations close to the 10,000 ft altitude level, from (clockwise) between 180 and 330 degrees.

b) Carson-Walker: For ground seeding cloud level wind directions from 135 to 270 degrees as verified by the weather stations near Conway Summit and in the Wassuk Mountains.

c) Ruby Mountains: Wind directions in the cloud layer from 190 to 330 degrees as verified by the NWS Elko radiosonde, or remote weather station data.

d) Tuscarora area: Wind directions in the cloud layer from 90 to 270 degrees as verified by the NWS Elko radiosonde, or remote weather station data.

e) Toiyabe Mountain area: Wind directions in the cloud layer from 90 to270 degrees as verified by remote weather station data, or upper air weather maps.

4. Wind speeds at or near 700 mb should not exceed 30 m s^{-1} (~60 kt) in order that adequate time is available for growth of ice crystals initiated by seeding. Mountain top weather stations, NWS Reno and Elko upper air soundings, SMUD soundings, and NEXRAD radars will provide verification of wind speed.

5. The existence of supercooled liquid water in clouds is a condition necessary for successful cloud seeding. This quantity is not routinely measured over all the target areas, but the observation of icing at Slide Mountain (or other mountain top site), or the observation of liquid water from one of DRI's microwave radiometers should be given strong consideration in the decision to initiate a seeding operation in any area where these data are available. When available these data will be used in postseason evaluations of seeding operations.

6. To increase the likelihood of ice crystal formation by AgI seeding aerosols from ground generators, the temperature near 10,000 ft should be -5°C, or colder, as verified by data from the mountain top weather stations, or Reno, Elko, or SMUD soundings. Operations may be initiated at a temperature as warm as -3° C, provided the -5° C threshold is forecast to be met within 0 to 3 hours.

7. For aircraft seeding in the Truckee-Tahoe or Carson-Walker regions, winds can have a wide variety of wind directions. The airborne seeding contractor, in coordination with the DRI meteorologist, will determine suitable wind conditions based on radar observations, soundings, or NWS upper air charts. Flight levels will be selected to ensure that seeding material is released at temperatures colder than -5°C. The presence of supercooled liquid water must be verified for aircraft seeding operations to be initiated or continued.

The project meteorologist is responsible for forecasting and verifying seedable conditions, and also for initiating and terminating operations. Logs documenting the weather conditions during an operation will be kept on file at DRI by the meteorologist or other staff members.

Created: 7/21/1994
Revised: 8/23/2006

APPENDIX D

NEVADA STATE CLOUD SEEDING PROGRAM
Personnel, Facilities, and Project Work Cycle

Personnel:

For the 2005-2006 winter field program the following people were assigned to the Nevada State Cloud Seeding Program. The full time equivalent (FTE) participation of each person is noted. This past year about 0.25 FTE was allocated for technical services covering radio and electronics repair and development, computer programming and data reduction and processing. This FTE fraction was spread over several DRI staff and a graduate student. Although the FTE allocations of each person are indicated, the actual FTE contributed and billed to the project can be somewhat more or less.

Program Director and Project Meteorologist: Arlen Huggins (0.50 FTE)

Mr. Huggins has overall responsibility for the activities of the State Seeding Program. He establishes the meteorological guidelines for the Program and ensures that it is operated on a sound scientific basis. With guidance from the operations staff and from an assessment of the State's water conditions, he determines the seeding resource allocation for each cloud seeding season. During the operational season, Mr. Huggins is the project's forecaster and determines the timing of cloud seeding operations in each of the targeted basins and monitors meteorological conditions that can lead to suspension of seeding activities. Mr. Huggins is responsible for the evaluation and assessment of the project, including the compilation of an annual report that is distributed to water managers in Nevada and California.

