# Hail Suppression Data from Western North Dakota, 1969–1972

J. R. Miller, Jr.,[1] E. I. Boyd,[1] R. A. Schleusener[2] and A. S. Dennis[1]

*South Dakota School of Mines and Technology, Rapid City 57701*

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ABSTRACT

Four seasons of hail data were gathered on a randomized cloud seeding project aimed at reducing hail damage and increasing rainfall in western North Dakota. Hail on seed days was generally less severe than on no-seed days. Statistical tests of data from passive hail indicators do not permit rejection of the null hypothesis at the 90% confidence level, but application of rank tests to crop-hail insurance loss data indicates that the seeding reduced crop damage from hail.

Post-analyses of related data indicate that 1) the ratio of rainfall amount to hail energy was greater for seed days than no-seed days, and 2) radar characteristics of seeded storms differ from those of unseeded storms. In addition, case studies of 34 storms indicate that damaging hail was usually suppressed when their updraft areas were seeded continuously.

## 1. Introduction and project design

The North Dakota Pilot Project (NDPP) was a four-year cloud seeding project conducted in western North Dakota during the summer months of 1969 through 1972. The primary purpose of the project was to gain knowledge relating to the feasibility of increasing rainfall from convective clouds in the northern Great Plains region. In view of the history of damaging hailstorms, county Weather Modification Authorities (co-sponsors of the project) directed that seeding for hail suppression be included as part of the North Dakota Pilot Project and that first priority be given to hail threat seeding opportunities.

The project design called for 75% of the days to be selected at random to be seed (S) days. The remaining 25% of the days were designated as no-seed (NS) days. The no-seed days served as a control sample for evaluation purposes. The schedule of seed and no-seed days was selected randomly in advance of each project season. Table 1 shows the actual distribution of no-seed days and includes a summary of seasonal seed versus no-seed days.

Seeding was conducted primarily by aircraft using silver iodide in acetone generators flying below cloud base.[3] A 3% silver iodide-sodium iodide in acetone solution was burned during 1969 and 1970. As a result of studies indicating increased nucleation efficiencies at warmer temperatures using silver iodide-ammonium iodide in acetone solutions (Blair *et al.*, 1973), ammonium iodide was substituted for sodium iodide in 1971 and 1972. A 10% solution of silver iodide was used in 1971 and a 4% solution was used in 1972. Operational difficulties were encounted in the use of the 10% ammonium iodide solution in brass fitted generators (Davis and Schleusener, 1972). During the last project season two aircraft were equipped to carry approximately 340 kg of a hygroscopic seeding agent (powdered sodium chloride).

A project meteorologist directed all seeding operations using ground-to-air communications, ground-based radar, and an aircraft tracking system. Cloud seeding was conducted primarily during the hours of 1000 to 2200 CDT. Nighttime hail suppression operations were conducted during 1972 to the extent permitted by flight safety considerations.

## 2. Comparison of hail on seed and no-seed days

The NDPP used the randomized no-control design, which Schickedanz and Changnon (1970) have also called the single-area random design. The primary evaluation is therefore based on a comparison of hail within the target area on seed and no-seed days.

### *a. Analysis of hail indicator data*

A passive hail indicator of aluminum foil mounted on a styrofoam pad as described by Schleusener and Jennings (1960) was located at each raingage site (Fig. 1). This network yielded an average of one observational point per 35 mi² (90 km²) in McKenzie County

[1] Institute of Atmospheric Sciences.

[2] Vice-president and Dean of Engineering.

[3] During 1969 and 1970, a few ground-based generators were available but used only two days of each year in conjunction with the airborne seeding. Seeding procedures are described in detail in Report 73-3, available at no cost from the Institute of Atmospheric Sciences, South Dakota School of Mines and Technology.

