How the Transport and Dispersion of AgI Aerosols May Affect Detectability of Seeding Effects by Statistical Methods

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ABSTRACT

Trace chemical measurements of the silver content of snow have been used to investigate the transport and dispersion of silver iodide cloud seeding aerosols into and around two large target areas in the central Sierra Nevada between 1978 and 1992. The background concentration of silver in snow samples in this region is extremely low [B_{Ag} = 2.0 parts per trillion (ppt); standard deviation, σ = 1.0 ppt], and the silver from the seeding activities is readily detectable. The studies, in winter snowstorm conditions, show that targeting of the seeding aerosols was modest to poor with large variability both spatially and temporally. Analysis of several thousand snow samples over a period of several years has demonstrated that only 20% (average) of the precipitation that fell within the intended target area during seeding activities contained silver from the silver iodide seeding aerosol above the assigned "threshold" concentration of $B_{Ag} + 2\sigma$ = 4.0 ppt. Targeting of one of the catchment areas under southerly flow storm conditions was particularly poor (less than 8% of the sampled snow containing detectable silver above the "threshold" value).

Evidence is also presented of the transport of silver iodide in directions and into areas other than those intended including upwind control areas used for estimating seeding effects in the target. In one period of the study between 1987 and 1990, emphasis was placed on southerly flow storms. It was found that contamination of two control areas in the Lake Almanor region generally occurred in the early phases of these southerly flow storm periods when winds at the lower levels were from northeast to southeast prior to frontal passage. The method used for estimating the layer-averaged wind prior to storm classification for seeding purposes in this project placed equal emphasis on winds at all levels from 2000 m, the approximate elevation of the ground generators, to the −10°C level. Hence, aerosols released at ground level were often transported inadvertently toward the control areas by these low-level winds. The problems that these results raise in regard to the traditional use of precipitation statistics for assessing seeding effects are discussed. The results of the studies indicate that it would be necessary to produce very substantial precipitation changes in the limited areas where the seeding silver *is* present in the snowfall to yield a statistically acceptable change over an entire target area. The trace chemistry results presented may explain why one of the randomized cloud seeding experiments did not achieve statistically significant seeding effects and why another statistically significant result may have been misinterpreted.

New seeding program designs and assessment methodologies need to be developed that not only will produce better targeting, but also positively identify the precipitation that has been impacted by the seeding process, so that seeding effects may be quantified with a higher degree of confidence.

1. Introduction and background

The primary purpose of large target area weather modification experiments conducted in the past 45 years has been to determine the effects of seeding on precipitation amount (e.g., Smith et al. 1963; Braham et al. 1971; Mielke et al. 1981; Gabriel 1970). However, as enunciated in the recent AMS Policy Statement on Planned and Inadvertent Weather Modification (AMS 1992), "satisfactory determination of the capabilities of cloud seeding to produce desired effects under various conditions has not resulted from the statistical analyses." The large natural variability of precipitation amounts from storm to storm or from one experimental period to the next, is the most generally cited major obstacle to the achievement of statistically significant results acceptable to the scientific community in large-scale randomized seeding experiments, irrespective of whether the result of the experiment appeared to be zero, positive, or negative. A second major obstacle affecting our ability to detect seeding effects has been enunciated in the recent WMO Statement on the Status of Weather Modification (WMO 1992), "It is also difficult to target the seeding agent from ground generators

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. . . upwind of an orographic cloud system." In addition, we might ask the question "to what extent can seeding materials be delivered to the appropriate cloud volumes at the times and in the concentrations prescribed by the seeding hypothesis over the large target areas (1000 km^2 or more) used in statistically designed seeding experiments?" This paper describes some of the successes and failures in this regard using ground-based releases of seeding aerosols. Allied work using aircraft releases have also demonstrated similar successes and failures (Deshler et al. 1990). In addition, the paper discusses the feasibility of simplifying the "detectability-of-effect" problem by distinguishing between the precipitation that may have been affected by the seeding and that which may have not. To do this, a "source–receptor" approach has been adopted in which trace chemical methods are used for measuring the quantities of seeding chemicals in the snowfall collected at receptor sites downwind of the source material release sites. This has been the basic experimental concept behind the earlier work of Lacaux et al. (1982), Parungo et al. (1969), Reynolds et al. (1989), Super et al. (1992), Warburton et al. (1968, 1972, 1982), and others, all of whom have shown that when AgI aerosols are dispersed into clouds, the silver can be readily detected in the precipitation from those clouds. Although the presence of the seeding chemicals in the snowfall is not evidence that seeding produced any precipitation, it does provide information on the dispersion and transport of the seeding aerosols and brackets times when seeding *could have* impacted the precipitation. It also provides information about times and locations where the seeding aerosols *have most probably not affected* the precipitation at all.

This paper describes studies of seeded and nonseeded snowfall in two large mountainous watersheds in the central Sierra Nevada using trace chemical methods and specially developed snow sampling techniques between 1978 and 1992.

2. Snow sampling and analysis methods

a. Field sampling techniques

The snowfall in the central Sierra Nevada has been sampled using two techniques. The first uses a 1.5-m-diameter collector lined with plastic sheeting from which the fallen snow is removed every 15–30 min throughout the snowfall event. This is to yield approximately 1000 mL of snowmelt water for the trace chemical analysis of each time-sequentially collected sample. Each sample is kept frozen until analyzed. The second method is to sample the snowpack as soon as possible after each winter storm by a vertical profiling (coring) method. These profilers have a square cross section of 200-cm^2 area. They are 1 m in depth and have horizontal slots cut in them. All components are made of acrylic plastic (tested to be contaminant free) and, prior to use in the field, are hygienically prepared in a Class-100 clean room environment and sealed in polyethylene sample bags to be opened at the sampling site. Each profiler is inserted vertically into the snowpack at a predetermined location and, before removal with the snow core inside, is subdivided into increments with partitioning plates inserted into the horizontal slots. The slots were 3.5 cm apart in the earlier model profilers and 2 cm apart in the more recent model. The snow in each segment generally represents 0.25–2 h of snowfall for the storms studied depending on snow density and precipitation rate. Each segment is placed in a separate plastic bag, sealed, and stored frozen until analyzed for both water and chemical content.

b. Laboratory analysis techniques

The silver concentration measurements were made in the trace chemistry laboratories with a flameless atomic absorption spectrophotometer located within a positive-pressure temperature controlled clean room. This was to ensure as much as possible a contaminant-free environment. The spectrophotometer is fitted with a controlled temperature furnace equipped with a rectangular carbon rod to allow the use of pure pyrolytic carbon microboats. Preconcentration of the samples is accomplished by repeated micropippeting portions of each melted snow sample onto the microboats followed by evaporation on a hot plate located in a laminar flow clean room hood.

