RECENT PROGRESS AND NEEDS IN OBTAINING PHYSICAL EVIDENCE FOR WEATHER MODIFICATION POTENTIALS AND EFFECTS

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ABSTRACT

Statistical and numerical modeling approaches to assess the effects of cloud seeding require the interactive input of, and understanding derived from, measurements that provide direct evidence of natural and altered development of precipitation. A brief review of recent progress in obtaining physical evidence to evaluate and verify potentials for and effects of precipitation enhancement and hail suppression is presented. Recent findings from the National Oceanic and Atmospheric Administration's Federal/State Cooperative Program in Weather Modification Research are emphasized, but other related results are included. In the context of many significant new advances toward proving hypotheses by direct measurement, a number of remaining needs for measurements and corresponding technologies are identified.

1. INTRODUCTION

Precipitation forms from many processes over many possible pathways in clouds. These processes and pathways may be altered by cloud seeding. The complexities and the natural variability of the processes and the consequent precipitation make it extremely difficult either to predict or to assess the effects of cloud seeding. Statistical and numerical modeling approaches to deal with the complexities and variability require the interactive input of, and the understanding derived from, direct measurements. To this end, some history, and some new advances, with a focus mainly on those from the National Oceanic and Atmospheric Administration's (NOAA) Federal/State Cooperative Program in Weather Modification Research (Reinking, 1985), are reviewed in this paper. In the context of these advances, some needs for other direct measurements and measurement technologies are identified.

2. BACKGROUND

Early cloud seeding experiments using rudimentary measurement technologies have demonstrated that precipitation can be stimulated to *form* and fall from relatively simple clouds. We define simple clouds as those that are either small, isolated or shallow, generally without natural ice, and with relatively uncomplicated internal structure and motions. Consider just a few examples to illustrate the foundation given to weather modification by the successes with simple clouds.

The supercooled stratocumulus cloud seeded by V.J. Schaefer in 1946 was not only dissipated but it was also quickly converted to precipitating snowflakes (see Dennis, 1980). Similarly, experimental and operational seeding of supercooled fogs has not only demonstrated a capability for dissipation; it has also shown that ice crystals that grow from the available liquid do indeed precipitate (e.g., Steele and Reinking, 1966).

Bethwaite et al. (1966) seeded isolated nonprecipitating cumuli from cloud base and measured subsequent rain at cloud base with a raindrop impactor. Cumuli with initial tops at −10° to −14°C that were seeded with 20 g of silver iodide-silver iodate produced rain volumes 13 times greater in the mean than those from nonseeded clouds. Substantially less seeding material (2 g) had no measurable effect. Kraus and Squires (1947) used dry ice to seed two cumuli in a seemingly uniformly sized population. Within 100 miles of the seeding aircraft, only these two clouds grew, explosively, above the general level of other tops, and produced radar echoes and rain.

New experiments using advanced measurement technologies quantify and confirm the early results. For example, an experiment with Alberta cumuli, using an aircraft with advanced "pointer" navigation and particle measuring probes to follow developing hydrometeors, is reported by Kochtubajda (1985) and Kochtubajda and English (1989). The size-concentration distributions of growing and precipitating ice crystals from seeding were tracked and measured from the nucleation levels to the melting level near or below cloud base, and the rain from the melt was tracked to near the ground. In clouds with lifetimes enduring 20–40 minutes after seeding, aircraft-measurable precipitation was tracked and detected near the ground below 71% of clouds seeded with dry ice, 74% of clouds seeded with silver iodide-silver iodate flares, and only 15% of nonseeded clouds; 37% of the seeded clouds and none of the nonseeded clouds produced S-band radar echoes. As expected, the silver iodide-silver iodate was observed to take some 6–10 min longer to act than the dry ice, due to the difference in nucleation mechanisms.

The reader is referred to the many additional physical demonstrations that leave "no serious doubt about the existence of convective clouds which respond to artificial glaciation with increases in size and increases in precipitation" (Dennis, 1980). The thorough historical reviews by Dennis and in the volume edited by Braham (1986) show that the same is true for relatively simple clouds of other types.