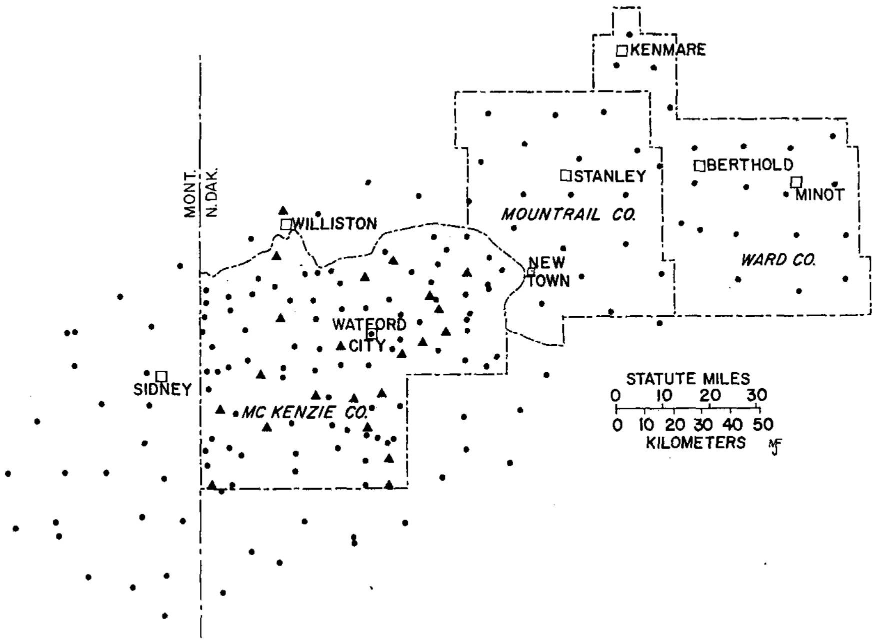


FIG. 1. Map showing the location of the NDPP and the raingage and hailpad network. The target area consisted of McKenzie County only during the first three project seasons; Mountrail and Ward Counties were added during the final project season. Triangles represent locations equipped with recording raingages. The project field headquarters were located in Watford City (1969–72) and Berthold (1972). Two cloud seeding aircraft were stationed each project season in Watford City. One plane was added at Stanley and two planes were added at Minot during the final project season.

TABLE 1. Number of North Dakota Pilot Project seed and no-seed days and actual dates of no-seed days.

| | Seed | No-seed | Total |
|---|---|---|---|
| 1969 Season: 15 May–15 August | 71 | 22 | 93 |
| May 19, 20, 29, 30<br>June 2, 3, 14, 15, 22, 23, 28, 29<br>July 4, 5, 16, 17, 22, 23<br>August 1, 2, 5, 6 | | | |
| 1970 Season: 25 May–15 August | 63 | 20 | 83 |
| May 29, 30<br>June 6, 7, 10, 11, 22, 23, 26, 27<br>July 10, 11, 18, 19, 26, 27, 28, 29<br>August 11, 12 | | | |
| 1971 Season: 1 May–15 August | 79 | 28 | 107 |
| May 3, 4, 11, 12, 23, 24, 27, 28<br>June 2, 3, 16, 17, 18, 19<br>July 2, 3, 8, 9, 14, 15, 24, 25, 30, 31<br>August 11, 12, 13, 14 | | | |
| 1972 Season: 1 June–31 August | 70 | 22 | 92 |
| May<br>June 1, 12, 13, 16, 17, 28, 29<br>July 8, 9, 16, 17, 24, 25, 30, 31<br>August 5, 6, 15, 16, 21, 22, 31 | | | |
| Four-year total project days | 283 | 92 | 375 |

(1969–72) and one per 100 mi² (260 km²) in Mountrail and Ward Counties in 1972.

Because the Mountrail and Ward County network existed for only one season and had only one-third the density of the McKenzie County network, analysis of the hailpad data was limited to the McKenzie County observations.

The aluminum foil dents were counted and measured to yield stone size distributions, hail depth (volume of ice incident per unit area), and the hail impact energy per unit area, a quantity shown previously to be well correlated with crop damage (Schleusener, 1962).

TABLE 2. Hail depth and energy data for McKenzie County 1969–72.

| | Normalized* total hail depth | | Normalized total energy | |
|---|---|---|---|---|
| | (in³ in⁻²) | (cm³ cm⁻²) | (ft-lb ft⁻²) | (J/ cm⁻²) |
| Seed days | 4.41 | 11.20 | 1136 | 1.66 |
| No-seed days | 4.59 | 11.66 | 1431 | 2.09 |
| S/NS ratio | 0.96 | | 0.79 | |

* No-seed data adjusted for the 75% seed, 25% no-seed randomization scheme; a 75:25 ratio was used even though the actual resulting seed to no-seed ratio was 283:92 or 75.4:24.5 = 3.08.

