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STUDIES OF STATISTICAL TECHNIQUES TO EVALUATE WEATHER MODIFICATION

Volume 1 of the Final Reports of OSET

*by Chin-Fei Hsu, Floyd A. Huff, Stanley A. Changnon, Jr.,
and Robert W. Scott*

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ILLINOIS STATE WATER SURVEY

at the
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TABLE OF CONTENTS

ABSTRACT

Operational cloud seeding projects, those designed to produce a desired change in the weather and that are non-experimental in nature, continue to be pursued widely in the United States. Evaluation of such projects is now recognized as having scientific benefits. This 2-year study addressed various techniques and statistical methods to perform evaluations and to learn more about how to modify weather.

Through simulated changes in weather conditions, some of the most promising techniques were compared. It was determined that the principal component regression technique was the most powerful evaluation method under more circumstances than others. If a small increase (10% or so) of precipitation is expected, one should opt for multi-responses permutation procedures. If the expected effects of seeding are non-constant, use of simple non-parametric tests will yield higher powers.

Several operational projects were selected for testing in the project. The use of synoptic weather information in evaluating two large-area projects, the Muddy Road aircraft seeding project and a project in northwestern Oklahoma using ground generators, helps delineate the seeding effects of these two programs. Efforts using historical data in evaluating a number of operational projects serve the purpose of testing the findings from the simulation studies, and the results are generally consistent.

Various relevant issues examined during the project appear in this report. They include study of statistical bases for using historical data in evaluations; the potential biases in the evaluation process; and the combination of several tests of significance.

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The continued efforts, advice and support of Professor K. Ruben Gabriel who has served as a consultant of this project over many years, is deeply acknowledged.

We thank Don Kostecki of Kansas for providing us the information on seeding operations of the Muddy Road project and his help in the process of the evaluation. Thanks are extended to Claude Baker of the U. S. Geological Survey in Kansas for providing us rainfall data. We also acknowledge the willingness of Dr. Irving Krick and Dr. Newton Stone who provided the operational information for the Oklahoma project. The data used in the evaluation of the Muddy Road hail suppression operations and the Texas Panhandle hail suppression project were provided free by the Crop-Hail Insurance Actuarial Association.

The computer program used in the MRPP simulation was adopted from a version kindly provided to us by Paul W. Mielke. The program used in the evaluation of the Texas Panhandle hail suppression was furnished by B. Flury. Finally, we thank K. R. Gabriel and A. Gagin for allowing us to use the data of the 2 Israeli experiments for testing the evaluation techniques.

KEYWORDS

Weather modification; precipitation enhancement; rainfall; METROMEX; evaluation; statistics; operational (commercial) project; hail suppression; power of test; principal component regression; trend; piggyback; storm; simulation; regression; sum of rank power test; two regressions; double ratio; covariates; historical comparison; operational criteria; multi-response permutation procedure; tests of ratio-differences; potential biases in evaluation.

1. INTRODUCTION

This report is the first of a two-volume final report, which summarizes the results of an NSF-sponsored research (Grant ATM 81-07027) relating to the development and testing of techniques to evaluate operational weather modification projects. This report (volume 1) contains an introduction to the background and goals of the research, results of various analytical studies, and other topics related to the evaluation of operational projects. Volume 2 (Hsu, 1984) is a bibliography, and contains a list of references on the general issues of evaluation, statistical techniques, and designs of weather modification efforts. The project was a 2-year effort starting in June 1981, and is a continuation of research carried out earlier under other NSF grants. Final reports on the earlier works were submitted to NSF, and can be obtained from NTIS.

1.1 Objectives and Background of Study

The original project, entitled "Operational Seeding Evaluation Techniques" (OSET), was proposed by the Illinois State Water Survey to the National Science Foundation in 1976, and was envisioned as a 3-year project. NSF furnished support for the first 18 months beginning in 1977, with the second 18 months dependent on progress. The major goals, as outlined in this NSF proposal, were:

1. development of statistical-physical techniques for evaluation of operational programs;

2. evaluation of a sufficient number of operational programs to test the techniques;

3. preparation of information for planning of future operational programs; and

4. translation of useable findings and evaluation techniques to the public, governmental agencies, and the weather modification industry.

With primary emphasis on methods of evaluating operational programs, development of techniques which could be used for non-randomized testing became a key ingredient of the research effort. The principal staff included Dr. Paul Schickedanz, Principal Investigator; S. A. Changnon, Jr., Head of the Survey's Atmospheric Sciences Section; and Dr. Chin-Fei Hsu, statistician. A 9-person advisory panel was established to review the project achievements and give advice at appropriate intervals.

The untimely death of the principal investigator (Schickedanz) at the end of the first 6 months of the initial 18-month effort led to personnel reassignments and some refocusing of the project. Stanley Changnon and Floyd Huff assumed the role of principal investigators and Dr. Hsu became principal scientist. The new principal investigators concluded that there should be more meteorological input to achieve optimum testing techniques and establish acceptance among the scientific community. The research was adjusted to accommodate the meteorological phase with NSF approval.

At the end of the 18-month initial effort, a new 2-year proposal was submitted to and approved by NSF for continuation of the research. Some changes in emphasis on objectives resulted not only from the findings of the first 18 months and available funding, but also from input from the project's advisory team, and from recommendations of the Weather Modification Advisory Board and its Statistical Task Force (WMAB, 1978). Their recommendations were incorporated into our research to the extent feasible with existing funding.

In the 2-year continuation effort (1979-1980), the basic goals and objectives of the original research plan were retained with the primary focus on the development of statistical techniques for evaluation of operational projects. However, due to restricted NSF funding, comments of the proposal reviewers, and consultant suggestions, other objectives and activities had to be altered or eliminated. As a result, the meteorological phase involving research on predictor and evaluation variables was greatly reduced in scope from that originally planned. In the continuation effort, upper air analyses were omitted and the research limited to a study of the feasibility and utility of surface variables in forecasting for and evaluating weather modification operational programs. Furthermore, research was limited to evaluation of convective precipitation programs; that is, warm season rain and hail seeding projects. Evaluation of selected operational projects through use of the better statistical techniques derived from simulation studies, remained an objective, but was conducted on a more limited scale than originally planned. However, increased emphasis was placed on development of criteria for weather modification operations and effective evaluation and translation of these OSET findings to interested users. The need for this information was strongly emphasized by the Weather Modification Advisory Board in their 1978 report.

