AN EVALUATION OF THE NORTH DAKOTA CLOUD MODIFICATION PROJECT: 1976-1982

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A Final Report To The
North Dakota Weather Modification Board

June 1985

ABSTRACT

An operational cloud seeding project in North Dakota, operated by the state during summer months of 1976 through 1982, is evaluated using an analysis of covariance. Seeding was accomplished via the release of silver iodide, both at cloud base and in-cloud for the purposes of reducing hail damage and increasing rainfall. Priority was given to the hail reduction objective. Target and control areas were defined based on the intent of the sponsor and downwind regions were defined daily based on a regional trajectory model. Comparisons were made between target and control, target and downwind, and control and downwind. Evidence was found indicating an overall increase in rainfall downwind of the target and within the target when large systems were seeded for hail suppression. Statistical significance was marginal in all cases.

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I. INTRODUCTION

The North Dakota Cloud Modification Project is a fully-operational summer-time cloud seeding project. The project is sponsored and operated by a state agency, the North Dakota Weather Modification Board, in cooperation with participating counties. County participation is determined by local voters through a petition process and local elections. Costs of the operation are shared by the state and the counties. The current project has been in place since 1976 (as a state project), succeeding a series of locally operated and funded cloud seeding projects which date back to 1961. The NDCMP offers a dual goal of reducing hail damage and increasing growing season precipitation. This study is an attempt to assess the project's success in attaining the latter goal.

Meaningful evaluations of the effectiveness of operational weather modification projects have never come easy. The absence of objective statistical controls (required by the non-repeatability of atmospheric events), combined with inadequate data sampling networks have generally made it difficult, if not impossible, to measure the relatively small effects induced by seeding clouds. When the further natural random variations present in cumulus cloud systems such as those treated in North Dakota are included, the difficulty of the problem magnifies considerably.

The North Dakota Weather Modification Board has conscientiously applied itself to obtaining useful evaluations. In its early years, the Board sponsored an evaluation based primarily on a state-operated project in South Dakota which operated under the same principles as the NDCMP (Pellett, et al., 1977). That study, which included one year of seeding in North Dakota (1976), provided indications of an increase in seasonal rainfall due to seeding on the order of 5 to 10%. Since 1980, the Board has actively sought to develop evaluation methods through the NOAA Federal/State Cooperative Project, whereby scientists from several university groups have cooperated with the private sector to increase the understanding of the processes at work.

The philosophy and procedures applied in this report have evolved through a series of efforts, mostly funded by the NDWMB but with some corollary work funded through the Bureau of Reclamation. Evaluations of cloud-seeding in North Dakota have included Eddy, et al. (1979) with its use of "detrended" daily rainfall and a consideration of "downwind" effects (indications of a 7% increase in daily rainfall attributable to seeding, averaged over the entire state during the early summer), Eddy (1981) in which trajectories were used to determine downwind areas, and Eddy, et al. (1982) which employed the analysis of covariance as an analysis tool. The latter two studies each portray significant increases in precipitation in and downwind of the seeding, but each has its weakness as an evaluation. In both studies the "seed" group includes only those situations actually seeded, while the unseeded group includes all others on those days. In keeping with the hail suppression mission of the project, only the most intense (hard raining) storms were included in the seed group, an advantage the control group did not have.

Two studies done within the Federal/State Cooperative Program (Johnson, 1983 and Johnson and Foster, 1985) laid the groundwork for this study by applying an analysis of covariance to radar and raingage data taken during the 1981 and 1982 NDCMP's. Covariates employed were taken from rawinsonde and cloud model data.

II. THE NORTH DAKOTA CLOUD MODIFICATION PROJECT

In response to frequent crop-losses due to hail damage, local groups in southwestern and western North Dakota began seeding clouds in the early 1960's. They apparently had at least the appearance of success in their efforts as the areas "protected" by the seeding grew steadily through the 1960's and the early 1970's (Schock, 1977). The seeding was performed by releasing silver iodide crystals from generators attached to the wings of aircraft flying below cloud base. A secondary mission of increasing rainfall was quickly added. The early projects consisted of aircraft, pilots, chemical and little else. During the mid 60's, weather radar was added to increase the lead time in treating hail storms. By 1975, nineteen counties were participating in cloud modification projects in the state. The financing was obtained from private solicitation and some county funds.

The state took over operation of the projects in 1976, combining all of them into one large project with the state supplying meteorological support and contracting for the services of the cloud seeding equipment. Eighteen counties participated in that initial season. An erosion of participation began almost immediately, and the 1977 season began with eleven counties participating. Attrition slowed after that and the 1982 project operated with seven counties, all in the western half of the state. No new counties enrolled in the project during that period. During 1976, three counties in northwestern South Dakota conducted projects in concert with the North Dakota operation. One of those counties has continued, usually employing the same operator as North

Dakota. The current study encompasses the period 1976 to 1982.

III. DATA SOURCES

Daily rainfall data were obtained from the National Weather Service Cooperative Network. Daily rainfall reports from within 300 km of the target area were averaged over pre-specified areas. The areas were

(a) within the target,

(b) within 50 km of the target and not downwind of it,

(c) within 12 hours downwind of the target as determined by a trajectory model initiated with 00 GMT winds, and

(d) within 300 km of a target area but not in (a), (b), or (c).

The rainfall of (a) was considered to be seeded and is area 0. The rainfall in the 50 km area around the target (b) is considered to be not seeded (control) and is Area 1. The rainfall in category (c) is called downwind of the seeding and is Area 2. The regional rainfall in category (d) was employed as a covariate in the statistical procedure which will be described later.

Covariates, in addition to the regional rainfall, were taken from NWS rawinsonde observations at Rapid City (RAP), Bismarck (BIS), and Glassgow (GGW). Data from the 12 GMT observations taken the day prior to the rainfall report (at the beginning of the 24-hour rainfall period) were utilized. Covariates included parameters normally obtained from rawinsonde observations such as temperature, humidity, winds aloft, etc. and quantitative output from the one-dimensional Great Plains Cloud Model (GPCM) described by Hirsch (1971). This model does not give a result if (1) temperature increases for convection are excessive, or (2) if the sounding is not complete through 200 mb.

The trajectory model employed to determine downwind areas is described by Hefter and Taylor (1975). The model uses rawinsonde winds to compute trajectory locations from a specified point at three-hourly intervals. Transport in a layer between 1000 and 3000 meters above ground level was assumed. The model was modified so that, in effect, the operational area outline was transported down stream. Any raingage location outside the target area that fell under the envelope produced by the trajectories was considered to be downwind of the seeding. The trajectory computations were carried out for 12 hours. An example target/control/downwind configuration from the 1982 project is shown in Figure 1. The outlined counties are the operational districts (target). The approximate control area is outlined in solid. The downwind area is crosshatched.