These focused measurements add to the direct and quantitative physical evidence that the fundamental principles of cloud seeding are sound. One of the clouds seeded by Kraus and Squires produced 12 mm of rain over 130 km^2, thus providing good reason to explore seeding for dynamic effects. However, the more common result is that simple clouds do not yield substantial precipitation. For example, the precipitation from Schaefer's stratocumulus sublimed after falling 600 m into dry air, and the heaviest rainfall from the seeded Alberta cumuli was equivalent to only 1.6 cm over 1 km^2.

For more complex clouds with more natural ice, which might produce more added precipitation, Cooper's (1986) review shows that cloud conditions do occur where ice crystal concentrations are the result of temperature-dependent nucleation, rather than other processes. These concentrations, as compared with those from secondary ice production, are reasonably predictable and substantiate the hypothesis that some clouds may be ice deficient, depending on the flux of liquid water, cloud lifetime, and precipitation mechanisms. Knowledge of these factors is required for the next step: understanding the potentials. Hail suppression is more difficult to understand than precipitation enhancement. There are no measurements directly linking seeding materials and their effects to decreases in number or size of hailstones, although theories, models, and some sound statistical experiments with hail pad measurements suggest that seeding for hail suppression can work (Dennis, 1980; Steering Committee, 1988; Farley, 1987; Flueck et al., 1987; Smith et al., 1987). Therefore, central remaining challenges are (1) to demonstrate to the satisfaction of users and scientists that net precipitation can be beneficially increased from larger and more complex cloud systems, by either static or dynamic seeding, over the area of a watershed, and (2) to determine if either the microphysics or dynamics of complex convective storms can be sufficiently and predictably altered to suppress hail, in support of modeling and statistical experiments that suggest real possibilities for both precipitation increase and hail suppression.

Research toward these goals in the NOAA Federal/State Cooperative Program (Reinking, 1985) is focused on four key subsets of problems: (1) determination of the presence, persistence, and natural utilization of supercooled liquid water, (2) determination of potentials and methods for effective delivery of the seeding material to the supercooled liquid water, (3) evaluation and verification of the effects of seeding, and (4) quantification of benefits of any increased precipitation or suppressed hail. Satisfying proof of hypotheses in these areas will come only with measurements that provide direct physical evidence.

3. PHYSICAL EVIDENCE: ADVANCES AND NEEDS

3.1 *Supercooled liquid water*

The invention of the dual-channel passive microwave radiometer (Hogg et al., 1983) to provide continuous measurements of liquid water and water vapor has heralded a wave of productive physical investigations centered on remote sensing. Many radiometer measurements show highly variable, commonly small, but often persistent levels of supercooled liquid water (SLW) in storms over mountains (e.g., Long, 1986; Long et al., 1986; Reynolds, 1988). The greatest advances are and will be made by applying sets and arrays of multiple remote sensors supported by airborne and surface measurements; for example, Long (1986), Long et al. (1986), Sassen et al. (1986), Snider et al. (1986), Meitín and Reinking (1989), Uttal et al. (1989) and others have applied combinations of Doppler and polarization radars, polarization lidar, and a radiometer to study orographic storms in Utah. These cases and composite studies spatially and temporally depict cloud and frontal structure; mesoscale kinematics; conditions for orographic enhancement, blocking with diversion or damming, gravity flows, etc; water release rates; precipitation generation processes; fluxes of water substance and forms of precipitating ice throughout storm passages. The coordinated use of satellite and radar remote sensing to follow the development and passage of warm cloud tops and rainbands, as was done in recent Bureau of Reclamation programs, is reviewed by Reynolds (1988).

The composite measurements are yielding an unprecedented but still partial understanding of the spatial and temporal evolution of SLW in relation to storm circulations and their interactions with the mountains. Such studies show in general that, for frontal/orographic storms, observable and potentially predictable "liquid water opportunities" occur within but not throughout storm periods, during periods with low and relatively warm could tops that minimize chances of natural ice formation, when either prefrontal or postfrontal moist air flow is perpendicular to the mountain barrier, or within embedded convective cells or bands. Concentrations of liquid water are greatly reduced when flow becomes oblique to the barrier, even though the regime may be under the influence of cyclonic convergence and lifting. The liquid water is most consistently observed close to terrain features that force lifting through the condensation level, rather than at higher altitudes in deep cloud systems or over the highest windward mountain slopes.