The objectives of the 2-year continuation were essentially accomplished with the exception of the predictor variable research. Techniques and methods for utilizing meteorological variables in the operation and evaluation of weather modification projects were developed. They appeared to have considerable applicability, particularly in optimizing prediction criteria for operations. However, funding limitations and needs for the statistical phases of the research prevented an independent testing of these meteorological techniques and methods, as planned.

In view of progress and findings during the 3.5 years of the OSET research, a new proposal was prepared to begin in June 1981 with Changnon and Hsu as principal investigators. Emphasis was to be placed primarily on various statistical studies that would complement findings of the previous 3.5 years. Testing of developed techniques against selected past operational projects was a major focus. The utilization of synoptic weather factors (storm movement, storm type, etc.) and weather radar observations were included in this 2-year proposal.

Review of the proposal and available NSF funds culminated in a 2-year project which required elimination or severe curtailment of several proposed studies, including meteorological investigations. Continuation of the predictor variable research on physical evaluation methods had not been proposed in view of previous reaction from project reviewers and consultants.

1.2 General Approach to Problem

The research in the project involved two highly coordinated investigations. The first of the two was the testing of a number of statistical techniques to ascertain which are the most applicable for verification of operational projects. Those tested were initially selected from a large number of statistical candidates as having characteristics which make them potentially useful in evaluating weather modification. This part of the study also included the selection and testing of various meteorological factors which were considered potentially useful as covariates (predictor variables) in the evaluation of operations and/or the prediction of weather conditions for seeding operations.

The second of the investigations involved testing the techniques developed in the project by analyzing several past operational seeding programs as well as the Israeli I and II experiments. These two investigations were aimed towards providing the best combination of verification reliability and minimum sample size requirements in the evaluation of operational projects.

The evaluation of statistical techniques was accomplished primarily through extensive simulation testing of assumed weather modification effects superimposed upon natural precipitation distributions. This was done for both rain and hail. The study on the integration of the meteorological covariates into the statistical evaluation of seeding effects was done on a storm or daily basis, since the covariates must be determined from existing synoptic weather conditions which vary greatly in time and space. Because of the size of the task and the funds allocated for this phase of the work, the covariate research was limited to the evaluation of surface meteorological variables.

Past seeding projects of the commercial type selected for testing of the statistical-physical techniques developed under the OSET research included several short-term (1 season) projects in Illinois, a 7-year hail suppression project in the Texas Panhandle area, a combined rain/hail aircraft project in southwestern Kansas, and a 5-year ground-based project in northwestern Oklahoma. Suitability was based upon location (climatically), length of project, goal of seeding (rain enhancement and/or hail suppression), and adequacy and availability of data. In addition, the analyses of the Israeli experiments provided us with an opportunity for testing the techniques on a randomized seeding data set.

Two projects, the one in southwestern Kansas and the one in northwestern Oklahoma, were evaluated by analyzing in great details the synoptic weather information over a broad area covering both targets. The analyses were done on selected seeding days, for which a synoptic weather type and a motion of dominant storm system passing over the target were determined. Rainfall data of the target and neighboring comparison areas were evaluated according to various stratifications of synoptic types and storm motions. In addition, a low-level plume wind stratification was determined for the Oklahoma evaluation. For target-control comparison, climatic rainfall normals in both project were used to adjust the seeding rainfalls.

Furthermore, historical data were used in evaluating these selected operational projects. The techniques studied in the simulations were applied to these data for testing the effectiveness and sensitiveness of the techniques, and the results were compared with the simulation findings.

Finally, some issues relevant to the evaluation of operational weather modification were studied. They included (1) historical comparison, (2) potential biases in evaluation, and (3) combination of several tests of significance.

2. DEVELOPMENT AND STUDY OF STATISTICAL EVALUATION TECHNIQUES

Our research attempted to study techniques for evaluating operational cloud seeding by using historical precipitation (or hail damage) data for areas considered as "target" on which seeding effects were simulated. It also used concomitant observations on neighboring control areas to adjust for spatial gradients and temporal variability of the response variables. We have studied and compared multiple regression (MREG), two simple regressions (2REG), principal component regression (PCR), double ratio (DR), sum of rank power tests (SRP), multi-response permutation procedures (MRPP) and ratio-difference (RD). These techniques either have been used in evaluating past seeding operations, or were developed in this project. Each of these techniques compared the simulated "seeded" precipitation (or hail damage) on the "target" with the remaining unseeded data, and used the neighboring control observations for adjustment. The techniques were compared in terms of their power to detect the seeding effects that were simulated.

Results of the simulation for some of the techniques have been reported by Hsu et al. (1981a, 1981b). Results of the two new techniques, MRPP and RD, are reported here and then compared with others. The technique of MRPP has been used in studying a number of randomized seeding projects (see for examples, Mielke et al. (1982); Wong et al. (1983)). The ratio-difference tests studied here consists of 12 statistics which resemble the double ratio (DR), a frequently used evaluation technique. These two techniques have potential for use in evaluating operational projects, thus are the focus of the present simulation studies.

2.1 Simulation Studies

To achieve the objective of comparing the performance of numerous statistical evaluation techniques, extensive simulation studies were carried out by superimposing assumed weather modification effects upon natural precipitation distributions. Five data sets from four areas were selected for simulations and their locations are shown in Fig. 2.1. The areas selected were a 10-county region in west central Kansas, a 16-county area in western Montana, and an area encompassing a dense raingage network in southwestern Illinois and eastern Missouri, which was operated as part of the Metropolitan Meteorological Experiment, commonly referred to as METROMEX (Changnon et al., 1977). Selection was based upon (1) absence of past weather modification efforts, (2) potential for future application of weather modification, and (3) availability of reliable data over a sufficient long period of time.

The simulation testing was restricted to warm season and convective precipitation. The data included monthly (May-September) and seasonal rains in (1) western Kansas and (2) east central Illinois (ILL-EC); (3) annual crop hail loss-cost values (defined as 100 x hail damage / insurance liability) in central Montana; (4) 48-hour (ILL-48) and (5) storm (ILL-ST) rains in southwestern Illinois. These represent a broad range of data commonly employed in the evaluation of weather modification projects. The rainfall data were obtained from the National Weather Service. The crop hail insurance data were furnished by the Crop-Hail Insurance Actuarial Association.