The use of the 12 GMT GPCM and the trajectory model initiated at 00 GMT implies an assumption that the rainfall observed is from cumuliform clouds which form during the late afternoon and persist through the evening. It is not expected that the trajectory model (which is regional in scale) traces the movement of the seeding material itself, but the rain producing units (mostly thunderstorms) should move in a manner influenced greatly by the computed trajectories, so a valid representation of downwind is obtained.

IV. STATISTICAL PROCEDURES

Evaluation of weather modification projects, especially non-randomized operations, is made especially difficult by the presence of large natural variations from cloud-to-cloud, day-to-day, and place-to-place which are greater than the expected effects of cloud seeding. The problem is compounded by the difficulty present in measuring the effects of

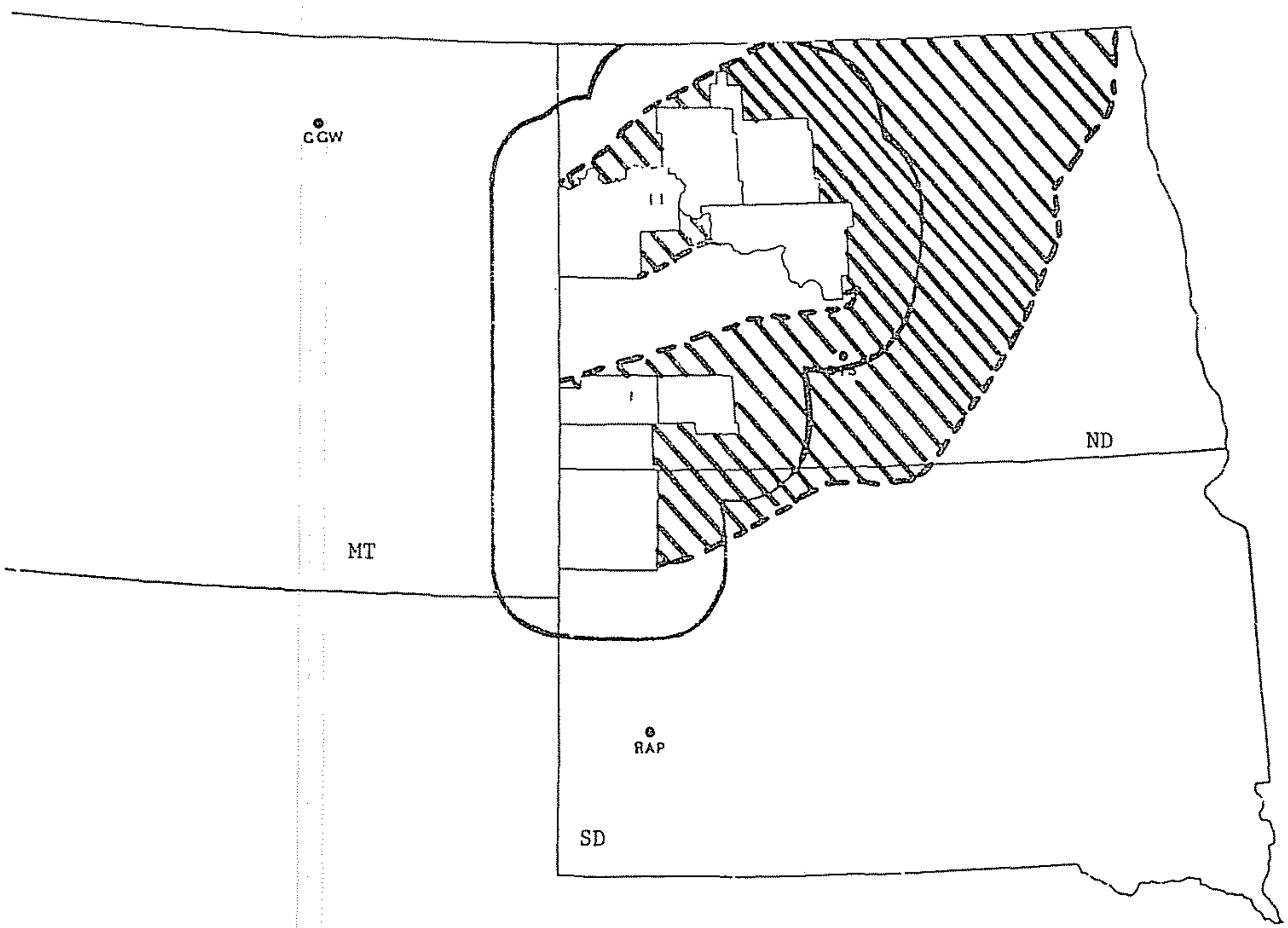

Figure 1: A typical target/control/downwind configuration with 1982 target counties.

seeding and the impossibility of repeating an experiment in a laboratory. The evaluation technique employed needs to be designed to minimize the effects of that natural variation.

The analysis of covariance is an established method by which much variation attributable to antecedent atmospheric conditions can be removed, thus allowing a better comparison for seeding effects. The technique's applications to weather modification problems are described in Eddy, Johnson, and Duchon (1982) and in Johnson and Eddy (1982). Direct application of analysis of covariance in evaluation of weather modification activities can be seen in Spar (1957), Mielke, et al. (1977), Eddy, et al. (1982), Johnson (1983) and Johnson and Foster (1985).

The mathematical form of the model as given by Affifi and Azen (1979) is:

$$(1) \qquad Y_{ij} = \mu + \alpha_i + \sum_k \beta_k (X_{kij} - \bar{X}_{k..}) + \varepsilon_{ij} \quad ,$$

where Y_{ij} = individual measurements of the response variable

μ = overall mean of the response variable

α_i = differential effect on the response variable due to the individual treatments (seeding)

β_k = regression coefficients of the covariates

X_{kij} = observed values of the covariates

$\bar{X}_{k..}$ = mean values of the covariates

ε_{ij} = residual error term.

The response variable is the logarithm (base 10) of the daily rainfall (in. x 100) averaged over the particular pre-specified area. A simple average of reports within the area was used and stations within 5 km of the target were included both in the average of the target and the appropriate non-target area average. Cloud seeding in the North Dakota project is primarily conducted on large existing or developing systems. An experimental unit was taken to be a day with at least 10% of the reporting stations in each of the target (area 0) and control (area 1) reporting rainfall, and an average rainfall of at least .01 in. within each area, thereby eliminating the effects of isolated or light precipitation events which normally are not seeded.

