Evaluation by Monte Carlo Tests of Effects of Cloud Seeding on Growing Season Rainfall in North Dakota

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ABSTRACT

Rainfall data collected at 67 gages in a 2750 mi^2 target area during a four-year randomized cloud seeding experiment in North Dakota have been stratified in a variety of ways and subjected to several kinds of statistical tests. Some stratifications related to cloud model predictions were possible for only the last two years when a rawinsonde station was operated as part of the project. Monte Carlo experiments simulating 500 reruns of the four-year experiment have been used to establish significance levels for the tests within each data stratification.

The analysis provides significant evidence that seeding convective clouds *on a determinate set of days* leads to 1) an increase in the frequency of rainfall events at the individual target gages, 2) an increase in the average rainfall recorded per rainfall event, and 3) an increase in total rainfall on the target. The set of days to which this evidence applies is those days with dynamic seedability; that is, days for which a cloud model predicted an increase in cloud top height under the influence of silver iodide seeding. Rainfall observations on days when the cloud model predicted no increase in cloud height show no significant differences between seed and no-seed days.

The possibility of bias has been checked by comparing the frequencies of wet and dry days and the averages of several meteorological variables for seed and no-seed days within each stratification, by cross-checking the stratifications, and by comparing rainfall on seed and no-seed days over an area of roughly 50,000 square miles surrounding the target area. There is no obvious bias to account for the significant differences between seed and no-seed days with dynamic seedability.

It is tentatively concluded that dynamic effects, including rainfall increases, were produced by light to moderate silver iodide seeding from below cloud base. The potential rainfall increase resulting from seeding below selected clouds on days with dynamic seedability is estimated at one inch per growing season.

1. The analysis

a. The project[3]

The North Dakota Pilot Project (NDPP) was a randomized cloud seeding experiment conducted in western North Dakota each summer from 1969 through 1972. The project was intended to test the effects of seeding upon both rainfall and hail. The target area through 1971 was McKenzie County. Mountrail and Ward Counties were added in 1972, extending the target area eastward beyond Minot (Fig. 1).

Twenty-five percent of the days were reserved in advance as no-seed days by a method described below. The four-year project included 277 seed and 91 no-seed days. Of the 277 seed days, 113 days were selected by by the project meteorologist as having suitable cloud seeding conditions. The remaining days were left unseeded; however, these days remain in the seed sample for analysis (compare Gagin and Neumann, 1974). Table 1 summarizes the project by seasons, including numbers of no-seed days, seed days, and days actually seeded. The normal seeding period extended from 1 May to 15 August, but seeding was suspended during periods of surplus soil moisture.

Most seeding was accomplished by releasing silver iodide crystals from acetone generators on aircraft operating in updrafts below cloud base. A project meteorologist using ground-to-air communications, ground-based radar, and an aircraft tracking system directed the seeding operations. Seeding treatments varied from as little as 10 or 20 g AgI for stimulation of rain from small cumulus to continuous seeding at rates exceeding 1 kg h^{-1} for suppression of large hailstorms. Heavily glaciated clouds were not seeded for rain stimulation regardless of their size. A 3% silver iodide-sodium iodide in acetone solution was burned in the generators during 1969 and 1970. During these two years a few ground generators were also available for use by the project meteorologist, but they were used on only two days each season. Thev were removed at the end of the

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[3] A detailed description of the NDPP is available in the form of the final report to the sponsors (Rept. 75–1). Copies may be obtained at no charge from the South Dakota School of Mines and Technology.

TABLE 1. Summary of project seasons, numbers of seed and no-seed days, and numbers of days actually seeded in the primary target area—McKenzie County.

	Project season				
	15 May–15 Aug 1969	25 May–15 Aug 1970	1 May–15 Aug 1971	8 Jun–31 Aug 1972	All 1969–72
Number of no-seed days	22	20	28	21	91
Number of seed days	71	63	79	64	277
Number of days actually seeded	31	25	26	31	113
Quantity of silver iodide used (kg)	22	49	17	11	99
Quantity of salt used (kg)	—	—	—	5400	5400

1970 season. Ammonium iodide was substituted for sodium iodide in preparation of AgI solutions in 1971 and 1972 on the basis of cloud chamber tests indicating this change would improve nucleation efficiency around −5°C (Blair *et al.*, 1973). A 10% solution by weight of AgI was used in 1971 and a 4% solution was used in 1972. Operational difficulties were encountered in use of the 10% solution in brass-fitted generators (Davis and Schleusener, 1972). During the last project season, some clouds were also seeded with powdered salt (sodium chloride) to promote rain formation through coalescence of liquid droplets.

A program of airborne sampling in 1969 showed very low background ice nucleus counts. Frozen particles were more common in seeded cells than in unseeded ones, with graupel particles over 2 mm in diameter occurring in seeded clouds near the −5°C level in concentrations of 10–50 m^{-3}.

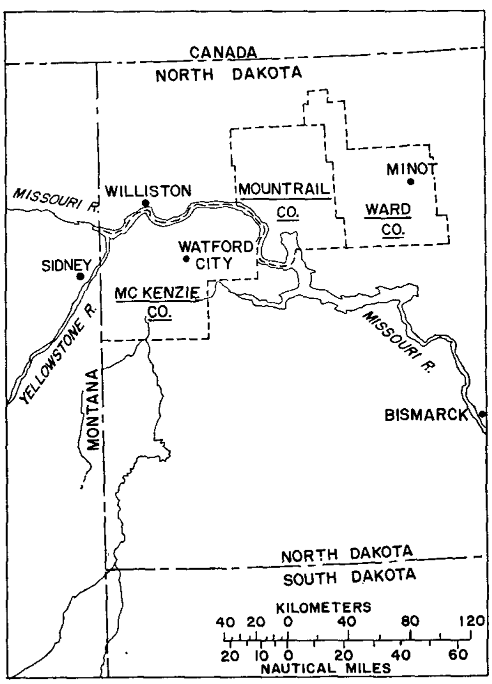

FIG. 1. Map showing the location of the NDPP target area in western North Dakota.

