

A REVIEW OF HYGROSCOPIC SEEDING EXPERIMENTS TO ENHANCE RAINFALL

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Abstract. Field experiments and computer modeling studies of the possibility to promote the coalescence process by hygroscopic seeding for rainfall enhancement are reviewed. Most previous experiments have focused on the use of water sprays or common salt particles, but the practical delivery of the massive bulk sources of these products has been a limiting factor. Although most past efforts have not provided convincing scientific evidence of seeding effects, they leave the impression that effects were generally consistent with the hygroscopic seeding hypothesis under investigation (i.e., broadening of the cloud droplet distribution, and triggering of coalescence which possibly alters echo morphology). Rainfall enhancement from hygroscopic seeding remains to be demonstrated. Seeding effects beyond those expected on the coalescence process may also be apparently possible. Effects on the initiation and evolution of ice may have been noted perhaps because of the enhanced presence of supercooled drizzle and rain drops, or because rime-splintering may have been enhanced by the presence of broader distributions of supercooled cloud droplet distributions in ice multiplication zones, or for perhaps both reasons. Indications of "dynamic" effects may have been found which possibly occurred either in conjunction with the latent heat of condensation, or from a more active conversion of supercooled water to ice, or for both reasons. Computer modeling has indicated that seeding at cloud base with appropriately sized cloud condensation nuclei to foster Langmuir-type precipitation growth trajectories may be a desirable seeding strategy, and that seeding does not necessary have to be limited to cold based clouds characterized by a marginal coalescence process. The use of "new" hygroscopic seeding flares at cloud base in deep warmer-based South African clouds has produced very encouraging results from a limited amount of experimentation, and the new seeding flares have apparently overcome earlier problems associated with transporting the seeding materials. Thus, the technique of hygroscopic seeding deserves reexamination.

1. INTRODUCTION

Recent investigations into the possible effects of artificial hygroscopic nuclei to enhance the coalescence process in the multicelled storms that grace the eastern Transvaal of South Africa (Mather 1991) have provided some indication of success. The clouds and the multicelled rain cloud systems of that region are similar in many ways to the convective summertime rain clouds that have been the subject of "dynamic seeding" experimentation in Illinois. For example, the convective rain clouds of the eastern Transvaal and those in Illinois tend to be warm based with similar distributions of cloud base temperatures (Johnson 1982). Clouds from both regions tend to initiate precipitation by the condensation-coalescence process, and both tend to originate ice by the coalescence-freezing mechanism (Braham 1986). The only major difference between the clouds being perhaps mean updraft velocities which is typically about 5 m s^{-1} for Illinois (Czys 1991) compared to 8 to 9 m s^{-1} for those in the eastern Transvaal. The similarity between clouds in both regions would provide broad common base from which to make inferences about seeding effects.

The possible successful result of hygroscopic seeding in the Eastern Transvaal, and its potential application in Illinois was cause for us to look back at previous investigation in order to place the recent work in South Africa into proper perspective. In the course of conducting this review, we uncovered an excellent review paper by Cotton (1982) which was prepared for the World Meteorological Organization (WMO) meeting on Warm Cloud Modification held at Kuala Lumpur, Malaysia in March of 1981. Other reviews on this subject have been made by Dennis (1980), Mason (1971), and Hess (1974). As best as we could determine little as been done with respect to hygroscopic seeding since Cotton's fine review was written. However, we believe that the status of warm cloud modification is cast in a sufficiently different light when the South African results are included to warrant revisiting the subject.

2. DEFINITIONS AND SEEDING TECHNIQUES

Since its inception, the term "hygroscopic seeding" has taken on slightly different meaning depending on the experimental design, type of seeding material used, and the

type of cloud that was the subject of experimentation. However, almost in all instances the ultimate goal has been to enhance rain fall by somehow promoting the coalescence process. As will be discussed, alteration of the coalescence processes may have implications on the origin and evolution of precipitation processes involving ice, and on overall cloud dynamics from the redistribution of energy in the form of latent heat releases associated with condensation as well as freezing. By the term "modification of warm cloud processes", we mean any influence that seeding would have on the coalescence process to enhance the production of rain drops. Seeding may help to initiate coalescence when it would otherwise not, or may help to allow coalescence to initiate earlier than it would naturally. The effects of seeding are not necessarily limited to cloud regions that never grow colder than 0°C, nor should the initial effects on the coalescence process not have implications for how other subsequent microphysical and/or dynamical processes might proceed.

The addition of "appropriately" sized cloud condensation nuclei (CCN) and the direct introduction of artificial rain drop embryos with either sprays of water or dilute saline solutions, are the most common previously used hygroscopic seeding techniques, although poisoning of CCN and stimulation of coalescence by electric fields have, at various times, been considered. In this review, we focus on use of water sprays and hygroscopic aerosol particles. The primary objective of adding "larger" CCN is to prevent the activation of the smaller natural CCN to lower the total concentration of initial cloud droplets, and thus, broaden the initial cloud droplet spectra. This is supposed to transform a cloud with a "continental" cloud droplet spectrum to one having a more "maritime" spectra. Thus, the process by which a cloud would initiate precipitation would either 1) enhance the coalescence process, or 2) shift from a mechanism more dependent on ice processes towards the condensation-coalescence mechanism. The primary objective of introducing artificial rain drop embryos is to short circuit the action of the CCN population in determining the initial character of the cloud droplet population, and thus, jump-start the coalescence process.

3. USE OF WATER DROPLET SPRAYS

The first experiments with clouds using hygroscopic seeding materials were made when condensation-coalescence theory was in its very infancy. In the late 1940's and 1950's there was considerable controversy over the importance of the warm rain process in midlatitude convective clouds, which is exemplified in such works as that of Langmuir (1948), Bowen (1950), and Battan (1953), because certainly every rain drop must originate from an ice crystal (Bergeron 1935, Findeisen 1942). In perhaps what was the first scientific attempt at hygroscopic seeding comes from a South African report (Anon: 1948) that rain was produced three hours after five gallons of calcium chloride solution were released into the tops of cumulus reaching about 18,000 ft. There were two other occasions when releases were made; a radar echo developed on one occasion, and on another there was no measurable effect. Thus, in the absence of establishing a direct cause and

effect relationship, these early experiments produced no conclusive evidence for seeding effects.