Covariates were selected from the pool of rawinsonde and GPCM output variables. The log of the mean rainfall outside the target, control and downwind areas and the fraction of those locations reporting rainfall were also considered. Potential covariates were screened through a stepwise regression eliminating those variables whose probability of having a zero coefficient was greater than .05. The analysis of covariance was then run repeatedly, eliminating the poorest covariate each time until all covariates were significant at the .05 level.

The statistical test of the null hypothesis that daily rainfall over three areas were not different from each other was performed on the "adjusted" response variable given by

$$(2) \qquad Y^*_{ij} = Y_{ij} - \sum_k \beta_{kij} \, (X_{kij} - \bar{X}_{k..}) \; .$$

This new response variable Y^*, adjusted for the value of the covariates has less variance than the raw response variable and biases due to unfavorable atmospheric conditions will also have been reduced, thus enhancing the value of the significance tests.

The significance test was performed using the statistic

$$(3) \quad F = \frac{MS_m}{MS_\varepsilon} ,$$

where MS_m is the mean square due to the model and

MS_ε is the mean square due to the error terms.

All statistical computations in this study were performed using the appropriate procedures supplied with the Statistical Analysis System (SAS) resident on the University of Oklahoma's IBM 3081 computer.

The logarithm of the mean rainfall was used as the response variable since it is distributed approximately as a normal variable and since the effects of seeding on rainfall (if any) are expected to be related to the amount of rainfall.

V. THE ANALYSIS

The seeding districts for each year are outlined and the raingages denoted by plus signs on the maps of Figures 2 through 6. Seeding methods and philosophy have changed little through the life of the project. The primary mission is to seed (heavily) the storm systems that are producing hail or that are considered likely to hail. Rain increase missions are relatively rare, especially during July and August. In practice, there are few efforts to produce rain where none would fall naturally. Daily rainfall reports and trajectory computations were used to calculate average daily rainfall in the target, in the control areas and downwind of the target. Since hail suppression is the primary mission, it was decided to include only the days when significant seeding was likely to have taken place (or would have in the control area had it been operational). No effort was made to determine the actual seeding practice

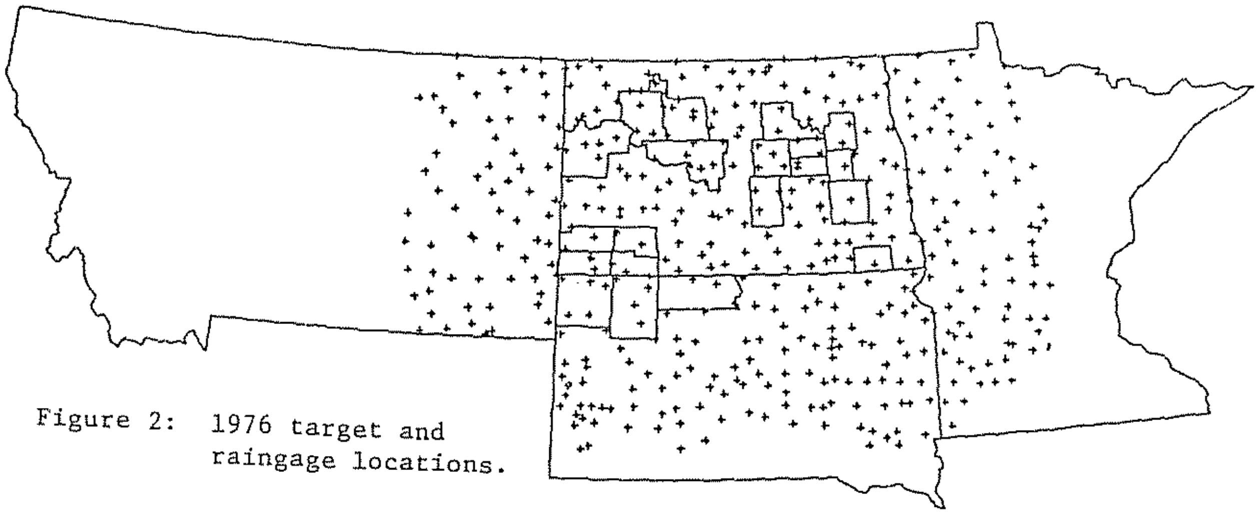

Figure 2: 1976 target and raingage locations.

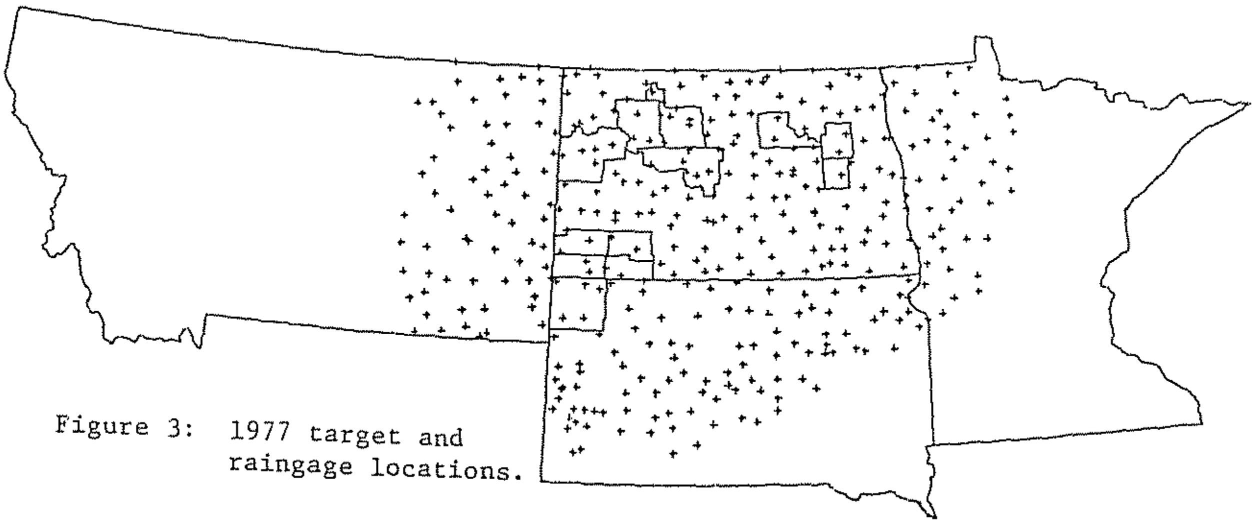

Figure 3: 1977 target and raingage locations.

