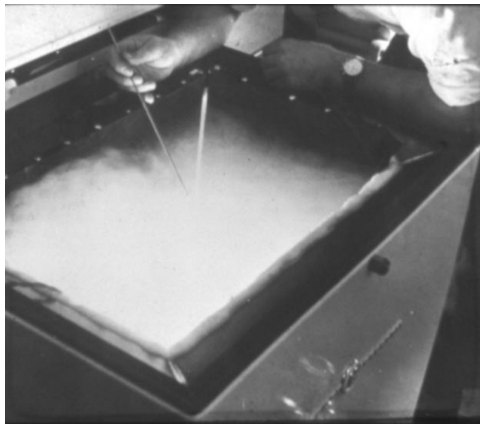
In late 2020 a journalist, Mary, asked me to review some of my cloud seeding background. So I prepared this document. It does not include all of my experiences. Some things do not directly involve cloud seeding. But it was fun finding old photos to go along with some significant times in my past. Some of the old photos have aged to reddish color. Her questions are in bold.

From: Mary....

Let's aim for email! I'd love to know a bit more about...

I'd love to hear more about your early work with cloud seeding. What was that like?

For reference, modern cloud seeding began in 1946 when Vincent J. Schaefer created snow from a supercooled cloud in a chest freezer in the GE Research Labs in Schenectady, New York, using dry ice as a chilling mechanism. In 1947 Bernard Vonnegut got a similar result using an aerosol of silver iodide (with a crystal structure nearly matching that of ice) as a nucleation agent. Experiments with real supercooled clouds and dry ice often had very visible results.



Vince Schaefer working with a cloud in a chest freezer to convert it to snow.

Visual results from an early cloud seeding with dry ice that made fuzzy snow while clearing the cloud.

My first encounter with modern cloud seeding was in the Summer of 1961 between my junior and senior high school years. I got into (as an alternate) a special NSF-sponsored course of physics and weather through the Natural Sciences Institute (eventually related to the State University of New York at Albany and the Atmospheric Science Research Center) and held at the Loomis School in Windsor, Connecticut. Only 40 male high school students from around the country were allowed in the program.

Halo and pillar optical effects like those seen in the Yellowstone movies, from dry ice seeding of hot spring clouds.

The weather course was taught by Dr. Vincent J. Schaefer, and he told of weather modification experiments, showed still and motion pictures of various projects, and showed his famous cold box experiment whereby he converted a supercooled cloud into snow crystals. Most spectacular were color movies about seeding surface clouds in Wintertime Yellowstone Park, filling the sky with ice crystals and rainbow-like arcs and spots.

The freezer used for my experiments.

I was given a laboratory project of trying to grow ice crystals on a Formvar plastic replica of actual snow crystals. I had a negative result, being unable to generate ice with the same crystal orientation as the snow crystal. However, Dr. Schaefer liked my effort and kept me in the NSI program elsewhere through 1968.

Dr. Schaefer and Ed Holroyd at Loomis School in 1961

When asked about a college education in preparation for weather research, Dr. Schaefer recommended getting a good background in math and physics, but no weather courses. They would be taught better in graduate school. So for college I commuted from home for 4 years, attending the University of Rochester. I added 6 courses of astronomy to his recommended program and got a B.S. in astrophysics in June 1966.

For July1962 Dr. Schaefer arranged for several NSI students to drive across the country (in a Land Rover) to Flagstaff, Arizona. There we were helpers in an actual cloud seeding operation with some of the top weather scientists in the country. They were seeding cumulus clouds to enhance rainfall. (There was also one poorly developed experiment to try to dry out a cloud and lessen the rainfall.) I was deployed at the airport, usually working in a hanger graphing instrument data gathered from the aircraft involved in the clouds. When an operation was in progress I was stationed in the control room of a weather radar, trying to keep the antenna beam passing through the experimental cloud to record on time-lapse movie film the aircraft positions and resulting precipitation. That radar was operated by Dr. Paul MacCready, a scientist who years later designed the first human-powered and solar-powered aircraft. All of us students were present in the team meetings of the scientists and crew for planning and debriefing the cloud seeding experiments. It was that program that convinced me that I wanted to be in weather research for a career.