Theoretical investigations into the coalescence process made by Bowen (1950), and by Ludlam (1951), suggested that it may be more efficient to introduce larger-than-average cloud droplets at cloud base rather than to introduce raindrops into cloud top. In the calculations, the growth of larger cloud droplets were traced during their upward trajectory from cloud base followed by their downward fall toward earth. These calculations indicated that a droplet with radius of 30 μm , transported upward at about 3 m s^{-1} from a cloud base at 20°C, would, after traversing an upward and downward trajectory, return to cloud base with a final size of 1.9 mm (achieving an increase of mass of nearly a factor of 2.5×10^5). Similarly, a 20 μm drop would return with a radius of 2.5 mm (nearly a 2×10^6 increase in mass). Thus, artificial raindrop embryos introduced at cloud base may have an advantage over those introduced at cloud top because the former experience growth over an upward and downward trajectory rather than just a downward trajectory and smaller cloud droplets (~20 μm) have a larger mass growth factor than larger cloud droplets (~30 μm) because the smaller ones experience a longer growth pathway, assuming of course, that sufficient cloud depth exists.

These concepts were tested in Australia using water drops sprays with median droplet radius of 25 μm and dispersal rates of about 30 gallons per minute (Bowen 1952a, 1952b). In-cloud treatments were made about 1,000 ft above cloud base. Results from these experiments supported findings from the original theoretical work. When the cloud thickness was less than 1.5 km (5,000 ft), treated clouds produced virga in six of seven cases, while nearby untreated clouds did not precipitate. When cloud thickness was greater than 1.5 km, rainfall or hail was observed in three of four cases shortly after seeding, while nearby unseeded clouds produced no rainfall. However, it is not possible to be sure that the results did not happen by chance in this small number of samples.

As part of the Cloud Physics Project sponsored by the United States Weather Bureau after World War II, Coons et al. (1948, 1949) reported on twenty-one cumulus clouds that received water spray treatment near cloud top during summertime operations in Ohio. In these experiments, fifteen clouds received drops at a rate of one gallon per mile and the remainder at a rate fifty times higher. Only one cloud in this study produced rain which reached the ground while seventeen showed a tendency to dissipate. This early experiment demonstrated several drawbacks to cloud top seeding with water sprays; the artificial embryos tended to wash out the cloud droplet population, and precipitate loading acted against vertical cloud growth.

Similar experiments involving much larger quantities of water were pursued as part of the Cloud Physics Project in the early 1950's (Braham et al. 1957). Operations occurred in the central United States and the Caribbean. The experiment was divided roughly into two treatment categories, the first was referred to as the "small valve experiment" and the second was called the "large

valve experiment." Only the large valve experiment produced effects that were detected in radar data. In contrast to the suggestions of Bowen (1950), water releases were made into cloud top because of the weak nature of the updrafts in Caribbean clouds. In the large valve experiment, roughly 450 gallons of water per mile were released (see Fig. 1). From data obtained from a series of drop tests over a spatial array of dye impregnated papers arranged on the runway at Chanute Air Force Base, drop sizes were determined to be between 100 and 1500 μm with an exponential decrease in the number counted with size. The water spray itself did not produce a radar echo. Pairs of clouds were selected for experimentation. Only one in each pair received the water spray treatment. A pre-determined randomization scheme was used to guide the decision to seed or not to seed.

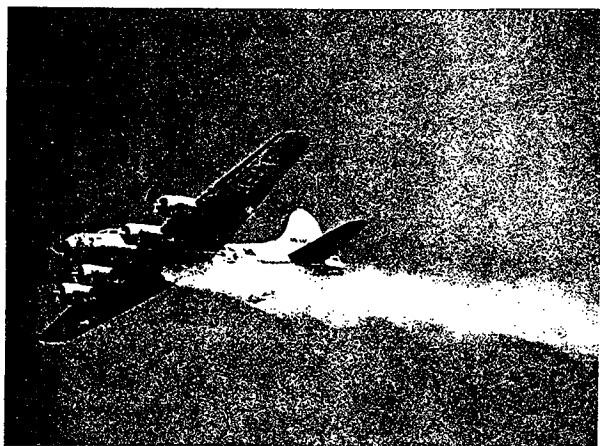


Figure 1. Photograph of the B-17 research airplane that was used to transport 450 gallons (3600 lb.) of water aloft and dumping a water drop spray in the cloud-top seeding that was conducted as part of Project Cloud Catcher (from Braham et al. 1957).

The results from the large valve experiment were much more encouraging than those originally reported in the earlier trials (Coons et al. 1948). Some results from the treatment of cumulus clouds in the Caribbean with the large valve are presented in Table 1. As can be seen in Table 1, there were 17 cases when the treated cloud produced an echo while the untreated cloud of the pair did not. In comparison, there were only 6 cases when the treated cloud of the pair did not produce an echo, while the untreated cloud echoed. The probability that these results occurred by chance was computed to be 0.017 under the null

hypothesis that treatment had no effect. However, the results indicate nothing about intensity or total amounts. The data were also used to compute the probability of an echo for the seeded and unseeded cloud pairs in the large and small valve experiments. These probabilities and corresponding 99% confidence intervals are shown in Fig. 2. The computations in Fig. 2 were interpreted to indicate that the large valve treatment increased the average probability of an echo from 23 to 48%. The time for the formation of an echo was also computed for these experiments. The computations were made after imposing several limitations on the use of the data including that the clouds were continuously observed, and time and space thresholds related to the characteristics of the radar set. The average time for precipitation initiation (time from treatment to first echo) in the untreated clouds was found to be 11.9 min. This time was computed to be 6.4 and 8.5 min. for the treated clouds in the large and small valve data. Thus, the time required for echo initiation was reduced by about 5 min. in the seeded pairs of the large cloud experiment. This difference was found to be statistically significant at less than the 1% level using a Wilcoxon test. Unfortunately, the sample of water-spray treated clouds in Ohio was too small to base any conclusion on.