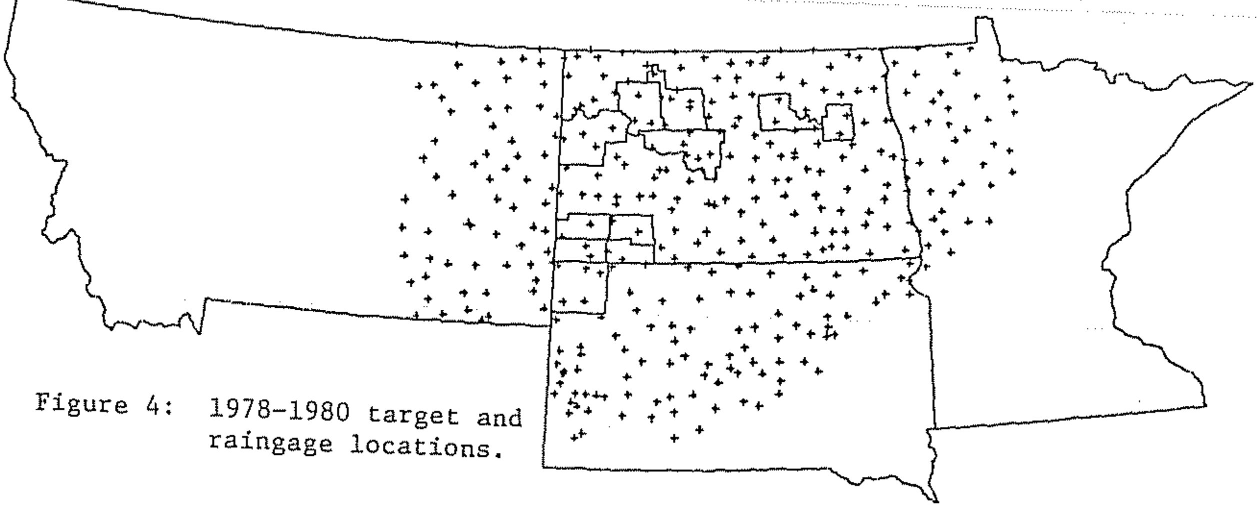

Figure 4: 1978-1980 target and raingage locations.

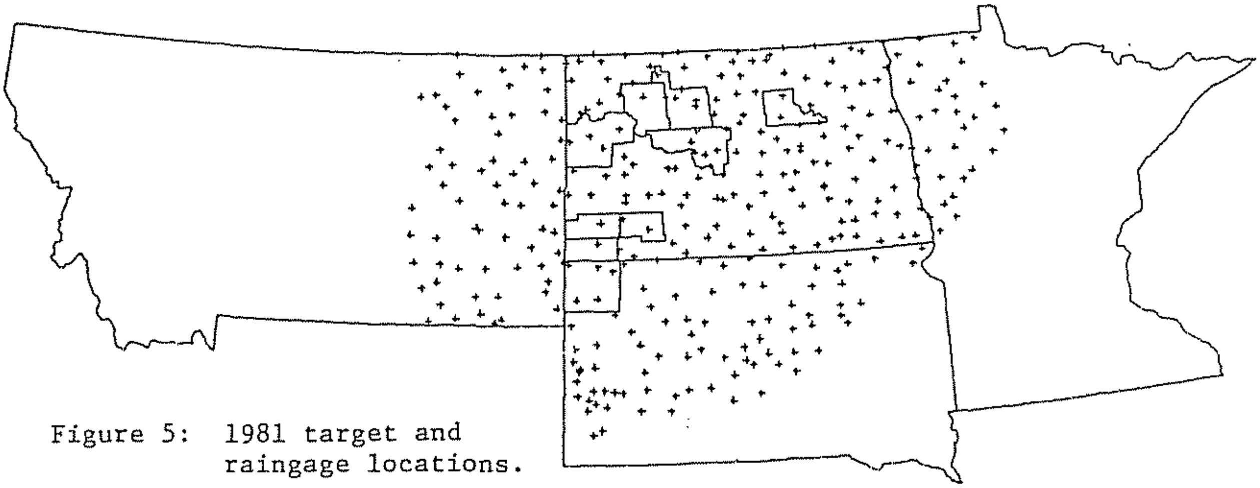

Figure 5: 1981 target and raingage locations.

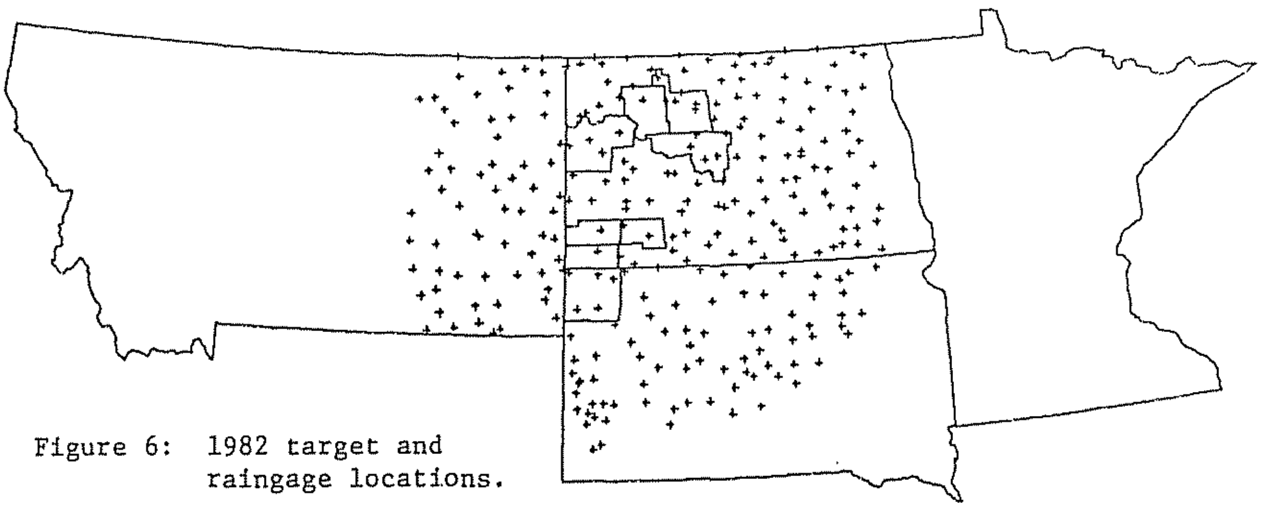

Figure 6: 1982 target and raingage locations.

since no objective determination of "seedability" could be made regarding events in the control area. Rainfall within the target was considered to be seeded, rainfall downwind of the target was considered to be downwind of the seeding and rainfall in the control was considered to be not seeded. It was assumed that if significant rain fell in the target that the clouds producing that rain would (or should) have been seeded at some time. Rainfall was determined for each day in June, July and August (the usual seeding period although some May operations have occurred) of the years 1976 through 1982. Rainfall outside the experimental area was treated similarly to provide covariate information. To reflect the usual project seeding practices seeding was assumed to have taken place if at least 10% of the reporting stations in each the target and control areas reported rainfall and if the overall mean rain in each area exceeded .01 inch.