Silver concentrations were determined from the atomic absorption values by comparing them with calibration curves using relevant concentration ranges of standard silver nitrate solutions. Analysis of variance methods were used to determine concentration errors. Up to 10 measurements on five separate aliquots of a melted snow sample were used to determine each silver value. The minimum detectable concentration of silver in a water sample using this equipment is 1.0 ppt, which in this geographical region is 50% of the natural background concentration. Typical calculated errors for the mean sample concentrations range between 10% and 30%.

3. Determining the natural background concentration of silver in snow

To determine the natural background concentration of silver in snow in the central Sierra Nevada, 847 snow samples were collected from 24 mountain sites surrounding Lake Tahoe during the 1983/84 winter season. Figure 1a gives the relative frequency distribution of the observed values. These snow samples were collected using the profiling method. Sampling procedures were similar to those used by Warburton et al. (1981) in Antarctica. No known seeding activities were being conducted within a range of 150 km of these sites at the times these snowfalls occurred.

Also in the winter of 1983/84, prior to the start of cloud-seeding activities in the Lake Almanor catch-

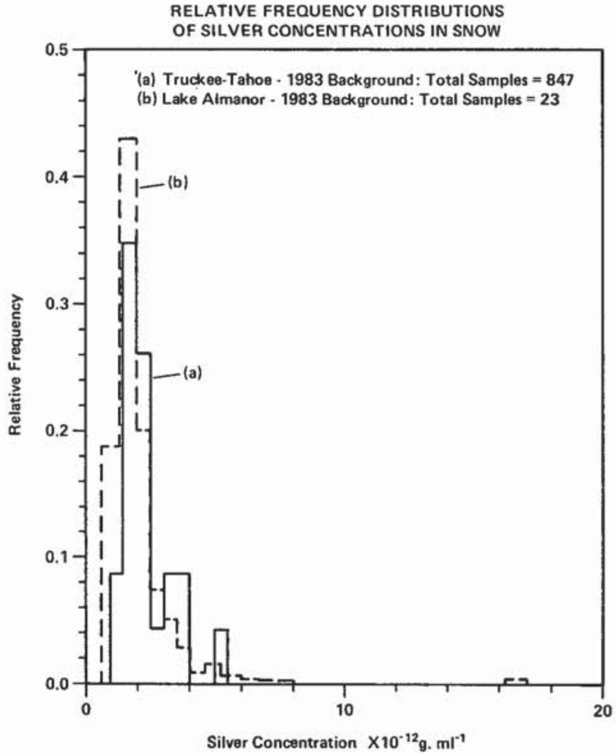


FIG. 1. Relative frequency of background silver concentrations for snow in (a) central Sierra Nevada and (b) Lake Almanor catchment area, 1983/84 winter season.

ment area of northern California (Fig. 2), two sampling expeditions were conducted into this catchment area on 14 and 15 December 1983. Twenty-three snow samples were collected from seven sites, the locations of which are shown. Table 1 and Fig. 1b give the details of the sampling and observed values. The same profiling methods were employed in collecting these samples.

It is concluded that Figs. 1a,b represent the natural background distribution of silver concentration in snow for the central Sierra Nevada.

A lognormal distribution was found to fit these results well and is given by

$$y = a_0 \exp\{-0.5[\ln(xa_1^{-1})a_2^{-1}]^2\},$$

where $a_0 = 0.431$ is the amplitude of the frequency distribution, $a_1 = 1.160$ is the peak center value of silver concentration, and $a_2 = 0.347$ is the width of the distribution at half-maximum of the frequency. This relationship has a correlation coefficient $r^2 = 0.994$, and a standard error of $s_e = 0.012$ ppt. There are no significant differences between the two distributions, and it seems apparent that fewer than 5% of the background samples contain silver concentrations of at least 4.0 ppt (henceforth used as the "threshold" value above which there is 95% confidence that the observed silver is due to seeding).

Several thousands of analyses made on snow samples collected in this region of the western United States from 1967 through 1992, show that the background concentration of silver in snow has remained relatively steady at $B_{Ag} = 2.0$ ppt. Values less than 3.0 ppt were reported by Warburton and Young (1968) and by Warburton et al. (1979) for unseeded snowfall for several seasons prior to the 1977/78 winter season. Recent measurements in the same region during the 1992/93 winter season by the present authors, confirm that the background value has not changed.

4. Estimating seeding rates and silver concentrations in precipitation after seeding with silver iodide

The cloud-top temperatures of orographic clouds in the central Sierra Nevada are generally $-15°C$ or warmer, and it is known that the concentration of naturally occurring ice nuclei present in the atmosphere varies inversely with temperature, ranging from 10 m^{-3} at $-10°C$ to 1 L^{-1} at $-15°C$. Hence, the seeding programs conducted in these areas hypothesize that increasing the ice nucleus concentration to about 10–20 L^{-1} of cloud volume, should produce sufficient additional ice particle growth to capture a substantial proportion of the available supercooled liquid water, which is known to exist at low levels in these clouds. Silver iodide release rates, therefore, are usually calculated to yield such ice nucleus concentrations.

It has been estimated by Ludlam (1955) that maximum precipitation efficiency would occur in 1 L of a supercooled mountain cloud in an updraft of 50 cm s^{-1} at a temperature of $-10°C$ if 20 ice spheres grew to a radius of 500 μm. Jiusto and Holroyd (1970) performed a similar calculation for lake-effect winter storms and showed that maximum precipitation efficiency would be achieved under conditions of temperature and updraft velocity similar to those used by Ludlum, with a concentration of around 200 L^{-1} of 100-μm-radius ice spheres. Additionally, it has been shown by Super and Heimbach (1988) in the Bridger Range program of Montana that, on average, about 10–20 ice crystals per liter were created over the target area when temperatures were about $-10°C$, and liquid water contents were near 0.1 g m^{-3} when a ground-based generator was releasing silver iodide at a rate of 30 g h^{-1}.

For the purposes of estimating silver concentrations in the precipitation falling in the Truckee–Tahoe and Lake Almanor watersheds described in this paper, let us assume that each silver iodide generator in use produces a concentration of 20 ice spheres per liter of seeded cloud at a temperature of $-10°C$. If each of these artificially produced ice spheres has a radius of 100 μm and contains one silver iodide particle in which the mean silver mass is in the range from 2×10^{-15} to 3×10^{-16} g as shown by Warburton et al. (1994), then the expected concentration of silver in the snowmelt

