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Summary of Studies that Document the
Effectiveness of Cloud Seeding for Snowfall Augmentation

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Introduction

A recent report completed for the National Academies of Science (NAS) entitled "*Critical Issues in Weather Modification Research*" (1) concluded that there was no convincing scientific proof of the efficacy of intentional weather modification efforts. The NAS report further stated that, "*In some instances there are strong indications of induced changes, but this evidence has not been subjected to tests of significance and reproducibility*". Several responses to the NAS report (*e.g.*, 2, 3) have pointed to many positive findings in both summer and winter cloud seeding experiments. The Weather Modification Association response (3) provides a very detailed summary of pertinent findings related to rain enhancement, hail suppression and snowfall augmentation. The intent of this paper is to summarize only the results of well designed research projects related to seeding winter orographic cloud systems, which the NAS report admitted showed "*strong suggestions of positive seeding effects*". Numerous carefully conducted winter orographic cloud seeding experiments in the 1980s, 1990s, and early 2000s contributed much of the positive evidence to which the NAS report refers. In many instances the results of small-scale experiments were repeatable and in some instances the results were statistically significant. It is this positive evidence that most in the field of weather modification believe validates the use of cloud seeding for practical operational snowfall enhancement projects.

What follows is a brief discussion which summarizes decades of research into the effectiveness of wintertime cloud seeding. With two exceptions, only peer-reviewed papers have been used as references. Included in the discussion is the generally accepted conceptual model for successful wintertime cloud seeding, and the findings of the most important experiments and projects that provided both physical measurements and statistical evaluations of results. The conclusion of this paper is that there has been ample evidence that wintertime cloud seeding is effective when the cloud conditions specified in the conceptual model exist. This paper also concludes and agrees with the NAS report finding that uncertainties still exist in this field, and should be rigorously studied in a broad new area of federally-supported research.

Cloud seeding programs with the purpose of increasing snowfall over mountainous terrain are based on results of research conducted over the past 40+ years, which has in large part been funded by federal agencies such as the U.S. Bureau of Reclamation and the National Oceanic and Atmospheric Administration. The research studies range from randomized statistical experiments conducted over entire drainage basins to highly detailed physical experiments conducted over the scale of individual seeding plumes from ground-based or aircraft seeding platforms. For cloud seeding programs conducted in mountainous regions of the western U. S. the following research results are the most applicable and have been used in the design of many of the ongoing operational snowfall augmentation programs in the U.S. and elsewhere.

Cloud Seeding Conceptual Model

As an introduction to the research results it is worthwhile to restate the generally accepted conceptual model for successful wintertime cloud seeding, which has evolved over the past 40 years, but is not substantially different now compared to its description in the design of the Bridger Range Experiment (BRE) in Montana (4). As stated, the model is based on seeding by an ice nucleant such as silver iodide (AgI) which has ice-forming capability at temperatures below about -5^{o} C. The model is depicted as follows:

1) Seeding material must be successfully and reliably produced.

2) Seeding material must be transported into a region of cloud that has supercooled liquid water (SLW).

3) Seeding material must be dispersed sufficiently in the SLW cloud, so that a significant volume is affected by the desired concentration of ice nuclei (IN) and a significant number of ice crystals (ICs) are formed.

4) The temperature must be low enough (depends on seeding material used) *for substantial ice crystal formation.*

5) ICs formed by seeding must remain in an environment suitable for growth long enough to enable them to fall into the target area.

Documenting the Chain of Events

Availability of SLW for Cloud Seeding

Before discussing experiments that have documented the steps in the conceptual model, it is important to note that numerous studies in mountainous regions of the western U. S. have examined the temporal and spatial availability of SLW and its temperature range. Successful cloud seeding depends on there being an excess of SLW in winter storms, and that the SLW exists at low enough temperatures for seeding material to be effective. Analysis of aircraft, microwave radiometer and mountain top icing measurements have shown some consistent SLW characteristics in wintertime storms. The more important ones are as follows. SLW is present at some stage of nearly every winter storm (5, 6), but also tends to exhibit considerable temporal and spatial variability (*e.g.* 5, 6, 8, 9, 11). A given storm passage may result in a number of SLW periods interspersed with other periods with none. (This implies that it is generally not practical to seed only the SLW periods because of these rapid natural changes.) The SLW is found predominantly over the windward slope of a mountain range, and often extends considerably upwind of the physical barrier (6, 7). The SLW decreases downwind of the mountain crest, or region of maximum lift, due to removal by precipitation and/or evaporation (7, 9, and 10). In the vertical the zone of maximum SLW generally extends from somewhat below the mountain crest to < 1 km above the mountain crest (8, 9, and 10).