A total of 358 days were included. Means for the target, control and downwind areas are presented in Table 1, along with annual and monthly means. Values are in hundredths of inches. Mean rainfall in the target exceeded that in the control during 5 of the 7 years studied, and exceeded the downwind rainfall in 4 years. The downwind rainfall exceeded the control rainfall every year except 1982. The overall advantage for the target was approximately 8% over the control. That advantage was obtained through a 12% increase in July and a 15% increase in August. A month-by-month listing of categorical rainfall is given in Table 2. The target had an advantage over the control in 15 of the 21 months of operation. The target led the downwind in 10 months. The downwind maintained an advantage over the control area in 15 months.

Table 1. Annual, monthly and overall mean values of daily precipitation in the target, control and downwind areas for the operational months of 1976 through 1982 (rainfall in hundreths of inches).

	Target	Control	Downwind	Days
All Years	14.24	13.17	14.39	358
1976	10.68	11.07	13.67	48
1977	13.02	12.39	13.19	58
1978	16.86	14.83	17.45	43
1979	14.19	12.94	13.87	44
1980	16.79	13.91	15.93	56
1981	15.11	14.00	14.21	58
1982	13.01	13.04	12.85	51
June	14.79	14.68	15.17	135
July	14.05	12.58	14.41	111
August	13.75	11.92	13.45	112

The analysis of covariance was performed using several stratifications in an effort to ascertain whether any meaning can be assigned to the above comparisons. The initial runs used all data with covariate information limited to the log of the mean rain outside the experimental areas and the fraction of outside stations reporting rain. Covariate information was available for all 358 rain days in the study. Model results are shown in Table 3. The model explained 54 percent ($R^2 = .54$) of the variance in the logarithmic transform of the rainfall. The model showed a slight advantage for the target over the control (not significant with a p-value of .58), a slight advantage for the downwind over the target (of some interest but not significant with a p-value of .28) and

Table 2. Monthly mean 24-hour rainfall by area 1976-1982 (hundredths of inches).

Month	Year	Target	Control	Downwind	Days
June	1976	15.66	16.17	20.10	22
July	1976	5.03	5.44	7.57	13
August	1976	7.91	8.08	8.87	13
June	1977	14.66	14.32	14.02	19
July	1977	16.38	14.29	15.73	16
August	1977	9.32	9.47	10.73	23
June	1978	17.09	16.55	14.34	17
July	1978	20.37	16.39	21.76	13
August	1978	13.06	11.03	17.22	13
June	1979	14.15	12.50	14.70	15
July	1979	16.56	14.24	15.69	17
August	1979	10.88	11.65	10.26	12
June	1980	14.47	13.39	14.98	19
July	1980	10.73	9.33	9.23	16
August	1980	23.51	17.88	21.88	21
June	1981	12.70	12.54	13.38	25
July	1981	15.24	15.12	16.06	20
August	1981	19.53	15.06	12.96	13
June	1982	15.50	17.62	14.22	18
July	1982	13.11	11.88	14.41	16
August	1982	10.27	9.29	9.94	17

an advantage for the downwind over the control area (quite interesting with a p-value, or confidence level of .10). Since the model is balanced (the same number of events in each category), the adjusted mean is identical to the mean of the response variable, but the adjusted variable varies less (the standard deviation is smaller by a factor of 2) increasing the chance for a small p-value. The p-value is the probability that the difference in the means is zero.

Table 4 shows the analysis for June, indicating no appreciable differences in the transformed rainfall. July results are contained in Table 5, indicating a considerable downwind advantage over both target and control with the downwind area's excess over the control being significant at .08. In August (Table 6) the target holds a considerable advantage over the control, with a p-value of .18. The difference between target and downwind disappears in August. It is interesting to note again, that most of the seeding for rain increase occurs in June when the crops are less vulnerable to hail damage. Emphasis shifts heavily to hail suppression seeding modes during July and August. Virtually all seeding in August is done in the hail suppression mode. (Accumulated flight hours by seeding mode can be obtained from the annual contractor reports to the NDWMB such as Weather Modification, Incorporated, 1983.)

Further analyses included data from the NWS rawinsonde sites and cloud model results as covariates and stratifiers in addition to the extra-area rainfall. The inclusion of rawinsonde data requires the exclusion of rainfall when rawinsonde or cloud model data are not available. The Bismarck sounding and cloud model explained 61 percent of the variance on 304 days. The results of that analysis are summarized

Table 3. Analysis of covariance using extra-area rainfall for covariates.

Stratification: All Months

$R^2 = .54$

AREA	N	RAIN	LGRAIN
0	358	14.24	.9656
1	358	13.17	.9545
2	358	14.39	.9879

P-MATRIX	AREA	0	1	2
	0	.	.58	.28
	1	.58	.	.10
	2	.28	.10	.

Table 4. Analysis of covariance of June rainfall using extra-area rainfall for covariates.

Stratification: Month = June

$R^2 = .54$

AREA	N	RAIN	LGRAIN
0	135	14.79	.9613
1	135	14.05	.9851
2	135	13.75	.9821

P-MATRIX	AREA	0	1	2
	0	.	.47	.53
	1	.47	.	.93
	2	.53	.93	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

Table 5. Analysis of covariance of July rainfall using extra-area rainfall for covariates.

Stratification: Month = July

$R^2 = .54$

AREA	N	RAIN	LGRAIN
0	111	14.05	.9760
1	111	12.58	.9600
2	111	14.41	1.0254

P-MATRIX	AREA	0	1	2
	0	.	.66	.18
	1	.66	.	.08
	2	.18	.08	.

Table 6. Analysis of covariance of August rainfall using extra-area rainfall for covariates.

Stratification: Month = August

$R^2 = .54$

AREA	N	RAIN	LGRAIN
0	112	13.75	.9607
1	112	11.92	.9121
2	112	13.45	.9577

P-MATRIX	AREA	0	1	2
	0	.	.18	.94
	1	.18	.	.21
	2	.94	.21	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

in Table 7. Indications of a downwind increase are present with no target/control difference noticeable. A similar analysis using Glassgow data (Table 8) utilized 306 days and also explained 61 percent of the variance. The downwind advantage over the control is still present, but any difference between target and control or target and downwind is not apparent. The analysis using Rapid City data provided an explanation of 59 percent of the variance for 322 days without any appreciably different results (Table 9). In each of these analyses, the outside area rainfall provided most of explanation of variance (about 50 percent).