Details on the project design and execution are given in work plans and annual reports to the sponsor.

b. Data base

Large amounts of quantitative radar data, rainfall and hail observations, and pilot reports were obtained from the NDPP. This paper deals with the analysis of raingage data. It presents an evaluation of the NDPP, according to its original design, based on comparisons of rainfall during the 12 h period ending at 2200 (all times CDT) on seed and no-seed days. The data base is provided by 67 raingages located in McKenzie County with a density of approximately 1 per 35 mi² (Fig. 2). These raingages were operated for the entire project without change in location. No evaluation is provided of data collected in Mountrail and Ward Counties in 1972.

Table 2 provides a partial summary of the rainfall data for various stratifications. The table shows the number of seed and no-seed days without rain at any gages (dry) and with rain at one or more gages (wet), the number of zero and non-zero rainfall observations at the individual gages, and mean rainfall per event,

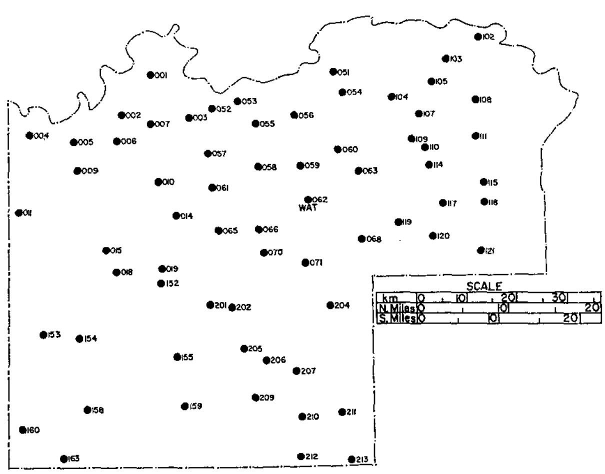

FIG. 2. Distribution of rain gages in McKenzie County. Cooperative observers provided 12 h rainfall readings throughout the four summer seasons. Data were sent weekly via preprinted postcards to the project headquarters located in Watford City (WAT).

Table 2. Distributions of days and of rainfall observations and mean rainfall per event for seed and no-seed days.

Stratification	Distribution of days: Seed No rain/rain	Distribution of days: No-seed No rain/rain	Distribution of rainfall observations: Seed Zeros/>0.01 inch	Distribution of rainfall observations: No-seed Zeros/>0.01 inch	Mean rainfall event (inches): Seed	Mean rainfall event (inches): No-seed
All	145/132	47/44	15814/2741	5266/831	0.27	0.24
Type 1a	74/30	14/9	6664/300	1410/131	0.16	0.18
Type 1b	38/29	17/19	3924/565	1954/458	0.12	0.24
Type 2a	2/8	2/0	385/285	118/16	0.39	0.05
Type 2b	6/11	4/3	841/298	385/84	0.36	0.35
Type 3a	17/18	8/5	1941/404	831/40	0.30	0.16
Type 3b	8/36	4/6	2059/889	568/102	0.33	0.27
1969–70	76/58	19/23	7547/1427	2305/509	0.35	0.30
1971–72	69/74	28/21	8267/1314	2961/322	0.19	0.15
Very warm	33/16	16/6	3029/254	1366/108	0.20	0.28
Warm	70/79	22/20	8193/1790	2508/306	0.34	0.22
Cold	30/29	8/18	3427/526	1325/417	0.12	0.24
No dynamic seedability*	33/28	16/10	3587/500	1528/214	0.20	0.16
Dynamic seedability*	31/41	12/9	4059/765	1301/106	0.19	0.11

* 1971–72 only.

where a rainfall event is defined as the occurrence of measurable rain at a gage during a 12 h observational period. It should be noted that summer rainfall in North Dakota tends to be spotty. A typical "wet" day produced measurable rain at only 5 or 10 of the 67 gages.

The all-days stratification shows 145 dry seed days and 132 wet seed days; on no-seed days, the numbers were 47 dry days versus 44 wet days. This comparison suggests that cloud seeding did not increase the total number of wet days and supports the likelihood of a fair draw between seed and no-seed days. Using the χ^2 test, one cannot reject the null hypothesis that no difference exists between seed and no-seed days in terms of the probability of a day being dry or wet. However, this does not rule out the possibility of differences, either natural or artificially induced, in the frequency of rainfall events at the individual gages. Examination of mean rainfall amounts shows that seed-day rainfall events averaged slightly larger, 0.27 inch compared to 0.24 inch, but the difference is not judged significant.

c. *Data stratification*

The rainfall data have been analyzed under a number of stratification methods, several of which were spelled out in the project work plans.

The data were stratified first according to an objective forecast scheme patterned after the Rapid Project (Dennis and Koscielski, 1969). Days with less than 0.75 inch precipitable water were classified as Type 1 days. Of the remainder, those with 850 mb winds in excess of 15 kt blowing from the north or east, that is, with wind direction between 270° and 120° clockwise, were classified as Type 2 days. The remaining days were classified as Type 3. The suffix a or b was added in each case to denote the absence or presence respectively of positive vorticity advection at 500 mb.

