Microphysical Effects of Wintertime Cloud Seeding with Silver Iodide over the Rocky Mountains. Part I: Experimental Design and Instrumentation

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ABSTRACT

A series of winter orographic cloud seeding experiments is described in which the seeding agent and associated changes in cloud microphysics are monitored to within 300 m of the target areas (Montana and Colorado), and at the surface (Colorado only). This, the first paper in a three-part series, discusses the underlying physical hypothesis and experimental approach, and describes in detail the instrumentation used. The results of the physical evaluations, presented in Parts II and III, show that marked microphysical changes were caused by both ground-based and aircraft seeding with silver iodide.

1. Introduction

It is widely recognized that improved physical measurements of the effects of cloud seeding are needed. One of the specific recommendations in the American Meteorological Society Policy Statement on Weather Modification (AMS 1985) is the pursuit of field research on the modification of the development and growth of precipitation particles caused by cloud seeding agents.

Past weather modification experiments usually relied primarily on statistical evidence with only limited (and often indirect) physical evidence (e.g., Mielke et al. 1981; Super and Heimbach 1983). A noteworthy exception was the work over the Cascade Mountains reported by Hobbs and Radke (1975), who developed innovative techniques for the physical evaluation of seeding using airborne, ground and radar observations.

More recently, the HIPLEX-1 experiment (Smith et al. 1984) and the Sierra Cooperative Pilot Project (Reynolds and Dennis 1986) have demonstrated the types of direct physical observations that can now be made to document the effects of cloud seeding. Of greatest importance to the present investigation is the availability of two-dimensional imaging probes, which allow estimation of ice particle concentrations, size spectra, and habit. These observations can also be used to estimate the precipitation rate at the sampled level (Holroyd 1987).

The experiments by Super and Heimbach (1988) discussed in Part II and by Super and Boe (1988) discussed in Part III provide direct evidence of the physical chain of events following the introduction of an artificial ice nucleant into winter orographic clouds over the Rocky Mountains. Recent observations indicate that such clouds often contain supercooled water but are frequently inefficient precipitation producers (Rauber and Grant 1986; Rauber et al. 1986; Super 1986; Super et al. 1986; Thompson and Super 1987). The clouds' persistence over many hours makes them excellent candidates for seeding experiments, especially when little or no natural precipitation occurs to obscure the seeding signal. They may also be good candidates for enhancing the seasonal snowpack. While their short-term, cross-barrier liquid water flux is often small (Thompson and Super 1987), the high frequency of their occurrence and their long duration can result in significant seasonal flux (Boe and Super 1986).

2. Experimental design and physical hypothesis

Two separate series of physical cloud seeding experiments were conducted during consecutive winters at different locations in the Rocky Mountains. These series were very similar in both their observational approach and in their analysis methods.

The first experiments were conducted during January 1985 over the Bridger Mountains of southwestern

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Montana. They involved airborne sampling of the microphysical characteristics of orographic clouds effected by seeding with silver iodide (AgI), which was produced by a single ground-based generator located on the upwind barrier slope.

The second set of experiments was conducted over the Grand Mesa of west-central Colorado during March 1986. The Grand Mesa experiments utilized both ground-based and airborne seeding with AgI. Evaluation of seeding effects was accomplished by airborne sampling of microphysical properties and by surface measurements of precipitation rates, ice crystal habits and concentrations.

a. Physical hypothesis

The following is a general physical hypothesis applicable to both series of experiments:

1) Large numbers of AgI particles will be produced by the combustion of a solution of silver iodide, ammonium iodide, and acetone. These particles will be functional as ice nuclei in supercooled liquid water (SLW) clouds colder than about −9°C.

2) These ice nuclei, released either aloft or from the ground, will be transported into orographic clouds that may contain SLW.

3) The AgI will be present in quantities sufficient for in-cloud detection of the seeding plume by an acoustical ice nucleus counter.

4) In sufficiently cold SLW cloud, the AgI will create ice crystals in concentrations significantly greater than natural background levels. (This zone of enhanced ice particle concentration is often referred to as the seeding signature or the seeding plume.)

