"REVIEWED"

EVALUATION OF A 2-MONTH COOPERATIVE GROUND-BASED SILVER IODIDE SEEDING PROGRAM

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Abstract. Field investigations to determine the effectiveness of ground-based AgI seeding generators to treat Sierra Nevada winter cloud systems were conducted by the Sierra Cooperative Pilot Project (SCPP) from November 3, 1986, to January 9, 1987. Of 18 randomized events, 12 were seeded and 6 were left unseeded. A postanalysis using the data collected by a variety of in situ devices and the results of a numerical targeting model identified periods which appeared to contain the best seeding potential and estimated the effectiveness of placing the effects within the desired target area.

Criteria used in real time for declaring an experiment may have been too lenient. Nearly one-third of the seeding cases were conducted when the -5 °C level was at an elevation that would not be expected to be reached by the ground-released nucleants.

A numerical targeting model, GUIDE (Rauber et al, 1988), adapted for ground release of seeding material, computed nucleation and fallout locations from each generator on a given day. Results indicated fallout downwind of the target, primarily due to a high -5 °C level and a strong southerly wind component. During southerly winds, nucleants released from low elevation sites were often predicted to travel parallel to the barrier, displacing fallout north of the target. Meteorological conditions with low freezing levels and light westerly winds were predicted to produce the most effective targeting allowing fallout a short distance downwind of the generator, especially for those above 2000 m.

Aircraft plume tracing studies, using airborne ice nucleus counters under both visual flight rules (VFR) and instrument flight rules (IFR) conditions, detected the plumes downwind of the release sites. The observations indicated a 10- to 15-degree angle of spread and an approximate 0.3 m s^{-1} rise rate for plumes over mountainous terrain. Although it was difficult to map the horizontal and vertical extent of the plumes, the GUIDE model appeared to provide reasonable estimates of plume transport and diffusion.

In addition to the above studies, a chemistry analysis of snowpack samples showed very limited silver dispersion, with less than 15 percent of the samples indicating any silver above background. This rather poor result may indicate inadequate generator coverage and/or poor generator performance.

1.0 INTRODUCTION

Operational cloud seeding programs have been conducted in California since the early 1950's in attempts to increase water supplies and hydroelectric power generation. Although the effectiveness of large scale cloud seeding operations still has not been firmly established, public and private programs continue their attempts to modify cloud systems for the purpose of increasing precipitation and runoff. Such expenditures are considered minimal when compared to the potential benefits that could assist in meeting the growing needs for water in California.

In 1976, the Bureau of Reclamation established the SCPP as a research-orientated weather modification program in the American River Basin (ARB) of California. Reynolds and Dennis (1986) reviewed the goals of SCPP and the seeding experiments conducted. These experiments demonstrated that aerial seeding produces identifiable "signatures" in both individual convective and widespread stratiform clouds (Marwitz and Stewart, 1981; Stewart and Marwitz, 1982; Huggins and Rodi, 1985; and Deshler et al., 1989).

Aerial treatment procedures have been used by SCPP researchers to ensure that favored cloud regions were directly seeded at temperatures where nucleation and ice crystal growth would be rapid. However, most large scale operational cloud seeding programs have depended on ground-based AgI generators to deliver seeding material to candidate clouds. Ground-based generators cost less to operate and provide a continuous supply of nucleants during storm periods. During the final year of SCPP, ground-based AgI generators were incorporated into the seeding program to study the effectiveness of ground delivery in conjunction with other research objectives. This paper reports on the results of these studies.

2.0 DESIGN

The SCPP ground-based seeding experiment was built around ongoing operational programs and took priority over the concurrent SCPP aerial treatment experiment. Ground seeding operations were not combined with aircraft seeding so that each delivery method could be evaluated separately. This allowed sophisticated equipment and techniques normally utilized for aerial treatment procedures to be used for physical evaluations of the effectiveness of ground releases.

Although shallow orographic clouds may comprise the most seedable conditions (Reynolds and Kuchiauskas, 1988), the seeding criteria used permitted a variety of cloud types to be treated. It has generally been accepted that AgI will not become effective until it reaches cloud regions where the temperature is colder than -5 °C and the cloud is at or above ice saturation. Since these conditions are difficult to forecast in advance, SCPP ground seeding operations were conducted whenever cloud and wind conditions would allow the ground-released AgI to reach cloud and directionally target the study area. This required only that the wind direction below 700 mb be between 170 and 360 degrees and cloud base be less than 1 km above ground as determined from a sounding near the crest of the Sierra Nevada.

The seeding criteria were kept simple so that more days would be likely to qualify for experimentation. However, seeding activities would be suspended if treatment might aggravate threatening weather situations, such as:

- Excess snowpack accumulations
- Rain induced winter flooding
- Severe weather
- Other special circumstances

No suspension criteria were met during the 1986-87 season. Treatment was made by 6-hour time blocks, long enough so that the accumulated seeding effects might be measurable in the precipitation gauges but short enough to obtain more units in a single season. A 2:1 randomization scheme ensured objectivity and provided some nontreated periods for comparison. However, one season was not expected to yield any meaningful results in terms of precipitation increases.

Special flight procedures were designed for two SCPP research aircraft to monitor the horizontal and vertical spread of the ground-released nucleants. In addition, snow samples were collected over a large part of the target to determine if trace quantities of silver accumulated in the snowpack could be detected. These studies were all in an attempt to verify the transport, nucleation, and fallout predictions generated by the SCPP GUIDE model.

3.0 OBSERVATIONS AND METHODS FOR SEEDING DECISIONS

For cloud seeding to be effective in producing additional measurable precipitation, the clouds must contain supercooled liquid water (SLW). In addition, the complicated air motions over the mountainous terrain must be understood to develop an effective and reliable seeding strategy that will assure the additional precipitation falls in the desired target area.

A variety of equipment was used to determine the suitability of treating portions of winter storms. The SCPP target area and instrument locations are shown in Figure 1. A weather forecast office in Auburn, California, had the following resources available for the ground seeding experiment:

- Weather maps and prognostic charts from the National Weather Service.
- A minicomputer capable of running the numerical targeting model.
- Animated and hard-copy satellite imagery.
- Hourly weather reports and observations.
- A variety of in situ observations, which were telemetered to the forecast office for near real time display. These included mountaintop meteorological stations that reported temperature, wind conditions, humidity, and icing rate information, and a radiometer located at Kingvale (KGV).
- Precipitation gauge accumulations from the SCPP network.
- Upper air information obtained from serial balloon soundings launched within the project area.

The mountaintop meteorological reporting stations were located throughout the target area as shown in Figure 1. Deiceable anemometers and directional vanes operated in conjunction with temperature and humidity sensors at each site. Rosemount icing rate meters provided direct measurements of SLW passing each site (Henderson and Solak, 1983). SLW content can be computed from the windspeed and the number of deicing "trip" cycles recorded by this device. These measurements proved to be very useful in nowcasting the occurrence of SLW, as well as for postseason stratification of the experiments.

High-resolution precipitation data collected by a network of 16 digital recording precipitation gauges reported to the forecast office each hour the precipitation accumulated within 5-minute increments (Price and Rilling, 1987).

Precipitation data were also collected by gauge networks operated by the Desert Research Institute (DRI), Sacramento Municipal Utility District (SMUD), Pacific Gas and Electric Company (PG&E), and Sacramento County (SC), but were not available in real time. Figure 2 shows the locations of all gauges.

Vertical profiles of wind, temperature, and moisture were derived from two rawinsonde launch sites within the study area (Fig. 1). A new cross-chain Loran atmospheric sounding system (CLASS) rawinsonde system (Lauritsen et al., 1987) was used by SCPP to provide higher resolution in the vertical. This system is not a radiotheodolite but uses Loran (long-range navigation) for positioning information and transmits radio signals back to the launch site. Incoming data are recorded and processed onsite by a minicomputer and can be displayed in real time. Some tracking problems at low elevations were due to weak Loran reception in the mountainous terrain. Balloon flights were made at 3-hour intervals during storms from an upwind location at Lincoln and from KGV (Fig. 1). The latest data served as input to the numerical GUIDE model to determine if the target area might be affected by the ground release of AgI.

The SCPP GUIDE model (Rauber et al, 1988) is a two-dimensional steady-state flow model that incorporates microphysical particle growth and fallout routines. The model was originally developed for aircraft delivery but was recently adapted to estimate the horizontal and vertical dispersion of aerosol plumes (using a Pasquill-Gifford neutral stability dispersion rate) released from the ground. Paired upwind-downwind soundings were used to produce constant mass flow channels over the barrier. Wind components parallel and perpendicular to the barrier are derived from this technique. Vertical motion is computed from the perpendicular wind component and the slope of the mass flow channels. The location in cloud where a sufficient number of nuclei are likely to be effective (-6 °C) is predicted along with the fallout point of a crystal initiated at this location.