Field Maintenance Supervisor: Tom Swafford (0.71 FTE)

Mr. Swafford is responsible for performing all ground seeding generator maintenance required both in the shop and in the field. He supervises and develops schedules for the field technicians who retrieve generators from field sites in the spring, overhaul them in the shop area during the summer, and reinstall the trailer-mounted generators in the fall. His job also includes keeping track of supply inventories and purchasing equipment and seeding solutions as needed. He ensures that seeding supplies are handled safely and mixed to exact specifications. Mr. Swafford maintains records and logs required for compliance with OSHA, EPA and fire department regulations. He is also responsible for the installation and maintenance of all the project's remote weather stations (five total). He supervises the hangar facility operations at Stead Airport, which houses the fabrication shops, offices, and the seeding materials storage. Mr. Swafford also overseers the maintenance of, and modifications to the communications networks.

Field Technicians:

The field technician positions cover the fabrication and maintenance of ground generators, weather stations, other special equipment used in the seeding program. These positions involve considerable travel to the various sites across northern Nevada and California. Much of the travel to seeding generator sites is by snowmobile to remote backcountry areas during winter. In recent years all the technicians have taken on the task of collecting snow profile samples for trace chemical analysis and project evaluation. The technicians are responsible for the specific activities listed below.

Bryan Loss (0.71 FTE)

Mr. Loss is the lead welder and generator fabricator. Under the supervision of Tom Swafford, Mr. Loss builds and repairs most of the hardware on the generator trailers and towers. He assists in the design of many special one-of-a-kind mechanical components. Mr. Loss also makes technical drawings of all cloud seeding equipment.

Jeffrey Dean (0.71 FTE)

Mr. Dean performs the basic activity of field technician, but is also responsible for the fabrication of electrical systems. He is the project's safety training officer, and uses his experience in backcountry survival to educate our staff in winter safety procedures. He conducts a winter survival training session each year. Mr. Dean also conducts the maintenance of specialized equipment such as the microwave radiometers and the NCAR ice nucleus counter.

<u>Facilities:</u>

With the move from the Stead Sage Building to the Northern Nevada Science Center (NNSC) in 1999, the space allotted for storage, maintenance and fabrication of the State Seeding Program equipment became inadequate. The bulk of the activities of the Program were shifted to a leased hangar facility at the Stead Airport. The lease expense has been offset by decreases in other operating expenses, resulting in no net increase to the Program's budget. The project director, program manager and budget manager have offices in the NNSC, and take advantage of the computer, business office and laboratory infrastructure for tasks related to meteorological data collection, budget management, and instrument development.

The leased space includes 2/3 of a hangar, a total of about 8,000 square feet. About 2,000 square feet are used for three offices, an electronics shop, a machine shop and three storage areas. The remaining 6,000 square feet are used for operations staging, chemical storage and equipment fabrication. About 2,000 square feet are used for the generator fabrication area, the welding area, the seeding solution mixing area, and storage (snowmobiles, trailers, tower components, and other equipment). Project vehicles typically occupy the main staging area and mobile generators (2 - 9, depending on time of year) which are being fabricated, refurbished, or maintained. Figure C-1 shows some of the equipment inside the hangar.

Project Work Cycle:

The Nevada State Cloud Seeding Program has a year-round schedule. There are two main periods of work, an operations season when the bulk of the actual cloud seeding is done, and a maintenance season when generators are either brought out of the field for maintenance at the hangar facility, or maintained by visits to the field sites. The maintenance period begins in May. This is also when data from the winter are compiled, and an assessment of operations is completed. The Annual Report is sent out in the summer. By July six to eight generators are brought to the Stead hangar for servicing. Servicing includes parts replacement, repair of damaged components, and painting. The communications systems are checked, and new calibrations are performed on the solution flow control system. In the fall field trips are made to the remainder of the generator sites (usually about eight) for a similar type of servicing in the field.

The silver iodide seeding solutions are also mixed during the summer and fall, enough to complete seeding operations for an average winter. In all about 25 batches of 55 gallons each are mixed. Mixing is a time consuming procedure, requiring careful handling, measuring, safety checks, and continuous logging of the chemical inventory.