Dr. Schaefer (left) and the other 8 students at Flagstaff, Arizona

The radar trailer in which I worked.

During a side trip to the South Rim of the Grand Canyon we students had our first experience of being in corona. With a thunderstorm nearby, the electric field had our hair standing on end. With a finger in the air we were getting half inch sparks when we touched others, and 3/4 inch sparks as we touched a guard rail. Of course we were ignorant that lightning could have struck nearby at any second.

Experimenting with electrical corona on the rim of the Grand Canyon

A cloud rising up Whiteface Mountain

For August 1962 we traveled back across the country to Whiteface Mountain in the Adirondacks of Upstate New York. It had a road to near the top and several buildings near the summit and one near the base. Clouds often enveloped the summit in a thick fog, letting us study clouds with our feet on the ground. During subsequent years the NSI program was spread among other sites around the country, but I chose to remain at Whiteface for the Summers through 1965.

We could study whatever we wished to investigate. I collected and sized cloud droplets. I did a hydrology project at a small summit watershed, documenting the runoff water flow after

A simple method of measuring runoff

rain. There was one memorable period after rainfall had ceased but clouds remained for another day or two. The needles of the balsam fir trees collected cloud droplets which added to the water runoff that was being measured. So I could determine the total amount of water coming only from the cloud droplets. (The end branches and needles collected so much water that one could easily get a mouthful of refreshing water by sucking beaded water that was still on the needles.)

Water beads on the Balsam Fir needles

Flag trees on Whiteface

I noticed that most of the summit trees had their branches oriented mostly on one side of the trunk, shaped by the prevailing winds during the growing season. They are called flag trees. Eventually in 1965 I hiked down every ridge of the mountain (usually with no trails) mapping those orientations. They showed a very complex flow pattern, including wind reversals in some locations. That gave me an appreciation for orographic wind patterns, which affect the delivery of cloud seeding chemicals to orographic clouds and subsequent precipitation fallout. It also resulted in a significant publication.

3D model of Whiteface with yellow arrow markers showing wind directions from flag trees

NOAA hurricane hunter aircraft. Dr. Paul MacCready at left in white shirt.

Summer 1966, after my college graduation, brought me westward to South Dakota and Colorado. The first month was in Rapid City to participate in a study (and seeding?) of hailstorms in Project Hailswath. Again there was a large team of scientists and aircraft. (I even got to fly in a DC-6 aircraft used for flying into hurricanes.) I soon deployed myself at a fire tower in the Black Hills each day to note the initial positions of the clouds that developed into thunderstorms. I wrote a report of my findings. (From the fire tower, I also was the first person to spot a smoke plume from a fire that started from a lightning strike the previous day, and watched a slurry bomber attack that fire.)

Fire tower on Bear Mtn, Black Hills, SD

Thunderstorm lifting yellow pine pollen in the Black Hills, viewed from Bear Mtn.

Pink slurry being dropped on the fire that I spotted, viewed from Bear Mtn. tower

Next I spent a week at Climax, Colorado, mapping the flag trees on the summit of Chalk Mountain, which during prior years had been the target for Wintertime cloud seeding. The flow was not as complex as at Whiteface and the trees were not as distorted by the wind. I also got a tour of the Climax molybdenum mining

Chalk Mtn. weather observatory

operation from a quarter mile deep under the mountain, and up through the mineral processing machinery.

The remainder of July was in Boulder, outfitting a refrigerated trailer for hail studies. That included chasing a few hailstorms to gather hail samples.

