Evidence of Dynamic Effects in Cloud Seeding Experiments in South Dakota

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ABSTRACT

Silver iodide seeding of convective clouds in a number of experiments in South Dakota has yielded mixed results, including both increases and decreases in rainfall and, apparently, decreases in hail. The results vary with the synoptic situation and with location with respect to the silver iodide release point; there is tentative evidence that they can extend upwind. Two dynamic effects of seeding are postulated, namely, increased growth of seeded clouds and the suppression of neighboring clouds at distances of some tens of miles.

1. Introduction

The importance of the dynamic effects which can be produced by the release of latent heat by artificial glaciation of supercooled convective clouds was first suggested by Kraus and Squires' (1947) dry ice seeding experiments in Australia. The concept of increasing precipitation from cumulus clouds by dynamically increasing the amount of water vapor processed in them has been exploited in recent years in several series of experiments dealing with individual clouds (e.g., Weinstein and MacCready, 1969; Woodley, 1970).

The first cloud seeding experiments conducted by the Institute of Atmospheric Sciences in South Dakota were designed principally to affect microphysical processes, but the experimenters were aware of the possibility of dynamic effects being produced simultaneously. On occasion, rapid cloud growth and shower formation followed silver iodide seeding in a manner reminiscent of Kraus and Squires' result (e.g., Donnan and Schleusener, 1968). In addition, certain aspects of the rainfall and hailfall statistics collected over the past several years can be best explained in terms of a combination of microphysical and dynamic effects.

2. The Rapid Project

a. Project design

The Rapid Project was operated just east of the Black Hills during the summers of 1966–68. It utilized a randomized crossover design with target areas of approximately 700 mi² each. The randomization provided for north-seed and south-seed days, with the unseeded target, in effect, serving as the control for each day. The days were objectively stratified in advance. Most of the seeding was conducted by releasing about 300 gm hr^{-1} of AgI in updrafts below cloud base with the objective of introducing one ice nucleus per liter effective at −10C into the growing portions of the convective clouds over the "seed" target area. The project was evaluated on the basis of rainfall accumulations during the 12-hr period ending at 2000 MST at each of a network of approximately 90 raingages distributed through the project area. More information on the experimental design and the operations is given by Dennis and Koscielski (1969).

b. Results of rainfall analyses

Rank tests were applied to the differences in daily rainfall between each station and the average of three controls in the other target area (Dennis and Koscielski). On showery days rainfall was heavier in the seeded than in the unseeded target area; on stormy days with north-

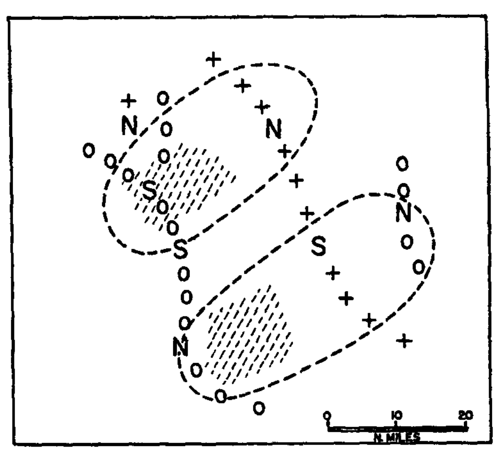

FIG. 1. Rapid Project results for southwest-flow storm days. N and S denote regions where rainfall tended to be heaviest on north-seed and south-seed days, respectively, while the plus marks and circles denote regions where apparent seeding effects were increases and decreases, respectively. Shading denotes areas where most seeding was accomplished.

TABLE 1. Hail impact energies (ft-lb ft^{-2}) and volumes (cubic inches per square inch of land surface) for the Rapid Project area. Data given are totals for all gages for all days with average rainfall >0.01 inch day^{-1} (after Schleusener *et al.*, 1969).

		Operational days				Non-operational days		
Year	Number of gages	Number of days	Hail energy	Hail volume		Number of days	Hail energy	Hail volume
1966	93	20	780	2.0		13	1360	2.2
1967	96	17	580	2.7		15	1220	3.5
1968	96	17	260	1.0		26	620	2.1
Total		54	1520	5.7		54	3200	7.8
Average per day			30	0.10			59	0.15

westerly winds aloft rainfall was lighter in the seeded target area. The situation for stormy days with southwest flow was more complex. The rank test statistics for these days suggest rainfall decreases due to seeding in the area where the AgI was actually released and even a few miles upwind (Fig. 1). However, increases are suggested about 20 mi downwind of the release area.