The vertically integrated precipitable liquid water has been observed to reach values of the order of 1 mm, but the probability of it exceeding 0.2 mm is only about 10% in the continental interior orographic storms in Utah and about 20% in storms over the Sierra Nevada or California. The liquid water can persist, albeit with high variability, for as long as 6 to 48 hours (Snider et al., 1986; Reynolds, 1988). Occurrences of lee-side losses of SLW to evaporation are often revealed by rimed trees on mountain crests. Such losses are not well documented, although measurements taken with scanning radiometers placed on or near crests could be used for this purpose. A significant opportunity to measure the budget of water vapor and liquid water fluxes over whole watersheds rests with the potential use of arrays of radiometers and wind profilers or Doppler radars.

Also needed are sensors to profile and horizontally locate the liquid water. The three-dimensional distribution of the liquid water in a cloud system might be measured using a technique of differential attenuation at two short radar wavelengths, as first suggested by Atlas (1954) and now being examined by NOAA's Wave Propagation Laboratory. Preliminary calculations show that ice particles would produce negligible attenuation in either the Ka-(0.86 cm) or the X-band (3.22 cm), but 0.2 g m^{-3} of liquid water would produce 2–way attenuation of about 0.5 db/km in the Ka-band and an order of magnitude less attenuation in the X-band. The difference is measurable with state-of-the-art radars over pathlengths of several kilometers, so a synchronized dual-wavelength method is promising.

A dual-channel microwave radiometer for airborne use has been developed by NOAA's Wave Propagation Laboratory; this will allow investigators to take the SLW and vapor measuring device to desired locations and altitudes in clouds to be studied.

Knowledge of the temperature of the cloud liquid water is crucial to understanding, predicting and modifying conversion of the water to ice. A major advance, a combination of a Radio Acoustic Sounding System (RASS) with a wind profiler radar (Strauch et al., 1989), offers a solution to the temperature profiling problem in both orographic and convective regimes and can now provide a capability to profile the temperature of the water, within convective as well as orographic mixed phase clouds.

3.2 *Delivery*

Given that ice particle deficiencies occur and that cloud volumes with significant liquid water can be identified, well-timed and well-dispersed delivery of seeding materials, to fill the cloud-liquid volumes, will require careful, innovative approaches. A recent assessment of experimental design considerations for transport and dispersion of seeding materials (Warburton et al., 1986) provides a good basis for discussing advances in gaining physical evidence for testing hypotheses of delivery. The questions of how to get the material to the target volume and how to mix it through the volume in stable or unstable air are very challenging.

Aerosol-hydrometeor interactions and the nucleation of ice depend on actual rather than average particle concentrations carried in a particular parcel or turbulent entity. Thus, the fraction of volume affected is pertinent, not the average concentration as derived from time-averaged Gaussian models; also, super-position of multiple Gaussian plumes overestimates the fraction of volume seeded. The ropes of aerosol or tracer need to become part of the theory, and the statistic most appropriate for determining the spread of the aerosol is not the mean concentration, but rather the concentration fluctuations enroute to and within the cloud volume (Warburton et al., 1986). Lagrangian particle diffusion and transport schemes are appropriate.

The plumes of aerosol released over complex terrain or into convection are best described as rope-like in structure; cloud- and meso-scale eddies do not mix two plumes, but cause them to weave or meander together. The history of an air parcel carrying a tracer depends on its path; the path varies for each passing section of a plume. Particularly in cloudy convection, successive steps in extension of the rope-like plume depend crucially on where the rope was in the previous "step" of the transport process. The meandering and the turbulence of eddies the size of the plume are the two physical mechanisms that produce concentration fluctuations.

The questions of delivery and verification are being effectively addressed by the use of airborne measurement technologies, SF_6 gas, indium oxide, oxygen isotopes, and silver (from AgI) to trace cloud motions and microphysical processes (Reinking, 1987; Smith et al., 1989).

Field research has proven the reality of the rope-like, spatially confined nature of plumes passing over complex terrain, by strategic sampling of fallen snow to find silver released as AgI from upwind ground-based, point source generators. While silver concentrations up to 35 times background have been observed in seeded Sierra Nevada snowfall, the "seeding silver" was present only 10–30% of the time in snow samples from periods of continuous seeding. The excess silver commonly appeared in narrow spatial and temporal zones as expected from narrow, meandering, precipitation-generating plumes. On some occasions, however, groups of silver sampling sites indicated relatively uniform dispersion in generating plumes and falling precipitation, throughout the area for extensive time periods during storms (Warburton, 1986; Reinking, 1987).