Hail study trailer (right)

The final project in August 1966 was at Colorado State University, Fort Collins. I was to measure the falling speed of tiny ice crystals only several minutes old after birth from cloud seeding. I built an apparatus with a strobe light and camera to record the falling speed and collected the crystals in Formvar plastic for size determinations. I was given a large room-sized freezer in the dairy building, normally used for making ice cream. I chilled the room and made a cloud with a pan of water on a hot plate. I could not run the cooling mechanism during the experiment because it would suck up and destroy the room-full of supercooled cloud. To trigger the snow I burned a short length of string that had been soaked in silver iodide. Thereafter it kept snowing in the room for a couple of hours until I had to chill the air again and remake the cloud. At the end of the week I had to clean up the freezer. I scraped up enough genuine snow from the floor to make six large snowballs. I took them outside. The afternoon temperature was about 95 degrees under clear skies. I threw the snowballs only against trees. (I also was dressed warmly as I came out of the freezer, so I suppose I got some curious looks.) My technique of creating a continuous supercooled cloud in a laboratory became important in the early 1970s.

For graduate school it seemed natural to go to the State University of New York at Albany, the home of the Atmospheric Science Research Center which operated the observatory on Whiteface Mountain and employed some of the early scientists of weather modification. One of the professors was Dr. Bernard Vonnegut. I lived nearby with Paul Schaefer, the brother of Vince, and his wife Carolyn, our cook at Whiteface. (Their home at 897 Saint David's Lane, Schenectady, is now a museum for the Preservation of the Adirondack Mountains.)

A line of lake-effect clouds coming off Lake Erie over western New York. (Most storms are not as picturesque.)

For research and eventual Ph.D. thesis I was assigned to study the lake-effect snowstorms of the Great Lakes. During those years there were two cloud seeding experiments successfully conducted over Lake Erie for a target in western New York.

One day, after about two days of lake-effect snowfall, there was a day with lake-effect clouds generated by Lake Erie but no snow falling from any of them. A team then burned silver iodide for about an hour from the Canadian shore. That created snow falling downwind and confirmed by the only radar echo of that day. I was the target on the ground, watching the approaching snow from a ridge. I adjusted my position by moving about a mile to the north and there experienced snow for about 45 minutes, collecting and preserving falling snow in Formvar plastic for later analysis.

The second experiment was during an intense lake-effect snowstorm. The thought was that by heavily seeding (with silver iodide) the resulting ice crystals would be competing for water vapor and thereby restricted in size. It was expected that the smaller crystals would then take longer to fall to the ground and would land significantly farther inland, away from the coastal transportation infrastructure. I was the target on the ground and kept sampling the snowfall. The expected temporary decrease in snowfall did not happen. Instead the abundant tiny crystals aggregated together into large snowflakes which fell out as fast as the natural snowflakes. So the seeding effect proceeded well but the intended result failed. A significant publication followed.

With my Ph.D. thesis approved but not yet typed, my wife Gail and I moved to Australia in late Summer 1971 to attend a weather modification conference and stay on for three years working for the government's Commonwealth Scientific and Industrial Research Organization (C.S.I.R.O.), initially Division of Radiophysics and then subdivided into our Division of Cloud Physics. The headquarters was in Epping, a northwestern suburb of Sydney, NSW. (Gail and I typed my thesis during evenings and weekends with IBM Selectric typewriters and correction fluid. The degree was then officially awarded December 1971.)