Type 1 days were supposed to be fair, Type 2 days to bring stratiform clouds, and Type 3 days to have showers and thunderstorms, with b days generally tending toward widespread cloudiness, if any.[4]

Other stratification schemes were based on observed cloud types, cloud base temperatures, years, and 500 mb temperatures (T_{500}). Several of these schemes proved fruitless and are not presented in this paper. They are, however, described in the final report to the sponsor. The operation of a rawinsonde station at Watford City in 1971 and 1972 permitted an additional and very important stratification method for those years. A one-dimensional, steady-state cloud model (Hirsch, 1971) was run with the rawinsonde data and various updraft radii to identify days with "dynamic seedability," that is, days with the possibility of increased cloud height due to AgI seeding.

In the model runs, the assumed effect of AgI seeding was the conversion of cloud water to cloud ice between −5 and −25°C rather than between −20 and −40°C. This change usually results in AgI cloud model tops a few hundred meters in excess of no-seed model tops. It was assumed in both cases that the first appearance of cloud ice froze all rainwater due to raindrop-cloud ice collisions.

The predicted increase in cloud top height, ΔH, due to these changes was noted for all updraft radii used in

[4] The NDPP Type 3b days correspond to the Rapid Project Type 4 (storm) days.

TABLE 3. Rainfall statistical test results.*

Stratifications	Pseudo chi-square tests		Pseudo gamma distribution tests				Pseudo rank-sum tests			
	χ^2 (1)	P_{500} (2)	γ_s (3)	γ_{ns} (4)	F (5)	P_{500} (6)	$\bar{U}$ (7)	+ (8)	− (9)	P_{500} (10)
All days	4.74	0.59	0.39	0.44	1.14	0.67	0.32	42	25	0.57
Type 1a	−45.25	0.14	0.32	0.29	0.86	0.28	−0.86	7	60	0.11
Type 1b	−50.42	0.13	0.29	0.46	0.51	0.18	−0.92	6	61	0.13
Type 2a	43.34	0.81	0.41	0.28	7.26	0.87	0.86	64	3	0.75
Type 2b	12.04	0.66	0.34	0.14	1.03	0.47	0.39	49	18	0.61
Type 3a	84.15	*0.92*	0.29	0.29	1.88	0.74	1.14	63	4	0.82
Type 3b	60.46	*0.92*	0.37	0.71	1.20	0.53	1.03	64	3	*0.93*
1969 and 1970	−7.30	0.35	0.41	0.46	1.17	0.69	−0.28	20	47	0.33
1971 and 1972	33.27	0.84	0.31	0.31	1.29	0.84	0.74	60	7	0.88
$T_{500} > -10°C$	0.19	0.51	0.22	0.59	0.70	0.16	0.09	37	30	0.50
$-10°C \geqslant T_{500} > -15°C$	79.29	*0.92*	0.39	0.30	1.52	0.87	1.12	64	3	0.86
$-15°C \geqslant T_{500} > -20°C$	−98.15	*0.02*	0.30	0.50	0.49	0.18	−1.25	1	66	*0.01*
$\Delta H \leqslant 0$ } 1971–72	0.00	0.38	0.28	0.36	1.23	0.51	0.04	35	32	0.41
$\Delta H > 0$ } only	62.08	*0.96*	0.32	0.18	1.67	*0.98*	0.99	63	4	*0.93*

(1) The computed pseudo chi-square value comparing frequencies of seed day and no-seed day rainfall events.
(2) P_{500} is the significance level for test of hypothesis that frequency of rainfall events was the same on seed and no-seed days.
(3) The seed-day shape parameter obtained by fitting the 12 h rainfall events to a gamma distribution function.
(4) The no-seed day shape parameter obtained by fitting the 12 h rainfall event to a gamma distribution function.
(5) The pseudo-F value obtained by forming the ratio of the seed and no-seed rainfall means of Table 2. Under assumption that shape factor γ is not changed by seeding [compare columns (3) and (4)], this is a test for differences in scale factors.
(6) P_{500} is the significance level for test of hypothesis that rainfall per event was the same on seed days as compared to no-seed days. [This significance level does *not* depend on assumption that γ is unchanged by seeding.]
(7) The mean value of the 67 Wilcoxon test statistics (U's) calculated for the given stratification.
(8) The number of positive Wilcoxon test statistics in the 67-gage sample.
(9) The number of negative Wilcoxon test statistics in the 67-gage sample.
(10) P_{500} is the significance level for test of hypothesis that number of stations with positive and negative U's was unaffected by seeding. It can also be interpreted loosely as the Monte Carlo probability that seeding increased rainfall.
* All values of $P_{500} \leqslant 0.10$ or $\geqslant 0.90$ are shown in italics.

the model runs. A positive value of ΔH for any radius was taken as evidence of dynamic seedability.

d. Statistical tests

Preliminary evaluations of the NDPP followed techniques previously used (for example, comparisons of average rainfall over the target area on seed and no-seed days). It was evident that the averaging process was throwing away information on the rainfall as observed by the network of 67 raingages. Intuitively one realizes that 67 observations carry more weight than one observation, but formulation of a test statistic based on more than one observation on a single day was hampered by the intercorrelations among the 67 raingages.