In recent experiments using aircraft with particle measuring probes and "pointer" navigation to follow advected and lifted air parcels, the enhancement of ice crystal concentrations above background by seeding has been documented quantitatively for both convective and orographic clouds. For example, Cooper and Lawson (1984) and Marwitz and Stewart (1981) have accomplished this in Bureau of Reclamation programs. Stith and Benner (1987) and Stith et al. (1989) have carried this another step in cumulus congestus clouds by identifying the ice due to seeding and separating it from natural ice by tagging the seeded air parcels with the SF_6 tracer gas. The rope-like structure of plumes during initial dispersion in convective clouds was confirmed, but turbulent mixing in the tops of convective currents tended to fill the volume and subsequent downdrafts. Also, Stith et al. (1989) compared, with some initial success, the concentrations of ice where SF_6 was detected to time- and temperature-dependent nucleation rates of the seeding material (AgI – AgCl) predicted from laboratory measurements.

For cloud-interactive seeding aerosols that do not immediately nucleate, there is the need to know whether the aerosol becomes involved in nucleation and both contributes to and is removed by precipitation, or whether it is merely removed by scavenging. Warburton et al. (1985) have approached this problem by releasing two tracers simultaneously at the same rates and locations: an active AgI ice-nucleating aerosol and a passive or inert (non ice-nucleating) indium sesquioxide (In_2O_3) aerosol. Both types of particles, as generated, were predominately submicron, and size distributions of the AgI complex and In_2O_3 were quite similar. If these particles were removed through precipitation by the same mechanisms, their masses in fallen snow would bear the same type of relationship to the water mass. Measured silver (iodide) contents showed a strong and positive correlation with the water mass of fallen snow; this is contrary to the normal negative correlations observed for atmospheric impurities scavenged by precipitation (the inert particle correlation is consistent with scavenging proportional to volume or surface area of the precipitation particulates). The data suggest independence or a slight positive correlation of the indium (oxide) mass concentrations with the mass of snow, which, within experimental tolerances, equates to the inert particle correlation, and is very distinctly different from the silver-snow mass relationship. The measurable difference indicates an ice nucleating component active in the removal of the silver iodide aerosol.

Overall, this work on the questions of effective delivery shows that ice from seeding can be identified and separated from natural ice by tagging seeded parcels of air with tracers, and that seeding material is producing some snow from complex clouds. However, this work also shows that current methods of delivery and the limits of dispersion processes make it very difficult to properly time and fill either an orographic or a convective cloud volume with seeding material. New strategies may be appropriate. A strategy for delivery with a design for seeding materials to reach only a portion of the available liquid water would appear to further compromise already limited seeding opportunities when the static mode of seeding is optimal, but may be appropriate for the dynamic mode. Cost effectiveness is a factor here. For example, the value of added water or reduced hail must be considered if delivery by multiple aircraft is otherwise desirable.

The problem of properly timing the seeding of an evolving volume of SLW could conceivably be sidestepped by seeding whenever there is cloud cover during storm passage or convective cloud development. If such an approach is cost effective, it would still require assessments of the effectiveness of targeting and potentials for decreasing precipitation.

Ground-based generators are in wide use for operationally seeding orographic clouds, and they continue to be used, albeit controversially, to seed convective clouds. Thus the release of seeding materials into clear air below cloud base is a standard practice. Drainage flows and thermally driven up-valley flows in mountain valleys have been mapped in detail with measurements from pulsed infrared Doppler lidar (Post and Neff, 1986). This device senses a frequency shift in infrared energy backscattered from aerosols that is proportional to the radial components of winds carrying the aerosol.

Many of the unresolved questions of ground-based delivery might be answered by applying lidar instrumentation and techniques to map tracer or natural aerosol gradients and airflows in clear air.

If cloud seeding technology is to advance very far beyond its present state, careful, innovative approaches that include real time monitoring of dispersion and SLW will likely be required for either research or operational application.