Table 2.1 shows various parameters of these data used in the simulations. Two of the simulations, Kansas and ILL-EC, mimicked a long-term (5 years) summer operational rainfall enhancement project. The Montana data were for short- and long-term hail suppression simulation. The ILL-48 simulation mimicked a short-term (1 year) operational project, and ILL-ST simulation was for an experimental project with a dense raingage network and/or surface meteorological covariates. Fixed target and control areas were used in the hail simulations and for 48-hour, monthly and seasonal rainfall analyses. A moving target-control approach was used in the storm rainfall simulations, in which individual storm motions could be taken into account.

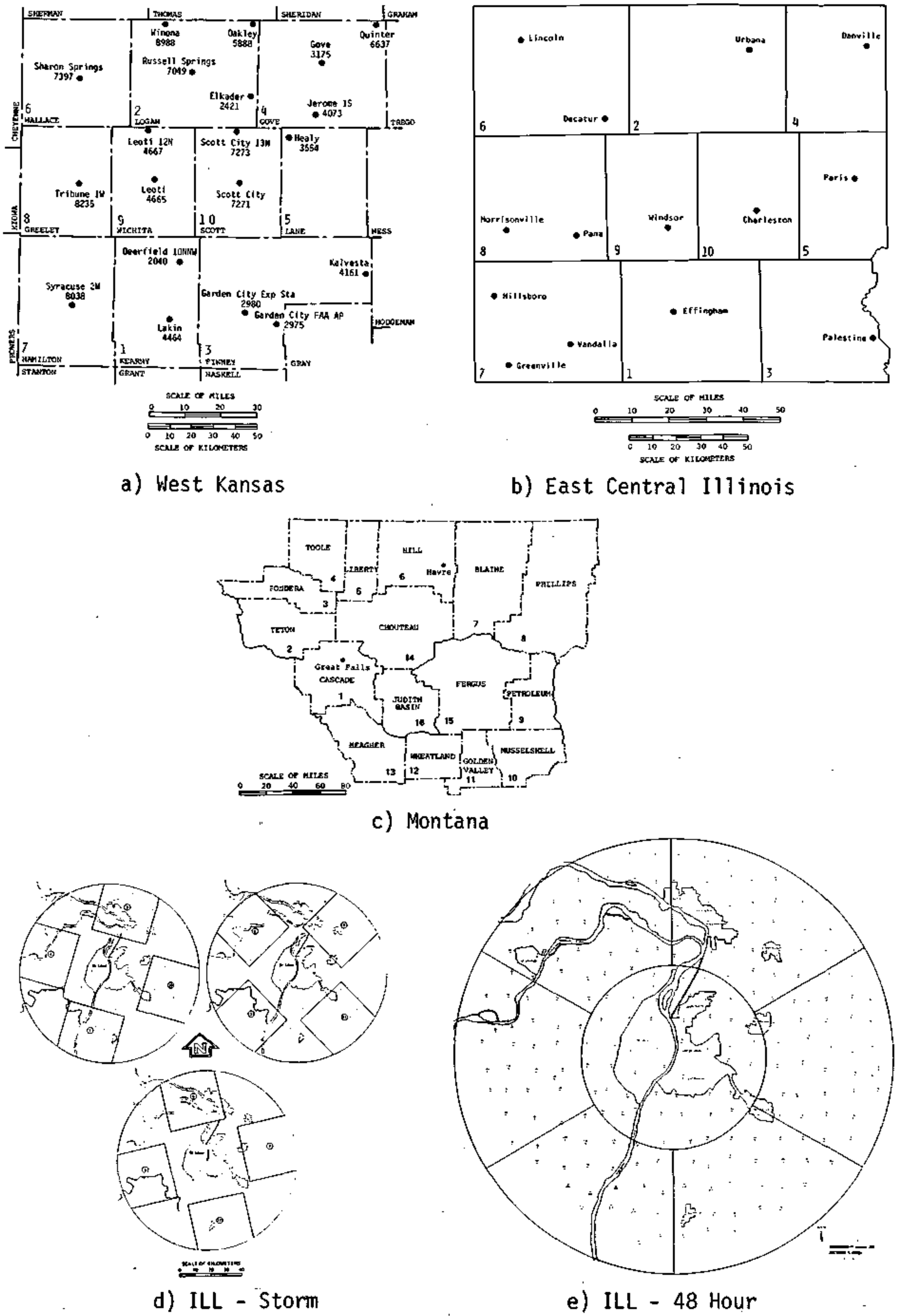

Fig. 2.1. Simulation Study Areas.

Table 2.1. Evaluation Elements Used in the Simulation Studies.*

Evaluation Element	Kansas	ILL-EC	Montana	ILL-48	ILL-ST
Precipitation type	rain	rain	hail	rain	rain
No. of years					
Seeded	5	5	3 or 6	1	1
Unseeded	0	30	26 or 23	4	4
Sampling unit	month	month	year	48-hr	storm
Design (T-C)	fixed	fixed	fixed	fixed	moving
Target area (sq. km)	2000, 4000	2000, 4000	5000, 25000	800	800
Seeding effect model	const.	const.	const.	const.	const./ varying
Predictor	no	no	no	no	yes/no
No. of runs	500	500	1000	500	500

* ILL-EC : east central Illinois; ILL-48 : 48-hour rainfall; ILL-ST : storm rainfall

The simulation study related to a fixed number of time units. There were precipitation (and hail loss-cost values) observations on the target as well as on several controls. All methods of analysis adjusted target rainfall for control rainfall (the same applied to hail data) when calculating the test statistics. A simple average of the controls was used for some of the techniques. These included : (1) the test of sum of powers of ranks (SRP) which is calculated from ranks of target to average control precipitation ratios; and (2) the double ratio (DR) which compares the seeded to unseeded ratio of target totals with the corresponding ratio of the totals of average control. All the regression comparisons use the seeded units' average target rainfall minus the values predicted for it from control rainfall, the prediction being based on regression equations fitted to unseeded data. The two regression (2REG) uses simple linear regressions on the average control; multiple regression (MREG) uses multiple regression on all controls; PCR[k] uses multiple regression on the largest k principal components of the controls. (For more details of the techniques, see Hsu et al., 1981a).