Presently, it is difficult to model accurately any events that may occur east of the Sierras because input data is based solely upon soundings upwind of the barrier. Therefore, caution is advised when evaluating plume trajectories downwind of the crest shown in this paper. Comparisons between predicted and observed winds upwind of the barrier have been described by Rauber et al. (1988), but this model has not yet been evaluated and verified for ground seeding; and thus the accuracy of its predictions is unknown. Results of this years operations may help evaluate the ground seeding parameterizations incorporated into the model.

4.0 GROUND-BASED SEEDING GENERATORS

A network of 24 ground-based cloud nuclei generators were operated in a coordinated fashion during the SCPP field phase--November 3, 1986, to January 9, 1987. The total network was comprised of four smaller networks belonging to PG&E, SMUD, DRI, and SCPP. These generators had been used in past operational programs except for the SCPP network, which was installed especially for this study. All generators, except PG&E's, burned a 3-percent by weight $AgI\text{-}NH_4I\text{-}NH_4ClO_4$ in acetone solution ignited by a propane flame. The PG&E generators did not use the NH_4ClO_4 additive. Burning this solution released approximately 30 g of AgI per hour from each generator while consuming about a gallon of propane per hour at each site. The SCPP generators were operated manually by local residents while the remaining generators were operated remotely.

Figure 3 shows the location of the generator sites in relation to the SCPP target area, which encompasses the American, Tahoe-Truckee, and Upper Mokelumne River basins. The PG&E, SMUD, and DRI networks had been installed in past years so as to be generally upwind of their respective target areas. The SCPP generators were strategically placed to affect clouds that would eventually pass the KGV area on Interstate Highway 80. SCPP chose these generator locations through the use of the GUIDE model. Mean soundings were constructed from a subset of rawinsonde soundings in which the 700-mb temperature was less than -5 °C and the wind had a westerly component. Running the mean soundings through the GUIDE model indicated the approximate location for the SCPP generators to affect the KGV area. The final sites chosen were a compromise between the GUIDE model predictions and the availability of residents willing to tend the equipment.

All observations were assembled daily in the forecast office to evaluate the likelihood of conducting seeding experiments. If the conditions were forecast to become favorable within the next 2 hours, an envelope was drawn that contained the randomized seeding decision. If a "no seed" was drawn, ground generators would not be lit and other research activities could commence. If the decision was "seed," then the five generator operators were instructed to ignite the burners for the prescribed 8 hours. Remote control dispensers were ignited by the various agencies per the SCPP forecaster request. This provided 2 hours to allow the ground plumes to disperse horizontally and vertically and a 6-hour time block for treatment effects to be evaluated. Not all generators were lit during each operation. Those predicted by the GUIDE model to miss the target area were not ignited. However, if winds changed later to a more favorable direction, these generators could be lit and run for the remainder of the experimental unit; but no generators were ever stopped early.

5.0 PRELIMINARY RESULTS

Each of the 18 randomized case days was analyzed by comparing the timing of SCPP operations with atmospheric temperature and liquid water information, and the accuracy of targeting based on GUIDE model predictions. Each operational period was thus compared to the following:

- Observed temporal variations in mountaintop SLW
- Observed temporal variations in mountaintop temperature
- Observed temporal and spatial variations in precipitation
- GUIDE model predictions of targeting effectiveness
- Timing of the operations with respect to most "seedable" conditions

Seedable conditions were defined as (a) cloud over the barrier with bases less than 1 km above KGV, (b) a westerly wind component, (c) liquid water observed by a mountaintop icing rate meter, and (d) temperature less than -5 °C at Squaw Peak (SQP) (2642 m).

Table 1 summarizes all 18 experiments with respect to seeding status, averaged values of SQP temperature and SLW content, the network averaged precipitation rate, and predicted targeting effectiveness. The timing of each unit in relation to observed SQP SLW is also tabulated, and a qualitative assessment of this is given.

From this table, it can be seen that many experimental units were well timed in relation to the presence of SLW at SQP. However, the GUIDE model predicted poor targeting for many of these cases. Predicted targeting was often fair to poor because of relatively warm temperatures and/or strong southerly wind components. This resulted in either no nucleation or else the predicted fallout trajectories impacted areas downwind of the intended target. Several cases were poorly targeted due to winds becoming northerly or easterly after the unit began. In addition, precipitation during most of the experiments was very light when normalized across the entire SCPP network. For the sake of brevity, only two experimental periods will be detailed in the following section to illustrate the physical plausibility of the GUIDE model predictions. Examples will be shown to illustrate the best targeting case and a marginal case.

5.1 Best Targeting Case - January 6, 1987

The best predicted impact on the SCPP target area occurred on January 6, 1987. The SQP temperature (Table 1) averaged -10 °C with a consistent but low average SLW content of 0.02 g m^{-3} for the entire treatment period.

Figure 4 displays the temporal aspects of the meteorological parameters and icing information recorded at SQP and Sierra Ski Ranch (SSR). Temperature, icing, and wind conditions were fairly consistent throughout the experimental unit from 0430 to 1030 (all times G.m.t.).

All generators except S2 were ignited at 0230 and continued to burn until 1030. In Figure 5, showing predicted plume trajectories based on the 0600 Lincoln and KGV soundings, nucleation is depicted as the first asterisk (*) downwind of each generator; and predicted fallout is shown by the second circled asterisk. The crestline is approximately 100 km along the X-axis of the model coordinates. The low-level winds were southwesterly, but aloft turned more westerly to northwesterly. The modeled windspeeds were generally light, ranging from 5 to 15 m s^{-1} throughout the levels reached by the ground plumes. The -5 °C level was near 2000 m m.s.l. so the plumes quickly reached temperature levels where nucleation could take place. Initial fallout was predicted to occur near the target's western boundary. High elevation generators such as P2 and P3 were shown to nucleate immediately and provide fallout approximately 20 to 30 km downwind of the generators. Plumes from lower elevation sites such as S5 were shown to drift about 30 km before reaching nucleation levels, and fallout was predicted to reach the ground about 10 to 20 km beyond the point of nucleation. The radical wind shift downwind of the crest exemplifies problems with the model in this region.

The results are encouraging in that they are very similar to the effects reported for cold westerly cases by Mooney and Lunn (1969) in the PG&E Lake Almanor studies and by Super et al. (1986) in the Bridger Range in Montana. Such impacts at short distances downwind are plausible during "cold and slow" cases when winds are light and generators are located at high elevations. These model results indicate that seeding cold storms, with low freezing levels, may help to ensure rapid nucleation and short fallout trajectories, which combine for more effective targeting albeit small volume filling.

Figure 6 is a spatial representation of total precipitation recorded during the experimental unit with the GUIDE predicted areas of impact shown as the dashed enclosed area. Treatment effects are not expected to be apparent in this figure. Precipitation amounts ranged from 0.0 to 1.5 mm within the predicted area of effect. Gauges at Blue Canyon and Yuba Gap, upwind of the predicted impact area, recorded the largest precipitation amounts during this time.

5.2 Marginal Targeting Case - December 5, 1986

The second experiment, on December 5, 1986, is a typical example of the GUIDE model predicting a marginal impact on the SCPP target area. Figure 7 displays the type of information that was available to the forecast office in near real time from the mountaintop meteorological stations. Some SLW was observed at SQP with temperatures near -5 °C, but no icing was recorded at SSR. For this experiment, all but three generators were lit at 0645; and allowing 2 hours for volume filling, the experimental unit ran from 0845 to 1445.

On the 1200 sounding at KGV (1685 m m.s.l.) wind directions and speeds showed little change with altitude above the inversion located at approximately 650 mb. However, the sounding at Lincoln (1625 m lower) lacked the strong inversion; and windspeeds increased with height. Figure 8 shows the predicted plume trajectories and locations of nucleation and fallout generated from these soundings. Winds were very southerly, and most fallout was predicted to occur north of the target area. Fallout from the low elevation sites impacted approximately 100 km downwind from the ground release points while the high elevation generators showed fallout within about 30 km. Therefore, even with cold temperatures, effective targeting is predicted to be more difficult with low elevation generator sites in this southerly wind case. The GUIDE model frequently predicted such results on other days especially during the early stages of storm development.

Figure 9 presents the spatial view of precipitation during this experimental unit. The GUIDE-predicted areas of impact are shown within the dashed area. Some Sacramento area gauges received more precipitation than many of the higher mountain stations. A temporal display of precipitation (not shown) showed that seeding began with the onset of precipitation. The maximum rates generally occurred during the seeding period, but light precipitation continued for up to 7 hours after the seeding had terminated. The GUIDE model predicted that Castle Valley and Talbot were the only digital gauges in the area that may have been impacted.

6.0 AIRCRAFT STUDIES OF NUCLEANT TRANSPORT AND DISPERSION

Aircraft operations traced ground-released nucleants to help verify vertical transport and dispersion and the GUIDE model output. Special flight procedures were devised for each aircraft to measure the transport and diffusion of nucleants during prestorm conditions as well as during actual seeding operations.