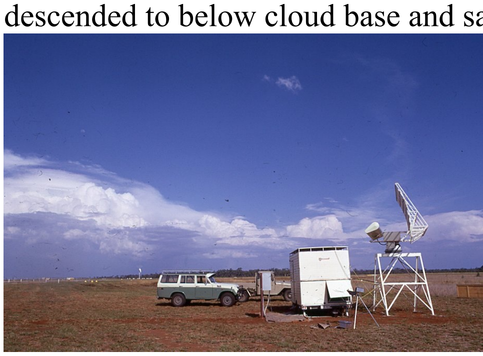

CSIRO Div. of Cloud Physics, Epping

My main assignment was to be part of a team doing cloud seeding experiments on Summertime tropical cumulus clouds in central Queensland, with the goal of increasing rainfall to fill a new dam near Emerald. We flew in a Cessna 402 light twin aircraft, unpressurized so that we had to use oxygen above about 14 thousand feet. Our operations were usually between 20 and 25 thousand feet to reach the supercooled levels of the clouds. We fired silver iodide flares out a side window into some of the cloud tops. We poured finger-sized dry ice pellets through a funnel and hole in the floor of the aircraft as we flew above or inside other clouds. I was more impressed with the dry ice results. About five minutes later, as we turned the aircraft around, we saw the cloud tops filled with snow and the entire cloud top rapidly falling. Years later I was able to analyze the impacts of sampled snow on aluminum foil to estimate how many crystals were produced by the masses of dry ice that we used. One day when there were no significant clouds to work on, we flew to a tall cloud (pyrocumulus) produced by a small forest fire. We dropped dry ice into its top to create snow. We then descended to below cloud base and sampled the resulting rain in the smoky air.


Our aircraft for seeding and research, flying into the tops of new thunderstorms


Intense rain out of a tropical cumulus

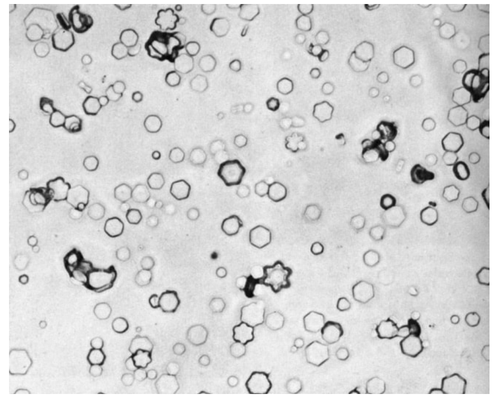

Pyrocumulus - produced by fire -that we seeded to produce some rain.


Our radar unit, with storm at left

I was involved in modifying a marine radar (used for ships) into a weather radar for rain shower documentation. Eventually my analysis of area rainfall measurements showed that to run a statistical cloud seeding experiment, with proper random seeding versus non-seeding, it would take about a hundred years to prove our ten or twenty percent expected rainfall increase in such variable rainfall. A single cyclone (hurricane) put about 7 years worth of water in the watershed and filled the dam to overflowing while we had taken a Christmas break. There was no further need of us and we abandoned that project area.


Fairbairn Dam overflowing after cyclone

During the Wintertime I worked instrumenting and calibrating a room-sized two-story freezer for experiments. I taught the team how to make a continuous supercooled cloud in a sheltered cloud chamber portion of the freezer, based on my work in Fort Collins in 1966. They showed me a seeding technique borrowed from a Japanese scientist. Small bubbles of bubble wrap were cut from sheets and inserted into a syringe. When squeezed into the cloud chamber, the bursting of the bubble would apparently chill some air colder than -40 degrees, forcing the creation of snow crystals. Eventually I calibrated it, showing that one bubble would create about 100 million ice crystals in the cloud. Subsequent experiments measured the growth rates of the young snow crystals at a range of temperatures, all published thereafter. Another team was investigating an “ice multiplication” process that seemed to occur in clouds at about -5 C temperature. They had failed to get insights until they began using my continuous cloud chamber style. Then they found that the cloud droplet size was important for quickly multiplying the snow crystal concentrations.