For each data set, the simulation investigation was carried out for either 500 or 1000 runs. A fraction of the observations was set aside as 'seeded' according to a permutation out of a pre-chosen reference set of 500-1000 permutations, and the rest as 'unseeded.' The Cyber Fortran function, RANF, was the main random number generator used in creating the reference sets. In each run, assumed multiplicative weather modification effects, either constant or varying, were superimposed onto the 'seeded' target rainfall to form a changed sample. The simulated seeding effects were as follows: For rainfall we simulated constant increases of 10, 20, 30 and 40% over natural rainfall; for storm rainfall, we also simulated varying effects according to four different models (see Hsu et al, 1981a) which defined what the effect was for each level of natural rainfall, e.g., high effects with low natural rainfall, no effects with high natural rainfall, etc. For hail supression we simulated 20, 40, 60, and 80% reductions in the hail loss-cost values.

Test statistics were calculated for the unchanged sample (Null), and for each of the superimposed samples (Alternative). A null distribution, and four alternative distributions of the test statistics (eight in the ILL-ST study) were then obtained. The criteria for comparing statistical techniques were their powers of detecting the various simulated effects at significance levels of 5 and 10%. For each combination of a data set, a simulated effect and a level of significance, estimates of the power of all the statistical techniques were obtained by simulations. Thus, for each such combination, one could see which technique was most powerful, next to most powerful, etc. Power values were computed as the portion of values in the alternative distribution which were larger than the critical value in the null distribution (naive method). Previous studies on the approximation of power have indicated that at both 5% and 10% nominal significance levels, powers computed by this method were, in general, slightly larger than those computed by the exact method (Gabriel and Hsu, 1983). The discrepancies were small, usually less than or equal to .05.

The test statistics were ranked by the powers at the 5% or 10% nominal significance levels, respectively, for each seeding effect imposed, each target-control setup, and/or each month. The techniques with highest average rank were thus decided as optimal.

2.2 Multi-Response Permutation Procedure

The non-parametric statistical techniques have been used to evaluate weather modification for many years. Frequently used such techniques included the 2-sample Wilcoxon test and sum of rank power (SRP) tests (see Hsu et al, 1981a). Examples of using these tests can be found in Adderley (1961), Gabriel and Feder (1969), and Dennis et al. (1975). When used together with the re-randomization procedure, the non-parametric tests provide a viable and robust means for evaulating cloud seeding projects. Indeed, previous simulation study has indicated that SRP is the optimal evaluation technique if effects due to seeding were not (constant) multiplicative (Hsu and Changnon, 1983a).

The multi-response permutation procedure (MRPP) was proposed as an extention to the non-parametric techniques for evaluating weather modification projects (Mielke, 1979; Mielke et al, 1976, 1982). In fact, MRPP was designated as the 'official' evaluation techniques in the HIPLEX design, and was later used to evaluate the the results of the single-cloud phase of the experiment (Dennis et al.. 1981). The technique was applied to re-analyze the results of Climax I and II cloud seeding experiments (Mielke et al.. 1981, 1982). More recently, Wong et al. (1983) used the technique to evaluate the Alberta hail suppression program.

Basically, the procedures take 2 steps: (1) each of the responses, seeded or non-seeded, is first regressed by a set of covariates not affected by the seeding treatments. Least squares or other robust methods, such as least absolute residuals, could be used in the fitting, although the latter is preferred. (2) All the residuals thus obtained, one for each response, were used to form a test statistic by permuting separately the residuals in the seeded and non-seeded groups (for details see Wong et al., 1983). In essence, MRPP is based on the Euclidean distance between objects (i.e., the vector of responses) in a multidimensional space, and treatment effects are reflected by comparing residuals of the seeded with the unseeded responses, both adjusted by the covariates.

The version used in the simulation was adopted from Mielke et al. (1979). Due to the large amount of computer resources required to carry out the simulation, one data set, ILL-EC, instead of all five was used in the simulation. This limited effort allows us to compare the powers of MRPP with others. Powers of the MRPP are shown in Table 2.2.

Table 2.2. Powers at 5% and 10% Nominal Significance Levels, MRPP, ILL-EC Simulations, Seasonal Average as Unit.

		5%				10%			
Target	Control	1.1	1.2	1.3	1.4	1.1	1.2	1.3	1.4
9	8	.42	.64	.72	.84	.42	.64	.72	.84
	Avg	.50	.68	.82	.90	.50	.68	.82	.90
	S	.36	.70	.86	.88	.58	.80	.86	.88
10	5	.44	.66	.74	.80	.52	.70	.76	.80
	Avg	.46	.64	.72	.78	.46	.64	.72	.78
	S	.44	.60	.70	.74	.44	.60	.70	.74
Avg	Avg	.48	.62	.78	.88	.48	.62	.78	.88
	S	.62	.78	.86	.88	.62	.78	.86	.88

*See Figure 2.1 for locations of the targets and controls; Avg is the average of targets or controls; S is the average of 3 south controls.

Comparing the powers of MRPP with those of the other techniques (shown in Table 2.8), it is clear that MRPP was the most powerful when the assumed seeding effect was in the 10% range. If the assumed effect was greater than 10%, other techniques were more powerful than MRPP. At the 10% assumed effect, the power excesses of MRPP over the next powerful technique were 0.20 (DR, Target 10, Control 5), 0.14 (DR, Target 9, Control 8), 0.13 (SRP-A_1, Target 9, Control Avg), and a few smaller ones. It appeared that MRPP is best suited for use in detecting small multiplicative changes of seeding effects.

2.3 Ratio-Difference Tests

The double ratio (DR) is probably one of the most widely used techniques in evaluating weather modification (see the bibliographies compiled by Hsu, 1981, 1984 for listings of such applications). The method is simple to calculate and very easy to interpret intuitively. To obtain the significance of test, a re-randomization procedure could be easily used.

In the present report, twelve techniques resembling the double ratio were studied by simulations, and compared with other techniques. They are named RD1, RD2, ..., and RD12 and are described in Table 2.3. In particular, RD4 is the double differences. These test statistics are combinations of target/control ratios and/or target-control differences. The tests reject the null hypothesis of no seeding effect if the statistic is large. All these techniques deal with a single target and a single control. For multiple targets or controls, averaged values can be used instead.