To circumvent the problem of intercorrelations, and possible difficulties associated with the randomization scheme, we resorted to Monte Carlo tests as described in Section 1e below for setting significance levels. Pseudo-test statistics were calculated from the data using standard procedures as with independent data. As the pseudo-test statistics do *not* have known sampling distributions, significance levels were *not* determined from tables of the chi-square, F distribution, etc., but rather from the Monte Carlo tests.[5]

The first of the three pseudo statistics is formulated from the familiar chi-square:

$$\chi^2 = \sum_{i=1}^{k} \frac{(f_i - F_i)^2}{F_i},$$

where f_i is the observed frequency and F_i the theoretical frequency. For a two-by-two contingency table the continuity correction (see, e.g., Dixon and Massey, 1957) results in the formula

$$\chi^2 = \frac{\left(|\text{ad}-\text{bc}| - \dfrac{N}{2}\right)^2 \cdot N}{(\text{a}+\text{b})(\text{a}+\text{c})(\text{b}+\text{d})(\text{c}+\text{d})}.$$

As an example, the distribution of rainfall events at

[5] Also called *computer experiments* by Gagin and Neumann (1974).

individual gages for the all days stratification is given by

	No-rain	Rain	Total
Seed	15,814 (a)	2,741 (b)	18,555
No-seed	2,566 (c)	831 (d)	6,097
	21,080	3,572	24,652 (N)

$\chi^2=4.74$

In the present work the pseudo chi-square was considered positive if ad<bc and negative if ad>bc, the former case representing a departure from a random distribution toward more rain observations on seed days while the negative values indicate more no-rain observations on seed days. We interpret significant positive departures of the test statistic as an indication that a larger portion of the target area received rain on seed days than on no-seed days. The pseudo chi-square test statistic is indicated in column 1 of Table 3 for each of the stratifications tested.

The second pseudo-test statistic is a test of magnitude of rainfall events on seed and no-seed days. Thom (1957) has fitted 12 h rainfall amounts to gamma distributions by estimating the scale parameter β and the shape parameter γ by

$$\gamma=\frac{1+\left(1+\frac{4A}{3}\right)^{\frac{1}{2}}}{4A}, \quad \beta=\frac{\bar{R}}{\gamma},$$

where $A=\log\bar{R}+(1/N)\Sigma\log R$, $\bar{R}$ is the arithmetic mean of observations, and N the number of observations. Olson (1973) has shown that, under the assumption that seeding does not alter the shape parameter γ, the test statistic for a scale change is simply

$$F=\frac{\bar{R}_{\text{seed}}}{\bar{R}_{\text{no-seed}}},$$

and, if the assumption regarding independence of the events is met, is distributed with an F distribution with $(2n\gamma_{\text{seed}})$ and $(2m\gamma_{\text{no-seed}})$ degrees of freedom, where n is the number of seed observations and m the number of no-seed observations.

Table 3 gives the shape parameters for the seed and no-seed populations of each stratification as well as the pseudo F-test statistic.

The third pseudo-test statistic was formulated from a combination of the rank test and the sign test (Dixon and Massey, 1957). The rank test used here is the Wilcoxon two-sample test corrected for tied observations. [Kruskal and Wallis (1952) give an extensive bibliography of the rank test.] The rank statistic is calculated by first ranking the pooled observations according to the magnitude of each event, zeros included. If there are ties, each observation is given the mean of the ranks for which it is tied.

The rank function becomes (for the seeded observations)

$$T=\sum_{i=1}^{N} k_i\phi,$$

where $\phi=0$ for no-seed observations, $\phi=1$ for seed observations, N is the total number of pooled observations, and k_i the rank of observations. The rank function T has an expected value of

$$E_0(T)=\frac{n(N+1)}{2},$$

where n is again the number of seed observations, and an expected variance of

$$\text{VAR}_0(T)=\frac{n(N-n)}{12N(N-1)}(N^3-\sum_{i=1}^{k} t_i^3),$$

where n is the number of seed observations, N the total number of observations, t_i the number of tied observations for rank i, and k the number of ranks.

Under the assumption $m\rightarrow\infty$, $n\rightarrow\infty$ with $m/n\rightarrow\lambda>0$, the limiting distribution of

$$U=\frac{T-E_0(T)}{[\text{VAR}_0(T)]^{\frac{1}{2}}}$$

is standard normal, N (0,1).

After obtaining the U rank statistic for each of the 67 gages, the average U and number of positive U's were compiled for each stratification. The values of $\bar{U}$ and the count of positive and negative U's are given in columns (7), (8) and (9) respectively of Table 3. The pseudo-test statistic for this case was formed by counting the positive U's. A significant number of positive U statistics is an indication that there were more or larger rain events, or both, at individual gages on seed days. We shall refer to it simply as an indication of "more" rain on the total target.

e. *Monte Carlo evaluation of the significance of the pseudo-test statistics*

The Monte Carlo evaluation is based on testing a large number of simulated seed/no-seed permutations of the 368 project days. The process of selecting the actual seed/no-seed days as well as any of the test permutations proceeded as follows. Each year of the experiment was randomized separately by first dividing the season into 8-day blocks, the first day of the first block being 1 May. Each block of 8 days was divided into four 2-day time blocks. From each 8-day block a no-seed, two-day block was selected by a call to a random number generator that supplied an integer from 1 to 4 (Table 4). Subsequent calls to the generator

TABLE 4. Randomization scheme illustrated by case where random number generator supplied integer 3.

	2-day time block							
	1		2		3		4	
Day	1	2	3	4	5	6	7	8
Seed/no-seed selection	S	S	S	S	NS	NS	S	S

set the no-seed 2-day block in each of the remaining 8-day time blocks for the season.

Test permutations for the Monte Carlo experiment were established in the same manner with all 500 permutations[6] generated in one computer run by successive calls to the same random number generators. Rotenberg (1959) has tested the generator and found that on a 48-bit binary computer[7] the full period is 2^{47} with serial correlation essentially zero.