One can postulate that there is an initial decrease due to a temporary overseeding condition, which reduces the precipitation efficiency of the clouds, and an increase 20 mi downwind due either to dynamic effects as additional water vapor is drawn into and processed in the invigorated clouds or to a second generation microphysical effect, in which ice crystals produced in the seeded clouds are entrained by new cloud towers. Decreases upwind of the release point, if real, could only be due to some dynamic effect, such as increased subsidence extending outward some miles from the seeded towers.

The randomized crossover design is efficient for rejection of the null hypothesis, but interpretation of results beyond that point is difficult. For example, although the Rapid Project results indicate that the seeded target area received more rain than did the unseeded target area on showery days, the experiment itself provides no means for insuring that this was due to increased rainfall in the seeded target rather than to decreased rainfall in the unseeded target area.

Effects in the unseeded target would not require physical transport of the seeding agent from one target area to the other. A decrease could arise, for example, from widespread subsidence related to the intensification of convection in the seeded target area. Dennis and Koscielski use the term "dynamic contamination" to describe changes in rainfall in the unseeded target area that might result from changes in the dynamics of convective clouds passing over that area, and note a requirement for area experiments in which no seeding whatever is done on certain days.

c. *Results of hailfall analyses*

During the conduct of the Rapid Project, it was noted[1] that hailstorms on operational days were usually light but that severe hailstorms were common on weekends and holidays when no seeding was being accomplished.

Schleusener (1968) and Schleusener *et al.* (1969) analyzed hailfall observations in the individual target areas for possible differences in hail energies recorded on north-seed and south-seed days, although the project had not been designed to test any hypothesis of hail suppression. No significant differences were detected; in fact, there was a suggestion that *more* hail fell in the *seeded* than in the unseeded area. This suggestion is in line with results of Grossversuch III (Schmid, 1967). Schleusener *et al.* (1969) conducted further analyses in which hail impact energies throughout the entire instrumented area on operational days were compared with those on non-operational days. It should be emphasized that the seeded target area on any operational day amounted to only one-third of the total instrumented region. Nevertheless, the hail impact energy and hail volume per day over the entire network were much less on operational days (Table 1).

Comparison of the results noted in the above two paragraphs shows that the hail suppression effect, if real, was not a primary effect of the microphysical processes occurring within the seeded cells, but rather a secondary effect spreading across both the seeded and unseeded target areas as well as the surrounding region. We are led to postulate a suppression effect due to suppression of convective activity in the region surrounding the storms actually seeded. While this is only a postulate, it could be tested by an experiment extending over a considerable area, say 10,000 mi^2. It is in agreement with observations that severe hailstorms in the Dakotas are usually separated by 50–100 mi and that the intervening regions are often practically clear.

3. The Grand River Randomized Project

a. *Project design*

During 1969 and 1970, the Institute conducted a randomized seeding program to study effects of seeding upon both rainfall and hail in the Grand River area of northwestern South Dakota. The target area encompassed Corson and Perkins Counties, which have a combined area of 5300 mi^2. The target area was

[1] Mr. A. Koscielski, project meteorologist (private communication).

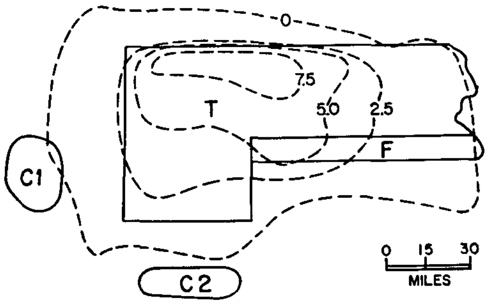

FIG. 2. Grand River Project target area, showing total silver iodide releases (gm mi^{-2}) during 1969–70: T denotes the target area, F the fringe area, and C1 and C2 the control areas.

therefore over seven times as large as a single target area of the Rapid Project. A complicating factor was the operation of a commercial hail suppression project, the Bowman-Slope Project, to the northwest. Operation of ice nucleus counters on the ground and (on a few occasions) on aircraft, and a limited program of precipitation analysis showed very little physical contamination from the Bowman-Slope Project in the Grand River area.