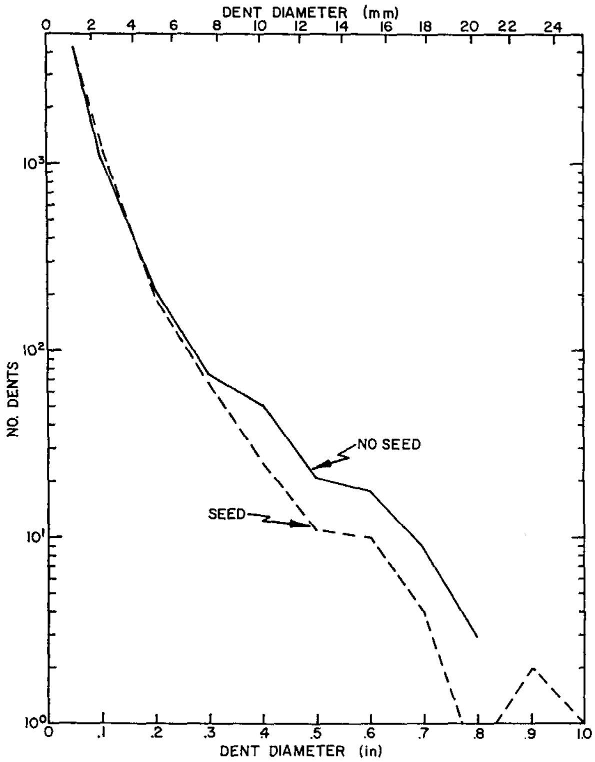


Fig. 2. Distributions of seed day and no-seed day hail dent diameters. The number of no-seed dents was multiplied by a factor of 3 to normalize for the ratio of seed/no-seed days. Note log scale on the vertical axis.

The results have been summarized by adding the computed depths and energies at all pads for all seed and all no-seed days (Table 2). The numbers, adjusted for the 3:1 ratio in the randomization scheme, show no significant difference in total depth but about 20% less hail impact energy per unit area on seed days as compared to no-seed days. The implication is that hailstones were smaller but more numerous on seed days.

Fig. 2, which shows dent diameter distributions for seed and no-seed days, also suggests a shift toward smaller stones on seed days. The hypothesis of equal size distributions for seed and no-seed days could be rejected at a confidence level of $>0.99$ using a $\chi^2$ test (Table 3) if each falling stone were an independent event (e.g., Siegel, 1956, pp. 104–111). However, the large number of small stones on seed days was due largely to occurrence of abundant small hail on one day, 6 July 1971. A Monte Carlo test using 100 random combinations of seed and no-seed days was used to establish a confidence level for testing the hypothesis that hailstone size spectra were not affected by seeding. This test showed 29 of 100 trials yielding test statistics exceeding the $\chi^2$ of 7.2 calculated from the data of Table 3. Therefore the null hypothesis is not rejected.

Table 3. Contingency table of stone sizes.

| | Less than $\frac{1}{4}$ inch | Greater than $\frac{1}{4}$ inch |
|---|---|---|
| Seed | 5659 | 118 |
| No-seed | 1812 | 59 |

$\chi^2 = 7.2$ (1 df).

Table 4. Four-year hailpad data for McKenzie County.

| | Seed | No-seed | Total | |
|---|---|---|---|---|
| Number of days | 29 | 11 | 40 | |
| Number pads hit | 173 | 64 | 237 | |
| | | | Rank test* statistic | Confidence level |
| Average number pads hit per day | 6.0 | 5.8 | −0.98† | 84% |
| Average hail volume per pad hit per day (cm$^3$) | 0.06 | 0.06 | 0.02 | 50% |
| Average hail energy per pad hit per day (J m$^{-2}$) | 3.3 | 3 3 | 0.17 | 43% |
| Average hail energy daily (J m$^{-2}$) | 572 | 633 | −0.35 | 64% |

* Negative test statistics indicate smaller values of variable in question on seed days.

† Note that rank test result gives indication contrary to that suggested by comparison of means.

A rank test (e.g., Siegel, 1956, pp. 116–127) was applied to several parameters derived on a daily basis from hailpad network data. No significant differences were found between seed and no-seed days under this type of analysis (Table 4).