5) The artificially nucleated ice crystals will grow at the expense of the SLW, and with habits characteristic of the prevailing moisture regime and temperature. Their size will rapidly exceed 0.1 mm, the detection limit employed for the aircraft-borne optical imaging probe.

6) The resulting enhanced ice particle concentration (IPC) will remain significantly greater than the natural background concentration as the plume crosses the target area.

7) Because of the enhanced IPC, the ice water content within the seeded volume will significantly exceed that in adjacent nonseeded volumes above the target area.

8) Melted-equivalent precipitation rates recorded at the surface in the target area, coincident with the presence of the plume aloft, will significantly exceed rates recorded immediately prior to or subsequent to the plume passage (tested only over the Grand Mesa).

b. Experimental design

The experiments had several objectives, all related to verification of the physical hypothesis. They included:

1) Demonstrating that properly conducted seeding operations result in significant populations of AgI ice nuclei reaching the targeted clouds.

2) Documenting the resulting microphysical changes within the seeded SLW clouds, specifically the ice particle concentrations, habits and sizes.

3) Comparing the microphysical composition of the seeded clouds with that of nearby nonseeded clouds.

4) Demonstrating that the growth of ice crystals initially generated by seeding with AgI eventually leads to enhanced precipitation at the surface.

If the first objective can be met, the second and third objectives should be obtainable by positioning the appropriate airborne instrumentation in the proper places at the desired times. The final objective, perhaps best described as "ground truth," can be successfully attained only when precipitation data are available at the ground in the target area, as in the airborne seeding experiments conducted over the Grand Mesa.

In keeping with these goals, key time- and position-referenced variables in the experiments were ice particle habit, size, and concentration; ice nucleus concentration; and cloud liquid water content. Supporting measurements included horizontal winds, air temperature, and stability parameters. In addition, cloud droplet spectra were recorded during the Bridger Range experiments.

3. Instrumentation

a. Aircraft

The National Center for Atmospheric Research (NCAR) Beechcraft King Air turboprop aircraft was used in the Bridger Range experiments. A Rockwell Turbo Commander 690A turboprop aircraft was operated by Aero Systems over the Grand Mesa. Both aircraft were capable of sustained flight in known icing conditions and were usually flown in the 85–100 m s^{-1} true air speed range during sampling passes.

The King Air's inertial navigation system (INS) position data were used in analysis, while Loran-C positions were the most accurate available from the Turbo Commander. Absolute differences from a known location measured prior to takeoff and after landing were usually less than 1.5 km with the INS and less than 1.0 km with the Loran-C. Relative differences from pass to pass should be very small with the INS (typical drift 0.4 km h^{-1}) and are believed to be usually less than 0.5 km with the Loran-C.

b. Optical array spectrometer probes

The primary aircraft probe for detection of seeding effects was the same on both aircraft. Particle Measuring Systems (PMS) 2D-C probes with a 25–800 μm range and a 25 μm resolution were used to examine IPC, crystal sizes and habits. The sampling volume of the 2D-C probe is about 5 L per 100 m of flight. Analyses for concentrations, size spectra, habits and calculated precipitation rates were performed according to the computerized techniques described by Holroyd (1987). Particles classified as graupel were assigned masses appropriate for graupel-like snow. Linear particles were considered to be planar crystals viewed on edge because the temperature regimes were not indicative of the development of needle or sheath habits. Questionable images, those with centers apparently out of the field of view, and those smaller than 0.1 mm (about 4 pixels long) were rejected. The habits of the remaining "valid" 2D-C images were estimated, and masses and terminal velocities were assigned for precipitation rate calculations. It is noteworthy that Holroyd achieved reasonable agreement between snowboard samples and his method of precipitation estimation, which uses a ground-based aspirated 2D-C probe. This was in spite of artificial increases in ice particle concentrations caused by the aspirator, in one case by a factor of 2.4 (Holroyd 1986). The use of an aspirator is not recommended by Norment (1987), a conclusion based on numerical studies simulating flows with water droplets and no turbulence. However, that study did not investigate the response to ice particles in air of normal turbulence. The size spectra were not changed significantly by the aspirator in the Holroyd case study, but more recent work by Deshler (1988) has suggested that the aspirated probe can oversample smaller particles and undersample larger particles.