The Grand River Randomized Project ran from 1 June to 15 August each year. Each season was broken into eight-day time blocks and a two-day time block in each eight-day block was randomly selected as no-seed days. This arrangement was adopted for convenience and to minimize carryover effects. The rainfall statistics show no significant day-to-day correlation, so the days can be analyzed individually.

Operations were controlled from a radar-equipped field office near the Lemmon Airport. All seeding involved the release of silver iodide from airborne equipment. Some photoflashes were dropped into towering cumulus clouds from the −8C level, but most seeding was done by operating acetone generators releasing roughly 300 gm AgI per hour in updrafts below cloud base. Further information on the equipment and seeding procedures is given in the Work Plans (Schock, 1969). Fig. 2 shows the distribution of silver iodide releases for the two years combined. Visual observations of cloud glaciation following seeding were common.

Rainfall and hailfall data were collected from a network of 90 stations covering the target area and a "fringe" area, and from nine stations in two control areas to the west and south (Fig. 2). The control areas were established as a guard against a bad draw in the allocation of seed and no-seed days; it was not intended to use target-control regression analyses in the interpretation of results (Schock, 1969). Rainfall observations were made at 0800 and 2000 MST.

b. Results

The results of the Grand River Randomized Project are described at length by Schock and Miller (1970) and by Schock and Gelhaus (1971).

Days were stratified in advance of operation according to objective criteria and after the fact on the basis of the clouds and weather systems observed. Rank tests were applied to the daily (2000 MST) rainfall data for the individual target and control stations and to the daily average rainfall in the two control areas: sub-target areas and the "target" area. A 10-mi strip along the edge of the seeded area was omitted from the "target" area analysis to minimize effects of possible contamination from the Bowman-Slope Project.

The tests were inconclusive under most stratifications, but the null hypothesis can be rejected for some sub-target areas and the control areas for the "all-days" stratification.

Significant results include the following:

1) Application of the sum-of-squared-ranks test (Mielke, 1967) to the average rainfall observed in control and sub-target areas for the "all-days" stratification shows that the seed days were significantly drier than the no-seed days in the controls and in the southwest part of the target (Fig. 3). Seed days were slightly drier throughout most of the target area under most of the stratifications used, but the results were generally not significant at the 10% confidence level.

2) Gamma distributions were fitted to rainfall occurrences in the target area and in the control areas on seed and no-seed days (Thom, 1957). The scale factors for seeded and unseeded days in the target were 0.76 and 1.04, respectively. The difference in scale factor is significant at the 5% confidence level, from which we conclude that rainfall occurrences in the target area on seed days yielded less water per occurrence than did rainfall occurrences on no-seed days. Scale factors for the control areas were 0.72 and 0.78 for seed and no-seed days, respectively. The latter difference is not statistically significant; the dryness of the controls on seed days was due mainly to a lack of rainfall events. The ratio of seed wet days to no-seed wet days in the controls was only 2.1 rather than the most likely value of 3.0. The ratio in the target was 2.9.

3) Maximum observed radar echo heights in the target area were greater on seed than on no-seed days (Table 2). Twenty-two seed days had echo tops above

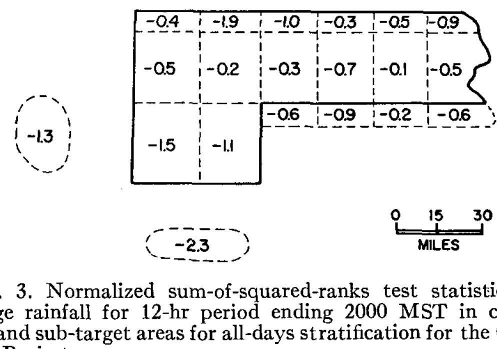

FIG. 3. Normalized sum-of-squared-ranks test statistics for average rainfall for 12-hr period ending 2000 MST in control areas and sub-target areas for all-days stratification for the Grand River Project.

40,000 ft compared to only three no-seed days. A chi-square test of the data in Table 2 shows that they depart from a random distribution at the 5% significance level.

Among results which cannot be accorded statistical significance, we note that more hailstorms occurred on seed days than on no-seed days, but that hail occurrences and hail damage showed a minimum in the middle of the target area, where most seeding was accomplished.

c. *Discussion*

Inasmuch as the control areas set up to guard against a bad draw were significantly drier on seed than on no-seed days, the experiment must be judged a failure and no firm conclusions can be based upon it. However, the data can serve as a basis for hypotheses to guide future field experiments.