*b. Analysis using hail-rain ratios*

Results to this point suggest a need for controls. A technique employed by Prophet (1960) and by Schleusener (1968) was to compare the ratio of average hail impact energy [$\bar{E}$, (J m$^{-2}$)] to the average rainfall [$\bar{R}$, (mm)] on seed and no-seed days. Doing this for convective[4] days with average rainfall in McKenzie County equal to or greater than 0.01 inch (0.254 mm) provided a data sample which excluded the fine days and days on which rain fell exclusively from stratiform clouds and on which no hail would be expected. The statistics in the present case are as follows:

$$\text{Seed days } \bar{E}/\bar{R} = 331.9/3.99 = 83.2$$

$$\text{No-seed days } \bar{E}/\bar{R} = 316.5/1.88 = 168.4$$

$$\text{Seed/no-seed ratio} = 0.49$$

These results indicate that considerably less hail energy per unit rain was received on seed days than on no-seed days. If one could assume that seeding did not change the total amount of rain, a hail suppression

[4] Convective days were defined as days experiencing towering cumulus or cumulonimbus type clouds.

TABLE 5 Seed versus no-seed day insured crop-hail damage ratios ($R$).

$$R=\frac{\text{Seed-day insured crop damage (\$)}}{\text{No-seed day insured crop damage (\$)}}\times\frac{\text{Number of no-seed days}}{\text{Number of seed days}}$$

| | |
|---|---|
| McKenzie County (1969-71) | $R=\frac{34199}{28399}\times\frac{70}{213}=0.40$ |
| McKenzie, Mountrail, and Ward Counties (1972) | $R=\frac{80904}{110189}\times\frac{22}{70}=0.23$ |

effect of about 50% is indicated. [In fact, the four-year normalized seed to no-seed rainfall ratio for all days was 1.23.]

*c. Analysis of insured crop-hail losses*

Insured crop-hail loss data for all four years of the NDPP were obtained from the Crop Hail Insurance Actuarial Association. Insured crop liability averaged about 10% of the total crop value during the project period.

Normalized seed day versus no-seed day insured crop-hail damage ratios are shown in Table 5. The ratio of 0.40 for McKenzie County (1969–71) suggests about 60% reduction in crop damage during the period when only daytime seeding was done, and a hail damage suppression effect of about 75% is suggested for the three-county area in 1972 when nighttime seeding was also done.

In order to assess the significance of the observed differences, a rank test was applied to daily crop-hail loss data organized by counties (Table 6). The results of the rank test are shown in Table 7. When zeros were included for days without hail losses, statistically significant differences were found for the six county-years combined at a confidence level of 0.92. However, the rank test did not indicate any significant difference when the data sample was limited to the actual hail loss events (Table 6). These combined results suggest that silver iodide seeding may have reduced the number of hail days.

## 3. Post-analysis: Comparison of radar and hailfall data from seeded and unseeded storms

*a. Data base*

This section presents comparisons of hail and radar data collected from seeded and unseeded storms in 1971 and 1972. All storms on no-seed days were assigned to the unseeded sample. Operational logs were used to determine whether storms on seed days belonged in the seeded or unseeded sample Where doubt existed, the storms were omitted from the analysis. The reader is reminded that this analysis departs from the original statistical design of the North Dakota Pilot Project.

The years 1971 and 1972 were selected for the study because of the higher quality of radar data obtained during those years and because additional effort was also made during those years to obtain information to supplement the data from the basic hailpad network (i.e., hailpad questionnaire forms were being filled out by area farmers and ranchers). Table 8 summarizes

TABLE 6. Insured crop-hail losses ranked in terms of loss per county per day.