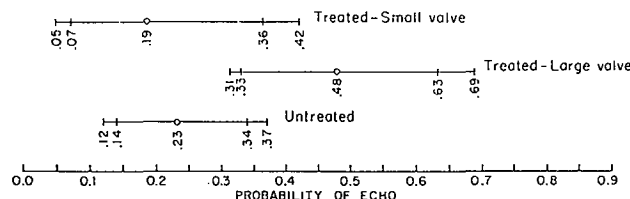


Figure 2. Probability of echo formation determined for untreated clouds, and clouds treated in the large valve and small valve experiments of Project Cloud Catcher (from Braham et al. 1957).

4. USE OF COMMON SALTS

One of the earliest investigations into the use of giant salt nuclei was made in East Africa (Davies et al. 1952) using "bombs" tethered from balloons. Each bomb contained a mixture of gun powder and sodium chloride. The bombs were released from the earth's surface and fused to explode in the length of time it would take for the balloon to carry the bomb to cloud base. When the bomb exploded about 15 g of salt particles, ranging in diameter from 5 to 100 μm , were dispersed. Treatments were delivered on the 38 days. On these days, the rainfall

Table 1. Contingency table for radar echoes from tropical cumuli treated in the large valve experiment (after Braham et al., 1957).

		Treated Cloud of Pair		Total
		Echo	No Echo	
Untreated Cloud of pair	Echo	5	6	11
	No Echo	17	18	35
	Total	22	24	46

downwind of the release was 6 inches greater than on the unseeded days. It was difficult to tell whether the seeding material had any effect because upwind rainfall on seed days was also greater than on treatment days by about 2 to 3 inches. Similar experiments were later repeated except that the seeding was carried out on alternative days over a 90-day period (Sansom et al. 1955). In these experiments 24 of the 33 seeded clouds produced rain such that the downwind rainfall was 2 to 3 inches higher than that on the unseeded days.

Experiments in which salt particles were released from ground based-generators have also been conducted over the Indian subcontinent around Delhi, Jaipur, and Agra (Biswas et al. 1967). In these experiments, hygroscopic particles were released into the boundary layer by either spraying a dilute salt solution into the air, or with a finely ground salt mixture. In the case of liquid sprays, particles in the size range from 7 to 25 μm were released at a rate of 10^9 per second, while estimated particle size for the powder release was 5 μm at a rate of 2×10^{12} per second. The experiment was designed around a four-way blocking scheme of control and target area on both seed and no seed days, and a method of double and single ratios was used to evaluate for seeding effects. Rain gage networks around Delhi, Jaipur, and Agra provided the basic data for analysis.

The experiment was conducted for 8 consecutive seasons beginning in 1960 for Delhi and Agra, and for four seasons beginning in 1960 at Jaipur. Positive seeding results were indicated at Delhi in 7 of the 8 seasons, 5 out of 6 seasons in Agra and 4 of four seasons at Jaipur. Accounting for the fact that the days with frequent or continuous rain were excluded from the experiment, the indicated increase in rainfall was 21%, uncorrected for the fact that seeding occurred for only a small fraction of the time that a 24-hour rainfall total had accumulated. However, because the generators were operated from the ground, there was no certainty that the particles indeed reached cloud base, and if they did, their concentrations were unknown. Thus, it was not possible to be certain that the apparent enhanced rainfall was due to seeding.

Kapoor et al. (1975) reported on effects of seeding on the cloud droplet size distribution for three different regions in India; Poona, Bombay, and Rihand. Operations were conducted during the summer monsoon of 1973. Treatments were delivered at nearly constant altitude of a few hundred feet above cloud base dispersing a mixture of common salt and soapstone in the ratio of 10 to 1 at a rate of up to 10 kg per km of flight path. Cloud droplet distributions were measured by impaction on to magnesium-oxide coated slides.

Cloud droplet data from all three regions showed marked changes in the cloud droplet distribution, consistent with that expected from seeding. Increases in maximum diameter, decreases in total droplet concentrations, increases in liquid water content and increase in median volume diameter were noted for each of the three regions. However, because of the operational procedures it was not possible to be absolutely certain that the observed changes did not happen by chance.

Fournier d'Albe and Aleman (1976) reported on ground-based salt seeding experiments in Mexico. In these experiments, salt was dispersed at a rate of 50 kg/h. The experiment was conducted during the summer and seeding performed during daylight hours when convective activity was at a maximum. The experiment was randomized with 54 days receiving seeding and 22 days being used for control. This experimentation suggested that there was less rainfall on seeded days than on control days. However, the results may have occurred because of exceptionally heavy rainfall on control days, rather than from a true decrease due to seeding.

Differences between the height and temperature of first echoes in salt seeded and unseeded clouds were studied as part of Project Cloud Catcher in the Dakotas (Dennis and Koscielski 1972, and Koscielski and Dennis 1972). A three-way randomization was used in this experiment with treatment being either 1) no seed, 2) AgI seed, 3) salt seed. AgI and salt treatments were not combined on a single day. Salt seeding was accomplished by releasing up to 50 kg of finely ground salt (NaCl) in updraft near cloud base during the first 30 minutes of the treatment. The salt was a 50/50 mixture (by initial bulk mass) that produced particles with mean mass diameter of 25 μm and 150 μm . Particle concentrations within the plume at 0°C were estimated to be one to more than ten per liter. In one exploratory case, Biswas and Dennis (1971, 1972) reported visual evidence that indicated the initiation of a rain shower by salt seeding. However, seeding effects were generally evaluated on the basis of radar data. The experiment produced a total of 22 unseeded cases and 16 salt seeded cases. Results for the salt seeded cases indicated that the average first echo height above cloud base was half that of the no seed cases (5,300 ft compared to 11,000 ft) and that this difference could not be accounted for by natural differences in cloud base heights, cloud base temperature, or maximum updraft velocity. Therefore, it appears that salt seeding in the High Plains may have been responsible for lowering the height of first echoes by initiating coalescence earlier than it would have otherwise.