The simulations were carried out by using the four rainfall data as described in Table 2.1. The hail data from Montana were not used because of too many zeros, which can not be used in a few divisions. Power values of RDs obtained from the simulations are shown in Tables 2.4 to 2.7. Powers of some RDs were considerably lower than others and were not included in these tables.

Table 2.3. Ratio - Difference.

$$RD\,1 = \Sigma_s\,(T_i/C_i)\;/\;\Sigma_h\,(T_i/C_i)$$

$$RD\,2 = \Sigma_s\,(T_i/C_i) - \Sigma_h\,(T_i/C_i)$$

$$RD\,3 = (\Sigma_s\,T_i - \Sigma_s\,C_i)\;/\;(\Sigma_h\,T_i - \Sigma_h\,C_i)$$

$$RD\,4 = (\Sigma_s\,T_i - \Sigma_s\,C_i) - (\Sigma_h\,T_i - \Sigma_h\,C_i)$$

$$RD\,5 = \Sigma_s\,T_i/\Sigma_s\,C_i - \Sigma_h\,T_i/\Sigma_h\,C_i$$

$$RD\,6 = (\Sigma_h\,C_i/T_i)\;/\;(\Sigma_s\,C_i/T_i)$$

$$RD\,7 = \Sigma_h\,C_i/T_i - \Sigma_s\,C_i/T_i$$

$$RD\,8 = (\Sigma_s\,T_i - \Sigma_s\,C_i)\;(\Sigma_h\,\frac{1}{T_i - C_i})$$

$$RD\,9 = (\Sigma_s\,T_i/C_i)\;(\Sigma_h\,C_i/T_i)$$

$$RD10 = (\Sigma_h\,C_i)\;(\Sigma_h\,\frac{1}{T_i})\;/\;(\Sigma_s\,C_i)\;(\Sigma_s\,\frac{1}{T_i})$$

$$RD11 = (\Sigma_h\,C_i)\;(\Sigma_h\,\frac{1}{T_i}) - (\Sigma_s\,C_i)\;(\Sigma_s\,\frac{1}{T_i})$$

$$RD12 = (\Sigma_s\,T_i - \Sigma_s\,C_i)\;/\;(\frac{1}{\Sigma_h\,C_i} - \frac{1}{\Sigma_h\,T_i})$$

Table 2.4. Powers at 5% Nominal Significance Level, Ratio-Difference, Kansas Simulations, Seasonal Average as Unit.

T	C	Change	RD1	RD2	RD4	RD5	RD9
9	8	1.1	.166	.168	.220	.182	.162
		1.2	.330	.338	.484	.374	.338
		1.3	.548	.568	.756	.636	.560
		1.4	.734	.752	.900	.786	.746
	AVG	1.1	.214	.224	.304	.264	.224
		1.2	.478	.488	.748	.702	.494
		1.3	.788	.808	.972	.956	.806
		1.4	.964	.978	1.000	.996	.970
	S	1.1	.144	.152	.246	.232	.150
		1.2	.268	.276	.572	.498	.288
		1.3	.430	.442	.852	.796	.468
		1.4	.672	.702	.966	.932	.728
10	5	1.1	.266	.272	.288	.288	.270
		1.2	.616	.632	.694	.672	.622
		1.3	.856	.868	.910	.882	.856
		1.4	.970	.972	.988	.982	.968
	AVG	1.1	.272	.282	.290	.294	.278
		1.2	.638	.648	.644	.656	.650
		1.3	.872	.880	.882	.884	.876
		1.4	.982	.986	.986	.986	.984
	S	1.1	.208	.216	.264	.232	.216
		1.2	.454	.472	.580	.530	.472
		1.3	.718	.734	.816	.792	.736
		1.4	.884	.892	.952	.922	.892
AVG	AVG	1.1	.344	.348	.456	.418	.348
		1.2	.742	.756	.880	.852	.762
		1.3	.970	.978	.992	.992	.974
		1.4	1.000	1.000	1.000	1.000	.998
	S	1.1	.162	.164	.326	.282	.172
		1.2	.370	.384	.712	.614	.402
		1.3	.658	.676	.916	.876	.688
		1.4	.848	.884	.986	.958	.888

* See Figure 2.1 for location of targets and controls, S is the average of 3 south controls.

Table 2.5. Powers at 5% Nominal Significance Level, Ratio-Differgnce, East-Central Illinois Simulations, Seasonal Average as Unit.

T	C	Change	RD1	RD2	RD4	RD5	RD9
9	8	1.1	.272	.278	.260	.280	.272
		1.2	.598	.608	.628	.650	.604
		1.3	.880	.888	.896	.900	.882
		1.4	.982	.986	.980	.988	.978
	AVG	1.1	.364	.368	.334	.336	.366
		1.2	.836	.840	.808	.838	.836
		1.3	.986	.986	.980	.990	.986
		1.4	1.000	1.000	.998	1.000	1.000
	S	1.1	.312	.322	.314	.314	.328
		1.2	.694	.710	.720	.712	.712
		1.3	.930	.938	.954	.954	.928
		1.4	.990	1.000	.994	1.000	.996
10	5	1.1	.228	.236	.242	.242	.236
		1.2	.494	.512	.554	.536	.518
		1.3	.744	.766	.832	.798	.768
		1.4	.894	.901	.950	.932	.900
	AVG	1.1	.374	.386	.356	.422	.390
		1.2	.810	.818	.816	.864	.810
		1.3	.968	.970	.962	.984	.966
		1.4	.998	1.000	.996	.996	.996
	S	1.1	.450	.462	.434	.456	.454
		1.2	.868	.876	.880	.896	.864
		1.3	.980	.980	.984	.982	.976
		1.4	1.000	1.000	1.000	1.000	1.000
AVG	AVG	1.1	.592	.609	.588	.612	.590
		1.2	.960	.964	.964	.980	.960
		1.3	1.000	1.000	1.000	1.000	1.000
		1.4	1.000	1.000	1.000	1.000	1.000
	S	1.1	.542	.546	.566	.572	.542
		1.2	.940	.942	.976	.966	.934
		1.3	1.000	1.000	1.000	1.000	1.000
		1.4	1.000	1.000	1.000	1.000	1.000

*
See Figure 2.1 for location of targets and controls; S is the average of 3 south controls.