| Loss ($) | County | Date | Remarks |
|---|---|---|---|
| 98562* | Mountrail | 8- 5-72 | |
| 23744 | McKenzie | 7- 3-69 | Early seeding by one burner only. |
| 23152* | McKenzie | 7- 9-71 | |
| 16829 | Mountrail | 8- 1-72 | $8840 of this damage from unseeded storm. |
| 16252 | Ward | 8- 1-72 | |
| 16234 | Mountrail | 8-19-72 | $10400 from unseeded storm. |
| 9682 | Mountrail | 7-22-72 | Hail streak being produced when seeding began. |
| 5970 | Mountrail | 8-14-72 | Early a.m.; unseeded. |
| 5003 | McKenzie | 7-13-70 | Intermittently seeded. |
| 4730* | Ward | 7-31-72 | |
| 4473 | Ward | 8-12-72 | Widespread storms at night. |
| 4346 | Ward | 7-22-72 | |
| 2938* | Ward | 8- 5-72 | |
| 2620* | McKenzie | 6-16-71 | |
| 2510* | Ward | 6-12-72 | |
| 1951 | Ward | 8-19-71 | This part of storm not seeded at night. |
| 1480 | McKenzie | 6- 6-71 | Seeded only for rain increase purposes. |
| 1363 | Mountrail | 8-10-72 | Early a.m.; unseeded. |
| 1196 | McKenzie | 6-23-71 | Hailfall before seeding began. |
| 1183 | Mountrail | 8-12-72 | Occurred at night after seeding terminated. |
| 1028 | McKenize | 7- 7-69 | Unseeded during nighttime. |
| 950* | McKenzie | 8- 6-69 | |
| 923* | McKenzie | 7-11-70 | |
| 921 | McKenzie | 6-29-71 | One airplane using two burners. |
| 854 | Ward | 8-14-72 | Early a.m.; unseeded. |
| 548 | Ward | 8-13-72 | Early a.m.; unseeded. |
| 496 | McKenzie | 7-14-69 | Unseeded at nighttime. |
| 487* | Mountrail | 8-21-72 | |
| 416 | Mountrail | 6-27-72 | Seeded for rain increase only. |
| 386* | McKenzie | 7-10-71 | |
| 331 | McKenzie | 7-30-70 | |
| 322* | Ward | 7-17-72 | |
| 283* | Ward | 7-25-72 | |
| 276 | Ward | 8-10-72 | Early a.m.; unseeded. |
| 262* | Mountrail | 8-15-72 | |
| 230 | Mountrail | 8-29-72 | Early a.m.; unseeded. |
| 207 | Mountrail | 6-26-72 | Early a.m.; unseeded. |
| 204* | McKenzie | 8- 2-69 | |
| 164* | McKenzie | 7- 2-71 | |
| 90 | Mountrail | 8-13-72 | Early a.m.; unseeded. |
| 51* | Ward | 8-21-72 | |
| 44* | Ward | 7-24-72 | |

* No-seed day.

Table 7. Results of rank test† on insured crop-hail loss per county per day.

| Data samples | Without zeros Cases | Without zeros U test | With zeros Cases | With zeros U test |
|---|---|---|---|---|
| McKenzie County, 1969–72 | 15 | −0.37 | 375 | −0.82 |
| Mountrail County, 1972 | 13 | −0.34 | 92 | −0.05 |
| Ward County, 1972 | 14 | 1.09 | 92 | −2.48* |
| All combined | 42 | 0.72 | 559 | −1.82* |

* Significant ($1.65 \leqslant |U|$) at 90%
† Mann-Whitney U test.

the parameters used in this comparison. It was not possible to collect adequate data to define all of the parameters in every case. Consequently, the number of data points used in the individual comparisons made in the following sections varies. The data points used in each case below were limited to those in which the authors were convinced that the data in hand were sufficient to be included in a study sample.

### b. *Rank test statistics on storm parameters*

A Mann-Whitney U rank test (Siegel, 1956, pp. 116–127) was used to test for differences between the seeded and unseeded storm parameters (Table 8). In each case the null hypothesis is that the parameters of the seeded and unseeded storms are drawn from the same population. The number of storms included in each sample, parameter means, and rank test results are summarized in Table 8.

Testing the seeded and unseeded samples for differences in average echo height shows one population. The tests on the three remaining parameters show significant differences between the unseeded and seeded samples. The lower equivalent radar reflectivity factors ($Z_e$), reduced hail energy values, and smaller stone sizes for the seeded storm samples support the concept that cloud seeding reduces hail damage.

### c. *Further comparisons of storm parameters*

Many previous investigators (e.g., Geotis, 1963) have noted that the probability of hail increases with in-

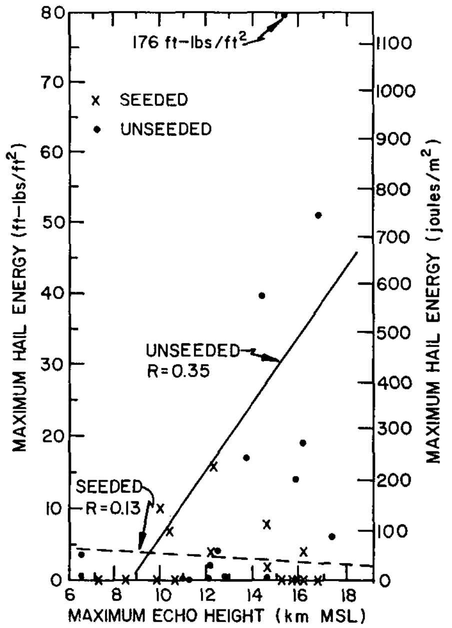


Fig. 3. Variation of maximum hail energy (HEMX) with maximum echo height (MEH) in seeded and unseeded storms.