Although the analysis using Rapid City data explained slightly less variance than the others, the presence of a larger rainfall data set led to its use in exploring some other stratifications based on atmospheric or cloud model information. Covariates employed, in addition to the outside rainfall variables were: temperature at 850 mb, temperature at 400 mb, wind speed at 850 mb and v-component (southerly component) of the wind at 850 and at 200 mb. The first stratification, shown in Tables 10 and 11 was according to stability as determined by the lifted index (LI < 0 is considered unstable). No statistical significance can be ascribed to any of the results. Stratification according to the cloud top temperatures forecasted by the cloud model, using a moderate sized storm (Table 12 for cold and Table 13 for warm clouds) showed a similar result, although the relatively small warm top data set produced at p-value of .12 that the downwind differed from (greater than) the control area. The reader should be reminded here that these were days which actually did produce significant rainfall.

Table 7. Analysis of covariance utilizing Bismarck rawinsonde and cloud model information.

Covariate Rawinsonde: BIS

Stratification: None

$R^2 = .61$

AREA	N	RAIN	LGRAIN
0	304	14.54	.9683
1	304	13.39	.9612
2	304	14.54	.9955

P-MATRIX	AREA	0	1	2
	0	.	.73	.18
	1	.73	.	.09
	2	.18	.09	.

Table 8. Analysis of covariance utilizing Glassgow rawinsonde and cloud model information.

Covariate Rawinsonde: GGW

Stratification: None

$R^2 = .61$

AREA	N	RAIN	LGRAIN
0	306	14.73	.9673
1	306	13.51	.9563
2	306	14.37	.9838

P-MATRIX	AREA	0	1	2
	0	.	.60	.42
	1	.60	.	.18
	2	.42	.18	.

Area 0 = Target
Area 1 = 50 miles radius of target, not downwind
Area 2 = Downwind of target.

Table 9. Analysis of covariance utilizing Rapid City rawinsonde and cloud model information.

Covariate Rawinsonde: RAP

Stratification: None

$R^2 = .59$

AREA	N	RAIN	LGRAIN
0	322	14.28	.9577
1	322	13.12	.9479
2	322	14.22	.9787

P-MATRIX	AREA	0	1	2
	0	.	.63	.31
	1	.63	.	.14
	2	.31	.14	.

Area 0 = Target
Area 1 = 50 miles radius of target, not downwind
Area 2 = Downwind of target.

Table 10. Analysis of covariance for stable days.

Covariate Rawinsonde: RAP

Stratification: Stable (LI ≥0)

R^2 = .59

AREA	N	RAIN	LGRAIN
0	170	12.71	.9005
1	170	11.76	.8869
2	170	12.62	.9208

P-MATRIX	AREA	0	1	2
	0	.	.63	.48
	1	.63	.	.23
	2	.48	.23	.

Table 11. Analysis of covariance for unstable days.

Covariate Rawinsonde: RAP

Stratification: Unstable (LI <0)

R^2 = .59

AREA	N.	RAIN	LGRAIN
0	149	16.12	1.0221
1	149	14.70	1.0160
2	149	16.11	1.0443

P-MATRIX	AREA	0	1	2
	0	.	.84	.47
	1		.	.35
	2	.84	.47	.

Area 0 = Target
Area 1 = 50 miles radius of target, not downwind
Area 2 = Downwind of target.

Table 12. Analysis of covariance for days with model predicted cold cloud tops.

Covariate Rawinsonde: RAP

Stratification: Model Predicted Cold Tops (3-km updraft radius)

$R^2 = .59$

AREA	N	RAIN	LGRAIN
0	249	14.22	.9679
1	249	13.13	.9639
2	249	14.27	.9842

P-MATRIX	AREA	0	1	2
	0	.	.86	.49
	1	.86	.	.39
	2	.49	.39	.

Table 13. Analysis of covariance for days with model predicted warm cloud tops.

Covariate Rawinsonde: RAP

Stratification: Model Predicted Warm Tops (3-km updraft radius)

$R^2 = .59$

AREA	N	RAIN	LGRAIN
0	73	14.47	.9231
1	73	13.06	.8933
2	73	14.06	.9599

P-MATRIX	AREA	0	1	2
	0	.	.49	.39
	1	.49	.	.12
	2	.39	.12	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

Tables 14, 15, 16 and 17 include summaries of results using "advection-type" stratifications based on the winds at 300, 500 and 850 mb, described by Elliott (1973) and discussed at length by Elliott and Griffith (1984). The advection types are closely related to the synoptic situation (at the observing location, at the time of observation). The four types are "cold over cold" (cooling aloft and near the surface, Table 14), "cold over warm" (Table 15), "warm over cold" (Table 16), and "warm over warm" (Table 17). It is expected that the "cold over warm" class would be the most important, since it normally occurs ahead of a surface front, with an upper air trough approaching. Even in the absence of such triggers, the tendency is to de-stabilize the air mass. However, the only discernable difference among the groups is that the "warm over cold" type (frequently producing stratiform precipitation) appears to be less conducive to precipitation than the other three. Perhaps a more important interpretation would be that the early morning rawinsonde at Rapid City is too distant in time and space for such a stratification to be useful. The downwind area does hold a considerable advantage over the target with advection type "warm over warm" (Table 17).

Tables 18 and 19 present summaries of an analysis based upon the presence of a dynamic growth potential (an important difference in height between a seeded and non-seeded cloud according to the GPCM). An arbitrary division was made declaring a day to have dynamic potential if a seeding related growth of .3 km was produced by any sized cloud. Slightly more rain occurred on days without dynamic potential, and no comparisons regarding target proximity were meaningful. A final

Table 14. Analysis of covariance for advection type cold over cold.

Covariate Rawinsonde: RAP

Stratification: Advection Type Cold over Cold

$R^2 = .60$

AREA	N	RAIN	LGRAIN
0	94	14.69	.9686
1	94	13.37	.9531
2	94	13.95	1.0014

P-MATRIX	AREA	0	1	2
	0	.	.69	.39
	1	.69	.	.21
	2	.39	.21	.

Table 15. Analysis of covariance for advection type cold over warm.

Covariate Rawinsonde: RAP

Stratification: Advection Type Cold over Warm

$R^2 = .60$

AREA	N	RAIN	LGRAIN
0	100	14.41	.9693
1	100	12.75	.9513
2	100	13.78	.9542

P-MATRIX	AREA	0	1	2
	0	.	.63	.68
	1	.63	.	.94
	2	.68	.94	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

Table 16. Analysis of covariance for advection type warm over cold.