Table 2.6. Povers at 5% Level, Ratio-Difference, ILL-Storm Simulations.*

	Control	Change	RD1	RD2	RD4	RD5	RD6	RD7	RD9	RD10	RD11
Total Rain	1	1.1	.078	.084	.150	.094	.082	.076	.104	.092	.084
		1.2	.120	.140	.266	.174	.114	.106	.158	.138	.126
		1.3	.162	.188	.432	.268	.158	.138	.210	.182	.170
		1.4	.212	.248	.570	.384	.210	.182	.278	.240	.212
	2	1.1	.084	.116	.134	.080	.086	.086	.100	.092	.086
		1.2	.128	.176	.240	.130	.118	.110	.146	.126	.118
		1.3	.156	.202	.390	.230	.168	.142	.176	.168	.150
		1.4	.182	.208	.536	.334	.240	.198	.192	.226	.184
	3	1.1	.082	.090	.124	.120	.072	.068	.120	.084	.074
		1.2	.140	.162	.256	.204	.106	.090	.194	.130	.118
		1.3	.220	.246	.418	.326	.124	.116	.282	.166	.144
		1.4	.294	.330	.602	.438	.154	.134	.358	.208	.182
	AVG	1.1	.078	.082	.078	.122	.110	.108	.084	.088	.080
		1.2	.098	.106	.104	.236	.160	.156	.118	.144	.122
		1.3	.126	.146	.132	.370	.230	.200	.176	.180	.162
		1.4	.160	.208	.196	.554	.278	.246	.220	.242	.200
Max Point Rain	1	1.1	.110	.114	.168	.118	.108	.104	.136	.124	.118
		1.2	.170	.182	.356	.242	.170	.156	.226	.210	.200
		1.3	.266	.298	.520	.362	.262	.222	.310	.318	.282
		1.4	.344	.372	.702	.498	.336	.308	.434	.418	.374
	2	1.1	.062	.064	.138	.106	.102	.096	.070	.104	.096
		1.2	.072	.088	.272	.204	.138	.126	.090	.184	.162
		1.3	.100	.132	.472	.350	.206	.182	.158	.304	.274
		1.4	.132	.188	.664	.506	.280	.240	.208	.426	.364
	3	1.1	.090	.092	.148	.124	.106	.102	.084	.116	.116
		1.2	.134	.146	.282	.230	.164	.148	.152	.200	.188
		1.3	.190	.210	.456	.356	.234	.218	.234	.302	.280
		1.4	.248	.280	.662	.496	.298	.276	.298	.388	.368
	AVG	1.1	.116	.124	.160	.170	.122	.116	.126	.102	.096
		1.2	.190	.210	.304	.314	.218	.200	.210	.194	.176
		1.3	.272	.290	.486	.514	.312	.294	.306	.316	.292
		1.4	.370	.400	.664	.682	.426	.386	.434	.462	.416
Avg Rain	1	1.1	.132	.144	.162	.116	.112	.102	.158	.096	.088
		1.2	.230	.250	.316	.218	.166	.154	.298	.168	.158
		1.3	.352	.386	.504	.342	.226	.208	.434	.254	.224
		1.4	.482	.522	.668	.508	.320	.282	.574	.326	.308
	2	1.1	.096	.100	.134	.104	.088	.086	.110	.112	.110
		1.2	.136	.156	.244	.192	.144	.130	.154	.174	.152
		1.3	.174	.192	.438	.288	.218	.194	.184	.260	.236
		1.4	.198	.208	.572	.432	.286	.252	.212	.342	.320
	3	1.1	.098	.104	.138	.122	.094	.092	.094	.090	.088
		1.2	.176	.196	.286	.244	.162	.150	.202	.146	.140
		1.3	.288	.324	.484	.370	.222	.200	.322	.226	.200
		1.4	.414	.448	.674	.496	.284	.256	.448	.326	.272
	AVG	1.1	.134	.144	.138	.140	.142	.136	.118	.134	.128
		1.2	.246	.266	.322	.282	.240	.228	.262	.216	.192
		1.3	.392	.414	.556	.524	.372	.332	.402	.342	.300
		1.4	.522	.570	.722	.688	.472	.446	.560	.460	.422

Table 2.6. (continued)

	Control	Change	RD1	RD2	RD4	RD5	RD6	RD7	RD9	RD10	RD11
Total Rain	1	A	.236	.268	.310	.212	.320	.276	.284	.410	.330
		E	.314	.360	.560	.368	.534	.408	.414	.578	.460
		C	.108	.116	.034	.046	.134	.118	.128	.208	.184
		M	.114	.134	.318	.200	.094	.090	.148	.108	.104
	2	A	.140	.186	.274	.168	.360	.296	.160	.420	.332
		E	.170	.208	.522	.326	.534	.430	.186	.578	.478
		C	.068	.082	.032	.046	.132	.122	.074	.184	.160
		M	.138	.190	.290	.162	.104	.100	.158	.102	.096
	3	A	.390	.416	.320	.272	.180	.148	.442	.368	.298
		E	.530	.568	.616	.442	.280	.216	.624	.498	.396
		C	.150	.162	.044	.060	.088	.082	.184	.188	.154
		M	.128	.142	.304	.236	.088	.082	.184	.100	.086
	AVG	A	.178	.202	.124	.280	.450	.380	.224	.430	.352
		E	.230	.280	.208	.544	.626	.550	.330	.598	.478
		C	.094	.096	.060	.070	.186	.162	.100	.208	.174
		M	.100	.104	.108	.268	.144	.128	.118	.112	.096
Max Point Rain	1	A	.422	.474	.562	.400	.482	.418	.504	.714	.642
		E	.630	.680	.860	.664	.712	.630	.722	.904	.862
		C	.154	.166	.116	.082	.162	.152	.188	.312	.284
		M	.158	.166	.376	.252	.142	.130	.208	.152	.150
	2	A	.104	.172	.528	.394	.426	.350	.210	.702	.630
		E	.204	.300	.820	.632	.672	.566	.314	.910	.850
		C	.058	.064	.088	.082	.142	.132	.068	.298	.264
		M	.080	.098	.298	.222	.118	.114	.104	.128	.116
	3	A	.314	.356	.524	.398	.404	.346	.384	.660	.606
		E	.482	.520	.820	.636	.658	.548	.576	.874	.814
		C	.116	.130	.096	.094	.144	.132	.134	.308	.280
		M	.116	.132	.302	.244	.144	.140	.130	.146	.146
	AVG	A	.390	.426	.530	.550	.662	.594	.480	.778	.712
		E	.598	.664	.826	.846	.884	.830	.732	.952	.910
		C	.156	.166	.106	.110	.242	.212	.164	.314	.284
		M	.186	.196	.316	.336	.174	.158	.202	.126	.122
Avg Rain	1	A	.526	.570	.422	.314	.496	.428	.592	.588	.498
		E	.760	.792	.750	.550	.736	.656	.820	.842	.748
		C	.172	.180	.054	.060	.168	.156	.198	.268	.234
		M	.234	.250	.352	.246	.130	.124	.292	.116	.112
	2	A	.168	.190	.354	.262	.464	.374	.196	.606	.548
		E	.212	.240	.638	.482	.664	.586	.294	.810	.742
		C	.080	.084	.052	.060	.142	.130	.090	.266	.234
		M	.152	.166	.284	.208	.122	.112	.164	.132	.124
	3	A	.438	.482	.416	.350	.394	.344	.490	.544	.494
		E	.656	.718	.758	.560	.640	.530	.722	.770	.680
		C	.138	.152	.054	.074	.134	.122	.150	.234	.214
		M	.168	.186	.334	.264	.142	.142	.196	.102	.098
	AVG	A	.546	.586	.466	.456	.706	.656	.574	.758	.712
		E	.788	.838	.796	.750	.930	.878	.814	.926	.878
		C	.154	.164	.036	.060	.278	.256	.152	.348	.312
		M	.246	.264	.366	.330	.198	.182	.260	.172	.160