An ice nucleus counter developed by the National Center for Atmospheric Research (NCAR) was flown aboard each aircraft to detect the presence of nucleants. The ice nucleus counter (Langer, 1973) is somewhat inexact, especially when used during aircraft survey flights, because of problems associated with the response and relaxation time of the instrument. Tests performed this season with airborne releases of AgI have shown a lag of approximately 20 to 40 seconds for the instrument to respond to the interception of nucleants within the turbulent wake of the seeder aircraft. After leaving the plumes, up to 3 minutes was needed to purge the chamber of nuclei. Therefore, it is difficult to accurately measure plume dimensions when the aircraft is traveling at 90 to 100 m s^{-1}. Typically, the aircraft was required to penetrate the plumes from opposite directions after allowing several minutes for the chamber to clear. Unfortunately, this was not always possible when flying close to the mountain barrier during IFR.

Ice nuclei concentrations are also difficult to quantify because of a loss of nucleants and ice particles to the inside walls of the chamber. Langer (1973) estimates a 10-percent counting efficiency, but Sackiew et al. (1984) report that the NCAR counter may be only 1-percent efficient in quantitatively estimating ice nucleus concentrations. Therefore, the ice concentrations described here may be from 10 to 100 times too low. Using the 10 L min^{-1} sampling rate of the counter as determined for both aircraft, one count would equate to six nuclei L^{-1} active at -20 °C without the factor of 10 to 100 adjustment. For the results shown in the following cases, all the nuclei observed are for an effectivity of -20 °C. These may be reduced two orders of magnitude when considering effectivity at -6 °C.

6.1 Prestorm Test Flights

Flights during prestorm conditions were conducted before the onset of IFR conditions over the barrier but after the arrival of middle and/or upper level clouds from an approaching storm. These flights consisted of a series of profiles normal to the wind direction at 10- to 20-km intervals downwind of a generator (Fig. 10). Each profile was flown at various altitudes starting at a minimum safe altitude above ground level. Usually, the generators sampled were on specific mountain peaks so often it was possible to fly downwind and slightly below the elevation of the generators.

A good example of this flight procedure occurred on November 7, 1986, when a weak shortwave brought middle and high clouds over the ARB. A plume tracing study of generator D5 (Duncan Peak, 2179 m) was initiated while DRI personnel were onsite at the generator to verify its operation. The 2100 KGV sounding (not shown) revealed that the storm consisted mainly of a thin cloud deck based at 2750 m (-8 °C) with a well-mixed atmosphere below. Cloud top was near -17 °C. Winds below cloud veered from southwesterly to northwesterly at cloud base and remained northwesterly through the depth of the cloud. The vertical profile of acoustic sounder winds (not shown) revealed light southwesterly to northwesterly winds up to 2200 m with a mixing depth to at least 2700 m. DRI personnel reported a very light snowfall at D5.

Figure 11a shows a portion of the flight track of the Wyoming aircraft on several north/south passes downwind of the generator at 2200 m elevation with the plume trajectory predicted by the GUIDE model also shown. Since the generator was higher than most of the surrounding terrain, the aircraft was able to begin plume measurements at the same altitude as the generator. Substantial nuclei, 115 to 130 counts per pass (10 L^{-1}), were detected during the close-in passes (approximately 2 km downwind). On two additional passes at 2800 m, 11 km downwind of the generator, counts averaged 30 to 50 per pass (near the 6 L^{-1} detectable limit). The approximate plume dimensions as derived from the nuclei counts (after allowing for time lag) are also shown in Figure 11a. The GUIDE model predicted the flow to be slightly north of west while the aircraft measured winds and plume location indicated that the flow was slightly south of west. From these airborne measurements, the plume was estimated to be approximately 2 km wide at a distance of 11 km (10-degree spread). The plume had risen 600 m or an average of 0.3 m s^{-1}. In addition, two regions of slightly enhanced ice crystal concentrations (2 to 3 L^{-1} above a background < 1 L^{-1}) were measured by the aircraft in an area near the region (assuming plume meander) where nuclei were detected and where the GUIDE model had predicted nucleation to occur. These crystals were of a size and shape consistent with aircraft seeding signatures observed previously in SCPP (small hexagonal plates).

6.2 Instorm Transport and Diffusion Flights

During actual seeding operations, flights were made to determine if the ground-released nucleants were reaching the -6 °C temperature level in sufficient concentrations and in time to cause precipitation within the target area. A series of passes were made by each aircraft at the minimum obstruction clearance altitude (MOCA) to detect nuclei with their onboard NCAR counters. In addition to the MOCA runs, the aircraft would frequently make MOCA descents along the 230-degree radial off the Lake Tahoe (LTA) VOR, which carried them over the middle fork of the American River.

a. December 13, 1986

On December 13, 1986, a randomized ground seeding experiment was conducted while the aircraft performed transport and diffusion studies. All ground generators except S2 were ignited at 1645, and the aircraft were launched at 2320. The 0000 KGV sounding showed the cloud deck to be shallow and stable with southwesterly winds that increased in speed with height. Between 0000 to 0200, the acoustic sounder located at Blue Canyon measured southerly winds at elevations of 1600 to 2300 m with winds increasing to 10 m s^{-1} between 1900 to 2100 m. The mixing depth was calculated at 2000 m.

Figure 11b shows the first flight sequence flown by the aircraft super positioned on the GUIDE predicted ground plumes. Marked on the flight tracks are regions where nuclei were measured. The 30- to 35-second lag has not been accounted for in these representations. What is most apparent is that nuclei were being observed to the west of the SCPP generators and a few to the west of the SMUD generators below 1600 m. Apparently, some of the material was moving downslope especially down the North and Middle Forks of the American River. However, the highest and most continuous nuclei were measured north and east of the SCPP generators and 300 to 400 m above their elevation. Figure 11c shows the continuation of this flight sequence with the aircraft climbing to 1900 m and measuring nuclei within the region anticipated by the GUIDE to contain plumes from the SCPP generators. The GUIDE model predicted the top of the plumes in this region to be 300 m (1000 ft) below the sampling level of the aircraft. Given the plumes are 30 to 40 minutes downwind and 700 to 800 m above the generators, an approximate rise rate of 0.35 m s^{-1} would be required. This is very similar to November 7 and what might be expected due to forced ascent from the slope of the terrain (3 km rise in 100 km; 0.3 m s-1 using a 10 m s-1 upslope wind).

During the final minutes of this flight, the aircraft was sampling between 2200 and 3400 m elevation. The counts were rather sporadic but definitely above background levels. Assuming a background level of three counts in 5 minutes, 21 counts might be expected in 35 minutes. Here 71 counts were measured. The data indicated that some of the nuclei reached levels of supercooled water, but the temperatures were warm enough (-2 to -4 °C) that the AgI could not activate sufficiently.

In summary, this flight in rather stable storm conditions showed nuclei reaching levels of 600 to 1500 m above the generators. Sufficient concentrations (50 to 100 L^{-1} using x 10 factor) appear to be found in the lowest 1000 m above the generators. It is not possible to say much about the GUIDE model on this day other than the plumes appeared to be traveling northeast and that the highest nuclei concentrations were lower down in the cloud. No nucleation was predicted or expected in the ARB based on the fairly warm temperatures observed.

b. <u>December 19, 1986</u>

This day was an example of a much more convective day although the convection was embedded in a stratiform cloud. The sounding from KGV, taken at 2100 near the start of the transport and diffusion study, showed the lower cloud region was neutral to slightly unstable. Saturation was noted above the lower cloud on the sounding. Winds in the lower cloud level were south-southwesterly with winds to 15 m s^{-1} at 3000 m.

The acoustic sounder data (not shown) indicated winds to be southerly to southwesterly at from 7 to 10 m s^{-1} between 1600 to 2200 m. The calculated mixing depth was only 100 m. Between 1600 and 2300, all generators were ignited except B4, B5, and D4. Liquid water values were rather variable but above background during the whole experiment.

The flight sequence was similar to that of December 13 except several passes were made over the crest (Fig. 11d). Substantial counts were noted above background (42 counts) in this flight sequence as seen in Figure 12. Several regions of high ice nuclei counts corresponded with elevated regions of ice crystal concentrations and regions of low liquid water content. The region measured between 2110 and 2115 was associated with a broad region of updrafts. The ice particles noted were very small (300 to 800 m) with very high concentrations (> 150 L^{-1}). The temperature as noted on Figure 11d was near -11 °C at this time. This corresponds with other aircraft seeding signatures seen, but it cannot be ruled out that the natural convection was producing these high ice concentrations. More than likely, the source region for these nuclei was the DRI generators.

As the aircraft began its run along the 5,000-ft MOCA at (2130 to 2140), 12 counts were measured or only slightly above background. This run was approximately 10 km west of the SCPP manual generators of which four had been ignited. Flying along the 7,000-ft MOCA from 2140 to 2147 (900 m above the SCPP generators and 1500 m above the SMUD generators), the aircraft entered the predicted plumes from the SMUD and SCPP generators. The plumes were not continuous nor of high concentrations but were significantly above background levels. Individual convective elements were probably lofting the seeding material to the aircraft altitude. As the aircraft flew along the 9,000-ft MOCA (2147 to 2155), 1500 m above the SCPP generators, counts were above background with most counts apparently coming from SCPP's generator B6. Only a few regions of enhanced ice crystal concentrations were noted although ice nuclei and liquid water at temperatures colder than -6 °C were coexisting for a portion of this flight segment.