Because of the harsh winter operating conditions each generator requires a complete refurbishment about every four to six years. Typically this is done to about two generators per year. All equipment is stripped out of the units, the solution plumbing is redone with new tubing and fittings, and the electrical systems are rewired. Depending on the degree of wear, solar panels, cables and many other components might also be replaced. Refurbishment typically starts in the summer, but is usually not completed until sometime during the winter.

By the end of summer the technicians begin returning the repaired generators to their field sites to meet the fall deadline for testing all units in the field. The initial site installation includes refueling, tying down the generator and tower, and doing a basic test of all operational systems. Once the entire network of generators in installed a complete remote test is performed on each unit. Additional field trips are then completed to bring the network into 100% operational status by mid- to late October.

The seeding operations can begin, at the latest, by 1 November. The technicians service the generators, as needed, during the winter. At least one major seeding solution refueling trip is required if the winter has an average to above average number of storms. The forecasting and operations scheduling are continuous until May. For at least half the sites, servicing must be by snowmobile once a snowpack has been established. The completion of work on generator refurbishment is usually accomplished by early spring. The fabrication of new generators, if called for, is initiated. Planning for the next season, including budget development begins to take place. All the major supplies for the next year of cloud seeding are ordered. By May the cycle starts over again.

Figure D-1. Nevada State Cloud Seeding Program facility at the Stead Airport. At left is one of DRI's microwave radiometers, used to remotely measure cloud liquid water and water vapor. Pictured at left is a field maintenance vehicle with mobile seeding generator attached for transport.

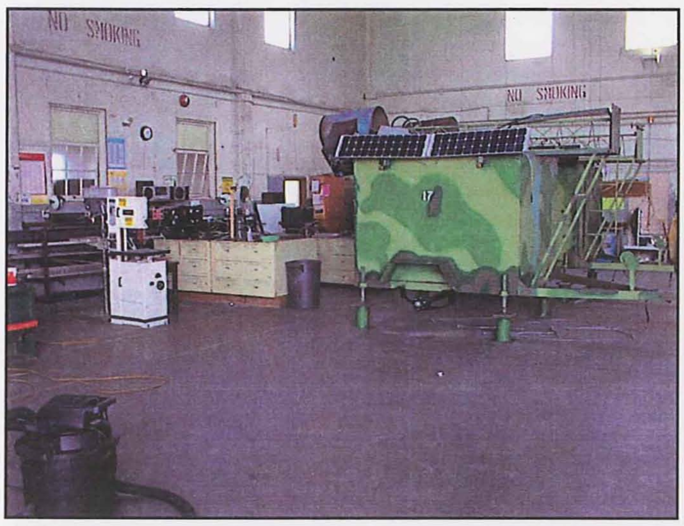

Figure D-2. Inside view of the hangar showing seeding generator fabrication area and shop tools.

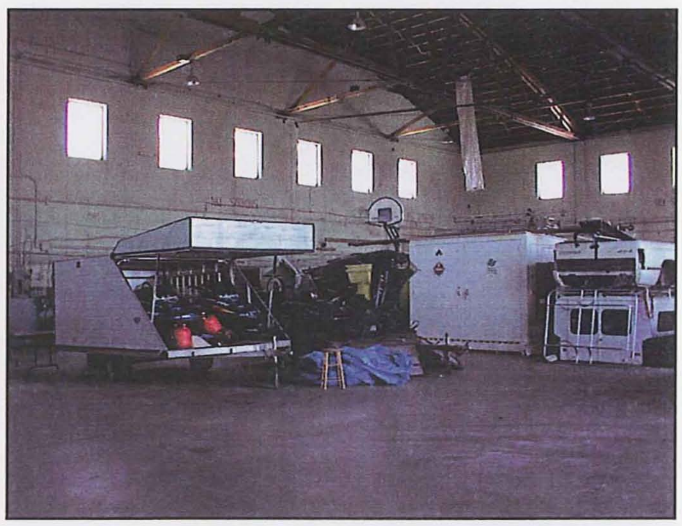

Figure D-3. Inside view of the hangar showing over-snow equipment and chemical storage area.