Precipitation Augmentation---Summer Convective Clouds

Much attention focused on the dynamic seeding technique to invigorate cloud growth, and thereby, augment precipitation. It is significant that a number of dynamic seeding experiments with slightly different designs collectively produced the impression that rainfall enhancements may have occurred, at least as estimated from radar, at the scale of the multi-cloud mesoscale (dimensions on the order of a few tens of kilometers) system. However, results are not statistically significant and are not always consistent with one or more steps in the conceptual seeding model that was being tested. Dynamic seeding experiments were conducted in west Texas and Illinois in the United States, in Thailand, and in Cuba. Interest also renewed in stimulating the coalescence process for precipitation enhancement through hygroscopic seeding.

Exploratory dynamic seeding experiments were conducted in west Texas initially as part of the Bureau of Reclamation-guided Southwest Cooperative Project (SWCP) and later as part of the NOAA-AMP. Seeding trials were performed during the summers of 1986, 1987 [*Rosenfeld and Woodley, 1989*], 1990, and 1991 [*Rosenfeld and Woodley, 1993*]. Analysis focused on individual convective cells and the small mesoscale convective clusters containing the cells. Cloud selection criteria, seeding technique and dosage, and analysis procedures followed those that were developed for the Florida Area Cumulus Experiment (FACE). The west Texas experiments used an innovative ``floating'' annulus target/control area that permitted experimental units (mesoscale cloud clusters), treated clouds towers (cells), control clouds and environmental clouds to be well defined.

A computer software package with three-dimensional pattern recognition techniques was used to track the treated cells over time and calculate the radar properties of each cell at each time step [*Rosenfeld, 1987*]. Six basic response variables were used to analyze for seeding effects: maximum echo top, reflectivity, area, rain volume, total rain volume, and duration. Analysis suggested that radar-estimated rainfall may have been enhanced, apparently without an increase in vertical growth of the individual treated cloud towers, as would be expected from the original conceptual seeding-effect model for west Texas [*Rosenfeld and Woodley, 1989*]. Precipitation increase was more closely tied to a possible increase in the area and duration of the seeded cells.

Precipitation enhancements were also noted at the scale of the mesoscale convective cloud cluster suggesting that seeding effects were transferred to larger spatial scales. A ``focused area'' analysis was conducted to identify the link between the cell scale and the mesoscale cloud cluster and precipitation enhancement. This analysis suggested cell mergers leading to a larger mesoscale convective cloud system as a possible cause for the enhancement.

The conceptual model for Texas was modified to give more attention to possible microphysical processes linked to cloud dynamics [*Rosenfeld and Woodley, 1993*]. In the revised model, some or all of the increased buoyancy from seeding is now viewed as being spent on suspending the precipitation load aloft in the form of graupel which grows at a faster rate than liquid drops of equivalent mass

[*Johnson,* 1987]. Thus, a seeded cell may experience precipitation enhancement without pronounced vertical growth. The seeding effect is supposed to be communicated to larger scales because eventually the precipitation load falls from the upper cloud volume resulting in enhanced downdrafts and subcloud convergence which promotes the initiation of new cells and mergers, just as it did in the original model.

The Precipitation Augmentation for Crops Experiment (PACE) conducted exploratory seeding trials during the summers of 1986 and 1989 [*Changnon et al., 1991*]. These experiments were designed around the dynamic seeding hypothesis modified for Illinois [*Ackerman, 1986*]. Results from the 1986 experiment [*Czys, 1991*; *Westcott, 1990*] encouraged testing that was carried out in 1989. The 1989 field trials resulted in an analysis based on 12 experimental units yielding a total of 67 echo cores for analysis: 32 treated with sand and 35 with silver iodide (AgI). The 1989 field experiment revealed three different types of seeding effects: visible effects, initial effects on individual clouds, and subsequent effects on rainfall from the cloud system as a whole.

Visual observations were recorded at the end of each flight by the pilot and the flight meteorologist. Both observers demonstrated an ability to visually detect the use of AgI, even though the actual treatment type was not divulged until well after field operations were terminated. This implies that dosage, transport, and dispersion of the seeding agent were sufficient to be seen, and raised hope that changes from seeding could be detected in the radar data.