The research aircraft repeated the flight track along the 6000-ft contour over the barrier at 2203 observing one region of high ice nuclei counts and high ice crystal concentrations apparently just downwind of generator B3. Again, these crystals were less than 300 m in size, showing the crystals to be fairly new with their size and shape again similar to seeding effects seen in previous aerial seeding experiments. As the aircraft continued its flight along the MOCA, few nuclei were noted.

In summary, this day was the most convective of any transport and diffusion flight this season. Ice nuclei from ground generator releases were noted to be from 1000 to 1500 m above release points in limited regions of the ARB. In several regions where the temperature was colder than -6 °C and liquid water and ice nuclei coexisted, elevated ice crystal concentrations were noted. These crystals were representative of seeding effects observed from aerial seeding experiments. Thus convective processes provided a mechanism to loft seeding material to colder regions of the cloud but only over a limited region of the ARB.

7.0 SNOW CHEMISTRY ANALYSIS

The goal of this part of the study was to determine the targeting effectiveness of the coordinated seeding program--a snowpack sampling and chemical analysis program. This would help determine if, when, and where AgI released from the network was reaching the target area. Evidence of seeding effectiveness was to be obtained by measuring the amount of silver in snowfall samples at 15 sites in the project area.

Several snow sampling expeditions were conducted during and after the experimental field season from December 1, 1986, through March 15, 1987. A total of 1,681 individual snow samples were collected for chemical analysis at 14 of the 15 sites shown in Figure 13. Each profile was partitioned into 2-cm increments so that silver and water content could be measured as a function of depth. The profiler cross-sectional area is 200 cm^2, giving each partitioned increment a chamber volume of 400 cm^3. Each 400-cm^3 volume of snow represents a sample for chemical analysis.

A helicopter provided rapid access to the remote sites so individual snow samples had shorter resolved time intervals and, in general, improved quality for chemical analysis. The helicopter allowed rapid transport of the snow samples back to the freezers at the staging area. Transportation time is important because density profiles from each of the sites become easier to relate to one another and samples are less likely to undergo change due to aging or melting.

7.1 Laboratory Analyses and Data Processing

The analyses were made in two DRI clean room laboratories. One contains a laminar flow dual-beam flameless atomic absorption spectrophotometer, which is housed in filtered Class 100 air and uses an automated sample injection system for better contaminant control. A clean room sample preparation area is located immediately outside the main clean room but within the positive pressure envelope. The sample preparation area also houses an ion chromatograph for an analysis of major cations (Na, Mg, Ca, K, NH_4, etc.) and anions (SO_4, NO_3, Cl, etc.). The second clean room laboratory is used entirely for rare heavy metal analyses for elements such as Ag, Cs, Rb, and In. This laboratory contains a single-beam flameless atomic absorption spectrophotometer. Each individual snow sample has been analyzed five times by flameless atomic absorption techniques. This number of analyses permits the reduction and computation of a statistical uncertainty in the silver concentration measurements for the individual samples. Blanks and standards are processed continually throughout the laboratory analysis program. The analytical procedures used produce silver concentrations with typical calculated uncertainties of 10 to 20 percent (Warburton, 1977; and Warburton et al., 1968, 1977, 1982).

7.2 Results

All the 1681 samples actually collected have been analyzed for silver. Figure 14 shows the average percentage of samples that contain silver in concentrations greater than 4.0 parts per trillion for all samples. This figure is the silver background concentration +2 σ, hence confidence is high that the samples containing silver greater than this contain a component due to the seeding activity.

The results show that the PG&E program to the south consistently targets well into the more southerly portions of their project area, but these sites are located at the upper ends of valleys into which the seeding aerosols are channeled. These results are quite consistent with earlier results obtained for this area by DRI investigators. The more northerly sampling sites in the PG&E area are not targeted as consistently as the southerly sites even though the predominant wind trajectories across the region are from the west and southwest during seeding.

The other well-targeted area is in the northern Truckee-Tahoe catchment area, which was seeded jointly by DRI and SCPP generators. This consistent targeting also included the basin of the North Fork of the American River. Surprisingly, targeting into the Tahoe Meadows region, northeast of Lake Tahoe was not good. DRI researchers had found this region well-targeted in previous years; perhaps certain, more southerly generators in the DRI network were not always fully operational during the seeding operations. By contrast, the upper regions of the Middle and South Forks of the ARB targeted by SMUD gave consistently poor results. Some seeding generators in this project may need relocation.

8. CONCLUSIONS

This 2-month investigation of ground seeding leads to a number of insights into the feasibility of ground seeding operations in the ARB. Unfortunately, the 1986-87 winter field season provided few storms for research so the effectiveness of these operations cannot reasonably be determined. Only suggestions as to predictability of useful seeding periods and on the expected results of the transport and dispersion of ground seeding material can be given.

These preliminary studies indicate that the criteria used this past winter for initiating an experimental unit may have been too broad. On nearly one-third of the ground seeding cases, the temperatures were warmer than -5 °C at elevations that might be expected to be reached by the ground-released nucleants. This may have reduced the accuracy of targeting the seeding effects.

The numerical GUIDE model frequently predicted that the target area may not have been impacted primarily due to high freezing levels, strong southerly wind components, and low elevation generator sites. Nucleants released from the low elevation generator sites were frequently shown to have trajectories parallel to the barrier, i.e. the air moved around the mountain rather than over it. Therefore, nucleation was often delayed; and fallout was usually predicted to impact areas north of the target. Meteorological conditions with low freezing levels and light westerly winds were anticipated to produce the most effective targeting of precipitation in the desired region. These conditions combined to produce fallout predicted to occur a short distance (10 to 30 km) downwind, particularly from the higher elevation generator sites.

Aircraft plume tracing studies began the task of verifying the GUIDE model predictions of ground-released plume trajectories. These limited studies revealed that airborne ice nucleus counters could detect the plumes downwind of the release sites. Although it was difficult to map the horizontal and vertical extent of the plumes, the measurements indicated that the GUIDE model appeared to be providing reasonable estimates of both the horizontal and vertical dispersion of ground released plumes. That is, one can assume a 10- to 15-degree angle of spread and an approximate 0.3 $m\ s^{-1}$ rise rate of the plume.

As expected, the highest concentrations of nucleants were often observed near the surface; but nucleants above background levels were also observed at heights greater than predicted. In several cases, interesting regions of higher ice crystal concentrations were observed in conjunction with ice nuclei. In one case, this region was close to the location predicted by the GUIDE model. These observations suggest that the GUIDE model may provide a useful predictive and/or diagnostic to the utility of ground seeding. However, many more research flights of this type will be needed for verifying the GUIDE model with direct observations.

Silver sampling indicated a fairly low percentage of silver in snow over most sampling areas. The most favorable regions were the extreme southeast corner and the extreme north end of the target area. Other sampling sites showed almost no silver. These are disturbing results, even if one considers only scavenging, in that the AgI must not have passed over large regions of the target during precipitation events. Much of the AgI may be transported westward or northwestward at low levels, effectively not passing over the barrier.

These results may be specific only to the central Sierra Nevada. In the colder intermountain regions of the west, generators can be placed well above the -5 °C level and thus are not limited by temperature. However this still requires the generators be sited at high elevations to expose the nuclei to the free air flow and ensure transport to the desired cloud regions.

9.0 ACKNOWLEDGMENTS

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10.0 REFERENCES

Deshler, T., D.W. Reynolds, and A.W. Huggins, 1989: Physical response of winter orographic clouds over the Central Sierra Nevada Mountains to airborne seeding using dry ice or silver-iodide. Submitted to J. Appl. Meteor.

Elliott, R., and J.O. Rhea, 1984: Comparison of observed and predicted model winds over an orographic barrier. Preprints Ninth Conf. Weather Modification, AMS, Park City, 83-84.

Henderson, T.J., and M.E. Solak, 1983: Supercooled liquid water concentrations in winter orographic clouds from ground-based ice accretion measurements. J. Wea. Mod., 15, No. 1, 64-70.

Huggins, A.W., and A.R. Rodi, 1985: Physical response of convective clouds over the Sierra Nevada to seeding with dry ice. J. Climate Appl. Meteor., 24, 1082-1098.

Langer, G., 1973: Evaluation of NCAR ice nucleus counter. Part I: Basic operations. J. Appl. Meteor., 12, 1000-1011.

Lauritsen, D., Z. Malekmadani, C. Morel, and R. McBeth, 1987: The cross-chain Loran atmospheric sounding system (CLASS). Preprints Sixth Symp. Meteor. Observations and Instrumentation (New Orleans, LA).

Marwitz, J.D., and R.E. Stewart, 1981: Some seeding signatures in Sierra storms. J. Appl. Meteor., 20, 1129-1144.