Heating associated with condensation of water vapor on sodium chloride particles has also been noted. The theoretical amount of heat in humid air for particular values of temperature, pressure and relative humidity has been found to be proportional to the weight of salt added (Woodcock et al. 1963). Woodcock and Spencer (1967) conducted experiments along these lines around Hawaii and found that the salt-laden air was warmer than the ambient air by 0.35°C on average. In their experiments, dry sodium chloride particles, in the size range from 0.5 to 20 μm diameter, were released from an airplane flying about 400 to 500 m above the ocean. Release rates from the 400 kg load were intended to produce airborne salt concentrations of 40 mg per kg of air.

Dynamic responses to salt seeding have also been noted in warm monsoon clouds. Ramachandra Murty et al. (1975) made visual and in-cloud measurements of six cloud complexes in which a total of 32 cloud seeding traverses were made a few hundred meters above cloud base. The seeding material used was a pulverized mixture

of salt and soap stone mixed in a 10 to 1 ratio with a mode diameter of 10 microns. The seeding rate varied between 10 and 30 kg for every 3 km of flight path, traveling at a mean air speed of 180 kmph.

From this small sample, Ramanchandra Murty et al. (1975) reported that it appeared that deeper clouds tended to show a dynamic response by a gain of cloud top height, and in some cases, a gain in lateral dimensions. On two occasions, when the cloud samples were between 1,000 and 1,500 ft deep, dissipation was observed along with a decrease in horizontal dimension as seeding progressed. One cloud complex approximately 5,000 ft deep was observed to gain 2,000 ft vertically along with a lateral increase in size. Peak liquid water content reportedly increased from 0.5 g m^{-3} to 2.8 g m^{-3} as seeding proceeded. The initial maximum temperature in cloud (16°C) was 2°C colder than the environment, but was observed to increase by about 1°C as seeding proceeded. This cloud group was observed to rain at which time the internal cloud temperature was noted to decrease. A cloud group with initial depth of 4,000 ft was observed to gain 2,000 ft with seeding and also shared similar increases in liquid water content and temperature as did the other 5,000 ft deep complex. Finally, cloud complexes with initial depths of 7,000 and 10,000 ft showed vertical increases in cloud top height of approximately 4,000 ft following seeding both with increases in width and changes of liquid water content from 0.6 to 1.0 g m^{-3} prior to seeding to about 3 g m^{-3} before rain began to fall from these clouds.

Chatterjee et al. (1978) used an X-band 3 cm radar set to evaluate for salt seeding effects on warm maritime cumulus clouds. Their analysis was based on data collected over a six day period in September during which time four isolated cumulus were selected for seeding. For each of the seeded clouds, a neighboring cloud was left unseeded and used as control. They concluded that the seeded clouds lasted longer than the control clouds. The details of the time variation for one of the cloud pairs indicated that the aerial coverage of echo may have initially decreased. However, 12 minutes after, seeding area coverage remains constant and then increases to a maximum about 40 minutes after seeding began. Echo tops which also initially showed a decrease, showed increases shortly after seeding began with two maximum, one 8 minutes, and the other 40 minutes after seeding began. The control cloud in this pair was observed to dissipate 10 minutes after it was selected as a no seed cloud. However, in this small sample, it is not possible to tell whether or not the results occurred by chance.

Parasnis et al. (1982) computed one-dimensional temperature spectra (Corrsin 1951) for one clear air case and for five cloud cases using data primarily collected as part of the salt seeding experiments conducted by Ramanchandra Murty et al. (1975) around Bombay and Puna, India. In this type of analysis, it should be noted that a $-5/3$ slope is indicative that turbulence is isotropic and that energy input and dissipation are balanced. An increase in the $-5/3$ slope indicates higher energy dissipation rates. The release of latent heat of condensation generates large wavelengths of spectra while shorter wavelengths represent smaller scale turbulence (Warner 1970).

Paresnis et al. (1982) found that the slope of the spectra in salt seeded cases increased with a net energy gain at larger wavelengths (greater than 540 m) and the net loss at shorter wavelengths.

5. COMPUTER SIMULATIONS

Klazura and Todd (1978) developed and used a one-dimensional steady-state condensation-coalescence model to better understand the physical chain of events that occur with hygroscopic seeding. Drop break-up and freezing were simulated in their model. The model was used to trace the growth trajectories of hygroscopically initiated particles. The sizes of the seeds varied from 5 to $400 \mu\text{m}$ diameter and updraft speeds ranged from 1 to 25 m s^{-1} . Effects on warm- and cold-based clouds were explored. Model results indicated that the relationship between updraft velocity and initial seed diameter must be conducive to the development of raindrops big enough to undergo break-up and set off a Langmuir-type (1948) chain reaction for seeding to be effective. Assuming that sufficient cloud depth exists to allow condensation, coalescence, drop break-up, and freezing to proceed uninterrupted, model results for cloud base temperatures and updraft velocities close to those characteristic of Illinois clouds (5 m s^{-1} and 19.4°C) indicated that smaller "seed" diameters had a growth advantage over larger "seed" diameters because they followed longer (in time and space) growth trajectories; much the same as that originally suggested by the theoretical work of Bowen (1950) and Ludlam (1951). It should be noted that this advantage diminishes for finite cloud depth, and as updraft velocity increases because at high updraft velocities the "seeds" are carried to cloud top, experiencing little growth, and thus remain suspended as part of the cloud's anvil.

The work of Klazura and Todd also produced the following findings:

1. for a given updraft speed, small hygroscopic seeds require a greater cloud depth to grow large enough to fall against the updraft and perhaps experience break-up;
2. a greater cloud depth is required for higher and colder cloud bases for the "seeds" to grow large enough to fall;
3. large hygroscopic seeds will result in drop break-up lower in cloud at any particular updraft speed;
4. stronger updrafts require larger hygroscopic seeds to produce drop break-up and vice versa;
5. vertical depth of the drop break-up regime increases as cloud base temperature increases because longer coalescence growth and later particle freezing combine to expand the drop break-up zone; and
6. hygroscopic seeding was found to produce the greatest water yield from the warmest based clouds.