* See Figure 2.1 for location of controls; for change modes A, E, C, M, see Hsu et al. (1981a).

Table 2.7. Powers at 5% Nominal Significance Level, Ratio-Difference, ILL-48 Simulations.

Control	Change	RD1	RD2	RD4	RD5	RD9
		Total Rain				
Upwind	1.1	.094	.162	.148	.148	.106
	1.2	.172	.202	.296	.282	.136
	1.3	.202	.202	.480	.452	.164
	1.4	.202	.202	.642	.598	.178
AVG	1.1	.120	.126	.180	.174	.118
	1.2	.232	.250	.392	.364	.236
	1.3	.378	.404	.592	.578	.368
	1.4	.506	.542	.768	.758	.484
		Max Point Rain				
Upwind	1.1	.126	.136	.160	.170	.112
	1.2	.178	.184	.314	.338	.156
	1.3	.206	.206	.522	.548	.200
	1.4	.206	.220	.708	.724	.232
AVG	1.1	.132	.136	.164	.190	.128
	1.2	.226	.246	.328	.424	.242
	1.3	.342	.378	.570	.670	.384
	1.4	.494	.546	.730	.814	.544
		Average Rain				
Upwind	1.1	.112	.120	.166	.152	.122
	1.2	.190	.206	.336	.342	.222
	1.3	.286	.332	.528	.498	.352
	1.4	.406	.442	.714	.674	.468
AVG	1.1	.144	.152	.212	.218	.180
	1.2	.350	.378	.442	.444	.408
	1.3	.580	.604	.688	.688	.616
	1.4	.722	.750	.834	.840	.778

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*See Figure 2.1 for locations of target and controls.

Table 2.8 Powers at 5% and 10% Nominal Significance Levels, ILL-EC Simulations, Seasonal Average as Unit.*

			5%				10%			
Technique	Target	Control	1.1	1.2	1.3	1.4	1.1	1.2	1.3	1.4
DR	9	8	.28	.64	.89	.98	.37	.76	.97	.99
		Avg	.34	.82	.99	1.00	.48	.91	1.00	1.00
		S	.30	.69	.94	1.00	.43	.83	.98	1.00
	10	5	.24	.51	.79	.92	.35	.63	.85	.96
		Avg	.42	.85	.98	1.00	.54	.91	.99	1.00
		S	.45	.89	.98	1.00	.59	.94	.99	1.00
	Avg	Avg	.61	.98	1.00	1.00	.71	.99	1.00	1.00
		S	.56	.96	1.00	1.00	.69	.99	1.00	1.00
MREG - D	9	All	.30	.75	.96	1.00	.48	.87	.98	1.00
		S	.29	.67	.93	.99	.41	.79	.96	1.00
	10	All	.39	.77	.96	1.00	.48	.86	.98	1.00
		S	.39	.83	.98	1.00	.52	.90	.99	1.00
	Avg	All	.57	.94	1.00	1.00	.71	.99	1.00	1.00
		S	.53	.93	1.00	1.00	.69	.97	1.00	1.00
PCR[1] - D	9	All	.33	.80	.98	1.00	.47	.91	.99	1.00
	10	All	.37	.82	.97	1.00	.52	.90	.99	1.00
	Avg	All	.59	.97	1.00	1.00	.68	.99	1.00	1.00
2REG - T	9	Avg	.31	.79	.99	1.00	.45	.90	1.00	1.00
		S	.28	.69	.94	.99	.42	.83	.97	1.00
	10	Avg	.37	.81	.97	1.00	.50	.90	.99	1.00
		S	.40	.85	.98	1.00	.53	.92	.99	1.00
	Avg	Avg	.58	.97	1.00	1.00	.68	.99	1.00	1.00
		S	.57	.96	1.00	1.00	.70	.98	1.00	1.00
SRP - A_1	9	8	.27	.60	.84	.98	.39	.75	.93	.99
		Avg	.37	.78	.99	1.00	.50	.87	1.00	1.00
		S	.30	.68	.94	1.00	.49	.82	.98	1.00
	10	5	.18	.41	.69	.89	.26	.53	.80	.92
		Avg	.32	.77	.94	.97	.46	.85	.96	1.00
		S	.39	.79	.92	.99	.52	.88	.96	.99
	Avg	Avg	.55	.92	1.00	1.00	.66	.95	1.00	1.00
		S	.30	.68	..94	1.00	.45	.82	.98	1.00

*See Figure 2.1 for locations of targets and controls; Avg is the average of targets or controls; S is the average of 3 southern controls.

