Summary of the Effectiveness of Summer Cloud Seeding to Increase Rainfall and Reduce Hail

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Introduction

Modern efforts to increase rainfall and reduce damaging hail from summer thunderstorms date back to the late 1940s, built upon the landmark discoveries by General Electric scientists Langmuir, Schaefer and Vonnegut, which ushered in the scientific era of weather modification. In the six decades following their work, cloud seeding projects have proliferated across the United States and dozens of countries around the world.

The 2003 National Research Council (NRC) (1) study *"Critical Issues in Weather Modification Research"* included the statement that "there is still no scientific proof of the efficacy of intentional weather modification efforts." The issue of "scientific proof" was a subsequent point of significant debate between the NRC panel and the Weather Modification Association (WMA) (2). The WMA authored a detailed rebuttal to many of the NRC assertions leading to a joint paper published in the Bulletin of the American Meteorological Society (BAMS) (3), while the NAIWMC authored a response to the NRC report published on its web site (4).

The purpose of this paper is to summarize the more important research and evaluation results of summer cloud seeding efforts that demonstrate its efficacy. The research cited here spans more than 50 years of work in the areas of rainfall enhancement and hail suppression. Much of the research summarized below was conducted through programs sponsored by the U.S. Bureau of Reclamation (USBR), the National Oceanic and Atmospheric Administration (NOAA), and state and local government entities.

The Conceptual Model

The cloud seeding conceptual model for summer convective clouds has been developed and refined over the years through physical measurements, numerical cloud modeling and observations. There are presently two general methods used to treat summer convective clouds: atmospheric conditions dictate the conditions suitable for each.

Glaciogenic seeding requires at least a portion of the target cloud be "supercooled", or in other words, colder than 0°C (32°F). Here nature provides an interesting situation as these clouds often have significant amounts of water, still in liquid form, but colder than 0°C. The goal is to assist the conversion of this supercooled liquid water (SLW) to ice crystals, which form the building blocks of precipitation.

In this process, microscopic ice nuclei (IN), usually silver iodide complexes, are introduced into the cloud to assist with the transition of SLW to ice crystals. Natural clouds are oftentimes slow to create ice due to a lack of natural IN in the atmosphere, and because natural IN are usually inefficient until much colder temperatures (-15°C or colder) are reached. These tiny particles of silver iodide operate efficiently at much warmer temperatures (-5°C), thereby providing the seeded cloud with a head-start in precipitation development. Through a number of in-cloud interactions, seeding increases the cloud's precipitation efficiency, leading to increased rainfall and reducing its ability to produce large, damaging hail.

Hygroscopic seeding takes a different approach, acting upon the raindrop formation process in the lower, warmer portion of a cloud. Hygroscopic seeding materials are usually a type of salt, including sodium chloride (common table salt), potassium chloride, or calcium chloride. When released in or just below a growing cloud these tiny salt particles attract moisture and form small droplets that grow by coalescence – bumping into and combining with other droplets to form raindrops.

Hygroscopic seeding works well in clouds that have large numbers of very small droplets, but few large enough to initiate the coalescence process. This situation often occurs in continental interior regions such as the Great Plains of the U.S. When introduced into the cloud, the larger, more efficient cloud condensation nuclei (CCN) act preferentially over smaller, less efficient CCN accelerating the precipitation process and improving the seeded cloud's efficiency (5). The end result is more rainfall over a larger area than unseeded clouds.

Documenting the Chain of Events

Fundamental processes govern the ability of convective clouds to produce precipitation. Basic and applied research has been supported through many local, State, and Federal-funded programs during the last six decades to better define and understand these processes.

Transport and Dispersion Studies

Understanding the transport and dispersion of convective air currents, water vapor and cloud water in precipitation-forming clouds was an early target of study. Significant research has been applied using trace-gas detection of sulfur hexafluoride (SF_6) and the TRACIR (tracking air with circular-polarization radar) technique using near-microscopic aluminum-coated chaff fibers tracked with radar. The original landmark study (6) found that plume dispersion from cloud base and mid-cloud releases was limited until mixing at cloud top. Results have improved operational targeting and confirmed cloud-base seeding methodologies.