There is a possibility that the negative departures (seed days dry) in the control areas are the result of chance. While a Monte Carlo experiment in which the days were randomly classified 50 times as Class A and Class B and then tested for differences has shown that the rank statistics are well behaved and that departures of the magnitudes noted for the actual seed/no-seed classifications occur no more frequently than predicted by statistical theory, this check does not rule out the possibility of a bad draw for the controls and one should not conclude yet that seeding dried up the control areas.

However, if *all* the apparent differences between the seed and no-seed days in the target area are attributed to chance, one must reconcile the facts that 1) the target area received somewhat less rain on seed than on no-seed days, 2) the storms in the target area were significantly taller on the seed days, and 3) the amount of rain per occurrence in the target area was less on seed days.

It is possible that the seed days were characterized by tall, isolated storms and the no-seed days by widespread rains with low echo tops. This could explain the rank test results, but does not seem an adequate explanation for the apparent shortage of *rain per rainfall occurrence* on seed days. Radar observations in the Rapid City area show that the amount of rain produced by a convective storm is correlated with the storm height and approximately doubles for every 3000 ft increase in height (Fig. 4). It is reasonable to conclude that seeding did affect the precipitation patterns in the Grand River area in 1969 and 1970, but in some complex and so far undefined fashion. The data are consistent with any (or all) of the following:

1) An increase in cloud heights in the target area.
2) A shift toward lighter rains in the target area, achieved either by the initiation of light showers or by the suppression of heavy rainfalls, or both.
3) A decrease in rainfall in the control areas, due mainly to a decrease in the number of rainfall events.

TABLE 2. Distribution of daily maximum echo height for all days with rain in target on Grand River Randomized Project over the period 1969–70.

	Seed	No-Seed
Above 40,000 ft	22	3
Below 40,000 ft	33	16

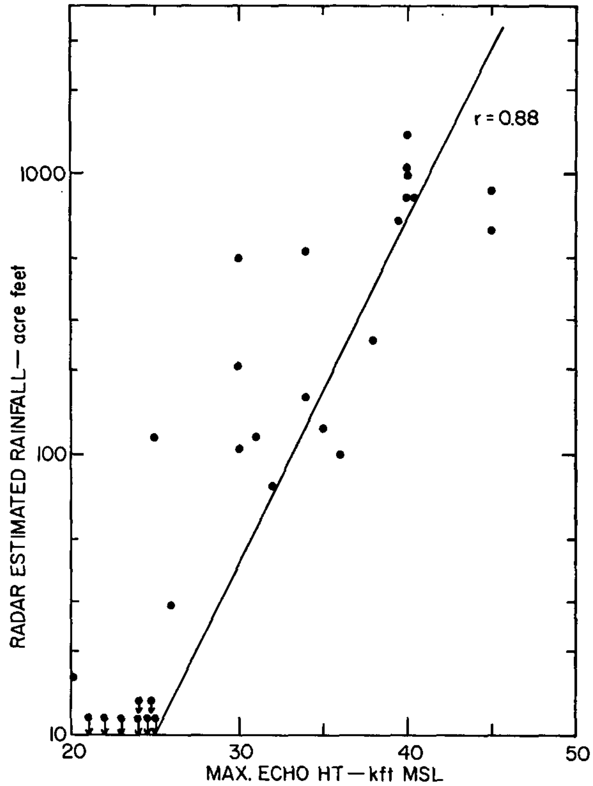

FIG. 4. Radar estimates (X band) of rainfall from unseeded convective showers near Rapid City vs maximum echo height.

4. Summary

Evidence in hand suggests that seeding convective clouds has two principal effects: 1) a microphysical effect which may increase or may decrease the precipitation efficiency of the clouds, and 2) a dynamic effect which causes some seeded clouds to grow but may suppress other cloud developments at distances up to some tens of miles.