Mooney, M.L., and G.W. Lunn, 1969: The area of maximum effect resulting from the Lake Almanor randomized cloud seeding experiment. J. Appl. Meteor., 8, 68-74.

Price, G., and R.A. Rilling, 1987: A high resolution, infinite capacity weighing snowgauge for use in remote areas. Preprints Sixth Symp. Meteor. Observations and Instrumentation (New Orleans, LA), 249-252.

Reynolds, D.W., and A.S. Dennis, 1986: A review of the Sierra Cooperative Pilot Project. Bull. Amer. Meteor. Soc., 67, 513-523.

Sackiew, C.M., J.W. Robataille, J.W. Mason, and F.D. Barlow, 1984: Comparison tests of NCAR ice nucleus counters. Preprints Ninth Conf. Weather Modification (Park City, UT), 12-13.

Stewart, R.E., and J.D. Marwitz, 1982: Microphysical effects of seeding wintertime statiform clouds near the Sierra Nevada mountains. J. Appl. Meteor., 21, 874-880.

Super, A.B., and J.A. Heimback, 1984: Evaluation of the Bridger Range winter cloud seeding experiment using control gauges. J. Climate Appl. Meteor., 22, 1989-2011.

Warburton, J.A., 1977: Interrelationships between the physics and chemistry of precipitation. Presented at ICPM Symposium, Joint IAGA/IAMAP Assembly (Seattle, WA).

Warburton, J.A., G.O. Linkletter, and R. Stone, 1982: The use of trace chemistry to estimate seeding effects. Jour. Appl. Meteor., 21, 8, 1089-1110.

Warburton, J.A., M.S. Owens, A.V. Anderson, and R. Stone, 1977: Temporal and spatial distributions of seeding material in a ground-based seeded target area. Proc. Seventh Conference on Inadvertent and Planned Weather Modification (Banff, Canada).

Warburton, J.A., and L.G. Young, 1968: Neutron activation procedures for silver analysis in precipitation, J. Appl. Meteor., 7, 3, 433-448.

Table 1. Summary of SCPP ground-seeding experiments - 1986-87

Experiment Date	Experiment Time	Status	SOP temp. (°C)	SOP SLWC (g m^{-3})	GUIDE-predicted targeting	Unit timing	Area PCP rate timing (mm h^{-1})
861119	0800-1400	Seed	-0.4	0.11	Poor - No nucleation or fallout	Excellent	0.41
861121	0800-1200	No seed	-1.7	0.06	Poor - Nucleation east of crest	Good	1.98
861129	0100-0700	Seed	-3.2	0.00	Fair - Fallout northeast of target	Too early	0.17
861205A	0245-0645	No seed	-0.7	0.00	Poor - Fallout far north of target	Poor	0.00
861205B	0845-1445	Seed	-4.9	0.02	Fair - Fallout in target from high elevation generators	Too early	0.98
861206	0130-0730	Seed	-4.3	0.01	Fair - Fallout east of crest	Too late	0.001
861213	1845-0045	Seed	-1.7	0.03	Poor - No nucleation	Too early	0.012
861218A	1600-2000	No seed	-4.3	0.12	Good - Most fallout on crest north of target	Excellent	0.56
861218B	2200-0400	Seed	-4.3	0.07	Fair - Most fallout east of crest	Excellent	0.79
861219	1800-2400	Seed	-4.4	0.06	Good - Fallout on crest, some north of target	Good	0.49
861220	0500-0900	No seed	-6.7	0.03	Poor - Easterly wind flow	Good	0.08
861222	1700-2300	Seed	-5.0	0.05	Poor - No nucleation	Too early	1.80
861223	0400-0800	No Seed	-3.4	0.11	Poor - Northerly wind flow	Excellent	0.02
861231	1530-2130	Seed	-4.4	0.07	Good - Fallout near crest, some north of target	Good	0.26
870103	1530-2130	Seed	-4.7	0.03	Fair - Fallout east of crest	Excellent	4.77
870104A	0230-0830	Seed	-8.5	0.00	Good - Short trajectories, most fallout west of target	Good	0.33
870104B	1330-1730	No seed	-8.8	0.02	Poor - Northerly wind flow	Poor	0.00
870106	0430-1030	Seed	-10.0	0.02	Excellent - Fallout in target	Excellent	0.13

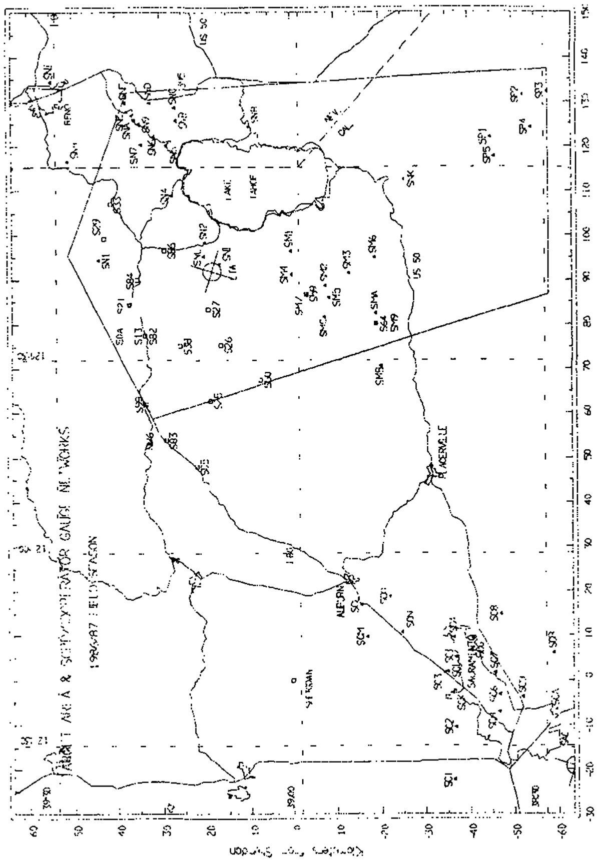

Figure 2. SCPP and cooperator precipitation gauge network for the 1986-87 field season.

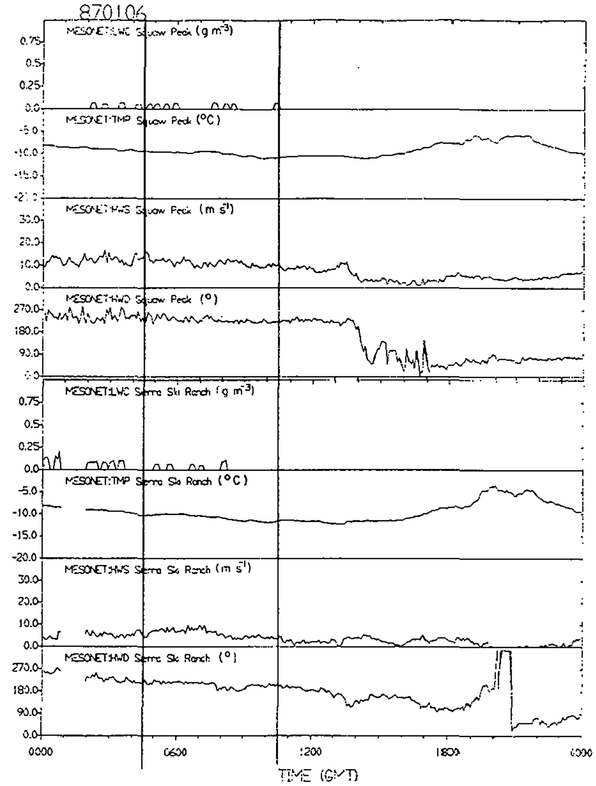

Figure 4. Temporal plot of mountain weather information for January 6, 1987, for two sites--Squaw Peak and Sierra Ski Ranch. For each site, liquid water content (LWC) from a Rosemount icing meter, temperature, and wind direction and speed are displayed from top to bottom. Data are plotted every 5 minutes.

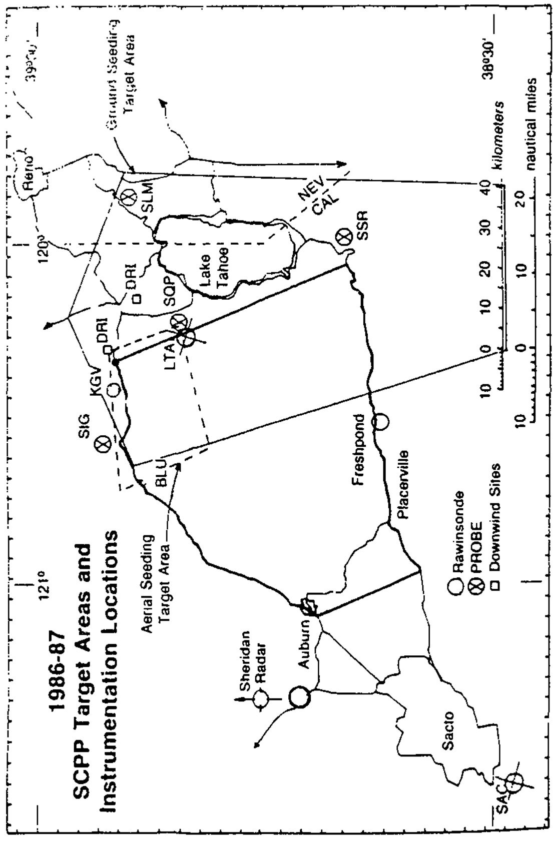

Figure 1. 1986-87 SCPP target areas and instrumentation locations.