Follow-up research further established transport and dispersion mechanisms in convective clouds. An excerpt from Stith et al., 1990 (7) states: *"The tracer and accompanying aerosol filled most of the cloud containing supercooled liquid water at the -4°C level within 11 minutes after the beginning of treatment. The materials were even more fully dispersed across the cloud on subsequent penetrations at higher levels in the cloud…The observations are consistent with early ice formation in the cloud by the AgI-AgCl aerosol at temperatures low enough for it to produce significant ice particle concentrations."*

Yet another study from the North Dakota Tracer Experiment (1993) indicated that the seeding methods used in North Dakota deliver the seeding material to the desired locations in seeded clouds (8). *"Cloud-base releases of ice-forming nucleants by aircraft are the main means of delivery in North Dakota's operational hail suppression program. This experiment, among others during NDTE, showed that chaff (or equivalently, seeding* *aerosol) from a cloud-base release can be ingested and delivered to desired altitudes and temperatures by a feeder cell, even in systems with only modest vigor."*

<u>*Quantifying Supercooled Liquid Water (SLW), Cloud Condensate and Water Vapor*</u>

Without SLW the idea of glaciogenic seeding is a non-starter. SLW is the raw material from which ice-phase precipitation is made, and thus a subject of research to establish its freezing mechanisms, quantities and preferred locations in convective clouds (*e.g.* 6, 9, 10, 11). This research has shown SLW to be often present, especially in the new growth areas of convective storms.

Physical measurements of SLW have been made in numerous studies. The study area of aircraft icing has contributed much to the knowledge base of SLW, better defining its boundaries and conditions under which it forms (12, 13). Presence of SLW at temperatures of -20°C or colder are common, and documented occurrence of SLW at temperatures as cold as -37.5°C, very near its homogeneous freezing temperature (the theoretical minimum temperature at which all liquid water must freeze) of -40°C has been found in vigorous convection in Argentina (11). Availability of SLW at those extreme temperatures is a significant issue for hail suppression cloud seeding programs.

Numerical modeling has elucidated much about the vagaries of SLW (*e.g.* 10, 14, 15) including its role in precipitation formation and the effects of latent heat release from freezing. In more general terms, numerical modeling has addressed hypothesis development, assessment of "seedability", experimental design, operational decisions, project evaluation, and furthered the understanding of seeding effects (16).

As discussed earlier in this document, hygroscopic seeding does not necessarily involve an ice-phase process in its conceptual model. Thus, SLW is not the primary issue, but cloud condensate and water vapor are of greater interest. Considerable research has focused on the microphysical characteristics of convective clouds as it relates to cloud condensation nuclei (CCN) and cloud droplet spectra. Hobbs et al., (1985) found that background concentrations of CCN in the High Plains were probably produced by gas-to-particle conversion, with other natural and anthropogenic sources of CCN superimposed on this background (17). Further, they found that CCN concentrations varied cyclically with time, going from low concentrations to high concentrations and then decreasing again over several days to several weeks time. These findings, in conjunction with those from Mather et al., (1997) (6) open a window of opportunity to intervene in cloud microphysical processes through hygroscopic seeding.

DeMott et al. (1996) (18) found that during an 18-day period near Bismarck, N.D. in July, 1993, the average CCN concentration active at 1% supersaturation was 300 cm^{-3}. The cumulative frequency distribution, however, showed that droplet concentrations less than the average occurred 25% of the time, indicating that "maritime" aerosol conditions can occur a significant fraction of the time in continental regions. As the current hygroscopic seeding model requires a more "continental" droplet spectrum as a prerequisite to successful cloud treatment, these findings (17 and 18) suggest initial conditions must be known prior to hygroscopic seeding operations. More recent research (19) has sought to develop a proxy method by which air masses could be characterized on a day-to-day basis, thereby identifying situations where hygroscopic seeding may be appropriate.

Microphysical Effects

Studies of the initiation and growth of ice crystals have conclusively confirmed that well-timed and properly placed seeding with silver iodide or dry ice pellets accelerates the development and increases the concentration of ice crystals in cumulus clouds (*e.g.* 7, 20, 21, 22, 23 and 24). A few are summarized below.

A study in South Africa, where clouds were randomly chosen for seeding with dry ice pellets, silver iodide, or left unseeded found that clouds seeded with dry ice pellets and silver iodide more often produced radar echoes greater than 10dBZ and contained significantly more ice crystals than placebo (unseeded) clouds (20). Research in Alberta found that clouds seeded with dry ice pellets and droppable silver iodide flares produced precipitation on the ground within 20 minutes after seeding, while a third unseeded cloud produced no precipitation (23). A third study (22) during HIPLEX (High Plains Experiment) in Montana found the structure of clouds seeded with dry ice to contain ice particle concentrations with the potential to enhance precipitation in comparison to unseeded clouds. Work in Texas (24) found that seeding of clouds with supercooled rain drops led to 1) fast freezing of the supercooled drops and its continued growth as graupel, 2) enhanced growth rate of the graupel as compared to supercooled rain drops, 3) fast glaciation within the active updraft, increasing buoyancy and invigorating the updraft, and 4) more rapid removal of the cloud water as compared to clouds without seeding.