Covariate Rawinsonde: RAP

Stratification: Advection Type Warm over Cold

R^2 = .60

AREA	N	RAIN	LGRAIN
0	57	11.96	.9600
1	57	11.47	.9263
2	57	12.28	.9543

P-MATRIX	AREA	0	1	2
	0	.	.49	.91
	1	.49	.	.57
	2	.91	.57	.

Table 17. Analysis of covariance for advection type warm over warm.

Covariate Rawinsonde: RAP

Stratification: Advection Type Warm over Warm

R^2 = .60

AREA	N	RAIN	LGRAIN
0	70	15.42	.9175
1	70	14.72	.9492
2	70	16.78	.9946

P-MATRIX	AREA	0	1	2
	0	.	.47	.08
	1	.47	.	.30
	2	.08	.30	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

Table 18. Analysis of covariance without dynamic growth potential.

Covariate Rawinsonde: RAP

Stratification: Dynamic Growth Potential < .3 km

$R^2 = .59$

AREA	N	RAIN	LGRAIN
0	129	14.85	.9632
1	129	13.65	.9448
2	129	14.63	.9852

P-MATRIX	AREA	0	1	2
	0	.	.57	.50
	1	.57	.	.22
	2	.50	.22	.

Table 19. Analysis of covariance with dynamic growth potential.

Covariate Rawinsonde: RAP

Stratification: Dynamic Growth Potential ≥ .3 km

$R^2 = .59$

AREA	N	RAIN	LGRAIN
0	193	13.89	.9541
1	193	12.76	.9499
2	193	13.95	.9743

P-MATRIX	AREA	0	1	2
	0	.	.88	.45
	1	.88	.	.36
	2	.45	.36	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

stratification, using the 500 mb wind direction as a stratifier, indicated that larger rainfall amounts were associated with a southerly component than with a northerly one. The southerly component group also showed indications of a downwind effect (especially relative to the control area). The information is summarized in Tables 20 and 21.

Since the analysis of covariance employing rawinsonde data added little information and the differences in the means between target and control disappeared under the logarithmic transformation, consideration was given to a stratification based on rainfall intensity. Indeed, the frequency distributions of rainfall and log-rainfall in the three areas, shown in Figures 7 and 8, suggest that the differences in the overall means occur due to the presence of more extreme values (both large and small) in the target than in the control. The downwind area's advantage over the target appears (through visual inspection) to arise from events slightly larger than the mode (.04 to .12 inches). A logarithmic transformation, therefore, would produce a mean target value that was much closer to the control mean than would the original data. The downwind area would be affected less than the target.

Rank-sum tests were performed to ascertain whether the rainfall data sets were consistently different from each other without recourse to parameters of the distributions. The results were:

(1) A probability of .15 that downwind values were not greater than control values,

(2) A probability of .29 that downwind values were not greater than target values, and

(3) A probability of .77 that target values were not greater than control values.

Table 20. Analysis of covariance when 500 mb wind has northerly component.

Covariate Rawinsonde: RAP

Stratification: 500-mb Wind from North

R^2 = .59

AREA	N	RAIN	LGRAIN
0	125	8.74	.8014
1	125	8.27	.7921
2	125	9.06	.8069

P-MATRIX	AREA	0	1	2
	0	.	.78	.87
	1	.78	.	.65
	2	.87	.65	.

Table 21. Analysis of covariance when 500 mb wind has southerly component.

Covariate Rawinsonde: RAP

Stratification: 500-mb Wind from South

R^2 = .59

AREA	N	RAIN	LGRAIN
0	197	17.79	1.0569
1	197	16.19	1.0467
2	197	17.50	1.0876

P-MATRIX	AREA	0	1	2
	0	.	.70	.24
	1	.70	.	.12
	2	.24	.12	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

FREQUENCY DISTRIBUTION OF RAIN(IN X 100) BY AREA

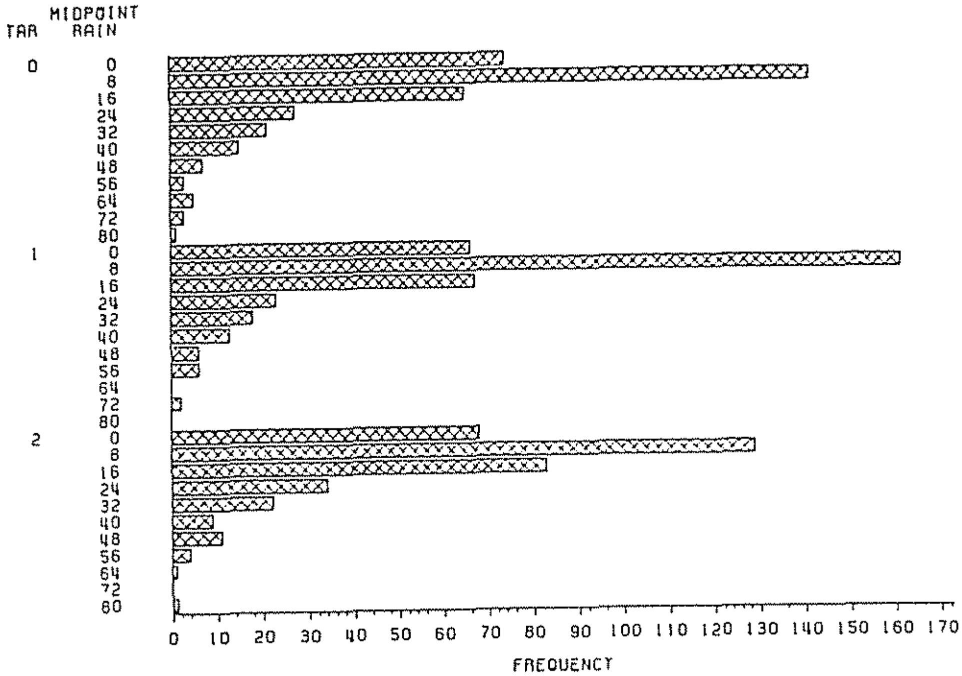

Figure 7: Frequency distribution of mean rainfall (in. x 100) by area.