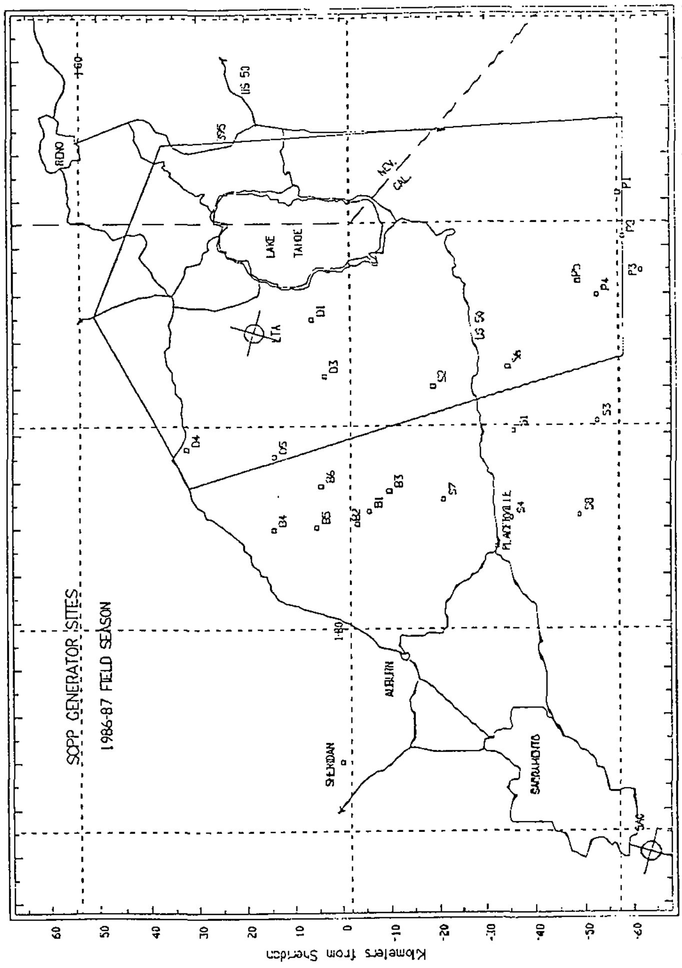

Figure 3. 1986-87 ground generator network (letter identification: B = Bureau, S = SMUD, P = PG&E, D = DRI).

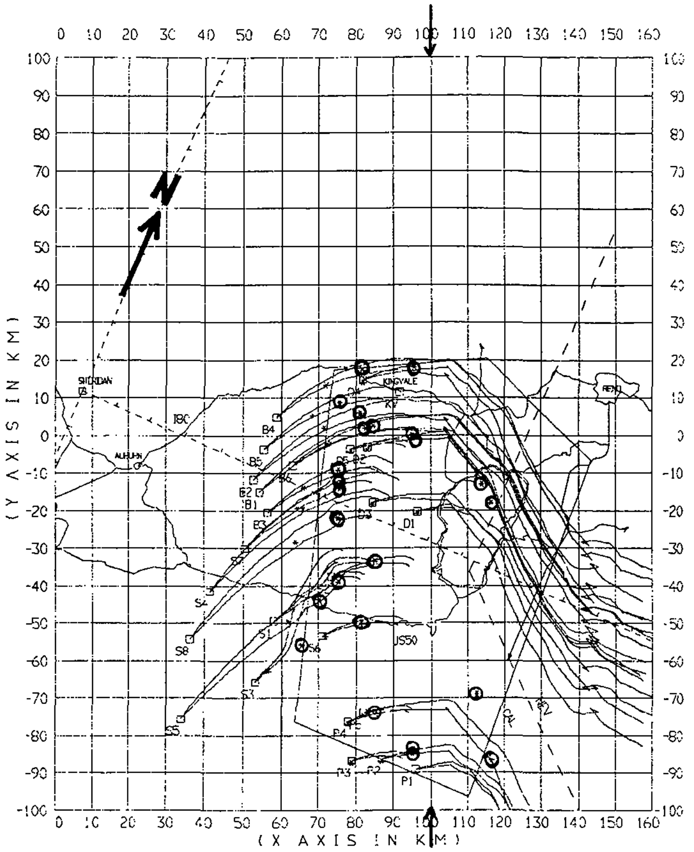

Figure 5. Output from the numerical targeting model (GUIDE) showing seeding plumes superimposed over the target area for January 6, 1987, using the 0600 G.m.t. soundings. The first asterisk denotes the predicted location of nucleation at the -6 °C level, and the second asterisk denotes the fallout point of this crystal.

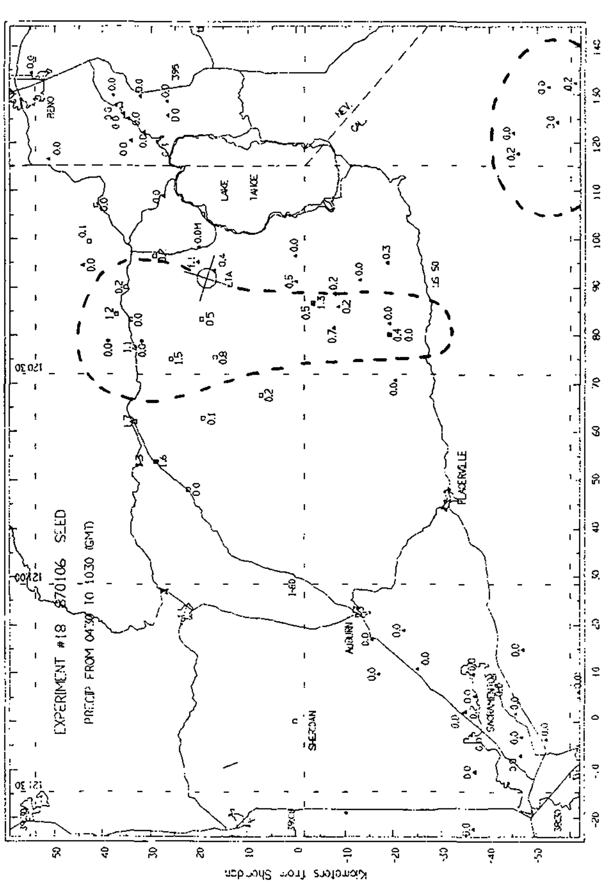

Figure 6. Six-hour precipitation totals for the January 6, 1987 case measured by the precipitation gauge network. Dashed area denotes fallout footprint predicted by the targeting model.

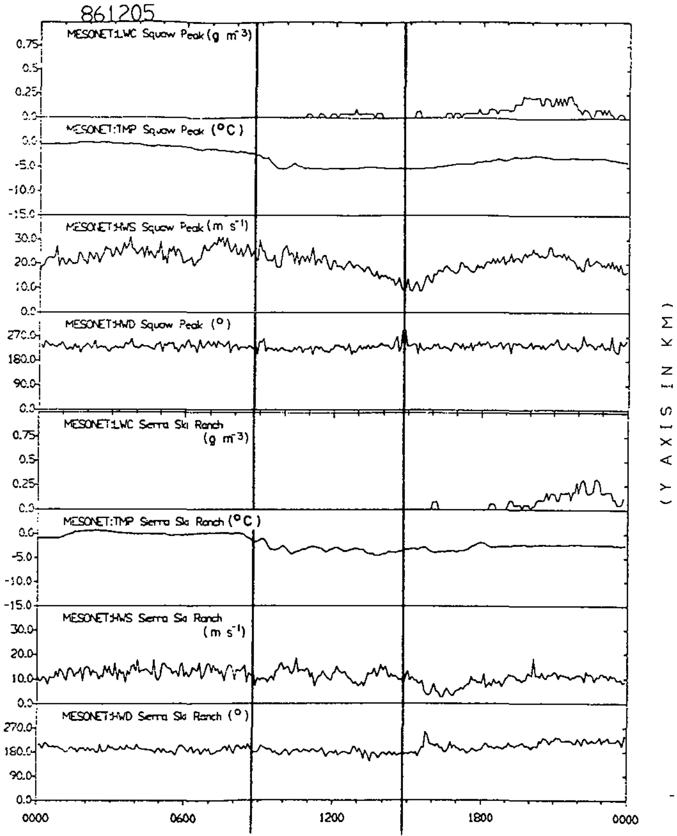

Figure 7. Temporal plot of mountain weather information for December 5, 1986, for two sites--Squaw Peak and Sierra Ski Ranch. For each site, liquid water content (LWC) from a Rosemount icing meter, temperature, and wind direction and speed are displayed from top to bottom. Data are plotted every 5 minutes.