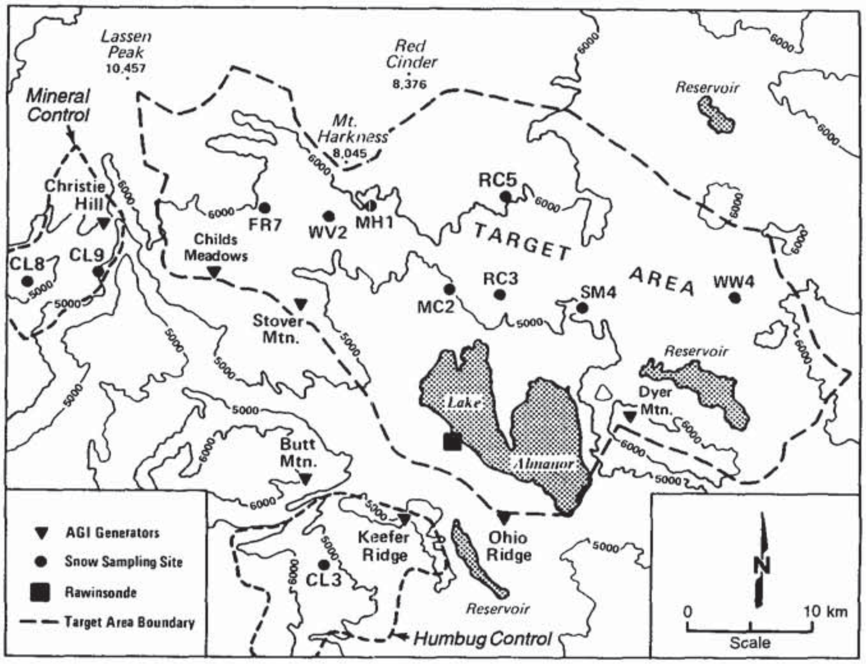


FIG. 2. Target area and control sites of the Lake Almanor cloud seeding program, showing locations of seeding generators, snow sampling, and rawinsonde releases.

water produced by those seeded ice crystals would be between 1 ppb and 80 ppt. The highest value observed in the Lake Almanor program was 400 ppt, and typical values in both programs are as shown in Figs. 4–8. Lower values than this would be expected because of dilution of the ice crystal concentrations by additional accreted water capture during their passage to the ground and by nonseeded natural ice crystals contained within the melted snow sample undergoing chemical analysis. If the observed silver concentration in the snow were at the detection limit of 1.0 ppt above background (see Fig. 1), this would indicate either substantial dilution of the silver in that snow sample or that the ice crystal concentration achieved by the seeding in the cloud at a temperature of $-10°C$ was very low and similar to that being produced by natural ice nuclei. This would make changes in precipitation efficiency caused by seeding difficult to detect.

5. Observed concentrations of silver in precipitation after AgI seeding

Both seeding programs discussed here use generators that consume 20–30 g of AgI per hour, generating about 10^{13} particles of AgI per second. The number of these that act as ice nuclei varies of course with temperature. Observed concentrations of *silver* in the snowfall collected from these projects range from 2 to 400 ppt, most being less than 100 ppt. It is considered reasonable to assume that if silver is detected in the precipitation significantly above the "threshold" value at any specific location, then this is evidence that the silver iodide has

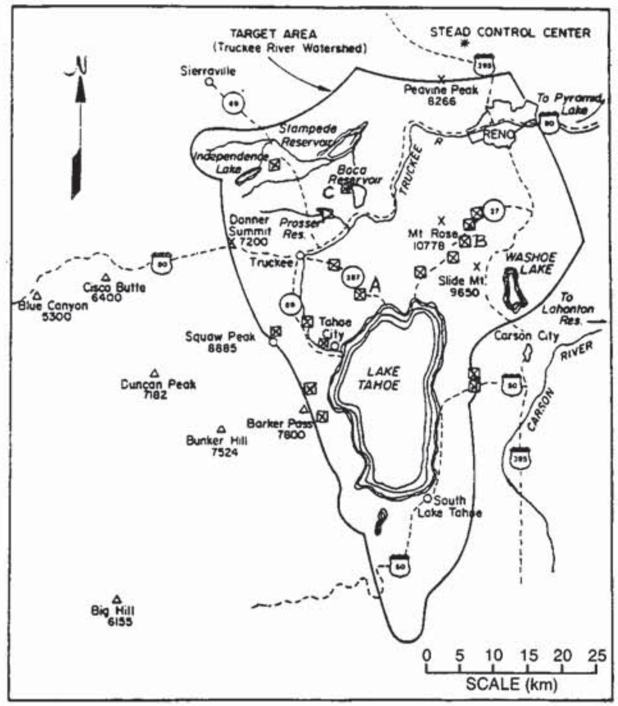
TABLE 1. Natural background silver concentrations in snow—Lake Almanor Project.

Sample site name: code	Elevation (m)	Snow depth (m)	No. of samples	Mean Ag concentration ($\times 10^{-12}$ g mL^{-1})
Feather River: FR7	1900	0.74	4	1.9 ± 17%
Warner Valley: WV2	1700	0.38	3	1.8 ± 16%
Mt. Harkness: MH1	1850	0.79	3	2.6 ± 19%
Mud Creek: MC2	2000	0.43	3	2.4 ± 15%
Rock Creek: RC3	1730	0.24	3	1.6 ± 23%
Rock Creek: RC5	2000	0.68	4	2.8 ± 17%
Swain Mtn.: SM4	1670	0.24	3	3.2 ± 12%

Mean silver concentration $\mu = 2.3 \times 10^{-12}$ g mL^{-1}
Standard deviation $\sigma = 0.95 \times 10^{-12}$ g mL^{-1}

somehow become involved in the precipitation at that location. A failure to detect silver in the precipitation is treated as evidence that the silver iodide plumes have had considerably less involvement with that precipitation, possibly including being transported out of the target area completely. The detection of the silver might then be used for stratifying other features of the ice-phase precipitation such as amounts, rates, ice crystal types, and degrees of riming.

To take the next step to determine the proportion, if any, of the silver iodide that has acted as an ice nucleant and the proportion that has been removed in the precipitation by "passive" scavenging processes, it is necessary to use another non-ice-nucleating submicron-sized aerosol released at the same times and locations as the silver iodide. This has been done by Warburton et al. (1994) using indium sesquioxide particles. On the average, when winter storms were seeded with the two aerosols simultaneously from ground-based generators in the central Sierra Nevada, one quarter of the silver observed in the snowfall was most probably captured by scavenging processes and three quarters by ice nucleation.



△ Locations of Silver Iodide Aerosol Generators

⊠ Locations of Snow Sampling Sites

FIG. 3. Truckee–Tahoe catchment area showing sites for snow sampling and of seeding aerosol generators.

6. Transport and dispersion of silver iodide in experimental seeding projects

Experiments have been conducted in several mountainous regions of the western United States to determine the spatial and temporal variations of silver from silver iodide in snowfall during seeding treatment periods. These include the central Sierra Nevada by Warburton et al. (1979), Stone (1986), and Reynolds et al. (1989); the Bridger Range, Montana, by Super and Heimbach (1983), Heimbach and Super (1988); and the Wasatch Range, Utah, by Super and Huggins (1992).