Initial ice crystal growths

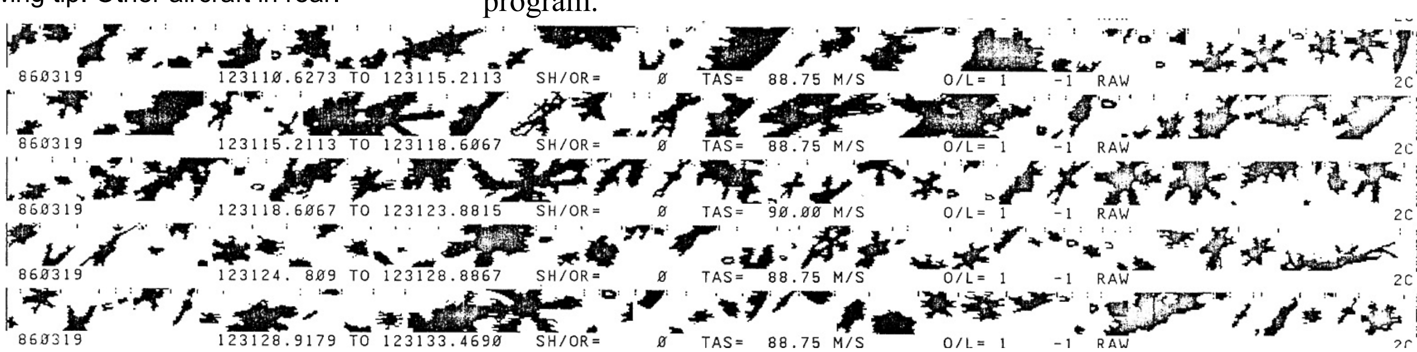

Our weather radar in the prairie setting at Miles City, Montana

In December 1974 I was hired by the U.S. Bureau of Reclamation to participate in the Hiplex program of seeding Summertime clouds for rainfall increases. There were three initial field sites: ours at Miles City, Montana, and others at Goodland, Kansas, and Big Spring, Texas. For the first operational Summer I was in the research aircraft, choosing the clouds to work on. We had another aircraft at cloud base and one aircraft delivering seeding material. We soon found that our aircraft were too slow in getting to the clouds. Then we hired a LearJet to drop either silver iodide flares or dry ice pellets. We hired a KingAir aircraft for research flights. By that time I was switched to analysis of data gathered from the aircraft during their operations, rather than actually flying, and extracting what we needed to know about the flight pattern, atmospheric structure, and cloud behavior. During Summer 1981 we had a special program with 14 research aircraft flying in our project area, including our own.


Armor-plated aircraft at left for flying in hail. Several cloud and precipitation particle instruments on LearJet nose and wing tip. Other aircraft in rear.

We had seeding rules to never do cloud seeding if severe storms were expected, though we could study the natural clouds. The Kansas operations were eventually ceased because all suitable clouds came in areas of severe storm warnings. Texas and Montana operations continued until budget cuts terminated the Hiplex program.


2D-C instrument on a post at Grand Mesa. The laser beam passes between the tips to record shadows of snow.

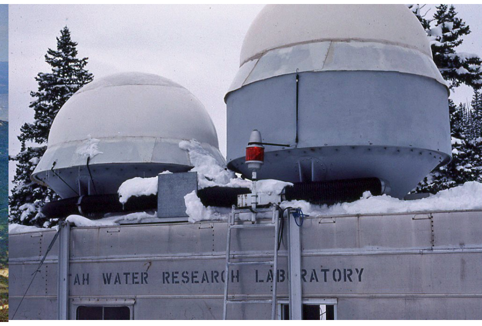


Sample 2D-C snow crystal shadows during an aircraft flight

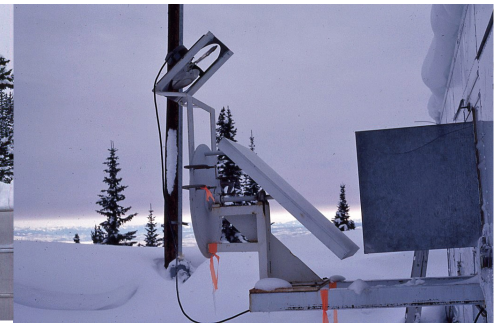
A special instrument normally carried on aircraft was a 2D-C which recorded shadows of snow particles passing through a laser beam at the tops of the probe. We later developed methods of mounting it on a post on the ground and still later on a truck and eventually a tower. I developed software to analyze those snow particle images for sizes, concentrations, and general shapes to get an estimate of snowfall rate.