Also included in the King Air data acquisition system was a PMS 2D-P optical array probe. Analogous to the 2D-C probe, the 2D-P had a 200 μm resolution and 200–6400 μm range. The primary difference between the probes lies in their magnification optics. The sampling volume of the 2D-P is about 170 L per 100 m of flight.

The ice particle size spectra calculated from the 2D-C probe were compared with those from the King Air's 2D-P probe on several passes through seeded cloud. Good agreement was found in the overlapping 0.6–1.0 mm range, but the 2D-C concentrations were only 25% to 75% of the 2D-P values for the 1.0–1.6 mm range. The 2D-C concentrations were even smaller fractions of the 2D-P values at larger particle sizes, yet a substantial portion of the calculated precipitation rates from the 2D-C data will be shown to have been contributed by particles greater than 1.0 mm diameter. Because of these and other uncertainties, 2D-C precipitation rates estimated according to Holroyd's scheme should be interpreted only in a relative sense, with the expectation that they are usually underestimates, especially when particles larger than about 1.0 mm are involved. Quantitative comparisons between seeded and nonseeded snowfall estimated from the 2D-C probe should therefore be treated with caution. Unfortunately, surface precipitation observations were not practical in the Bridger Range, so 2D-C precipitation estimates at the lowest aircraft sampling level offered the only documentation of a key variable.

Usually 10 to 30 valid hydrometeor images were stored in each of the two buffers of the 2D-C (or 2D-P) probe data acquisition system. A buffer would fill, and while it waited for the opportunity to write the information to magnetic tape, the second buffer would be filling. The rate of buffer filling depended on particle concentration and size, but the data systems were limited to recording no more than one 2D-C buffer per second on the Turbo Commander and either a 2D-C or a 2D-P buffer per second on the King Air. When encountering high IPC, a buffer might fill in a fraction of a second, so that sampling might occur only during a portion of the period between recording times.

A 62-channel, one-dimensional spectrometer probe (PMS 260X) covering the size range 10–620 μm was also carried by the King Air. Particles occulting the end elements of the 64-element optical array were excluded. The first three channels are difficult to interpret because sample volume is a sensitive function of particle size; the 260X concentrations referred to in Part II were for the size range 40–590 μm. Since the 260X particle concentration was routinely calculated for each second of flight (unlike the 2D-C), it is referred to for general information on cloud conditions.

c. *Aircraft liquid water observations*

All airborne SLW measurements over the Bridger Range were derived from the PMS Forward Scattering Spectrometer Probe (FSSP). The size bins selected for the FSSP started at 1.0 μm. In all plots of SLW content, the value was set to zero unless the FSSP detected at least 10 droplets cm^{-3}. This eliminated frequent cases in which one to a few relatively large particles cm^{-3} (presumably ice) would yield a calculated SLW content of 0.01–0.03 g cm^{-3}, while the other liquid water sensors detected no SLW.

A Johnson-Williams (J-W) liquid water content meter, factory reconditioned prior to the field season, was used over the Grand Mesa. Once zeroed outside of cloud, it exhibited little drift and appeared to have a resolution near 0.02 g m^{-3}. As shown by Strapp and Schemenauer (1982), a properly maintained J-W system can yield measurements of reasonable accuracy.

The J-W device was compared with a Rosemount 871FA icing rate meter (designed for aircraft use) using observations from 18 March 1986, one of three experimental days discussed in Part III. The Rosemount meter, which cycles by heating the probe to shed ice once a given mass adheres to it, was calibrated in a small, locally designed wind tunnel with 3 m s^{-1} flow using droplets near 10 μm diameter. The mass of ice required to cycle the unit was carefully weighed after each of 11 tests and found to range from 0.032 to 0.045 g. The mean value of 0.039 g was used, along with the aircraft true air speed, probe cross-sectional area, and time required to cycle the unit to calculate the SLW content, for 17 cases having continuous liquid water over the distance required for one cycle of the probe. Droplet collection efficiency was considered to be unity at typical aircraft flight speeds. Cycle times ranged from 11–70 s and resulting mean SLW contents were from 0.22–0.03 g m^{-3}. These were compared with the mean J-W contents for the same time intervals. The correlation coefficient for the 17 data pairs was 0.975. The J-W tended to be about 0.01 g m^{-3} higher for values near 0.05 g m^{-3}, while the Rosemount tended to be about 0.03 g m^{-3} higher for values near 0.15 g m^{-3}. This comparison indicates that the J-W SLW content values were reasonably accurate.