Investigations in the 1977/78 Sierra Nevada winter season used three fixed site laboratories shown as A, B, and C in Fig. 3. A total of 178 fresh snowfall samples were collected at 20–40-min intervals throughout eight seeded storm periods between November 1977 and April 1978. Six silver iodide ground-based generators were used, and the seeding was conducted only when the temperature at the weather station on Slide Mountain (9650 MSL) was less than or equal to $-5°C$ and the winds were from 190° to 350° at speeds below 100 km h^{-1}. This was to ensure that the storms being seeded had cloud temperatures cold enough for AgI seeding and transport of the seeding aerosols would be toward the target area as shown in Fig. 3. All generators in use were controlled remotely by telemetry and their behavior was monitored continuously throughout each seeding operation. This monitoring included flame temperature, silver iodide fluid flow, and propane gas flow.

The samples of snow analyzed represented 131 h of sampling time. Silver above the background concentration was present for 23.5 (18%) of these hours at those sites. The results also showed that while seeding was continuous for periods of 12–48 h, silver appeared in the snowfall at any one site for blocks of time ranging from 30 min to 4 h. Possibly a good example of this behavior is shown for 7 February 1978 in Fig. 4. Nineteen snow samples were collected sequentially and in real time from 1100 to 1630 PST at the Brockway summit high-altitude laboratory (site A) above the western shores of Lake Tahoe. This site is downwind of the ground-based generators releasing the silver iodide during westerly flow storms as shown in Fig. 3. On this day, four of the six generators shown were operating. Three of them (Blue Canyon, Big Hill, and Barker Pass) seeded continuously from 0832 PST 6 February 1978 until 1708 PST 7 February 1978, and the generator at Cisco Butte operated from 1245 PST 7 February 1978 until 1707 PST 7 February 1978. The total amount of silver iodide released during these time intervals was 4 kg. The generators at Blue Canyon and Cisco Butte released 42.6 g of silver iodide per hour, while those at Big Hill and Barker Pass released 22.5 g h^{-1}. The concentrations of silver (in parts per trillion) in the snow samples are plotted as a function of time. These concentrations are determined from measurements in five separate aliquots of the melted snow sample. Each is measured 10 times and the means and

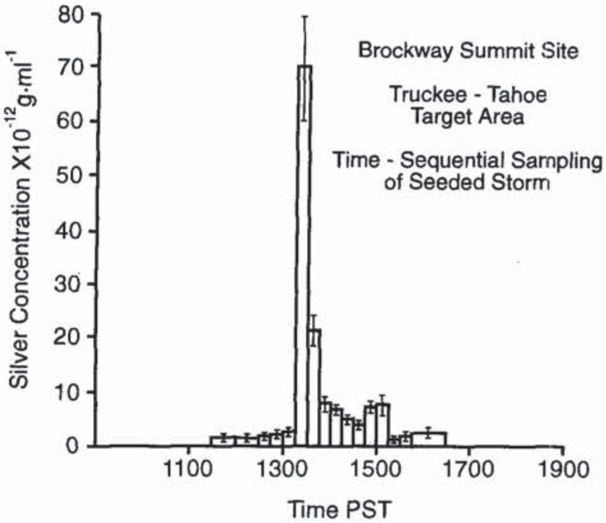


FIG. 4. Silver concentration of snow samples collected time sequentially at Brockway Summit (site A) west of Lake Tahoe on 7 February 1978. Storm was seeded; winds were southwesterly. Error bars (plus/minus standard deviation) are shown for each value.

standard deviations determined. The error bars (usually 10%–30% of the observed value) are shown for each determination. The results show that there is no seeding silver above the background for the period 1130–1315 PST during this seeded storm, followed by a strong to medium signal of silver content in the snow from 1315 to 1515 PST and nondetection from 1515 to 1645 PST.

These temporal variations are also apparent, as are spatial variations, from analyses of snow obtained from vertical profiles collected from 10 sites in the same target area. A total of 779 snow samples were collected by this method following 7 of the seeded winter storms between 22 December 1977 and 10 April 1978. Each 3.5-cm depth increment of each core was analyzed for its silver content. Figures 5 and 6 are examples and show silver concentrations in parts per trillion observed as functions of snow depth at Mt. Rose (site B) and Brockway (site A) in the target area (Fig. 3). This sampled snowpack resulted from a consecutive series of discontinuous snowfalls that occurred between 2300 PST 12 January and 1000 PST 17 January. Seeding was carried out with all six generators as shown in Fig. 3 for 56 h of this 4.5-day period whenever cloud and wind conditions were deemed suitable for seeding. A total of 8.4 kg of silver iodide was released. The two sampling sites are 24 km apart; Fig. 5 (site B) shows silver in concentrations well above the background of 2 ppt (σ = 1 ppt), for most of this seeded snowfall period, whereas Fig. 6 (site A, the same site where silver was detected in the 7 February case) shows no silver above the background during the same period. Results of this type led Warburton et al. (1979) to the conclusion "that the seeding silver was present in only 10%–20% of the snowfall sampled in this target area." The

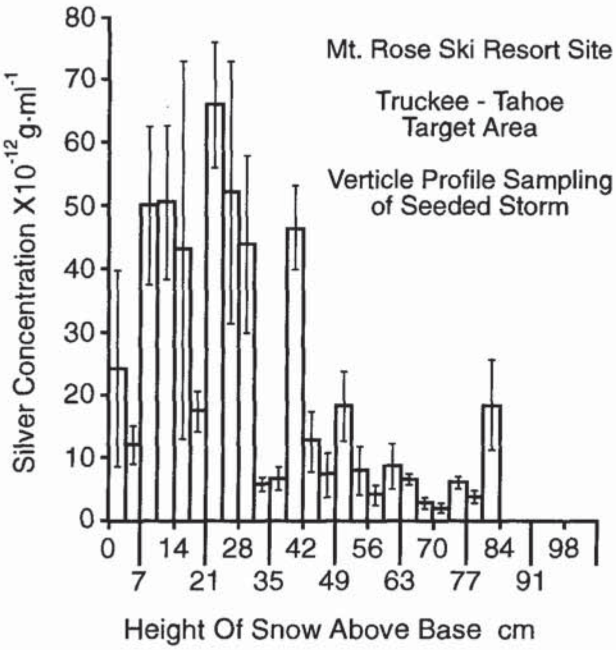


FIG. 5. Silver content of snow samples collected by profiling the snowpack vertically near Mount Rose ski area (site B) in the Truckee–Tahoe catchment area following silver iodide seeding 12–17 January 1978. Error bars for each value are shown as for Fig. 4. Top of profile is the latest snow that has fallen.

same conclusion has been drawn by Reynolds et al. (1989) for Desert Research Institute analyses of profile-collected snow samples in the Sierra Cooperative Pilot Project study in the winter of 1986/87, and this has