I

Looking south at the west end of the Grand Mesa, Colorado



Special radar for detecting small cloud and precipitation particles above Grand Mesa



Antenna outside trailer for a microwave radiometer instrument that measures total water vapor and liquid water above Grand Mesa

In 1983 we moved and switched to Wintertime orographic cloud systems. Our team went to Montrose, Colorado, and did work on the high plateau of Grand Mesa to the north. We studied the physics of the orographic clouds and simulated and actual seeding plume dispersal and shape. Though that was an excellent research site, with a road over the top, our program there did not last long. We got directed to study Winter clouds in Arizona and occasionally help our team working out of Auburn, California. In February 1988 another budget cut stopped all of our research and dispersed our team. I was moved to the Denver Federal Center headquarters of the Bureau of Reclamation and put into the remote sensing team for other types of work.

Truck-mounted 2D-C to detect seeded snow crystals passing over highway

However, my former supervisor during the previous years was able to get funding from NOAA for Wintertime cloud seeding experiments on the Wasatch Plateau of central Utah. It was there that we began using liquid propane as a seeding agent, in addition to silver iodide. We had pulsed seeding in the orographic clouds and detected the results at ridge top about 4.3 kilometers uphill from the seeding sites. There was no need for statistical analysis though we did randomized pulses of seeding. I was eventually, in the mid-1990s, able to see in our snow crystal observations whether we were using one or two nozzles for releasing liquid propane. Then that program got shut down prematurely. That was my last involvement in official cloud seeding experiments.

Target station for detecting seeding effects, including 2D-C on tower

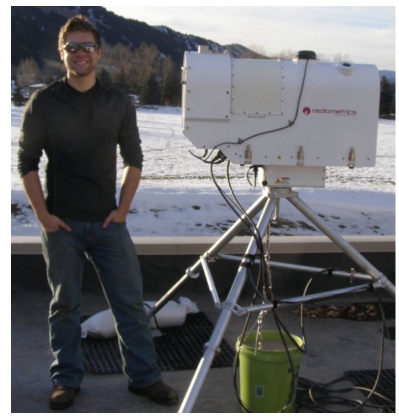
There were several times when a supercooled fog filled our back yard in the evening. I illuminated that cloud with a flood light and used a short burst of a CO2 fire extinguisher to seed the cloud. Shortly thereafter the back yard was filled with sparkling snow crystals.

For many of the past decades I have performed my “Instant Snowstorm” demonstration for a variety of audiences, but mostly at Water Festivals for upper elementary students, making it snow repeatedly in a classroom for a live audience. I do so the same way that Dr. Schaefer made his 1946 discovery, in a chest freezer. For decades I used bubble wrap to trigger the snow. However, modern American bubble wrap has been made weaker intentionally, for degradation purposes, and it no longer gets the required chilling when the bubbles are popped. In 2017 I found some sheets of stronger bubble wrap in Beijing, China, and brought some home. I also get dry ice from a grocery store to guarantee that I will get a successful snowstorm exactly the way that Dr. Schaefer discovered it. (See http://www.EdHolroyd.info/snowstorm for instructions.)

How has cloud seeding evolved since then?

The many field experiments of the early decades used randomized seeding and statistical analysis to calculate the yields and confidence levels of success. The field experiments took a long time to build up cases and were usually subjected to critical evaluations. Operational seeding programs justified themselves showing that the potential water supplies created were worth much more than the costs of seeding operations, but such programs had only weak proofs. So I liked direct observations of pulsed seeding of continuous orographic clouds. It was easier to see the resulting changes in the clouds and snowfalls.