Farley and Chen (1975) used a detailed microphysical model to simulate hygroscopic seeding. In their model, condensate was represented by 52

logarithmically spaced size categories covering a size range from 2 μm to 5 mm radius. Their model simulated the evolution of water drop size distribution as a result of vertical advection, condensation/evaporation, stochastic coalescence, and drop break-up. Seeding was simulated by the introduction of a distribution of raindrop embryos at cloud base.

After making allowances for errors they made in the condensation growth equation and an error in the Raoult effect for the growth of salt particles, model results indicated that raindrop break-up was necessary for cloud seeding to be effective. Because larger drops were introduced at cloud base, they found that rather large (greater than 10 m s^{-1}) updraft velocities and large cloud depths were required for break-up to initiate. When the model was run without break-up, cloud seeding was found to have little effect other than to produce a few raindrops at cloud base. Thus, some sort of raindrop multiplication process must spread throughout the cloud.

Rokicki and Young (1978) used a Lagrangian parcel model to simulate water drop seeding at cloud base. The size of the droplets in the spray was chosen so that the fall speed was not larger than one tenth of the updraft velocity. They simulated deep clouds which eventually carried the condensate aloft where it supercooled. From their model results, they concluded that water spray seeding may have potential use in mid-latitudes as well as in the tropics, and that effects may be potentially larger than can be obtained with AgI seeding without the possibility of overseeding.

Johnson (1980) performed a series of salt seeding simulations that took into consideration that the natural cloud had a broad size distribution of CCN. The particle spectrum included nuclei greater than a few tens of micrometers. Johnson (1980) pointed out that overlooking these potentially important, naturally present, giant nuclei, can make model calculations overly sensitive to salt particle or droplet seeding. Figure 3 shows an example of the type of time-height cross sections that were obtained from Johnson's trajectory model. The shade region indicates the region of the simulated cloud where reflectivities were computed to be in excess of 10 dBZ. The shaded region ends abruptly with a vertical line in each case when the reflectivity, at any level, reached or exceeded 30 dBZ. When this occurred the calculation was terminated. In Fig. 3a, the seeding was delivered at 0.5 km above cloud base, and in Fig. 3b the simulated cloud was seeded at cloud base. The calculation applies to a simulated cloud with base at 5°C , updraft velocity of 4 m s^{-1} , and model runs for salt concentrations of 10^{-2} g m^{-3} and 10^{-4} g m^{-3} . For these rather heavily seeded clouds Fig. 3 clearly suggests that the treatment results in the formation of first echoes slightly lower than the unseeded model run and approximately 5 to 7 minutes sooner than the no seed case. Differences between seeding at cloud base or slightly above are less dramatic, but it does appear that seeding at cloud base results in slightly lower and later echo formation than when seeding at 0.5 km above cloud base. One of the main conclusions from this work was that very large salt concentrations (on the order of that shown in Fig. 3) would be needed to initiate rainfall faster than would occur naturally, implying that hygroscopic seeding may not have

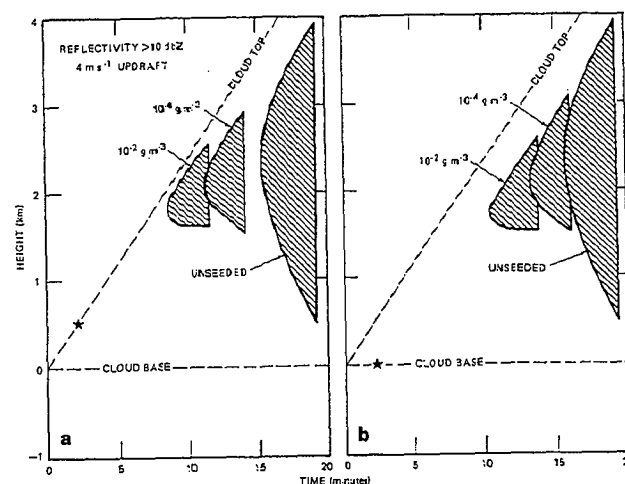


Figure 3. Example of the time-height cross sections obtained from a trajectory cloud model comparing the unseeded case and two seed cases for different seeding concentrations made 0.5 km above cloud base (panel a), and at cloud base (panel b) (from Johnson 1980).

a large effect on clouds with a naturally efficient warm rain process. This result stands in contrast to the model results of Rokicki and Young (1978) which suggested that concentrations on the order of 10^{-7} g m^{-3} would be sufficient to instill an effect.

Recent numerical simulations of the seeding of a warm-based Illinois convective cloud with and without ice multiplication active, have led to speculation about effects that warm cloud seeding may have on ice processes (Orville et al. 1993). In their simulation, a 2-dimensional, time-dependent model (Orville and Kopp 1977; Lin et al. 1983) with bulk water microphysics was applied to the 23 June 1989 exploratory cloud seeding trial conducted as part of the Precipitation Augmentation for Crops Experiment during 1989 (Changnon et al. 1991). Seeding was simulated as the release of AgI at approximately -10°C , as was the technique followed in PACE. Model runs with and without seeding were compared. In addition, two runs were made with ice multiplication active (Mossop and Hallett 1974, Hallett and Mossop 1974), one with and one without seeding.

The seeding simulation on the cloud without an ice multiplication process active, led to a clear signal in rapid transformation of rain to ice precipitation and a rapid increase in radar reflectivity. However, final precipitation at the ground was unchanged. Slight changes in vertical velocities were evident and a change in cloud temperature was positive in the seeded clouds. The results with ice multiplication showed that the seeding signal was almost completely masked by ice multiplication. This interesting result with regard to ice multiplication led to speculation about hygroscopic seeding effects on ice processes, because of the close link that exists between the presence of supercooled drizzle and raindrops, ice initiation, and ice multiplication by graupel interactions with supercooled cloud droplets.