creasing storm height and with increasing radar reflectivity. The results of the rank tests quoted above, showing differences between seeded and unseeded storms in reflectivity factors and hailstone sizes, but not in maximum echo heights, suggest possible differences in the interrelationships among these variables. A further investigation was therefore undertaken using a linear regression approach.

#### 1) Comparison of HEMX and MEH

Least-square regression lines were fitted to the seeded and unseeded storm data using the maximum echo height (MEH) as the independent variable and the maximum reported hail energy (HEMX) as the dependent variable. Sixteen seeded and 16 unseeded cases were available to generate the lines. The data along with correlation coefficients ($R$) are plotted in Fig. 3.

Table 8. Comparison of seeded and unseeded storms.

| Variable and units | Data source | Mean value and sample size: Seeded storms | Mean value and sample size: Unseeded storms | Confidence level for rejection of null hypothesis by Mann-Whitney U test |
|---|---|---|---|---|
| Maximum radar echo height (km) | M-33 and APS-42 3-cm radars | 12.9 (16)* | 13.1 (16) | 60% |
| Maximum equivalent radar reflectivity factors (dBZ) | 10-cm radar† | 58.8 (21) | 62.2 (16) | 97% |
| Hail energy maximum (J m$^{-2}$) | Hailpad network | 40 (21) | 333 (16) | 99% |
| Diameter of maximum hailstone (cm) | Hailpad network and hail questionnaire | 0.2 (19) | 1.5 (14) | 99% |

* Number in parentheses is the sample size.
† National Center for Atmospheric Research's NCPR-1, digitized system.

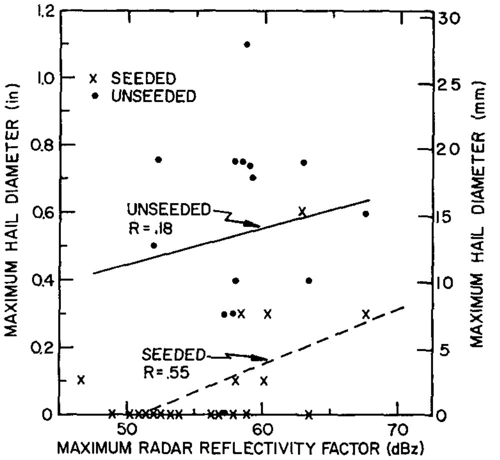


FIG. 4. Variation of maximum hail diameter (DMX) with maximum radar reflectivity factor (ZMX) in seeded and unseeded storms.

The results for the unseeded cases are consistent with earlier findings that hail size increases with increasing storm height (Geotis, 1963). The absence of a significant correlation for the seeded cases is suggestive of a change in the storm height-hail energy relationship, possibly a suppression of hail in the tall storms. The maximum hail energy data sample is not normally distributed and thus prevents the use of the most common tests for significance of apparent differences in the relationship between HEMX and MEH. In addition, the authors have elected not to use a data transformation or to fit other than straight lines to the data because of the limited sample size.

2) COMPARISON OF DMX AND ZMX

A least-squares regression line was fitted to the maximum reported hail diameter (DMX) as a function of the maximum equivalent radar reflectivity factor (ZMX) for 20 seeded and 14 unseeded storms. The data are plotted in Fig. 4.

A tendency for unseeded cases to lie well above the seeded cases is indicated by visual inspection.

3) COMPARISON OF HEMX AND ZMX

The maximum reported hail energy (HEMX) was studied as a function of the maximum equivalent radar reflectivity factor (ZMX) in seeded and unseeded storms. The least squares regression lines plotted in Fig. 5 were generated from 22 seeded and 17 unseeded cases. Visual inspection shows a tendency for HEMX to increase much more rapidly with increasing ZMX in unseeded storms than in seeded storms. These data suggest that seeded storms produce smaller HEMX than unseeded storms with comparable ZMX and that the effect is greatest at high ZMX values.