d. AgI detection

An NCAR acoustical ice nucleus counter was used to determine the approximate AgI plume position in each experiment. The acoustical counter will be discussed in some detail because it is not as commonly used as other aircraft instrumentation. Although a number of individuals or groups have had inconsistent results with acoustical counters, properly maintained and operated systems have provided consistent results in detection of AgI from day to day and location to location. For examples, see Super (1974) and Heimbach and Stone (1984).

Different but very similar counters were used on the two aircraft. They were improved versions of the counter discussed in detail by Langer (1973). Air from outside the aircraft cabin was sampled at about 10 L $\min^{-1}$ and had water vapor and cloud condensation nuclei added prior to injection into a refrigerated 17 L cloud chamber maintained near −20°C. This resulted in cloud formation near the chamber top with droplet concentrations well in excess of natural cloud. The high droplet concentration was intended to limit transient supersaturations to a few tenths of one percent and to partially offset the short chamber residence time (1–2 min for most particles), which is especially important for ice crystal formation that is due to contact nucleation. The work of Demott et al. (1983) suggests contact nucleation as the predominate mechanism with the type of seeding material used. In spite of the marked differences between natural clouds and those maintained in the acoustical counter, Langer and Garvey (1980) reported good agreement between measurements of ice nucleus concentrations with various AgI smokes using an acoustical counter and measurements obtained in the Colorado State University (CSU) isothermal chamber. The latter simulates natural clouds much better than the former.

Cloudy air was continuously drawn out the bottom of the counter chamber through an acoustic sensor, where ice crystals that had grown larger than about 20 μm produced audible clicks. These sounds were converted to voltages by a small microphone and the total "counts" then processed and recorded once per second by appropriate electronics. The formation of large droplets in the cloud chamber injection tube, which could also trigger the sensor, was avoided by slightly heating the tube to prevent condensation.

Laboratory work has revealed that only about 10% of the ice crystals formed in the cloud chamber reach the acoustic sensor due to losses on the glycol-covered walls and exit cone (Langer 1973). However, unless otherwise noted, the data reported are simply the counts as detected by the acoustic sensor.

The acoustical counters, operated at −20°C at both experimental sites, indicated that the background concentration of natural ice nuclei was almost zero. Whether numerically correct or not, this characteristic made detection of AgI straightforward, since experience showed that encounters of more than a few counts per minute were always downwind of an AgI source. As used in these experiments, the acoustical counters were essentially AgI detectors rather than natural ice nucleus detectors, and their response will be presumed to be due to AgI only.

The entry edge position of an AgI plume can be approximated by estimating the delay time to first counts. The width of a ground-released plume can be estimated by making pairs of passes in opposite crosswind directions as done by Super (1974), which assumes that plume meander is not significant in the several minutes between passes. This is not always valid, particularly in very stable conditions.

Each counter's delay time was empirically determined from ground tests in which varying amounts of AgI smoke were injected into the counter by hypodermic syringe over a few to several seconds. The delay time (Δt) was defined as the first second of the first seven-second period having three or more total counts. Because nucleation, growth and detection in the acoustical counter is a stochastic process, first-response time was well related to the total counts (C) per injection by a power curve of the form

$$\Delta t = AC^{-P}, \qquad (1)$$

where A and P were empirically determined constants. As an example, a correlation coefficient of 0.88 resulted from this power curve fit to the data from the counter used over the Grand Mesa, where $A = 50.6$ and $P = 0.10$. Individual data points were within ±3 s of the curve for total counts greater than 100, but some departures were as great as 6 s for lower amounts of AgI. Equation (1) was used to estimate the entry edge position on each flight through an AgI plume where C was the total counts recorded during the pass. However, (1) does not strictly apply because the time to traverse a plume was usually much longer than the AgI injection period in the ground tests. As a consequence, derived plume widths are narrower than the actual widths. The problem is not usually serious because, for example, the delay times from the counter used over the Grand Mesa ranged from only 27 to 34 s for total counts of 500 and 50, respectively. In any event, each estimated plume position should be approximately centered on its actual position so that the analyst knows where to search for enhanced IPC due to seeding.