The temperature in the SLW zone varies considerably depending in large part on the height of the mountain barrier and its geographical location. This indicates, therefore, that the most appropriate seeding methodology can also vary considerably from one location to another from storm to storm, and even within the same storm. Studies in the Rocky Mountains have shown SLW cloud bases typically in the temperature range of -2^o to -10^o C (9, 10, and 11), with aircraft measurements and radiometer-inferred estimates indicating temperatures at the top of the SLW layer are generally -10^o to -15^o C (10, 11). A general finding was that SLW was abundant in clouds with tops warmer than about -22^o C where natural snowfall was also found to be generally very light (7, 11). Lack of SLW was at times observed with colder cloud tops and higher natural snowfall rates, but SLW occurrence has also been observed during periods of moderate snowfall (9). In the Sierra Nevada cloud base is commonly above freezing and the top of SLW layer within 1 km of mountain top is generally -12^o C or warmer (6, 8).

Several studies calculated the total flux of SLW across a mountain barrier for a winter season and determined that the total SLW flux, if converted to precipitation, could increase the observed seasonal snowfall by 50-100% (5, 9, and 12). The overall conclusion of every study of SLW availability was that significant cloud seeding potential existed in winter storms over mountainous terrain provided the proper seeding technique could be applied at the appropriate time and location.

Transport and Dispersion of Seeding Material

In studying the effects of cloud seeding it is important to be able to verify the conceptual model, or what has come to be termed the cloud seeding "chain-of-events". All or portions of the chain-of-events have been documented by research studies in the Sierra Nevada of California, in the Rocky Mountains of Montana, Colorado and Utah, and in the mountains of northern Arizona. In the initial studies of the BRE in the 1970s (4, 13) steps 1-4 of the conceptual model were documented a high percentage of the time. With a combination of surface and upper air wind and temperature measurements, and documentation of seeding plume locations using an aircraft equipped with an ice nucleus counter, the authors indicated they "*...believed that the BRE has some of the most convincing evidence of successful targeting obtained in a winter orographic program*", and further stated that "*data are quite consistent with the concept that AgI* (the seeding material) *was transported rapidly up the west slope of the Bridger Range, crossed the Main Ridge and moved toward the intended Bangtail Ridge target area*". In addition, the authors presented some of the first evidence of successful cloud seeding targeting using the trace chemical analysis of snowfall for silver content. They found that

"…*increased Ag concentrations* (from the seeding material) *found on Bangtail Ridge lend further support to evidence of proper targeting…*"

In the late 1980s similar techniques were used to document very consistent and successful transport and dispersion of seeding material over the Grand Mesa in Colorado (14, 15) from both ground-based and aircraft releases of silver iodide. Additional verification of successful transport and dispersion of ground-released seeding material has been documented over the Wasatch Plateau in Utah (16). These and other transport and dispersion studies during the 1980s and 1990s began to include high-resolution model simulations of plumes that were verified by observations. Additional examples include Sierra Nevada studies (17) and Arizona experiments (18).

Microphysical Effects (Formation, Growth and Fallout of Ice Crystals)

Measurements which verified the initiation, growth and fallout of ice crystals were included in many of the experiments involved with tracking silver iodide seeding plumes. Some of the first evidence of this type was documented in the BRE (19). For clouds containing SLW it was found that ice particles were significantly enhanced and estimates of precipitation in seeded regions exceeded natural clouds by factors of two or more. No decreases in precipitation were found in seeded cloud regions. The best evidence of seeding was found in cloud regions colder than -9^{o} C with cloud tops generally warmer than -20^{o} C.

Similar experiments over the Grand Mesa of Colorado also verified plume transport over the intended target and ice crystal enhancement of at least 10 times the natural background in the seeded zones of both aircraft and ground-released plumes (15). The Grand Mesa experiments included measurements of precipitation rate increases at the surface that were typically many times greater than unseeded periods. Additional links-in-the-chain evidence exists for a number of ground seeding experiments from the Wasatch Plateau of central Utah. Seeding plume locations, ice particle enhancement, and precipitation increases within seeding plumes were carefully documented in four papers (16, 20, 21, and 22). As in the BRE the best results from AgI seeding came from the colder cases (25). Further evidence of the evolution of ice particles in seeding plumes released by aircraft was provided by cloud seeding experiments over the Sierra Nevada of California (23) and in a unique experiment conducted over the Mogollon Rim in Arizona (24), where analysis of polarized radar data and aircraft measurements revealed the formation and evolution of ice particles from seeding within a naturally precipitating cloud.

Evidence of Precipitation Increases

Some of the best evidence of seeding-induced precipitation increases came from the many experiments conducted over the Wasatch Plateau where both silver iodide seeding and liquid propane seeding methods were tested (25). Individual experiments revealed precipitation rate increases in seeding plumes of a few hundredths to >1 mm per hour (16, 20, 21, 22). The careful and repeatable documentation of seeding plume transport and dispersion, and microphysical effects, led to the design of a randomized experiment using liquid propane in this same region of Utah. The use of propane was thought preferable to AgI because of the high frequency of time SLW was found to occur over the Wasatch Plateau at temperatures too warm for ice formation by AgI (10, 12 and 25). Randomized experiments are considered the "gold standard" of experimental evaluations and are necessary to supply the "proof" referred to in the NAS report (1). Statistical analyses of weather modification experiments, where natural variability can be 100 times the expected seeding signal, are greatly improved by the use of covariates (*e.g.* 26, 27 and 28). The best covariates are control precipitation measurements (upwind or crosswind of a target area), and these were applied in the Utah study (29). The results of this 1-season experiment were statistically significant and indicated that seeded periods produced about 20% more precipitation than unseeded periods (29).