If hygroscopic seeding does indeed lead to an enhancement of raindrop concentrations prior to the parcel reaching 0°C, then ice may originate in higher concentrations than it would have naturally, if the cloud follows a coalescence-freezing mechanism (Braham 1986). This might result in higher initial concentrations of frozen raindrops, and thus a more active graupel process, thereby stimulating ice multiplication by rime-splintering. Thus, the enhanced rate of conversion of water-to-ice might have implications for future microphysical evolution, as well as dynamic effects from the release of latent heat.

6. A "NEW" APPROACH

Recently the potential for rainfall enhancement by promoting the coalescence process has been renewed by radar and aircraft measurements taken of clouds developing in the plume of a large paper mill (Mather 1991). The apparent effects of the paper mill were very similar to those noted by Egan et al. (1974) and Hindman (1976) on the microstructure and precipitation from small cumuli and stratus affected by paper mill effluent. The basic evidence reported by Mather (1991) suggests that large anthropogenic hygroscopic nuclei (perhaps 0.5 to 1 µm diameter) are transported by updraft air into cloud base where they act to promote the early formation of small drizzle drops while inhibiting smaller natural CCN from nucleating. The net effect resulted in a broadening of the initial cloud droplet spectra and earlier initiation of the coalescence process. Mather and Terblanche (1992) suggest that these early effects (determined at cloud base) then mix throughout the cloud and may possibly be transmitted to other clouds (echo cores) in the multicelled system.

7. PRELIMINARY USE OF THE "NEW" FLARE

Because of the large apparent "positive" seeding effect of the paper mill, experiments were pursued to replicate, as closely as possible, the effect of the paper mill effluent on cloud microphysics. This was attempted with the production of a 1,000 g pyrotechnic flare based on a formulation originally developed by Hindman (1978). The South African flare was composed of 5 percent magnesium, 10 percent sodium chloride, 65 percent potassium perchlorate, and 2 percent lithium carbonate, and produced a combustion product which was 21 percent sodium chloride, 67 percent potassium chloride, and 12 percent magnesium oxide (Mather and Terblanche 1992).

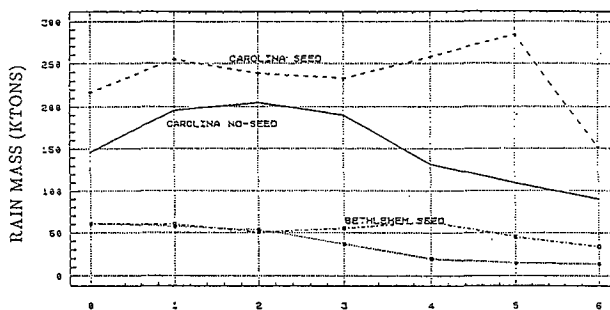
Randomized seeding experiments were conducted during the 1991-1992 summer season in two regions in South Africa, the Bethlehem region on the Highveld (where cloud base temperatures are approximately +7°C) and the Carolina region in the eastern Transvaal (where cloud bases are approximately +10°C). A total of 50 seeding trials were conducted, 25 of which were seed and 25 that were unseeded. Twenty-one of the experiments were conducted in the Bethlehem area and the other 29 were conducted in the Carolina area.

The experimental units in either the Bethlehem or Carolina areas were defined by multicellular convective systems that already had a radar echo of at least 30 dBZ.

This type of cloud selection is similar to that used in the 1989 Illinois experiment. Flares were ignited at cloud base in strong updraft. A maximum of 10 flares were used in each seed case. Radar estimated rain mass was calculated for the lowest radar scan (1.5° elevation) and at the 6 km level above mean sea level (approximately -10°C). Rain masses were sorted into 10 minute time windows starting 10 minutes before and ending 1 hour after the seed/no-seed decision. Figure 4a and 4b show the mean rain mass for the Bethlehem and Carolina regions at the lowest and the 6-km scan levels, respectively.

Figures 4a and 4b show that the Carolina storms had a much larger rain mass than the Bethlehem storms and that there was an initial bias in favor of the seeded storms in the Carolina area. In general, the rain masses follow the same trend during the first three time intervals, after which the rain masses diverge (approximately 30 to 40 minutes after seeding) with the seeded storms showing greater rain masses than the unseeded storms by about a factor of two. Figure 4 also shows that the apparent response to seeding at 6-km starts one time window earlier than the lowest scan. The high degree of consistency of behavior among the data is also noteworthy. Statistical analysis performed by the Centre for Applied Statistics at the University of South Africa indicated that the differences between the seed and no seed cases are significant at the 10% level.

(a) MEANS - LOWEST SCAN



(b) MEANS - CUT-OFF LEVEL

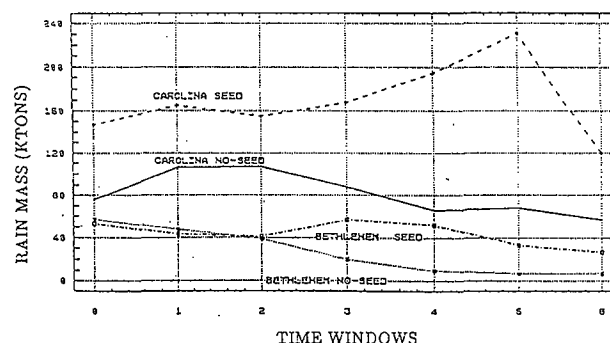


Figure 4. Radar estimated rain mass near cloud base (a) and near the -10°C level (b) sorted according to 10 minute time windows for South African storms at Carolina and Bethlehem using hygroscopic seeding flares just below cloud base (from Bruinjes et al 1993).

In the experiment, an attempt was also made to determine how the seeding material may have affected the initial cloud droplet spectrum. In this attempt, the cloud droplet spectrum were measured near cloud base with an instrumented aircraft flying behind the seeder aircraft. One of the cloud droplet spectrum obtained in the seeded and unseeded areas of cloud base are shown in Figure 5 (Bruinjes et al. 1993). The unseeded spectrum is shown as a dashed line, while the seeded spectrum is shown as a solid line. Figure 5 shows a distinct difference between the cloud droplet distribution in the unseeded area of cloud base, narrow distribution with a peak between 10 and 12 μm diameter; while the seed spectrum is broader, with a tail extending out to 26 μm diameter. Both distributions represent about the same liquid water content, 0.33 and 0.35 g m^{-3} for the seed and no-seed spectrum. However, the total concentration of the unseeded region was 508 cm^{-3} compared to 280 cm^{-3} in the seeded region.