3.3 Evaluation and verification

The questions and challenges of evaluation and verification of effects of seeding on the physical "chain of events" comprising the formation of precipitation are closely interwoven with the SLW and delivery problems, and much of the work already mentioned could equally well be examined in the evaluation and verification context. The liquid water must be available to form precipitation, and to determine and monitor its presence is to verify one link in the chain. Likewise, to determine that seeding material has reached the SLW and is producing ice crystals and snow is to verify that certain links in the chain have been modified.

The utilization of cloud water depends on the activity of various raindrop and ice processes. List et al. (1986) identify top priority laboratory experiments (which of late have been all too neglected in the scheme of obtaining meaningful measurements and insight): among these are production of secondary ice. Also included from the precipitation chain are ice crystal aggregation and large drop interactions with effects of electrostatic charging.

Pitter and Finnegan (1988), on the basis of laboratory observations, postulate a mechanism of secondary ice nucleation that proceeds only with aggregation and is correlated with high electrical freezing potentials of dissolved ionizable salts. Czys (1988) argues that shock-induced freezing (primary nucleation) may result from collisions of supercooled raindrops. The collisions may produce pressure fields which may induce local expansion and cooling of gas bubbles in the drops; the local cooling may cause nucleation on neighboring immersed nuclei. These new ideas are welcome because neither secondary nor primary ice is well predicted for complex clouds. This gap in physical evidence and understanding is limiting the utility of the advanced numerical cloud models, which have outpaced supporting observations.

Intense localized dynamics, large raindrops, and wet ice complicate our efforts to measure and understand isolated and embedded convective clouds. Determinations of the sum of factors affecting their precipitation efficiencies lag far behind those for more stratiform orographic clouds. Our inability to remotely detect and quantify first ice, particularly in the presence of large drops, is still a major obstacle. However, multiparameter radar measurement techniques offer hope of distinguishing various kinds of large ice particles and determining raindrop size distributions in mixed phase clouds (Bringi et al., 1989). This will help to identify active precipitation-forming processes and to quantitatively measure rates of precipitation in the varied forms.

Physical evidence from complex clouds that directly links released seeding material to precipitation on the ground has not been acquired, except in the physical-statistical experiments with simple cumuli reported by Kochtubajda (1985) and Kochtubajda and English (1989). Super and Heimbach (1989), for example, have effectively correlated AgI plumes and ice particle concentrations during a Bureau of Reclamation experiment; they conclude that "seeding the stable orographic clouds over the Bridger Range sometimes caused marked increases in ice particle concentration, presumably leading to more surface snowfall" (our underline). For a similar experiment with clouds over the Grand Mesa, Super and Boe (1989) concluded that precipitation rates estimated from ice particle images at flight level suggested increases within the seeded volumes" in eight tests. Correlated surface precipitation increases were observed in three of the tests and not evident in the others, and again, direct physical links between ice from seeding in the cloud and snow on the ground were not made.

This problem might be solvable by applying in combination, one or more of the gas and aerosol tracer technologies with the technique known as TRACIR (TRacking Air with Circular polarization Radar), which detects depolarized signal backscatter from chaff fibers released into a cloud. The chaff, which falls at velocities of small precipitation particles ($\sim$25 cm s^{-1}), may be used as a tracer (Moninger and Kropfli, 1987; Martner and Kropfli, 1989) to simulate or tag first echo from seeding and the trajectories of resulting precipitation. This could be combined with polarization lidar which has already been effectively used to identify and monitor types of snow particles falling from cloud base to the ground (Sassen et al., 1986; Long et al., 1986).

The various tracer technologies, including TRACIR, also offer opportunities to determine the feeder cell vs. main cell sources and transport of hail embryos, beyond in-storm trajectories analyzed from multiple Doppler radar studies (Steering Committee, 1988).

Lee-side sublimation of unprecipitated ice may represent the greatest loss of water from mountain storms; likewise, the losses to glaciation of convective clouds may be very significant. This phenomenon is pertinent to the overall water budgets of targeted clouds which need to be determined to estimate the effects of seeding in causing net increases or decreases in precipitation. While instrumented aircraft may be helpful in addressing this problem, a remote sensor to measure cloud ice mass and flux from large volumes of cloud is needed. Presently, K-band Doppler radars could be useful for crudely estimating the flux of large ice particles.