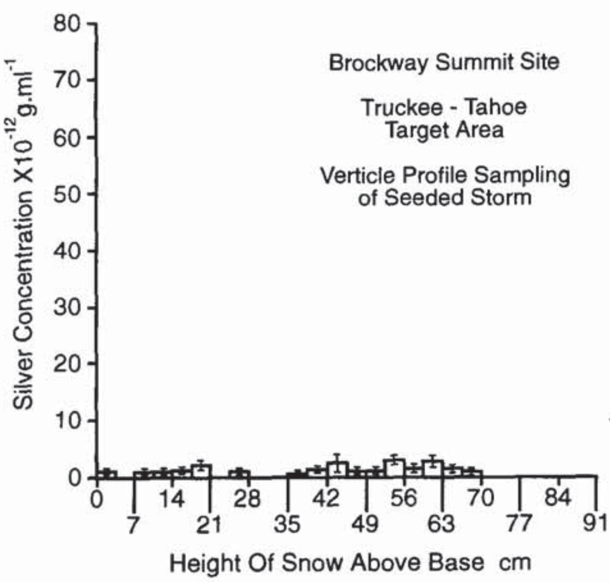


FIG. 6. Same as for Fig. 5 for snow at Brockway Summit (site A) in the Truckee–Tahoe catchment area during the same silver iodide seeding periods.

been found to be the case also during the winters of 1989/90 (17%) and 1990/91 (22%) for the Truckee–Tahoe seeded catchment area.

The nonuniform presence of "seeding silver" in the target area, both temporally and spatially, is consistent with plumes of aerosols remaining finite in width and meandering across the mountainous topography; a "directional" problem. The low-frequency of detection of silver in the snow might also be related to whether or not the AgI particles reached cloud temperatures cold enough and early enough after release to allow sufficient ice crystal growth for deposition in the target area; a "particle trajectory" problem. The results are not consistent with widespread mixing leading to uniform dispersion in the clouds at temperatures suited to ice nucleation, as may have been intended.

7. Relationship of chemistry results to statistical analysis of precipitation data

Assessing seeding effects by comparing the precipitation that has fallen in target or control areas during "seeded" periods with that which fell during "nonseeded" periods, has long been the approach used in statistical analysis of weather modification experiments (e.g., Mielke et al. 1981). Because of the need for eliminating bias in the analysis, the use of randomization in making the seeding decisions has been traditional. The primary purpose of such randomization is to provide datasets of precipitation amounts for which natural processes alone are responsible; hence, these data are normally the precipitation amounts that occurred during the randomized "unseeded" periods. Also because of the large natural variability of precipitation, it has usually been necessary to conduct these randomized experiments for many years to obtain a sufficient number of unit measurements of precipitation to which appropriate statistical analysis methods may be applied.

The initial trace chemistry results described above indicated that nonuniform and frequently inadequate transport and dispersion of seeding aerosols into the intended target areas may be primary causes for the failure of such long-term statistical experiments. For the Truckee–Tahoe project, for example, it has been found that 80%–90% of the precipitation falling in the target area during "seeded" periods did not contain detectable quantities of seeding material and, therefore, was very probably precipitation also produced by natural processes.

If the presence of silver in the snowfall at concentrations above the "threshold" value were used as a criterion that transport of the silver iodide to the target area had been successful, then substantial increases in precipitation would need to have been produced at the sites where the silver *was* detected, in order to produce a statistically acceptable increase in precipitation over the entire target area.

The challenge then is how to separate the treated from the nontreated precipitation (other than merely seeding some storms and not seeding others), and so improve the detectability of any seeding effect. The opportunity to investigate these issues was provided by a joint program of research with the Pacific Gas and Electric Company (PG&E) in the Lake Almanor region of the Sierra Nevada.

8. The Lake Almanor winter orographic cloud seeding program

a. The 1962–67 randomized experiment

Mooney and Lunn (1969) reported on the results of this 5-yr randomized cloud seeding experiment in the Lake Almanor catchment area (Fig. 2). This 1300-km^2 catchment is located on the north fork of the Feather River and extends 40 km west–east and 32 km north–south. The lake is located in the southern portion of the watershed and has an area of approximately 107 km^2. The watershed ranges in elevation from 1400 to 3200 MSL. The five winter seasons project used silver iodide aerosols released from ground-based generators located between 1800 and 2300 MSL. The seeding results were subdivided into four weather categories depending on wind direction and temperature. There were only 10 cases in the warm westerly category, which was too small a sample size to be analyzed. There were 78 cold southerly cases, 38 east target seeded, and 40 west target seeded. Seeding produced a 3% decrease that was not statistically significant. There was no significant effect of seeding the warm southerly storms. In the remaining category, characterized by westerly winds and cold temperatures, the "precipitation increase peaked at approximately 57% between 8 and 17 km downwind of the generators, and averaged 37% throughout the 33 km west–east extent of the project area." These results were reported as being statistically significant at the 0.05 level. The apparent annual precipitation increase on this watershed from seeding cold westerly storms has been estimated as 5% (cold westerly storms account for approximately 15% of the annual precipitation).

b. The 1971–74 randomized experiment

Bartlett et al. (1975) continued the earlier work by conducting a new randomized experiment in the same watershed for three successive winter seasons, 1971–74. The eight seeding generators were placed south and west of the target area because southerly or westerly airflow was associated with most of the precipitation. The generators were arranged in two groups, west and south. The west group was situated west of the target to affect the target under westerly wind conditions, and the south group was similarly arranged for southerly wind conditions. Four of the eight generators affect the target area under both southerly and westerly airflow. They also used two control areas that are shown in Fig. 2. When the storm type was stratified as southerly by the criteria given in Table 2, the target area was to be seeded during approximately one-half of the experimental periods. When the storm type was classified as westerly, the target area was to be seeded using a ten-to-one randomized seed/no-seed design. The control areas were not to be seeded at all. In the three-year program, 52 storms were classified as warm southerly. This category accounts for about 50% of the annual precipitation. Twenty-five of these were seeded and 27 not seeded. Statistical analysis of the snowfall amounts indicated that seeding had decreased the precipitation by 19%, the result being significant at the 0.05 level. The authors suggested that "overseeding" was a probable cause for the observed decrease. Precipitation data for cold southerly storms has not been published. In the other categories, warm westerlies were not analyzed because of the small sample size; cold westerlies were not reevaluated, the results of Mooney and Lunn (1969) already having indicated an average precipitation increase in the target area of about 37%. Hence, it is not possible to compare the statistical results from these two separate randomized experiments.

c. The 1983–90 research experiment

Based upon the aerosol targeting results obtained for ground-based seeding in the Truckee–Tahoe catchment referred to earlier in this paper, a research program was designed for the Lake Almanor weather modification project. This program would employ trace chemical methods for investigating the transport and targeting of the seeding aerosols, using the source–receptor approach. It would examine the spatial and temporal distributions of the silver content of the snow falling into that watershed. If possible, this data might later be used in combination with precipitation data to assist in quantitative evaluation of the seeding project.