Fig. 5 suggests how the combination of microphysical and dynamic effects may interact in the seeding of convective storms in the Northern Great Plains. The figure is speculative and is intended only to illustrate one particular, conceivable combination of effects. Increased amounts of water vapor drawn through the bases of certain convective clouds do not necessarily lead to great increases in rainfall from those clouds

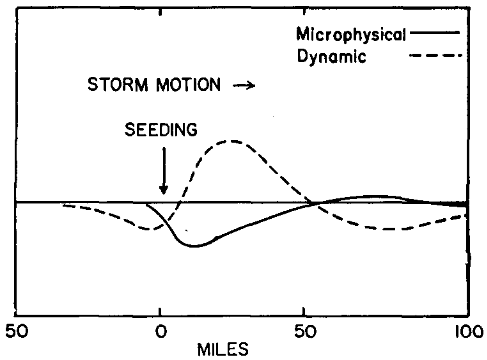

FIG. 5. Postulated seeding effects upwind and downwind of AgI release point in a strongly convective situation in the Northern Great Plains.

because of decreased precipitation efficiency due to heavy glaciation (overseeding). If decreases due to dynamic effects in surrounding areas are taken into account, the overall effect of seeding could well be negative in some instances.

All of the results of the Rapid Project and the Grand River Project can be explained on the basis of the two postulated effects. The difference between results to date in the Dakotas and the large rainfall increases from seeded clouds noted by Weinstein and MacCready (1969) and Woodley (1970) can be attributed to their concentration upon rainfall *from the test cloud only* and to the different characteristics of the clouds being seeded. The tropical cumuli treated by Woodley had weaker updrafts and were carefully selected to insure that dynamic growth would follow seeding (Simpson *et al.*, 1965).

The results presented above have certain implications for future seeding experiments in the Great Plains. Some of these are:

1) The results of seeding experiments aimed at individual clouds or small target areas cannot be extrapolated to predict accurately the effects of seeding over larger areas.

2) The development of numerical models incorporating the dynamic effects of seeding over areas up to several thousand square miles would assist greatly in the interpretation of our results. Unfortunately, numerical modeling of mesoscale systems is in its infancy.

3) Increased attention should be given to the use of common salt and other seeding agents which can initiate the precipitation process in convective clouds without producing the marked dynamic effects associated with silver iodide. In this way, it might be possible to produce changes in cloud microphysics which would lead to increased rainfall from the treated clouds with a smaller possibility of suppressive effects upon neighboring complexes of convective clouds.

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REFERENCES

Dennis, A. S., and A. Koscielski, 1969: Results of a randomized cloud seeding experiment in South Dakota. *J. Appl. Meteor.*, **8**, 556–565.

Donnan, J. A., and R. A. Schleusener, 1968: Field evaluation of pyrotechnic cloud seeding devices at Lemmon, South Dakota, 17–21 July 1967. Rept. 68-2, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City, 51 pp.

Kraus, E. B., and P. Squires, 1947: Experiments on the stimulation of clouds to produce rain. *Nature*, **159**, 489–491.

Mielke, P. W., Jr., 1967: Note on some squared rank tests with existing ties. *Technometrics*, **9**, 312–314.

Schleusener, R. A., 1968: Hailfall damage suppression by cloud seeding—A review of the evidence. *J. Appl. Meteor.*, **7**, 1004–1011.

——, A. Koscielski and M. R. Schock, 1969: Recent data on hail suppression by cloud seeding in South Dakota. *Preprints of Papers, 6th Conf. Severe Local Storms*, Chicago, Amer. Meteor. Soc., 338–339.

Schmid, P., 1967: On "Grossversuch III," a randomized hail suppression experiment in Switzerland. *Proceedings Fifth Berkeley Symposium on Mathematical Statistics and Probability*, Vol. V, 141–159, University of California Press.

Schock, M. R., 1969: The Grand River Randomized Project, Part I: Work Plans. Rept. 69-7, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City, 40 pp.

——, and J. W. Gelhaus, 1971: The Grand River Randomized Project, Part III: Evaluation. Rept. 71-4, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City, 46 pp.

——, and J. R. Miller, Jr., 1970: The Grand River Randomized Project, Part II: First-year evaluation—1969. Rept. 70-4, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City.

Simpson, J., R. H. Simpson, D. A. Andrews and M. A. Eaton, 1965: Experimental cumulus dynamics. *Rev. Geophys.*, **3**, 387–431.

Thom, H. C. S., 1957: A statistical method of evaluating augmentation of precipitation by cloud seeding. *Final Report of the Advisory Committee on Weather Control*, U. S. Gov't Printing Office, 5–25.

Weinstein, A. I., and P. B. MacCready, Jr., 1969: An isolated cumulus cloud modification project. *J. Appl. Meteor.*, **8**, 936–947.

Woodley, W. L., 1970: Rainfall enhancement by dynamic cloud modification. *Science*, **170**, 127–132.