Since a direct relationship exists between hail diameters and hail energies (Schleusener and Jennings, 1960),

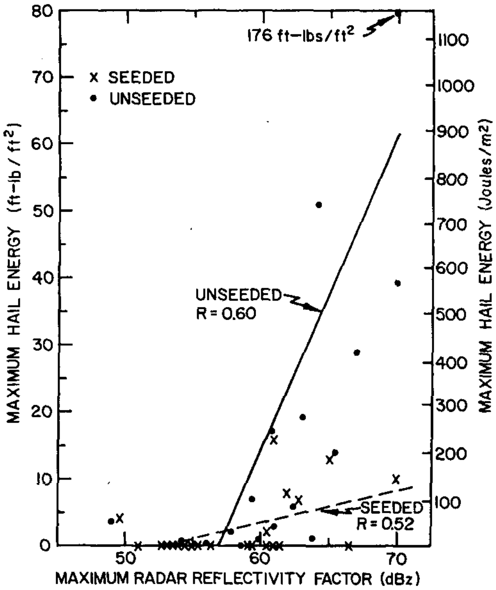


FIG. 5. Variation of maximum hail energy (HEMX) with maximum radar reflectivity factor (ZMX) in seeded and unseeded storms.

the suggestions that cloud seeding produced a reduction in hailstone diameters (Fig. 4) and in hail energies (Fig. 5) are consistent.

*d. Analysis of hailstorm case studies*

Case studies were made of 37 hailstorm seeding incidents during 1972. Cases were included in this study on the basis of availability of data to provide 1) a definition of the seeding done, 2) a record of hail damage, 3) an estimate of hail threat (radar data including reflectivity factors and cloud tops), and 4) an estimate of seeding effects. Data used in the case studies included passive hailpad data, hail questionnaires filled out by local farmers and ranchers, insured crop-hail loss data, digitized 10 cm radar data, time-lapse PPI film,[5] radar cloud top data, pilot reports, and meteorologist's logs.

A subjective evaluation of apparent AgI seeding effects was made. Four of the 37 cases studied were eliminated from the evaluation since one was seeded with salt only and the three others received only 1–3 min of generator seeding time. The evaluation was based on the investigator's best estimate of how the storm behaved beginning 15 min after the start of seeding.

The results (Table 9) show that in a majority of cases AgI seeding apparently deterred significant hail damage. The case studies suggest that 8 seeding attempts prevented hail, 16 decreased hail, 7 had no effect, and 2 resulted in an increase.

In an attempt to determine hail suppression effectiveness as a function of seeding rate, storms were

[5] Aircraft positions were recorded by integrating IFF returns onto the same PPI indicator being photographed.

Table 9. Listing of apparent AgI seeding effects from hail cases.

| Date | Case | Number Aircraft | Number Generators | Apparent effects on hailfall beginning 15–20 min after seeding began: Prevent | Decrease | Indeterminate | Increase |
|---|---|---|---|---|---|---|---|
| 11 Jun 72 | 1 | 1 | 1 | | √ | | |
| | 2 | 1 | 1 | | | √ | |
| | 3 | 1 | 1 | √ | | | |
| | 4 | 2 | 2 | √ | | | |
| | 6 | 2 | 2 | | √ | | |
| | 7 | 2 | 3 | | √ | | |
| 18 Jun 72 | 1 | 1 | 2 | | | √ | |
| 26 Jun 72 | 1 | 1 | 1 | | √ | | |
| 2 Jul 72 | 1 | 1 | 1 | | | | √ |
| 7 Jul 72 | 1 | 2 | 3 | | √ | | |
| 13 Jul 72 | 1 | 2 | 2 | √ | | | |
| 18 Jul 72 | 1 | 2 | 3 | | √ | | |
| 21 Jul 72 | 1 | 2 | 3 | | | √ | |
| 22 Jul 72 | 1a | 1 | 1 | | | | √ |
| | 1b | 1 | 2 | | √ | | |
| | 2a | 2 | 2 | √ | | | |
| | 2a | 2 | 3 | | √ | | |
| | 3 | 2 | 2 | | √ | | |
| | 4 | 4 | 7 | √ | | | |
| | 5 | 4 | 7 | | √ | | |
| 27 Jul 72 | 1 | 1 | 1 | | | √ | |
| 1 Aug 72 | 1a | 3 | 5 | √ | | | |
| | 1b | 2 | 4 | | | √ | |
| | 2a | 2 | 2 | | | √ | |
| | 2b | 3 | 5 | | √ | | |
| | 3 | 5 | 7 | | √ | | |
| 12 Aug 72 | 1 | 2 | 3 | | √ | | |
| | 2 | 2 | 4 | | √ | | |
| | 3 | 2 | 4 | √ | | | |
| | 4 | 1 | 2 | | √ | | |
| 19 Aug 72 | 1 | 4 | 6 | | √ | | |
| | 2 | 3 | 5 | √ | | | |
| | 3 | 1 | 1 | | | √ | |
| Totals | | | | 8 | 16 | 7 | 2 |