The number of possible permutations of the 2-day seed/no-seed time blocks for the project is equal to 4^{46} or approximately 10^{28}. All permutations are equally likely and therefore test permutations are viewed as random selections from the population of 10^{28}. The Monte Carlo technique was used to estimate the proportion p of these permutations which show a "worse" result than those observed in the actual experiment, a "worse" result meaning that the pseudo-test statistic obtained from the random permutation is less than that obtained in the actual experiment. This is equivalent to an estimation of a one-tailed significance level, since the significance level is defined as the area of the probability density function below the pseudo-test statistic observed for the actual experiment.[8]

If we let X be a random variable whose value is the pseudo-test statistic associated with a permutation and A be the set of pseudo-test statistics which are less than the one calculated from the actual experiment, then we may define W as

$$\left.\begin{array}{ll}\text{If } X\in A, & \text{then } W=1\\ \text{If } X\notin A, & \text{then } W=0\end{array}\right\}.$$

Thus W is a binomial random variable with parameters 1 and p. For this experiment we have a sample of 500 observations and therefore $X_1, X_2, \ldots, X_{500}$ defines $W_1, W_2, \ldots, W_{500}$. The best estimate for p is then

$$\hat{p}=\sum_{i=1}^{500}\frac{W_i}{500},$$

and since $\sum_{i=1}^{500} W_i$ is a binomial random variable with parameters 500 and p, $\hat{p}$ has a mean equal to p and a variance of $p(1-p)/500$. The estimate for this variance is $\hat{p}(1-\hat{p})/500$. By inspection, for any value of p with $0<p<1$, we have $p(1-p)/500\leqslant 1/2000$, and thus for all cases $S\hat{p}$, the standard error of the estimate for p, is less than or equal to $1/(2000)^{\frac{1}{2}}=0.0224$.

The same procedure was used in setting significance levels for each of the three pseudo-test statistics; therefore, the significance levels in columns (2), (6) and (10) of Table 3 have a standard error less than 0.0224.

This result was experimentally verified by breaking the 500 permutations of the all-days stratification of Table 3 into five subgroups of 100. Since five subgroups yielded results varying from 50 to 61% probability of less favorable results than those observed, the P_{500} result of 57% would appear to have a standard error in agreement with the theoretical calculation.

2. Results

a. General remarks

The significance levels determined from the Monte Carlo experiments for the various statistical tests are shown in Table 3. In each case the probability of a worse[9] result occurring by chance is shown. For example, the 0.11 shown for the pseudo rank-sum test for the Type 1a stratification means that 11% of the 500 Monte Carlo trials gave a worse result at the 67 target gages combined than the result actually obtained (7 positive versus 60 negative indications). This can be viewed as evidence for a rainfall *decrease* with a one-tailed significance level of 0.11. On the other hand, the 0.82 shown for the pseudo rank-sum test for the Type 3a days can be viewed as evidence for a rainfall *increase* at the 0.18 significance level.

b. Objective forecast stratifications

The results of Type 1 days show less rain on seed days than on no-seed days but the results fail to achieve statistical significance. Most Type 1 days were fair weather days. The results for Type 2 days are also inconclusive. This is not surprising as Type 2 days tended to produce stratiform clouds which were not considered good candidates for seeding.

It was stated in the NDPP work plans that evidence of rainfall increases on Type 3a days would be taken as confirming the Rapid Project results, which sug-

[6] The same set of permutations was used for each of the stratifications tested. For example, the seed days for permuation 187 for the "dynamic seedability" stratification were simply the seed days from permutation 187 for the all days stratification that showed dynamic seedability.

[7] We used the Rotenberg generator as supplied by Control Data Corporation for the CDC-3400 computer system; the proper configuration of the generator for a 48-bit computer was implemented.

[8] A similar interpretation was developed by Gabriel in his computer experiments to set significance levels for the rainfall ratios developed in evaluating the Israeli experiment (see Gagin and Neumann, 1974).

[9] For ease of expression, we denote a tendency for rainfall on seed days to exceed rainfall on no-seed days as "good" and the opposing tendency as "bad."

gested rainfall increases due to seeding on such days. The pseudo rank-sum result for Type 3a days does not achieve a 10% significance level, although the pseudo chi-square test for number of rainfall events does so. The results can therefore be interpreted as supporting the Rapid Project findings for shower days but not conclusively. On the other hand, the NDPP results contradict the Rapid Project indications of rainfall decreases due to seeding on storm days (Dennis and Koscielski, 1969). The NDPP observations on Type 3b days show more rainfall events at individual gages (0.08 significance level) and more rainfall (0.07 significance level) on seed days than on no-seed days.

c. Stratification by year

The seeding agent was changed at the start of 1971 from an AgI·NaI solution in acetone to an $AgI\cdot NH_4I$ solution in acetone. The results for 1971–72 are better than for 1969–70, but not significantly so.

The results for 1971 and 1972 have been computed separately (not shown) and found to be very similar, so one can draw no conclusions regarding the effects of the salt seeding in 1972.

d. Stratification by 500 mb temperature

The comparison of rain on seed and no-seed days yields different results depending on whether the 500 mb temperature is above or below −15°C. For cold days when the 500 mb temperature was between −15 and −20°C, seed days had fewer rainfall events (0.02 significance level) and less rainfall (0.01 significance level). However, application of a chi-square test to the data in Table 2 reveals that the probability of a cold seed day being wet was less than the probability of a cold no-seed day being wet ($\leqslant 0.10$ significance level). This result suggests either cloud seeding reduced the number of days with rain, or that a bad draw may exist in the cold, 500 mb temperature stratification. Although seeding could quite conceivably reduce the number of rain events at individual gages, it is hard to believe that it could create a dry day from a wet one by stopping all rain at all gages over a 12 h period.