More serious underestimation of the AgI plume can come about from depletion of the AgI itself through scavenging by cloud droplets and by ice particles. Ice particle scavenging is believed to be limited (e.g., Radke et al. 1970), although field observations are scarce. As Flossmann et al. (1985) point out, the efficiencies with which aerosol particles are scavenged, either by nucleation or impaction with drops, are not well known.

Whatever the mechanisms involved, the apparent rapid depletion of AgI shown in Parts II and III in SLW cloud and/or in high IPC zones (which implies SLW at an earlier time) can seriously degrade the acoustical counter's ability to delineate the entry edge of a seeded zone. Nevertheless, finding the core of the AgI plume located within a zone of high IPC strongly suggests that AgI seeding caused the ice particle enhancement. Conversely, failure to find any AgI within such a high IPC zone might suggest that the IPC maximum was a natural phenomenon.

e. Seeding generators

All ground-based seeding was done with the Montana State University generator developed and used for the Bridger Range Experiment (Super and Heimbach 1983). A 3% by weight AgI solution, complexed with NH_4I in acetone, was consumed at 30 g AgI h^{-1}. It was sprayed through a hypodermic needle into a jet of propane, where the solution was atomized prior to consumption in the burn chamber. Calibration of this system by the CSU Cloud Simulation Lab (Garvey 1975) showed an output of 6×10^{13} ice nuclei g^{-1} at $-10°C$ for natural tunnel draft. This is the appropriate curve to use because all seeding was done at sites with very light winds. Output increased to 3×10^{14} ice nuclei g^{-1} at $-12°C$ and 7×10^{14} by $-16°C$.

All aircraft seeding was done with the instrumented Turbo Commander upwind of the Grand Mesa. An Aero Systems, Inc. generator was used with a 2% AgI-NH_4I-acetone solution, burned at about 80 g AgI h^{-1}. The solution was sprayed into a burn chamber where it was mixed with air and ignited. Generator tests by the same CSU Lab indicated a yield of 5×10^{14} ice nuclei g^{-1} effective at $-10°C$, increasing to near 10^{15} ice nuclei g^{-1} for temperatures between -12 and $-20°C$.

f. Surface-based wind and icing rate detectors

Rosemount icing rate detectors designed for tower use were operated during the experiments, in close proximity to heated anemometers and wind vanes. The icing rate detectors were calibrated in a small wind tunnel in the same manner as the airborne unit discussed in section 3c. Several series of tests were run with each sensor, and individual values were within ±15% of the series means, which were typically near 0.07 g. The mean mass required to initiate a deicing sequence, its cross-sectional area, and the mean wind speed were used to estimate SLW contents, as discussed by Boe and Super (1986). This assumes unity collection efficiency for cloud droplets encountering the 6.35 mm diameter rod of the sensor. Underestimation of actual SLW contents is therefore likely when small droplets are present and winds are light (Hindman 1986).

A more serious underestimate is believed to have occurred due to the "lifting" of cloud base above the sensors, at least above the flat-topped Grand Mesa. It was visually observed that cloud base was often above the 70 m tower on the middle of the mesa even when considerably lower on the windward side. A vertically pointing microwave radiometer (not available during the experiments discussed in Part III) detected SLW with more than three times the frequency of the nearby tower-mounted icing rate detector on the Grand Mesa (Super et al. 1986). Similar comparisons were not done on the Bridger Range. Consequently, while detection of SLW by a tower-mounted probe is a clear indication of the presence of supercooled cloud, the converse is not necessarily true.

Tower-mounted Hydro-Tech wind sensors were used on the Grand Mesa. They were robust and internally heated, and performed well under icing conditions. The wind speed sensor on the Bridger Range was operated above heat lamps, which were usually sufficient to keep it ice free, although some instances of riming were observed. The Bridger Range wind direction sensor was unheated, but no instances were observed in which it did not respond because of riming.