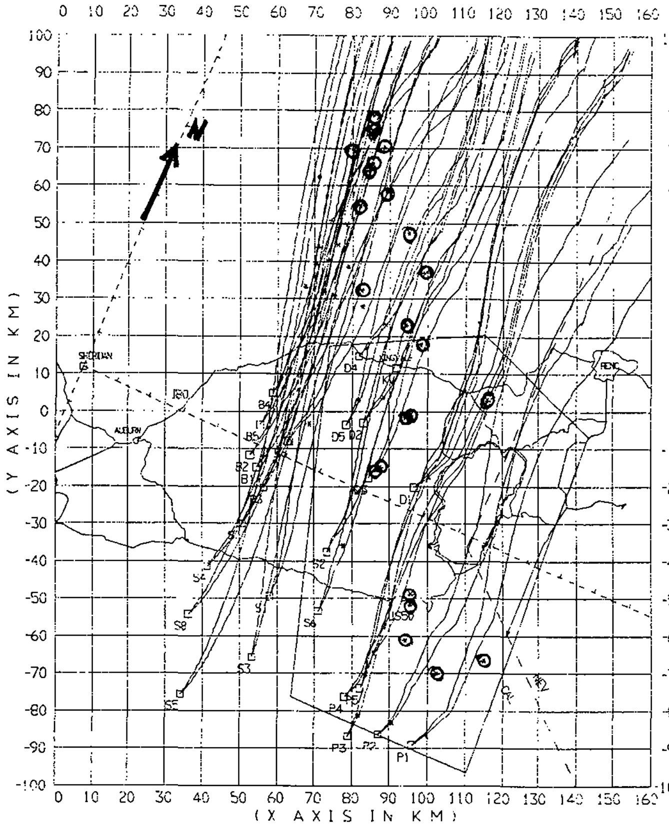

Figure 8. Output from the numerical targeting model (GUIDE) showing seeding plumes superimposed over the target area for December 5, 1986, using the 1200 G.m.t. soundings. The first asterisk denotes the predicted location of nucleation at the -6 °C level, and the second asterisk denotes the fallout point of this crystal.

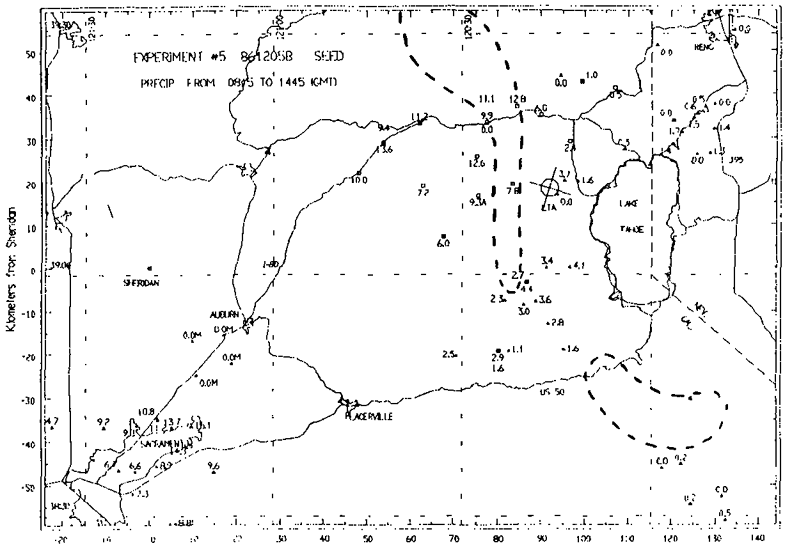

Figure 9. Six-hour precipitation totals for the December 5, 1986 case measured by the precipitation gauge network. Dashed area denotes fallout footprint predicted by the targeting model.

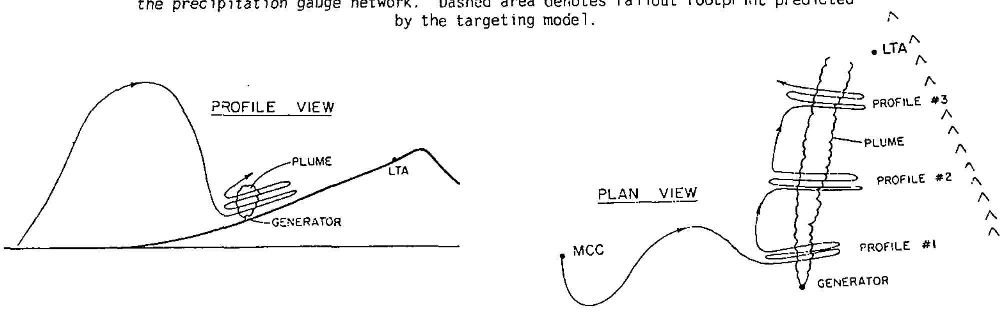

Figure 10. Flight track of the cloud physics or seeder aircraft for tracing ground-released AgI during prestorm conditions.

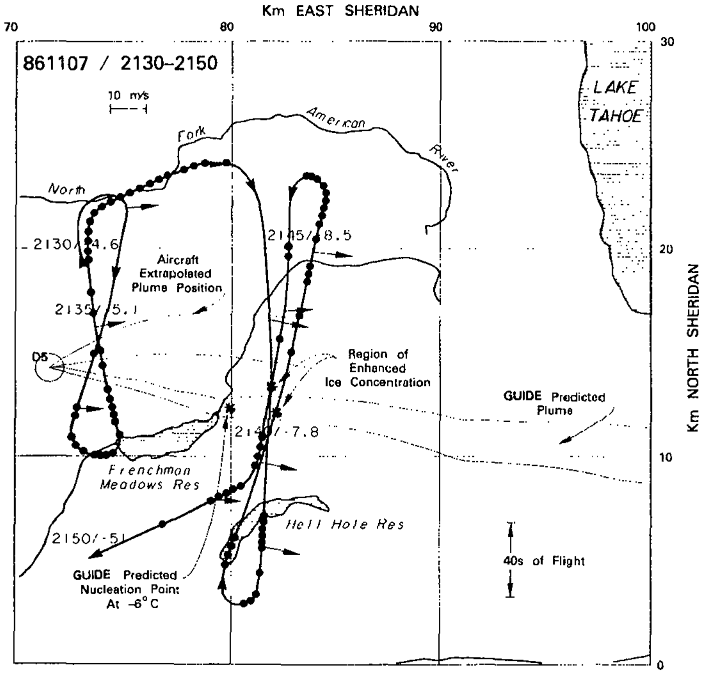

Figure 11a. Cloud physics aircraft flight track for the period 2130-2150 sampling downwind of a DRI generator. The time and temperature along with windspeed and direction (arrows) at flight level are shown periodically along the track. Dark circles along the track indicate locations of ice nuclei counts detected by the nuclei counter. Lag in response time has not been accounted for but can be estimated by noting the scale on the left of the figure showing distance traveled by the aircraft in 40 seconds of flight.

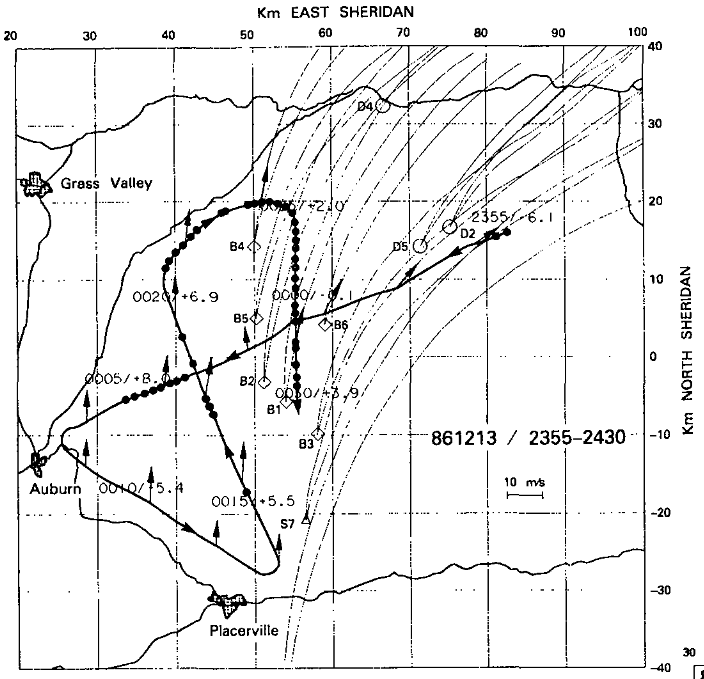

Figure 11b. Same as Figure 11a but for December 13, 1986.