There have been some technology advances since the early years. I developed software that made use of snow crystal shadow images as they passed through the laser beam of the "2D-C" instrument. Another useful instrument was a microwave radiometer that looked at the sky at two wavelengths to assess the amount of water vapor and liquid water along the line of sight of the instrument. It has since been miniaturized from trailer-size to a large mailbox-size by Radiometrics, Inc. It has been enhanced to get temperature profiles as well. Continuous monitoring by this instrument shows the presence and amount of supercooled water available for seeding. Special short wavelength radar with polarization is now available for detailed observations of cloud liquid water and snow contents. It is now likely that there are additional instruments that are useful for cloud and cloud seeding analyses.


Microwave radiometer by Radiometrics, Inc.

What are the strengths and limitations of cloud seeding today? Especially when it comes to how folks in the ski industry may use it?

I would like to see a winter orographic program (ski or snowpack) with monitoring of wind directions, remotely sensing supercooled water presence, and snow crystal detectors. It needs a network of ground seeding locations high up slopes, releasing AgI and/or liquid propane according to wind directions, cloud conditions, temperatures and stability. As long as clouds have enough supercooled water (are not already filled with snow) and seeding materials can be properly targeted, cloud seeding will essentially work as desired. It is a proper candidate for snowpack augmentation for water resources and the ski industry. The snow that is created behaves as natural snow and is much better for skiing than the frozen water droplets that are generated by the "snow making" machines.

Particularly out in the West, we're really experiencing the effects of climate change, notably with droughts and wildfires. Can cloud seeding help? Why or why not?

Droughts are often cloud-less. So we cannot do seeding. Snow pack should be augmented when conditions are suitable, except for suspension of seeding when snow pack is becoming excessive.

Seeding pyrocumulus is sometimes possible but rarely. Precipation might be generated that will fall downwind of fire. It creates snow (good) and maybe lightning (bad). Cloud seeding was tried in Idaho in about the 1950s but abandoned, possibly because of lightning enhancements. Once in Colorado I saw a good situation to seed a cold stratus to drop snow on a fire. But no one was set up to do so.

What are your thoughts on cloud seeding from the ground vs. an airplane?

Ground seeding is cheaper but targeting is risky. Flying aircraft in supercooled clouds is dangerous from icing. Flying above or below cloud is safer but not always available. Our findings were that seeding from the ground should be from sites about two-thirds up the windward slopes for better injection into supercooled clouds. Valley-bottom sites should be avoided because Wintertime inversions keep valley air trapped below the clouds, destroying any seeding effectiveness. As climate warms, it will become more difficult for silver iodide to rise from the ground to reach the supercooled parts of the clouds, preferably colder than -6 C. If supercooled cloud bases still occur on mountain slopes, liquid propane seeding could still be effective.

Anything else you think that readers should know about cloud seeding?

AgI is harmless to people and the environment, being so insoluble. When snow was sampled for proving silver iodide content, the people doing the sampling were told to avoid getting saliva in the sample. The silver from tooth fillings would swamp the seeding signature of silver in the snowpack. Natural silver and iodine concentrations in the environment greatly exceed what even operational cloud seeding releases.

The use of dry ice (solid carbon dioxide) for seeding is of trivial environmental impact. Surface and aerial vehicles and home heating generate much more of that gas.

The use of liquid propane is not a fire hazzard. A scientist friend tried to ignite a plume of propane released from nozzles but failed to get a flame.

There may be other gasses for cold cloud seeding, like liquid nitrogen. Their use would be based on economics.

Hygroscopic seeding is used for warm clouds (all warmer than freezing). It seeks to make larger cloud droplets to impact and coalesce with smaller droplets to speed up the development of rain, without involving the snow process. It is best for tropical atmospheres. I have not been involved in such experiments.

Thank you!
-Mary