PG&E's meteorological staff were responsible for evaluating each storm in relation to established seeding criteria, and for controlling the seeding operations. Upper-air soundings from the National Weather Service and rawinsondes released from the southern shore of Lake Almanor (see Fig. 2) were available to these forecasters. These soundings, taken prior to and during the seeding operations, were used to categorize storms into the four cloud-seeding modes used in the 1962–74 randomized experiments. The mode chosen determined which aerosol generators were to be operated. Seeding modes depended on temperatures at 2300-m altitude and the averaged wind direction in the layer from 1850 m to the $-10°C$ isotherm. Criteria are shown in Table 2, together with the locations of which generators were activated for each storm category.

The experimental design of this weather modification project required that each seeding event was to be 12 h in length, consisting of 11 h of aerosol generator operation. This was to be followed by a 1-h pause to allow the seeding agent time to be transported out of the area. A new seeding event could not be initiated before the previous event had completed its assigned time interval. When forecasted weather conditions did not materialize, the forecaster could terminate seeding early if the seeding interval duration was less than 7 h.

All seeding was accomplished from ground-based generators arranged in a general west–east arc around the southern and western boundaries of the target area. The generator configuration was reduced to five sites during the 1984/85 winter field season to facilitate simultaneous releases of AgI and In_2O_3. They were Christie Hill, Stover Mountain, Butt Mountain, Keefer Ridge, and Ohio Ridge (see Fig. 2). The generators were completely automated and radio controlled. A 3% solution of silver iodide-ammonium iodide in acetone was burned to produce a seeding release rate of 18.75 g h^{-1} of AgI per generator. Continuous precipitation measurements were recorded at eight snow-sampling sites in the target area. Both weighing and tipping-bucket gauges were used primarily for assigning times to the start and end of precipitation. These gauges had heated orifices to help prevent snow capping.

1) Use of silver content of snow for estimating transport of silver iodide across the Almanor target area

The seeding modes during the 1984/85 winter test period resulted in 6 warm westerly, 12 cold westerly, and 7 cold southerly (12 h) events occurring prior to the snow-sampling expeditions. The choice of generators activated was based on the observed meteorological conditions and the operational criteria listed in Table 2.

Four field expeditions were conducted during the season to collect snow profiles at the eight sites shown in Fig. 2. The silver and water content of each 2-cm increment of each profile were measured. The trace chemical data were used to determine the proportion of 2-cm snow profile increments, which contained silver significantly above the "threshold" concentration level of 4.0 ppt. The results are given in Table 3.

Of the 683 snow samples analyzed from the eight collection sites in the 1984/85 test period, 24% contained silver significantly above the background. The percentage with silver during westerly storms was 42%, and that during southerly storms was only 8%. The percentage of samples containing significant silver ranged from 0 at site MC2 during southerly storms to 79% at SM4 during westerly storms.

These highly variable targeting results for seeding aerosols released over complex mountainous terrain, show clearly the need to improve the methods for more adequately filling the appropriate cloud volumes with more efficient ice-nucleating agents. This points to the great need for detailed understanding of the air motions involved. Such understanding must come not only from this type of trace chemistry work but also from improved plume tracking experiments such as those

TABLE 2. Seeding criteria and stratification.

(a) The freezing level must be at elevations less than 2440 m.
(b) Cloud-top temperature must be warmer than −28°C.
(c) Mean wind speed between 1850 m and the −10°C isotherm must be less than 25 m s^{-1}.
(d) Mean wind direction in this same layer must be between 145° and 305°T.

Stratification of storm types to be seeded were as follows:
(a) Cold westerly: mean wind directions ranging from 235° to 305° and the height of the −5°C isotherm is less than or equal to the 2300-m level. Seeding generators activated are Butt Mtn., Stover Mtn., Christie Hill, Keefer Ridge, and Childs Meadows.
(b) Warm westerly: mean wind directions ranging from 235° to 305° and the −5°C isotherm is greater than the 2300-m level. Seeding generators activated are same as for cold westerly.
(c) Cold southerly: mean wind directions ranging from 145° to 234°; the −5° isotherm is to be at or lower than the 2300-m level. Seeding generators activated are Butt Mtn., Stover Mtn., Keefer Ridge, Ohio Ridge, and Dyer Mtn.
(d) Warm southerly: mean wind directions ranging from 145° to 234°; the −5°C isotherm is higher than the 2300-m level. Seeding generators activated are the same as for cold southerly.

used by Super et al. (1992), the use of low-level wind profiling equipment, and the application of theoretical terrain-following models such as those presently being developed by Clark (1990) and others.

2) SILVER IODIDE CONTAMINATION OF ALMANOR CONTROL AREAS AND EFFECTS OF WIND TRAJECTORIES IN SOUTHERLY FLOW CONDITIONS—1987–90 STUDIES

The results presented in Table 3 have shown that very few snow samples contained seeding silver during southerly flow conditions, and, therefore, may explain the Mooney and Lunn (1969) report of the absence of a positive seeding effect in these conditions.

It was also noted in these studies that the frequency of occurrence of seeding chemicals in the snowpack diminished when the "operational wind direction" (i.e., the mean wind used for seeding decisions), was less than 210° in the southerly seeding modes. Also, because the poor success of targeting during southerly flow conditions did not explain the apparent *negative* effects of seeding in these conditions reported by Bartlett et al. (1975), additional source–receptor studies were made concentrating on southerly flow storms during the winters of 1987/88, 1988/89, and 1989/90.

TABLE 3. Proportion of snow samples containing silver above "threshold"—Lake Alamanor Project.

Site code	No. of samples collected from west flow storms	No. of samples collected from south flow storms	No. of samples with silver $>4.0 \times 10^{-12}$ g mL^{-1} West flow	South flow
FR7	55	62	18	1
WV2	34	45	17	12
MH1	58	63	28	3
MC2	44	45	11	0
RC3	32	27	13	5
RC5	52	54	11	0
SM4	34	35	27	3
WW4	24	19	14	4
Totals	333	350	139	28

The silver iodide seeding generator site configuration was returned to its pre-1984 form of seven sites. Additionally, the number of snow sampling sites was augmented to include one in the Humbug control area (CL3), and two in the Mineral control area (CL8 and CL9) as shown in Fig. 2. All other aspects of the operational seeding program (procedures, seeding criteria, meteorological measurements, and sampling sites) remained the same as during the 1984–85 program. Source–receptor trajectories of the seeding aerosol plumes were then estimated based on the location and timing of samples containing seeding silver, combined with comparisons of the performance records of the seeding generators operated in each seeding event.

During the 1987 through 1990 winter seasons, 486 snow samples were collected from these three control sites immediately following 11 seeding operations under cold-southerly storm conditions. The dates and numbers of snow samples analyzed for each of the control sites are given in Table 4. For the 1989 and 1990 winter seasons only two sites were used, one in each control area, CL8 being eliminated because of its close proximity to CL9.