The results from statistical evaluations of the BRE matched very well with what was learned in the physical studies. Two seasons of a randomized seeding experiment produced results that showed significant differences between seeded and unseeded populations of events (4). The main findings were: a) Seeding increased snowfall in the intended target and sometimes downwind, when the ridge top (~2595 m) temperature was less than -9^{o} C; b) The seeding increase was found for the entire 100 days which met this criterion over two seasons, as well as when each season was analyzed separately; c) Positive seeding effects were suggested in the target and in the valley downwind of the target, also mainly for the colder cases; d) A seeding effect of about +15% was also found just a few kilometers from the seeding sites, and; e) Double ratios of target and control gage precipitation suggested seasonal increases of ~15% on seeded days, but increases as great as +50% were indicated when only the colder days were included in the analysis (a finding in close agreement with the microphysical observations).

Other statistical evaluations of wintertime cloud seeding have produced similar results, but none are nearly as well documented by physical observations as was the BRE. Another randomized experiment was conducted by the Pacific Gas and Electric (PG&E) Company in a region near Lake Almanor in the northern Sierra Nevada (30). A statistically significant result came from a cold-westerly storm stratification where a 32% increase in precipitation was indicated for seeded cases. Trace chemical evaluations of snowfall in the Lake Almanor project area (31, 32) have since helped substantiate the statistical indications. A common finding from the projects referenced here is that the most pronounced seeding effect occurred in relatively cold and shallow orographic clouds. Evidence indicated that precipitation can be increased by 50% or more in these storm periods, which can result in seasonal increases of snowfall by the ~15% augmentation that is quoted in capability statements of the World Meteorological Organization and the American Meteorological Society (33).

New Evaluation Technique: Trace Chemistry Analysis

Additional research on wintertime cloud seeding over the past 20 years has produced some very promising techniques for evaluating seeding effects over basin-sized areas. As shown in the BRE (4) the trace chemical analysis of snowfall can be used to verify targeting. The technique has now been used on numerous projects to determine if seeding material has reached the target area and to determine whether it arrived there as a result of ice nucleation by the seeding material (32, 33, 34 and 35). One operational program in the Sierra Nevada used this trace chemical technique to show that cloud seeding operations produced a seasonal 8% increase in the snowpack over a specific watershed (36). Such results from physical and trace chemical analyses compare well with earlier randomized experiments such as that of PG&E (30) which showed similar increases in the northern Sierra Nevada.

Conclusions and Recommendations

The studies and experiments summarized in this paper represent millions of dollars worth of research effort conducted over many decades by meteorologists, physical scientists, and statisticians. We are currently operating under a well defined cloud seeding conceptual model. We have documented the potential impact of cloud seeding, the cloud conditions needed and the chain-of-events in effective cloud seeding. We have continued to develop new and innovative techniques for operations and for evaluations needed to prove cloud seeding effectiveness and to refine cloud seeding programs. The NAIWMC concurs with the World Meteorological Organization’s policy statement that contends "*well designed and properly conducted cloud seeding programs will produce demonstrable results*". The NAIWMC also acknowledges recent advances in atmospheric modeling, remote sensing, and laboratory techniques and believes these new technologies can assist with advances in cloud seeding operations. We certainly concur with the main recommendation of the NAS report that a "*coordinated national research program*" is needed to apply the new technologies to key uncertainties in weather modification.

Recommendations for evaluations of current operational seeding programs and for future research in snowfall augmentation include, but need not be limited to, the following:

- Evaluate new or existing operational seeding projects (which have not done so) to document the initial steps of the conceptual model to ensure seeding in the SLW zone is actually occurring. The following techniques can be used.
    - Trace chemical analysis of snowfall in the target area.
    - Transport and dispersion studies using modeling, plume tracking, etc.
    - Air flow, temperature and SLW measurements over the project area.
- Continued testing of silver iodide and liquid propane seeding methods.
    - Conduct relatively small-scale randomized experiments, which have been done on only a very limited basis in the past 20 years.
    - Use accepted statistical techniques with the randomized studies to analyze the magnitude of seeding effects. Use predictor variables to strengthen the statistical analyses and reduce the number of experiments needed to obtain significant results.
    - Support any statistical study with observations sufficient to enable understanding of the physical processes.
- Test current, or develop new satellite and ground-based remote sensing techniques to detect cloud seeding potential and monitor seeding induced changes in clouds.

- Use the newest high resolution atmospheric models to predict seeding plume transport and dispersion. However, verification by observations is essential.
- Develop explicit microphysical modules for cloud models to predict microphysical and precipitation seeding effects. Verify with observations.
- Refine techniques, such as the trace chemical analysis of snowfall, to evaluate new or ongoing wintertime seeding projects over drainage basin-sized areas.
- Study the impact of air pollution on winter clouds and precipitation.

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