In related laboratory work, Finnegan and Pitter (1986) show how the dissolution of ionizable molecules of salts in ice crystals can cause aggregation, presumably by inducing electric multipoles. One can envision seeding nucleants with certain hygroscopic components to induce aggregation and enhance fallout. This kind of approach to enlargement of hydrometeors could be very important in reducing the lee-side losses to sublimation or in converting convective virga to precipitation.

3.4 Physical evidence of benefits

Recent analyses of measured physical effects of added rain or snow, or reduced hail are generally lacking. Two exceptions are those reported by Knapp et al. (1988) and Changnon and Hollinger (1988).

Knapp et al. (1988) interactively used a model and measurements of plant processes and infiltration of rain into varied soils to estimate the effects of added July and August rainfall on the soil moisture, crop water use, and stream flow in the Midwest. The model simulations, based on the measurements, suggest that a large increase in rain (10–25%) directly on the crops would be required to sufficiently affect crops under stress to help growth, because any rain during crop stress periods is normally light and actual additions to the light rain would be small. However, actual additions for the same percentage increases would be greater during wet periods, and most of any increased summer rain would go to increase groundwater flows. This would improve water quality during dry periods. Also properly timed irrigation from (increased) groundwater could alleviate crop stress and add to growth.

Field experiments to evaluate the actual effects of enhanced rain on crop production have been needed. The unique experiment by Changnon and Hollinger (1988) uses a 9-m × 48-m mobile, plastic-covered shelter with a sprinkler system to exclude natural rain but otherwise expose crop plots to the prevailing weather. Watering is quantified and timed to the historical rain-day precipitation record, for wet, dry and average summers, with water added to simulate modification. Initial results indicate that rainfall increases of 10–40% in Illinois increase corn and bean yields by 4–20% if rainfall is below or near average.

In a more general analysis, Garcia et al. (1987) used a long period of records of standard measurements to study the effects of technological advance and weather conditions on crop production. They found that an increasing absolute variability in Midwest corn yield has accompanied a continued long-term trend of increasing average yield, such that increased precipitation and moderated crop heat stress might reduce risk by alleviating extreme year-to-year changes in yield.

Examination of crop-rainfall relationships by Schaffner et al. (1983) suggest that expected increases in crop yields and associated economic benefits from a 3 cm increase in growing season rainfall would boost the North Dakota state economy by $0.7 billion annually.

Southwest North Dakota has the highest ratio of hail damage claims paid to insured crop liability within the United States (9–11%). An exploratory statistical analysis of 61 years of hail loss ratios, which are crude but practical measurements, suggest 43.5% less hail damage to crops during 10 years of operational hail suppression. This is not explained by climate variations. Such a reduction, if attributable to seeding, supports a benefit-to-cost ratio of 8:1 for the operations (Smith et al., 1987). Only direct physical evidence from specific cloud, precipitation and other meteorological measurements will confirm such analyses.

4. CONCLUSIONS

The physical evidence accumulated so far proves that cloud seeding enhances precipitation when the right kind and amount of material is applied at the right time and place in a cloud. The task of determining what is "right" in microphysically and dynamically complex clouds is very difficult. The realized and potential advances in capabilities for cloud and precipitation measurement have taken the science of cloud seeding well beyond the plateau of the 1970's. These capabilities provide input and verification for statistical, theoretical and numerical modeling approaches which continue to be appropriate to use interactively with direct measurements to gain more complete understanding and predictability of the natural and modified precipitation processes. The new and emerging technologies may now enable us to meet the challenges of <u>measuring</u> if and when a complex cloud system is "right," if and how seeding material can be effectively delivered, and whether <u>net</u> precipitation over an area can or cannot be beneficially increased or hail can be reduced.

Central to all of this, detection of substantial liquid water within the lifetime of a cloud element is to be recognized as a necessary but not sufficient condition for finding seeding potential, which also depends on all of the factors that determine the natural precipitation efficiency and on the consequent effect of seeding on the net water budget of the entire volume of targeted clouds. Natural precipitation (in)efficiencies of complex cloud systems are unknown and need to be measured and understood, as do the potentially modifiable links between hail embryos and hailstones.

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