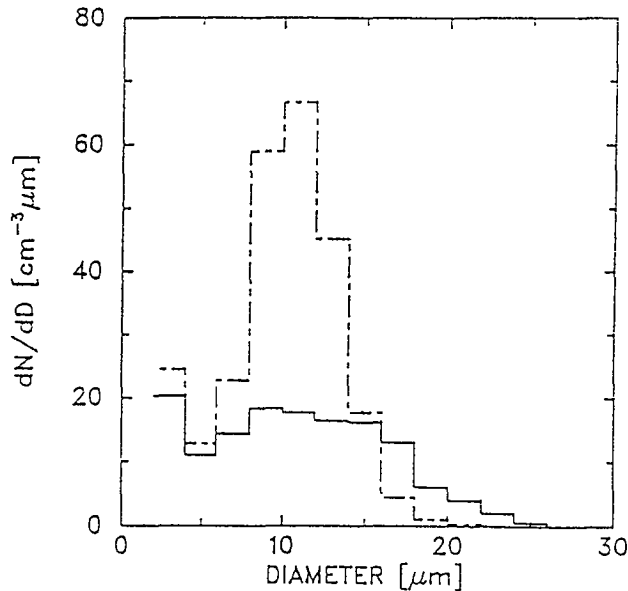


Figure 5. Difference of cloud droplet distribution from FSSP measurements probably taken in the affected (solid line) and unaffected (dashed line) region of cloud near cloud base (from Mather and Terblanche 1992).

Therefore, although it is possible that these differences in a small sample from a single summer may have happened by chance, and it is worrisome that such large apparent effects seem to result from such a modest amount of seeding, the overall results are consistent with the general seeding hypothesis and many aspects of earlier work in that coalescence appears to have been enhanced in the seeded clouds and the effect apparently spreads throughout the cloud system to result in higher radar estimated rain mass (i.e., precipitation enhancement).

8. POSSIBLE EFFECTS ON THE ICE PROCESS

Hygroscopic seeding at cloud base may also have influences on precipitation evolution involving ice because

of the strong link that exists between the presence of supercooled precipitation-size drops and the initiation of ice (Koenig 1963, Braham 1964, Czys and Petersen, 1992), and because of the dependence of the riming-splintering mechanism on concentrations of supercooled cloud droplets and on graupel size and concentration (Mossop and Hallett 1974, Hallett and Mossop 1974, Mossop 1976, Mossop 1978a, Mossop 1978b).

Exploratory measurements made in South Africa around the -10°C level in clouds affected by the paper mill (Mather 1991) and in clouds hygroscopically seeded (Mather and Terblanche 1992) have provided some clues about possible effects on the ice process. In one set of measurements, the seeding aircraft released seeding material from two flares, followed by the ignition of two more flares at cloud base with the pairs of ignitions being four minutes apart. Prior to and after these releases, the cloud physics airplane was sampling at -10°C in clouds roughly above the release area. Prior to the time that the affected cloudy air could have reached the -10° level, concentrations of supercooled cloud droplets as measured by the FSSP have distribution concentrations typical of natural clouds (see Fig. 6). However, shortly after, when it would have been possible for the seeding material to reach the sampling level, the concentration of FSSP particles with diameters greater than 32 μm was observed to increase by a factor of near 7, from 0.55 to 3.6 cm^{-3} , with a corresponding broadening of the size spectrum (see Fig. 6). Of course, uncertainty exists over whether or not this change in supercooled cloud droplet distribution is truly due to seeding because there is no direct evidence that the airplane sampled in affected cloud or that the airplane may have caused the perturbation itself (Rangno and Hobbs 1983, Rangno and Hobbs 1984, Kelly and Vali 1991).

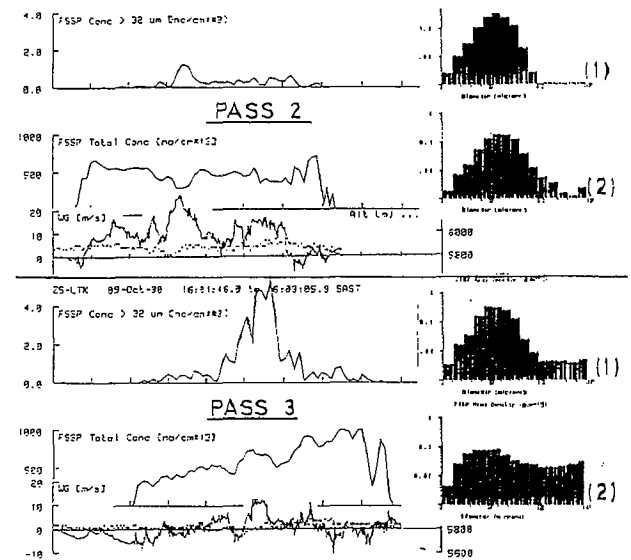


Figure 6. Selected microphysical measurements taken around the -10°C level of clouds in the recent South African experiments which suggest broadening of the spectrum of supercooled cloud droplets that occurred between pass 2 and pass 3 (from Bruinjes et al. 1993).

Assuming that the cloud droplet spectrum is broader at subzero temperatures, and that the presence of increased concentrations of supercooled drizzle and raindrops do indeed result from seeding, some further speculation can be made about effects on the ice process. First, increased concentrations of supercooled drizzle and raindrops may mean higher initial concentrations of "first ice" because first ice concentrations (in the form of frozen raindrops and then graupel) in clouds with an active coalescence process are highly correlated with concentrations of supercooled drizzle and raindrops (Koenig 1963, Braham 1964, Czys 1989, and Czys 1991). Thus, there may be a more active ice process involving graupel. This may in turn enhance precipitation development because of the advantages that graupel growth has over coalescence (Johnson 1987). Furthermore, a more active graupel process may enhance secondary ice production if other conditions exist to permit the rime-splintering process (Mossop 1976, Heymsfield and Mossop 1984).