Horizontal winds above the surface of the Grand Mesa were measured with an acoustic sounder at 30 m resolution up to 570 m agl. These winds, and especially those measured by a small network of unheated surface stations around the mesa, generally exhibited significant differences from the ambient winds measured by National Weather Service rawinsondes released from Grand Junction, about 45 km to the WNW. Such terrain-caused distortions are important to the problem of targeting the seeding materials, as discussed in Holroyd et al. (1988). Flow distortions over the Bridger Range were only qualitatively observed.

g. Surface precipitation measurements

Surface precipitation measurements were made only on the Grand Mesa. A network of 7 Alter-shielded high-resolution gauges were operated through the experimental period. In addition, snow particle characteristics were recorded at the "Snow Lab" on the Grand

Mesa in a sheltered clearing about 300 m south of and 100 m below the Mesa caprock. Winds were rarely more than 2 m s^{-1} at this location. Snow fell down a 31 cm diameter chimney onto cold glass plates for timed intervals. These plates were photographed with sufficient detail to identify the particle habits as well as the concentrations. The area of the collection plate photographed was always the same, so any possible tendency of the camera operator to select areas containing the larger or more interesting crystals was avoided.

4. Methodology

The ground-based seeding techniques used over the Bridger Range and the Grand Mesa were essentially identical, while the airborne seeding method used over the Grand Mesa employed a different approach. In each of the experiments, a single seeding generator was used.

a. Ground-based seeding experiments

For each of the ground-based experiments, a single AgI generator was operated well up the windward side of the barrier. The plume thus generated was advected up and over the barrier into the orographic cloudmass, as will be shown in Parts II and III.

An instrumented aircraft monitored the seeded cloud volume and neighboring natural cloud volumes by making constant-altitude passes downwind of the generator and approximately perpendicular to the wind. Aircraft altitude sometimes varied from pass to pass but was usually the minimum allowable: about 300 m above the highest terrain in the vicinity. Reciprocal passes at a single altitude were utilized to delineate the leading edges of the AgI plume as defined by (1), so that the width of the plume was approximated for each pair of passes. Any corresponding increases in IPC were presumed to be due to the AgI. Natural clouds crosswind on either side of the plume were evaluated as controls for comparison with the regions containing AgI and enhanced IPC.

b. Airborne seeding experiments

To initiate each airborne seeding experiment, the aircraft AgI generator was ignited and an arc flown at a constant distance from the surface target at the lowest permissible altitude. Each arc was centered on the line intersecting the surface target and parallel with the mean wind at the seeding altitude. The distance of each arc from the target was varied from experiment to experiment in an effort to assess the impacts on plume spreading, nucleation, and precipitation development.

After each seeding pass the instrumented aircraft made a series of sampling passes at the seeding altitude, over the Snow Lab and parallel to the mean wind. The evolution of the AgI plume as it spread, encountered SLW, and produced enhanced IPCs was thereby monitored. As in the ground-based experiments, regions having enhanced IPC coincident with AgI were presumed seeded. Some additional knowledge about the deformation and stretching of the plume was also obtained.

The ultimate evaluation of each airborne seeding experiment was based on the characteristics and intensity of the precipitation observed at the Snow Lab surface target, which were monitored for the duration of each experiment by means of the previously described ice crystal photography system.

5. Summary

Several winter orographic cloud seeding experiments were carried out over mountain barriers in Montana and Colorado. Silver iodide was released either on the windward slope or by aircraft. Recent advances in technology made it feasible to detect (i) the AgI in-cloud to within about 300 m of each target area's highest terrain; (ii) corresponding changes in ice particle concentration, habits and sizes; and (iii) corresponding changes in SLW content. Relative changes in the precipitation rate were estimated at aircraft levels with a recently developed computerized approach. In addition, surface observations of seeding-induced changes in ice particle characteristics and precipitation were made in Colorado.

In this first part of a three-part study, we have described the experimental design and physical hypothesis underlying the experiments and discussed in detail the instrumentation used, its associated calibrations and limitations, and the methodology employed in each type of experiment.

The results of applying the instrumentation and methodology [described here] are found in Parts II and III. They show that marked changes in cloud microphysics were detectable with both airborne and ground-based AgI seeding of winter orographic clouds.

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