Table 10. Distribution of storms in terms of AgI seeding rates and hailfalls.

| | Cell seeding rate ($g\ h^{-1}$) None | ∼200 | ⩾400 |
|---|---|---|---|
| No hail | 2* | 5 | 13 |
| | 10% | 38% | 72% |
| Light hail (HEMX ⩽ 20 ft-lb $ft^{-2}$) or DMX ⩽ 0.5 inch) | 7 | 7 | 4 |
| | 35% | 54% | 22% |
| Heavy hail (HEMX > 20 ft-lb $ft^{-2}$) and DMX > 0.5 inch) | 11 | 1 | 1 |
| | 55% | 8% | 6% |

* $Z \geqslant$ hail threshold [($Z \geqslant 50$ dBZ for 10-cm radar and 42.5 dBZ for 3-cm radar Dennis *et al.* 1970)].
1 ft-lb $ft^{-2}$ = 14.62 J $m^{-2}$.

categorized in terms of seeding rates and HEMX (Table 10). This categorization resulted in deletion of two more storms where seeding rates could not be determined closely, leaving 31 storms in the seeded sample. Twenty unseeded storms were obtained from no-seed days and from seed day situations where storms were left unseeded due to operational problems. When any doubt existed about whether or not a particular storm had been seeded for hail suppression, it was not included in the data sample.

It is assumed the crop damage from hail with maximum hail energy HEMX ⩽ 20 ft-lb $ft^{-2}$ (292 J $m^{-2}$) or maximum hail diameter DMX ⩽ 0.5 inch (1.3 cm) will usually be only light and that heavy damage is probable from higher hail energies and larger hailstones (Summers and Wojtiw, 1971). The tabulated data in

Table 10 show that seeded storms were less likely to produce heavy hail than were unseeded storms, and that heavily seeded storms were less likely to produce heavy hail than lightly seeded storms. While 55% of the unseeded storms produced heavy hail, only 6% of the storms seeded at rates $\geqslant 400\ \mathrm{g\ h^{-1}}$ produced heavy hail and 72% of them did not produce any hail. Storms seeded at approximately $200\ \mathrm{g\ h^{-1}}$ were less apt to produce heavy hail but more apt to produce light hail than were unseeded storms.

## 4. Summary

1) Measurements of hail energy and hail depths derived from passive hail indicators on seed days were not significantly different[6] than corresponding data from no-seed days.

2) Ratios of average rainfall to hail energy were greater for seed days than for no-seed days.

3) Crop-hail insured losses were lower on seed days than on no-seed days.

4) Post-analysis of data from samples of seeded and unseeded storms indicated that (i) the samples showed no difference in average storm height, and (ii) seeded storms differed from unseeded storms in having, on the average, lower radar reflectivity factors, smaller hailstones, and lower hail energies.

5) Case studies indicate that damaging hail was usually suppressed when storms were continuously seeded at cloud base.

## 5. Implications

The results from this four-year project in western North Dakota provide some evidence for the reality of hail suppression by silver iodide seeding.

Many groups have proceeded to develop applied hail suppression programs (Division of Weather Modification, 1974; Henderson and Changnon, 1972). User groups have proceeded without the benefit of full understanding of either the cloud processes involved in the formation of hail or the mechanisms by which damaging hailfall may be reduced by the introduction of artificial nuclei.

We note the unsatisfactory nature of data collected on the end product of hail suppression in the absence of information on intermediate steps in the process or satisfactory prediction of hail formation. High priority should be given to securing direct measurements of glaciation on hail clouds from seeding and development of adequate numerical models to provide the necessary prediction of hail formation.

[6] At the 90% confidence level.

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