In fact, limited evidence has been uncovered that rime-splintering may have been triggered in South African clouds affected by effluent of the paper mill (Mather 1991). This evidence was uncovered by the appearance of columnar crystals when they are not usually part of the kind of ice naturally encountered (see Fig. 7). The exact effect that an enhanced secondary rime splintering process would have on cloud and precipitation production is unclear and needs to be explored. Nonetheless, a more rapid glaciation seems physically possible, and this may have effects similar to those expected from dynamic seeding. Thus, hygroscopic seeding may potentially enhance rain production by not only promoting coalescence, but by enhancing ice processes and by dynamic effects that may promote cloud growth from latent heat releases related to freezing as well as condensation.

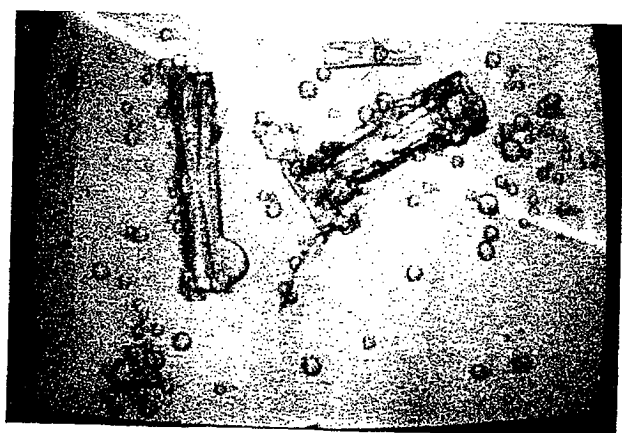


Figure 7. Photograph showing possible evidence of hygroscopic seeding on ice processes which may come about by the effect that broadening of the supercooled cloud droplet spectrum may have on the rime-splintering process (from Mather 1991).

9. POSSIBLE DYNAMIC EFFECTS

It is interesting to note that the clouds in the 1991-1992 South African hygroscopic seeding trials, as well as those supposedly affected by the paper mill (Mather 1991) also seem to have experienced dynamic effects from hygroscopic seeding. Figure 8 shows radar-measured cloud top heights (defined by the 30 dBZ contour) for the seed/no-seed storms, each for 10 minute time windows relative to the time of seeding. Figure 8 shows that the no-seed storm increased in height from time-window 1 to time-window 2, and then decreased thereafter. On the other hand, the seed clouds show a slight decrease from window 1 to window 2, and then show a steady increase. Positive effects on echo top growth rates have also been found in the South Africa data, as well as on heights and growth rates defined in the 45 dBZ contour. Thus, it appears that "dynamic" effects might also accompany microphysical effects in hygroscopic seeding, as was suggested in the earlier experiments. However, the extent to which these effects can be attributed to an enhancement of the latent heat of condensation, latent heat of fusion, both, or some other reason is uncertain and needs to be addressed.

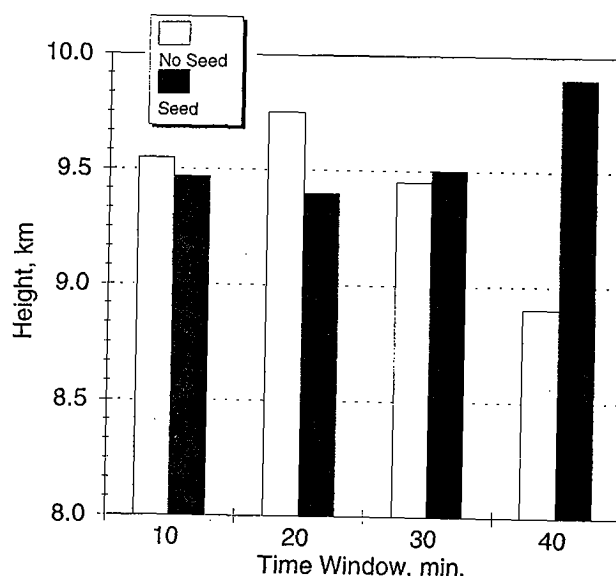


Figure 8. Bar chart showing possible evidence of dynamic effects due to hygroscopic seeding in the South African seeding trials.

10. SUMMARY AND CONCLUSIONS

From the very time that condensation-coalescence theory was accepted as a physical mechanism for the initiation and evolution of precipitation in mid-latitude clouds, attempts were made to use hygroscopic substances to promote coalescence, and thereby enhance rainfall. Although this seeding technique received a great amount of initial attention, interest has diminished over the years in favor of static mode and dynamic mode glaciogenic seeding. It is difficult to assess why interest was lost in hygroscopic seeding. However, one reason may have been the inherent difficulty of delivering adequate amounts of

appropriately sized water droplets or finely ground salts, compared to the relative ease of glaciogenic seeding. Handling is also a problem. Many hygroscopic seeding substances are very corrosive, and chemically incompatible with the materials from which aircraft are constructed.

Almost all of the scientific work related to hygroscopic seeding, was conducted prior to recent major advances in ground-based and airborne measurement systems, and computer modeling. Perhaps this helps to explain why almost all of the previous experiments have failed to provide convincing scientific evidence of hygroscopic seeding effects. More importantly though, many of the previous experiments failed to adequately document the physical chain of events that would have linked cause and effect. This too may have been the result of inadequate or unavailable technologies, if not from other constraints. Although the evidence is far from convincing, it seems that most experiments have shown possible effects that are consistent with that expected from hygroscopic seeding: cloud droplet distribution in some cases have been found to be broader than they would have been naturally, echoes may have formed sooner, lower, or when they otherwise may not. And there are limited indications of "dynamic" effects in the form of higher cloud tops, larger growth rates, or both. However, the earliest experiments never thoroughly tested what the original theoretical analysis indicated should be the most effective treatment technique; releases at or near cloud base in updraft with moderately sized artificial CCN. The most recent South African trials in which near cloud base treatments were tried have produced some encouraging results that deserve noting, and have renewed interest in the technique of hygroscopic seeding.

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