Comparing the numbers of wet and dry seed and no-seed days for warm days with the 500 mb temperature between −10 and −15°C reveals no significant difference in the probability of a *day* being wet or dry, but the probability of a rainfall event at an individual station was higher on the seed days. This suggests that AgI seeding increased the horizontal extent or the lifetimes of the showers, perhaps even to the extent of forming showers that would not have occurred otherwise.

e. Stratification by cloud model

The most consistently favorable results are those for days with dynamic seedability ($\Delta H > 0$). Seeding on such days was associated with more rainfall events (0.04 significance level), heavier rainfall events (0.02 significance level), and more rain on the target area (0.07 significance level). On the other hand, seed and no-seed days in the no-seedability stratification ($\Delta H \leqslant 0$) are indistinguishable. In addition, a chi-square comparison of the numbers of wet and dry seed and no-seed days suggests a fair draw for dynamic seedability days.

3. Further tests for bias

The Monte Carlo tests provide a first estimate of the significance of the differences between seed and no-seed days in the various stratifications. As noted in Section 2, the frequencies of wet and dry days in the no-seed and seed classifications of the cold day stratification cast some doubt on the results shown in Table 3 for cold days. Three further tests of the possibility of bias will now be described.

a. Statistics of meteorological variables

The statistics of several meteorological variables for the seed and no-seed days in the various stratifications are shown in Table 5. The results show no obvious differences between seed and no-seed days to account for the differences in rainfall indicated by Table 3.

b. Cross-checks among stratifications

Table 6 shows breakdowns of the days in the warm and cold stratifications and the no-seedability and dynamic seedability stratifications among the objective forecast types. Marked departures from the overall 3:1 randomization ratio, particularly among the Type 3 days, which gave most of the rainfall, would be indicative of possible bias. Considering Types 1a, 1b and 2a as predominantly dry types and Types 2b, 3a and 3b as wet types, one obtains the totals shown in the lower half of Table. 6. The only serious indication of bias is in the warm stratification, where 43% of the 149 seed days fell into the wet types compared to 33% of the 42 no-seed days. The dynamic seedability stratification shows an almost perfect balance in the seed versus no-seed/wet versus dry types breakdown.

c. Large-area analyses

Gelhaus *et al.* (1974) detected bias in the randomization on the Grand River Randomized Project (GRRP) by computing test statistics for about 130 climatological stations distributed over the Dakotas and eastern Montana. We have carried out a similar analysis for each stratification on the NDPP; the resulting rank-sum test statistics for warm days, cold days, and days with dynamic seedability are presented in Fig. 3.

In considering the rank-sum statistics plotted in Fig. 3 it is necessary to keep in mind that some statisticians (e.g., Neyman *et al.*, 1973) tend to interpret differences between seed and no-seed days over large areas as indications of seeding effects outside the in-

TABLE 5. Tabulation of four-year average values of meteorological variables by various stratifications.

Stratification	Averages—Seed/no-seed						
	P.W.	L.L.M.	C.C.L.	FZ.L.	L.I.	T_{500}	M.C.T.
All	0.67/0.68	7.0/6.8	2.6/2.8	3.5/3.5	2.1/1.4	−12.9/−12.7	8.7/10.0
Type 1a	0.52/0.57	5.6/6.0	2.6/2.7	3.3/3.4	4.0/2.9	−13.7/−13.2	8.0/10.7
Type 1b	0.59/0.57	6.9/5.8	2.8/2.9	3.3/3.2	2.4/2.4	−14.1/−14.1	7.3/9.5
Type 2a	0.76/0.99	6.8/9.7	2.4/1.8	3.2/3.3	2.4/−0.8	−13.8/−13.5	6.7/5.2
Type 2b	0.86/0.87	7.2/6.3	2.4/2.7	3.6/3.9	3.9/2.6	−11.9/−10.0	8.2/9.6
Type 3a	0.88/0.89	8.8/8.6	2.6/2.7	3.8/3.9	−0.7/−1.4	−10.7/−10.7	11.4/10.7
Type 3b	0.92/0.90	8.9/9.0	2.6/2.7	3.9/4.0	−1.3/−2.1	−10.7/−10.7	9.4/11.0
Very warm ($T_{500}>-10$C)	0.79/0.82	8.0/7.6	3.0/3.2	4.2/4.1	1.7/0.5	−8.1/−8.3	10.1/10.5
Warm ($-10\text{C}\geqslant T_{500}>-15$C)	0.72/0.71	7.3/7.3	2.7/2.7	3.7/3.7	1.3/0.5	−11.9/−12.3	9.0/12.2
Cold ($-15\text{C}\geqslant T_{500}>-20$C)	0.55/0.54	6.5/5.4	2.3/2.4	2.8/2.8	3.6/3.4	−16.2/−16.7	7.4/8.1
1969–70	0.71/0.71	7.0/6.7	2.8/2.8	3.6/3.5	1.4/0.7	−12.5/−12.7	7.3/9.9
1971–72	0.64/0.66	6.9/6.8	2.5/2.7	3.4/3.5	2.8/1.8	−13.1/−12.7	10.2/10.2
No dynamic seedability*	0.55/0.67	5.6/6.7	2.2/2.4	3.1/3.4	4.9/3.2	−14.2/−12.6	9.0/8.8
Dynamic seedability*	0.75/0.69	8.4/7.2	2.7/3.0	3.6/3.7	0.5/−0.3	−12.0/−12.5	10.9/11.8
	Standard deviations—Seed/no-seed						
All	0.23/0.23	4.1/2.2	0.7/0.7	0.7/0.7	4.2/4.0	3.8/3.5	3.2/3.2

* 1971–72 only.
P.W., precipitable water (inches).
L.L.M., lower level moisture (g kg⁻¹).
C.C.L., convective condensation level (km).
FZ.L., freezing level (km).
L.I., lifted index.
T_{500}, 500-mb temperature (°C.)
M.C.T., maximum (radar) cloud top (km).