However, analysis of the radar data with respect to echo core maximum height, area, and reflectivity suggested that AgI treatment did not have a pronounced initial effect on the behavior of individual echo cores. None of the analytical procedures resulted in convincing evidence that seeding produced taller, wider, more reflective, or longer lived clouds prior to merger with the complex cloud system [*Czys et al., 1993a*; *Czys et al., 1993b*].

Analysis of radar-estimated rainfall within the experimental unit suggested enhancements at least on certain days [*Czys et al., 1993b*]. By comparing experimental unit rainfall to that in the surrounding area, the enhancements appeared to have occurred despite the fact that individually seeded clouds did not show pronounced growth, and that extended area rainfall was not favored on days when AgI was used.

The Kingdom of Thailand began investigation of the use of dynamic and hygroscopic seeding methods to increase rainfall. Based on recommendations made by *Silverman et al.* [1986], experiments in Thailand were conducted in 1991 and 1993 through assistance from the United States Agency for International Development (USAID) with the U.S. Bureau of Reclamation (BurRec). In general, the dynamic seeding hypothesis, cloud selection and qualification criteria, and other operational procedures were closely patterned after those applied in west Texas [*Rosenfeld and Woodley, 1993*].

Fifteen experimental units (8 seed and 7 no seed) were obtained. *Woodley et al.* [1994] and *Rosenfeld et al.* [1994] reported that AgI seeding may have increased cell rainfall related to increased area and duration, but without an appreciable increase in the maximum top of the treated cells. They also partitioned their data into groups of clouds with warm cloud base temperatures (T > 16 C) and those with cool cloud base temperatures, reasoning that warm-based clouds would have high concentrations of supercooled drizzle and raindrops, therefore making the clouds more suitable for seeding because these would have greater latent heat release and after raindrop freezing have more graupel embryos. This partitioning showed an improved signal for rain enhancement for warm based clouds than for the total sample, suggesting that clouds characterized by an active coalescence process might be more effectively seeded with AgI.

Dynamic seeding experiments were conducted during the summers of 1986, 1987, and 1989 by the Institute of Meteorology of the Cuban Academy of Sciences in collaboration with the Central Aerological Observatory of Russia [*Martinez et al., 1989*; *Valdes et al. 1994, 1992*]. This experiment, which began in 1979, was divided into three stages: site and season selection, physical assessment of clouds and cloud systems [*Beliaev et al., 1989*], and seeding experiments. Isolated cloud cells (ICC) and the cloud system cells (CSC) with which they were associated were the focus of experimentation. These two categories roughly correspond to the scale of cells in the short-track and long-track analysis, respectively, of the west Texas experiment [*Rosenfeld and Woodley, 1989*], and the individual echo core and experimental units, respectively, in the PACE analysis.

Instrumented cloud seeding airplanes were used to obtain physical measurements in warm and cold cloud regions of treated clouds [*Perez et al., 1992*; *Zimin et al., 1992*]. Treatments were according to a 50-50 randomization scheme that delivered either AgI or no treatments. Radar measurements were used to evaluate for seeding effects in the ICC and CSC sample based on five radar response variables: radar-estimated rainfall, maximum echo height, sum of low-level area, maximum area, and reflectivity. The three years of experimentation produced 47 ICC (25 seed and 22 no-seed) and 77 CSC (39 seed and 38 no-seed) for analysis.

No statistically significant effects were found on the total sample of either the ICC or CSC, although single ratios for the ICC and CSC sample indicate that positive effects on rainfall might be linked to increased area and longevity. Examination for seeding effects was based on three different categories of cloud top height at the time of treatment: $H_{Top} < 6$ km, $6.5 \lesssim H_{Top} \lesssim 8.5$ km, and $H_{Top} \gtrsim 9$ km. Of these three categories, cloud tops between 6.5 and 8.5 km at the time of treatment indicated radar-estimated rainfall enhancements at better than the 0.05 significance level for both the ICC and CSC data. This positive effect on rainfall was accompanied by statistically significant increases in area and longevity, but not in maximum height or reflectivity.