Evidence of Precipitation Enhancement

Measurement and quantification of precipitation increases from cloud seeding is one of the biggest challenges to the weather modification industry. Due to natural variations in rainfall from one location to another and over time, it is not a trivial matter to find a seeding effect in a highly variable natural phenomenon. That said, however, both long-running operational cloud seeding programs and randomized research programs have demonstrated statistically significant increases in precipitation.

The North Dakota Pilot Project (25), a four-year randomized research project, found statistically-significant results that silver iodide seeding of convective clouds leads to: (1) an increase in the frequency of rainfall events at the target gauges (0.04 significance level, or 96% confidence), (2) an increase in the average rainfall recorded per rainfall event (0.02 significance level), and (3) an increase in total rainfall on the target area (0.07 significance level). The authors estimated a potential increase of one inch of rainfall per growing season for western North Dakota from cloud seeding. A similar randomized program in Texas found seeding with silver iodide more than doubled the rainfall volume from treated clouds (26). In addition, the seeded clouds lasted 36% longer and produced rain over a 43% larger area.

Hygroscopic seeding has also been evaluated for its ability to increase rainfall. Randomized experiments in South Africa (27), Mexico (28) and Thailand (29) all found strong statistical evidence of significant precipitation increases from clouds seeded with hygroscopic flares. Again, the seeded clouds lasted longer, produced precipitation over a larger area, and possessed a greater rainfall rate than their unseeded counterparts.

Operational programs have also shown evidence of precipitation increases. An objective, radar-based evaluation of two operational programs in Texas (30) found strong statistical support for rainfall increases from seeded clouds when compared to unseeded clouds. Overall percentage increases were greater than 50 percent from individual seeded clouds. These results were in good agreement with the Texas randomized seeding experiment (26) mentioned earlier. An examination of a multi-year rain-enhancement program near the Texas-New Mexico border found substantial rainfall increases due to seeding that translate into an estimated benefit/cost ratio of 235 to 1 (31). Other studies (32, 33) have been completed to elucidate the effect of cloud seeding on rainfall in North Dakota, finding percentage increases in the single-digits to low teens. The most recent (33) suggested a 4.2% to 9.2% increase in rainfall in and slightly downwind of the target area. Statistical significance in both cases was marginal, however. An analysis of rainfall data over a 15-year period ending in 1993 in western Kansas, where cloud seeding has been used to suppress damaging hail, found no significant changes in rainfall distribution even as reductions in hail damage were determined to be sizeable (34).

Evidence of Hail Suppression

Operational hail suppression programs worldwide have demonstrated evidence of reduced hail damage from cloud seeding. In the U.S., programs to reduce hail damage in North Dakota, Kansas, and Texas have demonstrated evidence that seeding of convective clouds leads to reduced crop-hail damage. A study of crop insurance data (35) found that cloud seeding in western North Dakota reduced crop-hail damages by 45 percent when compared to an adjacent upwind control area. The authors stated that the result "*… indicates that the crop hail insurance loss ratios in the target area during the NDCMP years were about 45% lower than would be predicted from the historical period.*" The statistical confidence in the result was high, at 0.025, or 97.5% confidence. A study from the western Kansas program found a 27 percent reduction in crop-hail losses (34), which translates into a savings of some $4 million per year.

International programs have found strikingly similar results. Studies of the Association Nationale d'Etude et de Lutte contre les Fleaux Atmospheriques (ANELFA) program in southwestern France have found crop-hail damages to be 41% lower in the seeded operational area (35) along with a maximum reduced hailstone number of 42% for the higher seeded hailfalls (36). A five-year randomized study in Greece (37) found seeded storms contained 38 – 100% fewer hailstones than control storms in 12 size categories with an average reduction of 55%. Crop-hail losses from seeded storms were also 18 – 59% lower than losses from non-seeded storms.

Conclusions

The work referenced here summarizes the current state of knowledge in the area of convective cloud seeding. Summer programs in the U.S. are mostly confined to the Great Plains, while winter cloud seeding programs are conducted primarily in the mountains of the western U.S. Based on evaluations from numerous operational and research programs, convective cloud seeding has shown the ability to promote additional rainfall and reduce damage from hail. As with any technology, there are limitations: cloud seeding is not advocated as a drought-busting tool, but numerous studies show an effectively designed, adequately equipped program can provide tremendous benefits at relatively low cost.

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