FREQUENCY DISTRIBUTION OF LOG(BASE 10) OF RAIN BY AREA

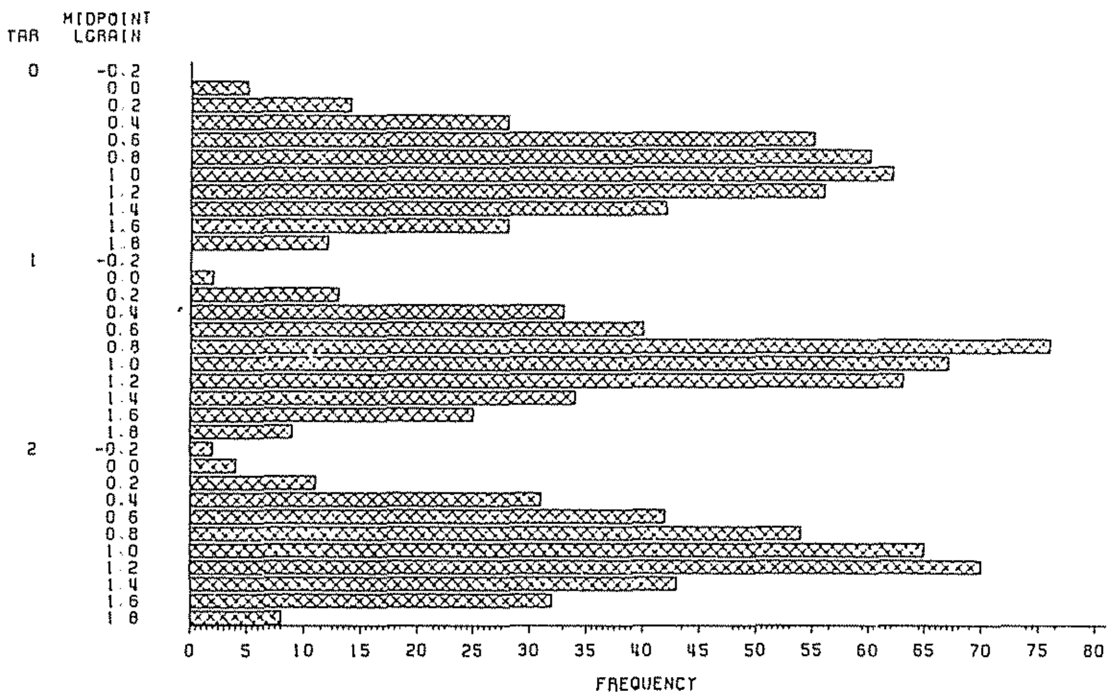

Figure 8: Frequency distribution logarithms (base 10) of mean rainfall (in. x 100) by area.

One can readily conclude that a case can be made for a downwind effect due to seeding (considering all cases), although statistical significance is weak. However, the rainfall advantage of the target over the control relies on the occurrence of a few relatively large mean rain values.

To test this assumption, rainfall was stratified according to the estimated intensity of rain. Days were classified as having "heavy rain" if the average rainfall of the stations reporting rain was greater than .5 inch in either the target or control. Otherwise, the rain was considered "light". The analysis of covariance using that stratification and without rawinsonde information produced the results shown in Table 22 and 23. The 67 days classified as having heavy rain produced a difference in the logarithmic transformation of rainfall between target and control that yields a p-value of .13. While not statistically significant by most standards, this result is highly suggestive of a predictable increase in precipitation in the target area on those days. The difference in the means indicate a 14% increase in rainfall in the target. No downwind effect is apparent. Conversely, on the days characterized by light rainfall, the downwind area has an appreciable advantage over the target and the control. Any target/control difference is negligible.

Interestingly, the apparent increase in rainfall in the target occurs at the "high" end of the intensity scale and similar increases in the target were seen in the July and August monthly stratifications. Almost all of the seeding done during those periods is done to suppress hail damage. This suggests that the advantage in rainfall within and downwind of the target could well arise from hail suppression seeding. If seeding

Table 22. Analysis of covariance for heavy rain days.

Stratification: Heavy Rain (average of non-zero reports > .5 in)

$R^2 = .54$

AREA	N	RAIN	LGRAIN
0	67	33.97	1.4366
1	67	29.82	1.3695
2	67	30.03	1.3979

P-MATRIX	AREA	0	1	2
	0	.	.13	.39
	1	.13	.	.52
	2	.39	.52	.

Table 23. Analysis of covariance for light rain days.

Stratification: Light Rain (average of non-zero reports < .5 in)

$R^2 = .54$

AREA	N	RAIN	LGRAIN
0	291	9.69	.8572
1	291	9.33	.8589
2	291	10.79	.8935

P-MATRIX	AREA	0	1	2
	0	.	.94	.09
	1	.94	.	.11
	2	.09	.11	.

Area 0 = Target
Area 1 = 50 mile radius of target, not downwind
Area 2 = Downwind of target.

primarily for rain enhancement within this project has had any effect it has escaped this analysis. It may be that "rain increase" cloud seeding is neglected or not pursued aggressively enough, it may be that such seeding is ineffective in the context of North Dakota's climate, or it may be that this analysis was ineffective at identifying any signature. Indeed, the evidence of a seeding effect (on rainfall) from the hail suppression seeding is not strong. Certainly no claim of a "proof" or of irrefutable evidence is tendered. It is suggested however that the data indicate a likelihood of increased precipitation from hail suppression seeding as practiced in North Dakota. It should be noted that the events in question occur, on an average, about 10 times during a 92 day seeding season.

VI. CONCLUSIONS

The analysis of covariance was used to evaluate the effectiveness of the operations of the North Dakota Cloud Modification Project in providing increased rainfall to the designated target areas. The evaluation period covered included the months of June, July and August of 1976 through 1982. A trajectory model was used to determine the extent and location of an area downwind of the seeding. National Weather Service Cooperative Observer Network data were used to provide daily rainfall amounts. A control area was established as a band 50 km wide up-wind and cross-wind of the target areas.

The analyses showed:

(1) Evidence of an overall increase in rainfall downwind of the target (relative to the control area) especially notable in July (15% increase significant at .08).

(2) Weak evidence of an increase in rainfall in the target relative to the control in August (15% increase significant at .18).

(3) Weak evidence of an increase in rainfall downwind of the target (relative to the target) when the Rapid City rawinsonde indicated warm advection both aloft and near the ground (9% increase significant at .08).

(4) Weak evidence of an increase in rainfall downwind (relative to the control) when the 500-mb wind at Rapid City has a southerly component (indicating a trough to the west: 8% increase significant at .12).

(5) Weak evidence of an increase in the target (relative to the control) on days with relatively heavy rain in either area (14% increase significant at .13).

(6) Evidence of an increase downwind (relative to the target and the control) on days with relatively light rain in both the target and the control (11% increase over the target significant at .09 and 13% increase over the control significant at .11).

The results are not statistically significant, but they are consistent with earlier studies. It appears that seeding for hail suppression in the mode employed in North Dakota likely increases rainfall. No evidence of the effectiveness of seeding for rainfall increases was found.

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