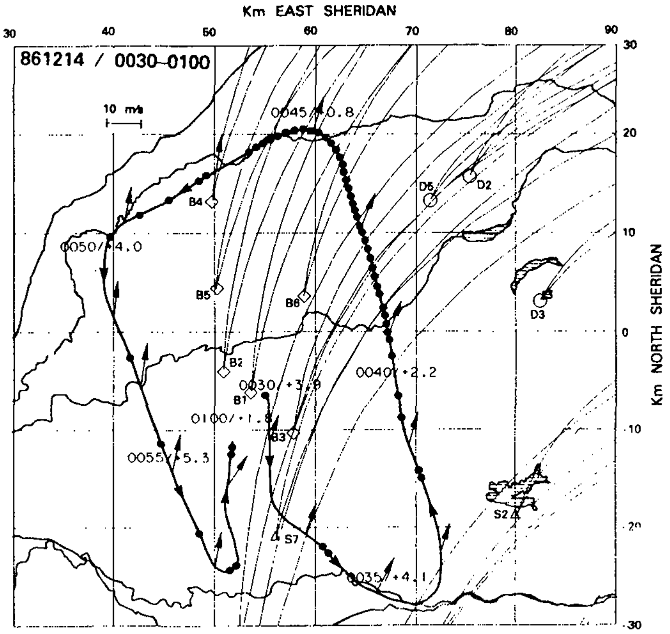

Figure 11c. Continuation of the flight profile from Figure 11a.

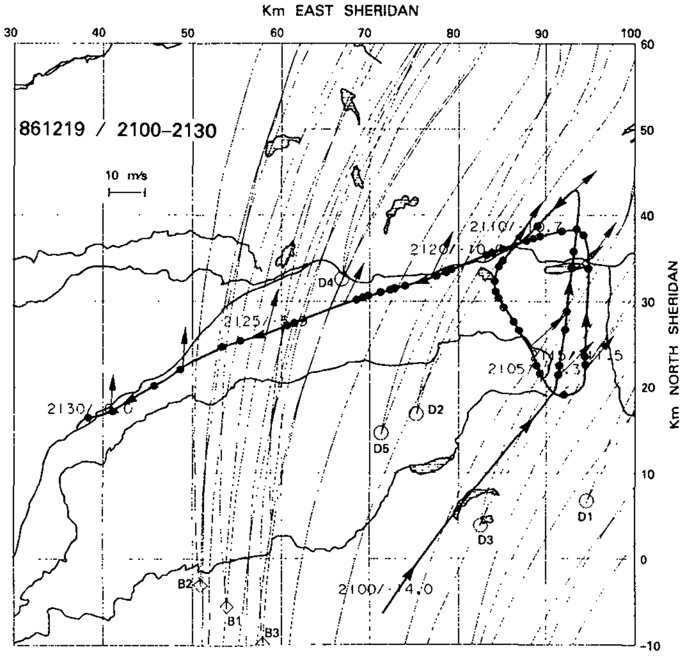

Figure 11d. Same as Figure 11a but for December 19, 1986.

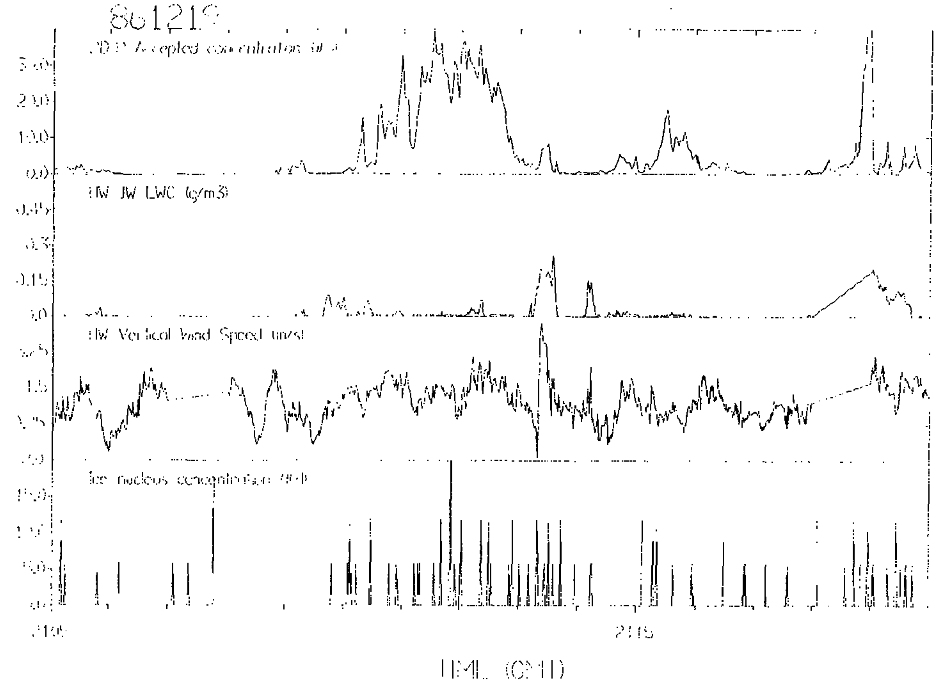

Figure 12. Parameters measured by the cloud physics aircraft as it flew over the crest of the Sierra on December 19, 1986. Top panel is 2D-Pice particle count after reject criteria applied. In the second panel is liquid water as measured by a Johnson-Williams probe. The third panel is aircraft-measured vertical velocity, and the fourth panel is ice nucleus concentrations (see text for further details).

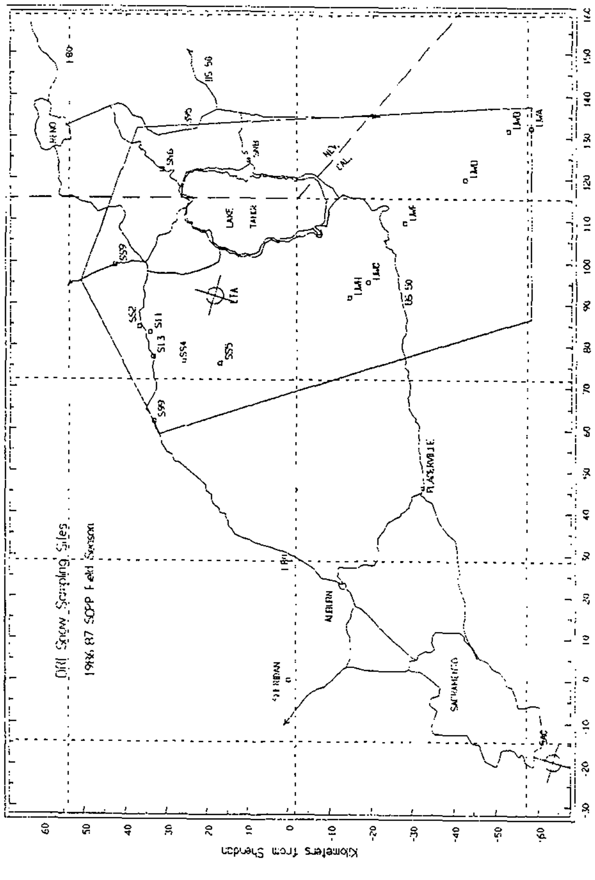

Figure 14. Average (in percent) of samples containing Ag greater than background levels (4×10^{-12} g Ag mL^{-1}).

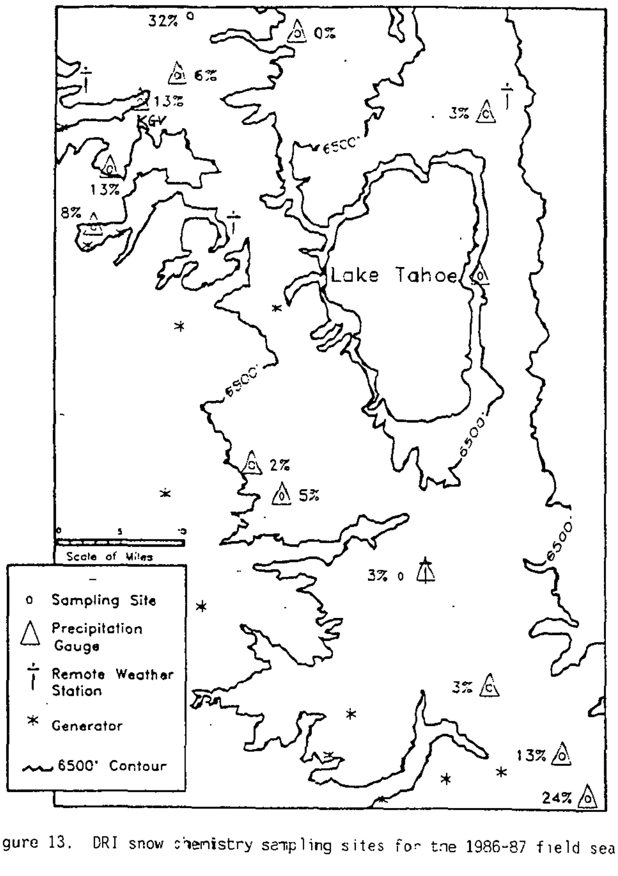

Figure 13. DRI snow chemistry sampling sites for the 1986-87 field season.