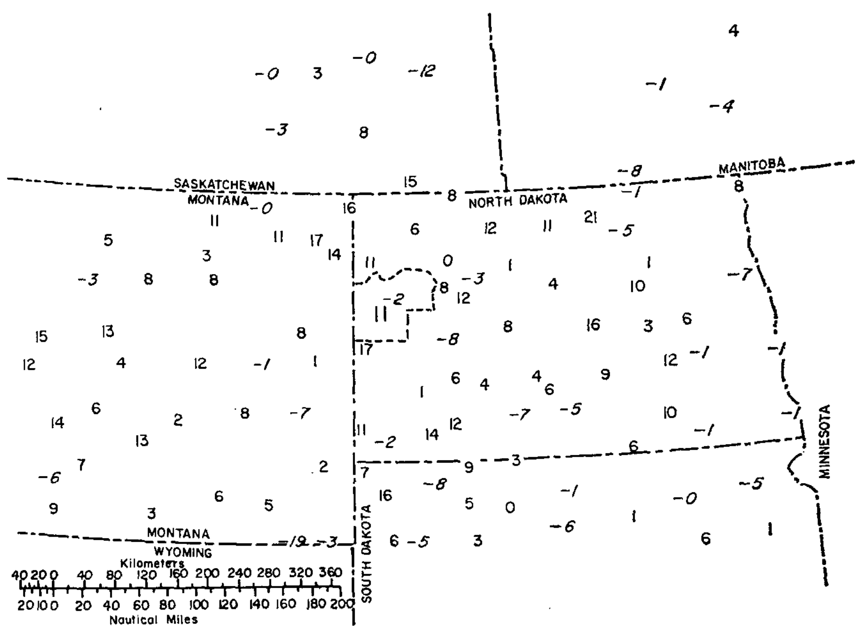

FIG. 3a. Normalized rank-sum test statistics for gages in the region surrounding the target area for warm days. Values are plotted in tenths. The average value over the region is 0.41 with a standard deviation of 0.70. The bold faced number in the target area reflects the average test statistic value for the 67 target gages. Negative values are italicized.

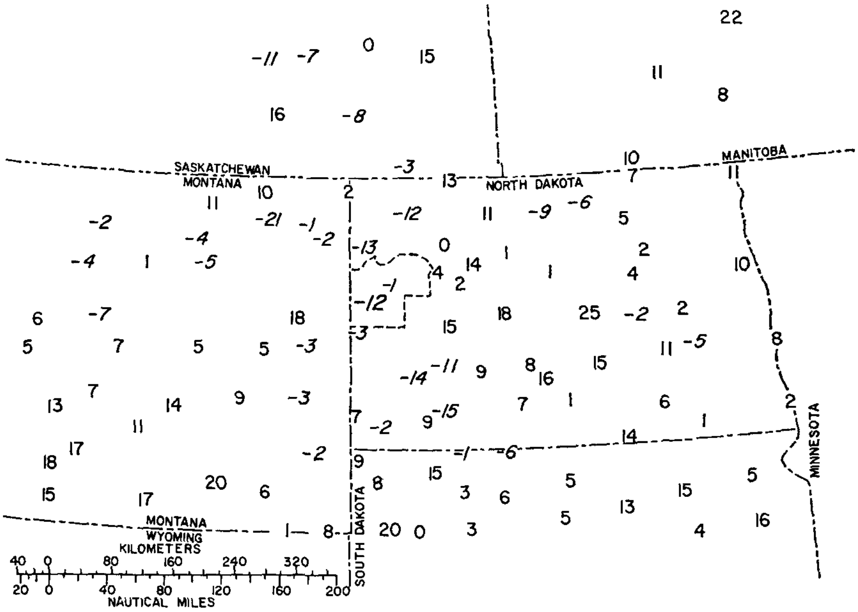

Fig. 3b. As in Fig. 3a except for cold days. The average value over the region is 0.48 with a standard deviation of 0.87.

tended target, rather than as evidence of bias in the selection of no-seed days. This possibility would seem to be greatest at stations close to the target area. Therefore, while one's first tendency in looking for bias might be to give greatest weight to stations close to the target area, one should consider the general pattern throughout the whole extended area.

Fig. 3a suggests that the excess rainfall on seed warm days was due in part to large-scale meteorological factors (see comments above on breakdown of warm days among types). However, there is little evidence in Fig. 3b that the rainfall deficiencies on cold seed days were related to large-area effects, despite the fact that they were related to an overabundance of totally dry seed days, as noted above.