Interest in hygroscopic seeding to enhance rainfall by promoting the coalescence process dates back to the inception of condensation-coalescence theory. Over the past several decades this seeding technique has not received the same attention as AgI seeding to instill dynamic effects on convective clouds [*Czys and Bruintjes, 1994*]. *Mather* [1991] reported that paper mill effluent was having a positive affect on the coalescence process in South African clouds. Based on five storms from a single season, he noted that storms influenced by the mill tended to last longer, grow taller, and rain harder than other unaffected storms on the same day. A comparison of aircraft measurements of clouds affected by the mill to those unaffected revealed a presence of supercooled rain drops at the -10 C level in the modified clouds and an absence in the affected clouds, suggesting an acceleration of the coalescence process. These effects are very consistent with those originally reported by *Hindman* [1976] for clouds affect by the emission of the paper mill in Port Townsend, Washington.

Mather [1991] reported that the effluent was being transported by updraft air through cloud base where it may have acted to promote the early formation of small drizzle drops while inhibiting smaller natural cloud condensation nuclei (CCN) from nucleating, to broaden the initial cloud droplet spectra and initiate the coalescence process earlier than would have occurred naturally. *Mather and Terblanche* [1992] suggested that these early effects (determined at cloud base) may then mix throughout cloud and be transmitted to other clouds in the mesoscale convective cluster, all possibilities originally discussed by *Hindman* [1978; 1976].

This led to experiments in South Africa to replicate, as closely as possible, the influence of paper mill effluent on cloud microphysics. Randomized seeding experiments [*Mather and Terblanche, 1992*] were conducted during the 1991-1992 summer season in two regions: the Bethlehem region on the Highveld

(where cloud-base temperatures average +7 C) and the Carolina region in the eastern Transvaal (where cloud base temperatures average +10 C). A total of 50 seeding trials were conducted (25 seed and 25 no seed). Of the experiments, 21 were conducted in the Bethlehem area and the other 29 in the Carolina area. Experimental units in either area were defined as multicellular convective systems that already had a radar reflectivity of $\geq$ 30 dBZ. In order to imitate the effect of the paper mill effluent, hygroscopic

seeding flares were manufactured according to a formulation developed by *Hindman* [1978] to produce artificial CCN. For each treatment, a maximum of 10 flares were ignited at the cloud base in strong updrafts.

The primary response variable in these experiments was radar-estimated rain mass calculated from the lowest scan (1.5 elevation) and at the 6 km level (approximately -10 C). Rain masses were sorted into 10-minute windows starting 10 minutes before and ending 1 hour after the seed/no seed decision. Approximately 30 to 40 minutes after seeding, rain masses for the seeded storms were found to exceed the unseeded storms by about a factor of two. Statistical analyses performed by the Centre for Applied Statistics at the University of South Africa indicate that these differences are significant at the 10% level.

In the South African experiments, an attempt was made to determine how the seeding material may have effected the initial cloud droplet spectrum by measuring just above cloud base with an instrumented aircraft flying behind the seeder aircraft. *Bruintjes et al.* [1993] reported a distinct difference between the cloud droplet distribution in the unseeded area of cloud base, that had a narrow distribution with a peak between 10 and 12 μm in diameter, and the broader seeded spectrum (having a tail extending out to 26 μm in diameter). Both distributions represented about the same liquid water content, 0.33 and 0.35 g m^{-3} for the seed and no seed spectrum, respectively, but had different total cloud droplet concentrations; 508 cm^{-3} in the unseeded region compared to 280 cm^{-3} in the seeded region.

Clouds in the 1991-1992 South African hygroscopic seeding trials, as well as those supposedly affected by the paper mill [*Mather, 1991*] may have also experienced a dynamic effect in connection with seeding. The dynamic effect may be due to an increased presence of supercooled drizzle and raindrops that may affect the origin and evolution of ice [*Braham, 1986*; *Czys, 1989*]. *Orville et al.* [1993] performed a series of numerical simulations of hygroscopic seeding that led to the speculation that large raindrops formed by seeding could establish an ice multiplication process leading to ice at temperatures warmer than would occur by AgI seeding. 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, showed that maximum cloud tops of seed storms were greater than those for no seed storms. Positive effects on echo top growth rates were also found, as well as on heights and growth rates defined by the 45 dBZ contour. However, as encouraging as these findings are, there is a need to address the extent to which the effects can be attributed to an enhancement by the latent heat of condensation, latent heat of fusion, both, changes of drop hydrodynamics in freezing, or for other reasons.