Of these 486 snow samples, 114 contained silver above the threshold value ($B_{Ag} + 2\sigma$). For the three seasons, the percentage of samples with silver above the threshold were 1987/88, 36% (see Figs. 7a–c); 1988/89, 14%; and 1989/90, 8%. The mean silver concentrations at CL3, CL8, and CL9 for 1987/88 were 8.9, 11.9, and 7.7 ppt, respectively. In 1988/89 the mean values were 12.2 and 6.9 ppt at CL3 and CL9 and were less than or equal to 4.0 and 8.5 ppt at CL3 and CL9 in 1989/90.

3) ESTIMATING WIND TRAJECTORIES TO PRODUCE OBSERVED SILVER IODIDE CONTAMINATION IN LAKE ALMANOR CONTROL AREAS

As shown in Table 2, the layer-averaged winds used to make operational seeding decisions included winds

TABLE 4. The 1987–90 Lake Almanor project control sites snow sampling following cold southerly seeded storms. The number of samples analyzed per site for each sampling date are shown.

Date	Site CL3 (Humbug 3)	Site CL8 (Mineral 8)	Site CL9 (Mineral 9)
18 December 1987	14	7	9
31 December 1987	15	17	20
12 January 1988	20	27	32
20 January 1988	20	20	18
29 December 1988	37	no samples collected	45
12 January 1989	15	no samples collected	21
16 February 1989	11	no samples collected	17
4 March 1989	24	no samples collected	23
20 March 1989	9	no samples collected	14
25 April 1989	4	no samples collected	9
13 March 1990	17	no samples collected	21
Totals	186	71	229

up to the −10°C level. In southerly flow storms, which are generally warmer than the westerly storms, this would sometimes include winds at altitudes greater than 3000 MSL.

By using the actual locations and times of occurrence of the snowfall in the control areas that contained the "seeding silver," and the times of operation of the seeding generators during southerly flow storms between 1985 and 1990, estimates were made of the *average* trajectories needed to transport the aerosols to those control sites. It was found that this required flows coming from directions between northeast and southeast. Such winds are most likely at the *lower levels* early in these storms, the winds coming from the south and on toward the southwest later in the storm periods as surface fronts pass through the watershed. This is consistent with conceptual models of frontal passage and structure found by Marwitz (1986) and others. Because these low-level winds were not emphasized in calculating the layer-averaged winds for the operational seeding decisions, and because the seeding aerosols are all being released from ground-based generators, it is reasonable to assume that such low-level winds played significant roles in transporting the aerosols into the control areas.

Referring back to the statistical evaluation of the 1971–74 Lake Almanor randomized seeding experiment, the apparent negative seeding effects in southerly flow storms, therefore, could have resulted from inadvertent seeding of the control areas rather than from overseeding in the target area, as suggested by Bartlett et al. (1975). For apparent negative seeding effects to be caused by seeding of the control areas, it would be necessary for the silver iodide to reach levels in the control area clouds where some of the aerosol particles could become active ice nuclei. Unfortunately, evidence on this issue is not available at this time.

4) South to north transport of AgI in Almanor storms classified as "westerly"

Another specific example of the wind trajectory issue is given in the chemistry of a snowpack profile collected at the Mount Harkness (MH1) sampling site from seeded storms, which occurred 7–8 February 1985. Only one silver iodide generator (Keefer Ridge in Fig. 2) was operating during the periods that silver was detected above the threshold value. The layer-averaged wind used to start seeding at 1400 PST 7 February established the storm as a "cold southerly," which continued until 0100 PST 8 February. Later on this day, the layer-averaged wind direction for the next two storm episodes was 240°, and they were classified as "westerly." Mount Harkness received 84 cm of snow from all three storm periods. The increments of snow in which silver was detected and the approximate time periods of the snowfall obtained from nearby snow gauge data are shown in Fig. 8. The density of the snow in each 2-cm increment was measured and the precipitation rates determined throughout the entire snowfall period. The rates varied from 1.12 cm of water per hour on 7 February to 0.18 cm h^{-1} on 8 February. The snow from the cold southerly seeding period on 7 February is represented by the lower sections of the profile in Fig. 8. Very few of these lower increments contained silver above the "threshold" of 4.0 ppt, consistent with the poor targeting of seeding aerosols in this project for storms classified as southerly. Markedly high concentrations of silver up to 160 ppt were detected in the upper 18 cm of the profile. The snow containing the seeding silver therefore fell during the two storm periods classified as warm westerly from 0400 to 1200 PST and as cold westerly from 1400 to 2145 PST on 8 February. However, the transport of the silver iodide from Keefer Ridge to Mount Harkness would appear to require winds originating from more southerly directions. Even though this south–north transport of silver iodide occurred during the storm periods classified as westerly, this would not have affected the statistical analyses results because Keefer Ridge was one of the three generator sites activated during both southerly and westerly classifications of storms as shown in Table 2.

5) Relationship of Almanor chemistry results to statistical analysis of precipitation data

As described in sections 8a and 8b above, the Lake Almanor randomized experiments of 1962–67 and 1971–74 were evaluated statistically using precipitation