The large-area analysis for the days with dynamic seedability (Fig. 3c) does not show any obvious bias, and certainly nothing of the magnitude found by

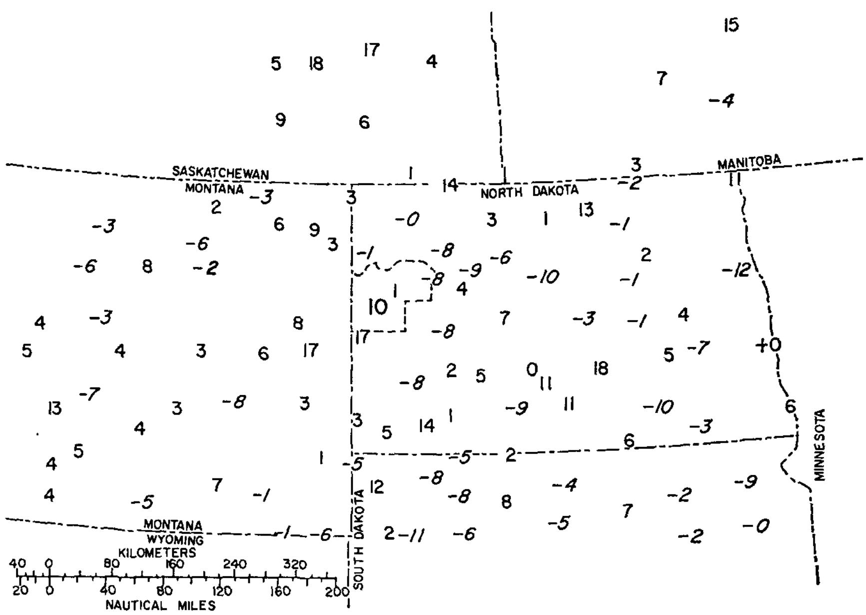

Fig. 3c. As in Fig. 3a except for days with dynamic seedability. The average regional value is 0.16 with a standard deviation of 0.70.

TABLE 6. Breakdown of days in 500 mb temperature and dynamic seedability stratifications according to objective type and seed/no-seed decision.

Type	Warm ($-10C \geq T_{500} > -15C$)	Cold ($-15C \geq T_{500} > -20C$)	No dynamic seedability	Dynamic seedability
1a	47/14	28/6	36/9	26/8
1b	34/13	18/16	10/10	7/3
2a	4/1	5/1	2/1	3/0
2b	13/2	3/1	3/0	2/1
3a	23/7	2/1	5/3	19/6
3b	28/5	3/1	5/3	15/3
1a+1b +2a (dry)	85/28	51/23	48/20	36/11
2b+3a +3b (wet)	64/14	8/3	13/6	36/10

Gelhaus *et al.* (1974) on the GRRP. The results of the tests for bias for the stratifications with significance levels less than 0.10 in Table 4 are summarized in Table 7.

d. Summary of tests for bias

After giving consideration to the statistical tests carried out according to the original project design and to the searches for bias, we are inclined to conclude that the differences between seed and no-seed days within certain stratifications are too great to be attributed entirely to chance, i.e., that they are due at least in part to seeding effects. In particular, the dynamic seedability stratification shows no obvious bias under any of the checks used.

4. Discussion and conclusions

a. Overlapping of results

In order to interpret the results, it is necessary to consider the overlaps among the different stratification systems. Returning to Table 6, the cold days are seen to be nearly all Type 1 days, which is not surprising in view of the low water vapor contents associated with cold air masses. The days common to the Type 1 and warm stratifications were generally stable and produced little rain, so we suspect that the weakly negative indications for Type 1a and Type 1b days are due principally to the cold days.

The results for Type 3a, Type 3b, and warm days are nearly identical. The suggestion is that the same days were responsible for the results for both the Type 3 and the warm days and that the Type 1 and Type 2 days in the warm column did nothing to change the results.

The average 500 mb temperature for the days with dynamic seedability is −12°C, suggesting that the good results on warm days merely reflected the inclusion of days with dynamic seedability. The intersection of the dynamic seedability and cold sets contains 15 days, which is hardly sufficient to show what the effect of seeding is on cold days with seedability.

TABLE 7. Summary of tests for bias in rainfall analysis. Evidence of bias indicated by X in appropriate square, lack of such evidence by check mark. Dash indicates test not appropriate to that stratification.

Stratification	Wet vs dry days	Statistics of meteorological variables	Cross-check among stratifications	Large-area analysis
3a	√	√	—	√
3b	X	√	—	X
Warm	√	√	X	X
Cold	X	√	√	√
Dynamic seedability	√	√	√	√

b. Potential for rainfall increase

The actual numbers in Table 2 for dynamic seedability days indicate an increase in the number of rainfall events by a factor of 2.1 and an increase in average rainfall per event by a factor of 1.7, so the seeding factor for total rainfall on the target area is about 3.5. There are about 50 days per summer with dynamic seedability. Without seeding, each such day wetted an average 5 gages out of the 67 with the average rainfall accumulation being 0.11 inch; with seeding, each such day wetted 11 gages with the average accumulation being 0.19 inch. These numbers suggest a potential for about 1 inch of extra rainfall per growing season for western North Dakota by silver iodide seeding below selected clouds on days with dynamic seedability.

c. Conclusions

Our tentative conclusions are:

1) Rainfall increases were produced by seeding on days when the cloud model predicted increases in cloud height would follow silver iodide seeding. It is likely, therefore, that the rainfall increases were due in part to enhanced cloud growth induced by silver iodide seeding.

2) The modeling studies indicate that dynamic growth can result from artificial glaciation beginning very slowly at −5°C and completed at −25°C. The experimental results tend to confirm this, in that dynamic effects apparently were induced by seeding at rates of a few hundred grams of AgI per hour from below cloud base. It is not necessary to induce total glaciation at −5 or −10°C with massive doses of silver iodide to produce significant dynamic effects.

3) The superposition of seeding for hail suppression at rates up to 1 kg h^{-1} of AgI does not preclude the

possibility of increased rainfall over a season. It is possible that rainfall from some hail-bearing cells is suppressed, but the NDPP results provide no evidence to this effect.

4) The seeding factor for days with dynamic seedability is about 3 or 4. This indicates a potential increase of approximately 1 inch of rainfall per growing season for western North Dakota.

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