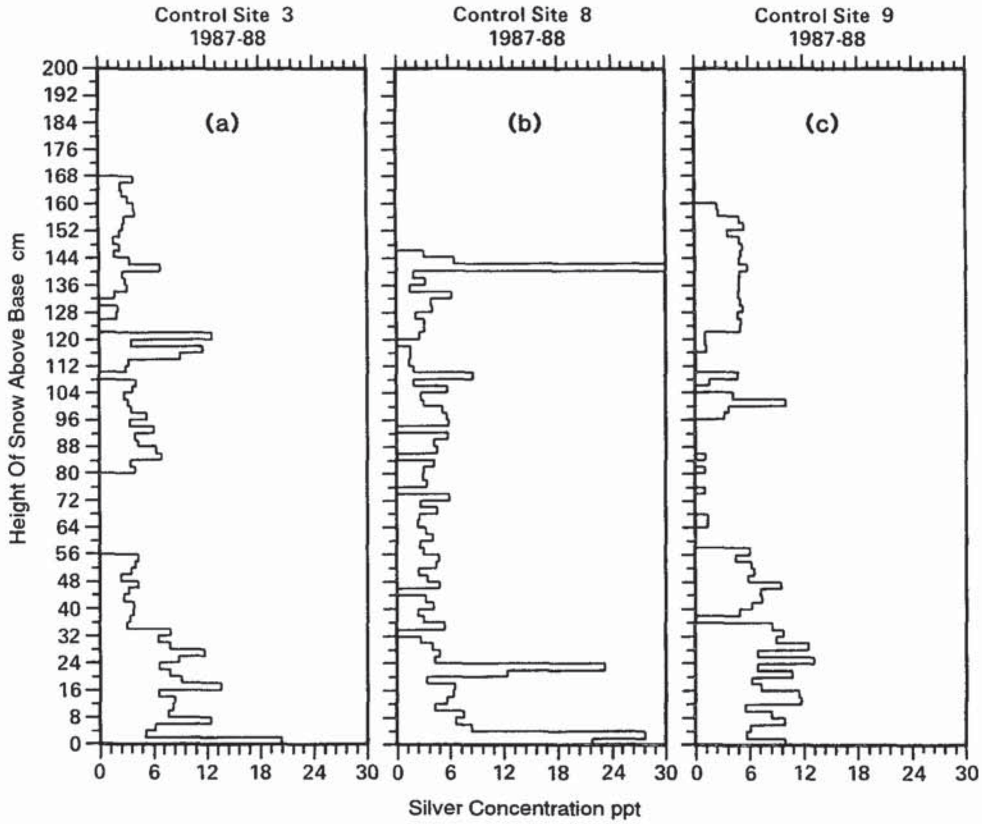


FIG. 7. (a)–(c) Silver concentrations in snowfall from three upwind control sites in the Lake Almanor cloud seeding project, 1987–88 winter season.

amounts occurring in the target area during seeded and nonseeded periods.

The 1962–67 experiment produced significant positive results when cold westerly storms were seeded. The chemical analyses described in this paper are consistent with such results as the targeting of the seeding agent in these meteorological conditions was found to be modestly satisfactory. However, no changes in precipitation amount were detected when southerly flow storms were seeded. These storms produce most of the precipitation in this region. The chemical analysis results presented earlier have shown that the targeting of the seeding aerosols was quite poor in these conditions, and this may be the cause for the null result. In the 1971–74 program, statistically significant negative results occurred when warm southerly storms were seeded. Analyses of rawinsondes and snow chemistry have shown that the method employed in assessing the layer-averaged wind direction for classifying the storms, as well as for deciding which aerosol generators were to be activated for seeding, did not place sufficient emphasis on the lower-level winds. As a result, it is very probable that the control areas were inadvertently seeded as appears to be evidenced in the 1988–90 chemical investigations. Hence, the apparent negative seeding effects under southerly flow conditions reported by Bartlett et al. (1975) may have resulted from transport of the seeding aerosols into the control areas, assuming of course that some of the silver iodide reached sufficiently cold temperatures to be activated as ice nuclei.

9. Conclusions

Atmospheric modification projects designed to augment precipitation in winter storm conditions in the central Sierra Nevada of the United States have been shown to face serious problems in transporting and dispersing silver iodide aerosols into target areas from networks of ground-based generators. Because the natural background concentration of silver in snow is extremely low in this region (B_{Ag} = 2 ppt, σ = 1 ppt), it was possible to detect the "seeding silver" in snow that had fallen into two large catchment areas of the Sierra Nevada during seeding experiments.

For the Truckee–Tahoe region, it has been shown over several winter seasons that no more than 20% (average) of the precipitation falling during seeding operations contains "seeding silver" greater than $B_{Ag} + 2\sigma$, referred to as the "threshold" value.

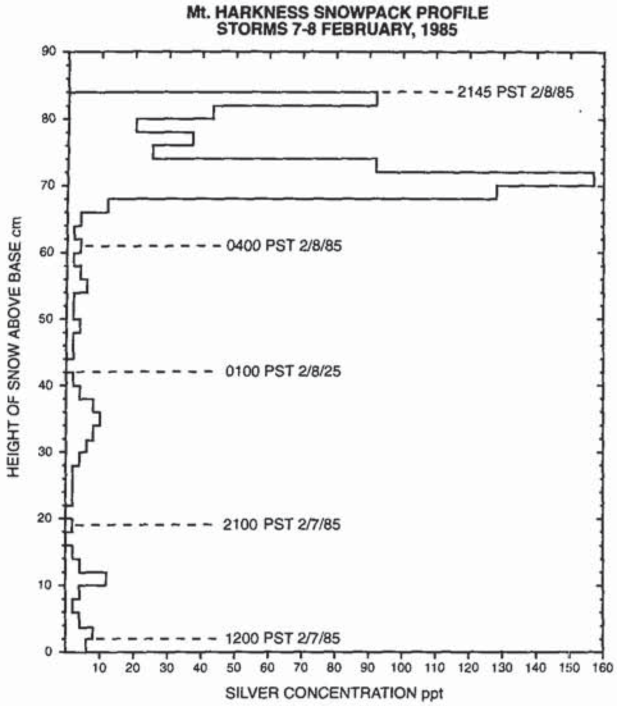


FIG. 8. Silver concentrations of snowfall in the Lake Almanor target area at Mount Harkness (site MH1 in Fig. 2) for storms of 7–8 February 1985. Top of profile is the most recent snow that has fallen.

For the Lake Almanor region in northern California, it has been shown that when seeding occurred during westerly flow wind conditions, the silver concentrations in the snowfall in the target area were above the "threshold" in 42% of the snow samples analyzed. When seeding occurred under southerly wind flow conditions, results were poor (8% of snow sampled with silver above "threshold").

It is considered reasonable to assume that when precipitation does not contain seeding silver above the "threshold" value then there has been very little, if any impact by the seeding process. Because this was the case in about 80% of the snow sampled in the two target areas, it is concluded that substantial precipitation increases would need to be produced in the other 20% of the snowfall during the seeded periods to achieve a statistically acceptable addition to the precipitation over whole target areas for all winter storm types being seeded.

It has also been shown that when storms penetrate from the south into the Almanor region, the seeding silver above "threshold" concentrations was often found in the snow in the upwind control areas. This was attributed to the lack of emphasis on the lower-level winds, which flow toward the west and northwest early in the southerly storm periods prior to frontal passage, when determining the layer-averaged wind direction for seeding decisions.

These results may provide an explanation for the failure of the Lake Almanor program to produce positive seeding results in southerly flow conditions. The observed contamination of the upwind control areas may also provide an alternative explanation for apparent negative seeding effects reported by Bartlett et al. (1975) for southerly flow storms in this catchment area.

Because winter orographic storms are considered both by the World Meteorological Organization and the American Meteorological Society as the weather systems most likely to yield precipitation enhancement by the cold cloud seeding process, it is further concluded that new seeding techniques and methodologies need to be developed that can 1) better target the seeding materials into these mountainous snowpack areas, and 2) improve the "seeding signal" detection process, which might be achieved by chemically distinguishing between the unseeded and seeded precipitation amounts as proposed by Warburton et al. (1994). This should improve our ability to determine when and where there may have been a seeding effect.

These techniques together with the latest plume tracing methods, which have been developed recently, and the terrain-following models, which are now available, place the scientific community in a much better position today to conduct successful seeding experiments than in previous years.

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