We also use the simulation results of ILL-EC (seasonal average rainfall) as an example for comparing the powers of RD_s (Table 2.5) with those of the other techniques (Table 2.8). For smaller assumed seeding effect, 10%-20%, powers of RD5 were almost identical to, sometimes higher than those of DR for the various target-control combinations. However, none of the powers of RDs at the 10% seeding effect was higher than the powers of MRPP, as discussed above. In the 20-30% range, powers of RD4 (double difference) were equal to or slightly higher than DR's. For 40% seeding effect, several RDs had near 1.00 powers.

It is worth notice that the double difference (RD4) was the most powerful among all techniques in the target vs south controls combination. In this example of using seasonal rainfall, the techqniques of ratio-difference were quite promising. RD4 and RD5 were at least as powerful as DR, the one previously found to be close to the most powerful technique. These 2 techniques provide viable methods for evaluation of seasonal rainfall if more than 10% of seeding-induced rainfall increase is expected.

2.4 Summary of Simulation Results

Findings of the simulation are summarized in Table 2.9. The table was constructed by counting how many times a technique had the highest or second highest powers in all the data subsets (e.g., months or season, various target-control combinations, different response variables) and all assumed seeding effects (10%-40%, varying).

It is evident that the principal component regression technique is generally the most powerful or next to the most powerful technique when assuming constant multiplicative seeding effects. With monthly or summer rains as sampling unit, a single principal component was sufficient to attain such power. For 48-hour rainfall data, three principal components were needed. For annual hail data, 3 principal components were also needed to achive higher power. This is consistent with the fact that the natural variability of hail or rainfall with shorter sampling unit is generally higher than that of rainfall with longer sampling

Table 2.9. Summary of Simulation Studies, Techniques with High Powers.

Data & Sampling Unit	Technique	Total Cases	No. of Highest Power	No. of 2nd Highest Power	Max. Diff. [1]
	Rainfall Enhancement				
Kansas	1. PCR[1]	24	10	6	.08
Month & Season	2. DR,RD4,RD5	24	9	4	
	3. MREG	24	6	1	
ILL-EC	1. PCR[1]	24	9	9	.ll[2]
Month & season	2. DR,RD4,RD5	24	6	8	
	3. MRPP	4	1	1	
Illinois	1. MREG	12	12	0	
48-hr	2. PCR[3]	12	0	9	.05
	3. DR	12	0	4	
Illinois Storm—[3]					
constant effect	1. MREG(PCR[3])	12	11	1	
	2. PCR[1]	12	3	8	.05
varying effect	1. Al	12	7	1	
	2. C2	12	2	5	
	3. MREG(PCR[3])	12	2	2	
	4. PCR[1]	12	1	2	(4)
	Hail Suppression				
Montana, Yearly					
3 seed years	1. PCR[3]	28	25	0	.14[5]
6 seed years					
(large target)	1. PCR[3]	4	2	1	.01
(small target)	1. DR	24	17	2	
	2. PCR[3]	24	3	6	(4)

(1) Maximum difference of powers between PCR and other technique with highest power.
(2) Except in June, the maximum difference is 0.02.
(3) A moving target-control was used in this simulation (see Hsu et al., 1981a).
(4) Power of PCR is generally not close to the highest, hence is not shown.
(5) The only 3 differences when PCR does not have highest power are .11 (A_1, A_2, A_3), .14 (DR), and .09 (DR); all at 20% assumed reduction.

unit, so more components are needed to retain a similar level of information (i.e., percent of total variance explained by the components retained).

In the case of using seasonal average as sampling unit, if the assumed seeding effect was small (10%), then MRPP was the most powerful among all the techniques studied. If the assumed effect was greater than 10%, other techniques were more powerful than MRPP. It appeared that MRPP is best suited for use in detecting small multiplicative change of seeding effects.

Though PCR was consistently the most powerful technique, occasionally, its power was lower than that of MREG or DR. Indeed, for short sampling units (storm or 48-hour), MREG seemed to be the most powerful; and for the hail project with a small target over 6 seeding years, DR was the most powerful. For variable seeding effects (used only in the storm simulation), the most powerful tests were SRP, namely, A_1 (the 2-sample Wilcoxon test) or C_2. As will be explained in the following chapters, when evaluating operational seeding projects, it is recommended to use long sampling unit to avoid biases in the selection of seeding occasions and to use historical data for proper comparison. Thus, from the operational evaluation points of view, the technique of principal component regression provides the most powerful and less-biased evaluation method.

It is not at present clear why these power differentials should have been found, but they seem to point to the advantage of using PCR for longer period units and MREG for shorter units if one assumes constant seeding effects. On the other hand, if the effects of seeding may be variable, one would do better to opt for simple non-parametric techniques.

3. EVALUATION OF OPERATIONAL PROJECTS USING SYNOPTIC WEATHER INFORMATION

Two operational seeding projects conducted over the Great Plains during the 1970's were evaluated statistically to determine if any seeding effects could be detected by using rainfall data from the National Weather Service's Cooperative Raingage Network (Fig. 3.1). The projects included a rainfall enhancement operation using ground-based generators located in northwestern Oklahoma during the summers of 1972-76 (hereafter called OK), and an aircraft-seeding program conducted for rainfall enhancement and hail suppression over southwestern Kansas called Muddy Road that was evaluated for the summers of 1975-79 (hereafter called MR). Due to the limitation of the data, the synoptic approach presented in this chapter was applied only to the rain phase of the two programs. The evaluation of the hail suppression is discussed in the next chapter.

In this study comparisons were made between measured rainfalls inside and outside the targets. General synoptic weather conditions in and around the target area(s) were analyzed and used in stratifying the data. In addition, climatological rainfall normals were used for adjusting the target rainfalls.

3.1 Synoptic Weather Analyses

Previous studies have indicated that weather modification effects from inadvertent sources do not have homogeneous influence on all types of weather situations. The Metropolitan Meteorological Experiment (METROMEX), which was carried out to study the effects of an urban environment on the weather over the St. Louis area, have shown that an urban-induced increase of approximately 30% in the summer rainfall was found a few kilometers northeast of the city in a region frequently downwind of the urban-industrial area (Changnon et al. 1977). Up to 28% rainfall excesses in the downwind areas were produced by squall line systems and by cold front storms from the southwest direction, when compared to upwind comparison areas. Air mass storms occurred most often and produced about one-

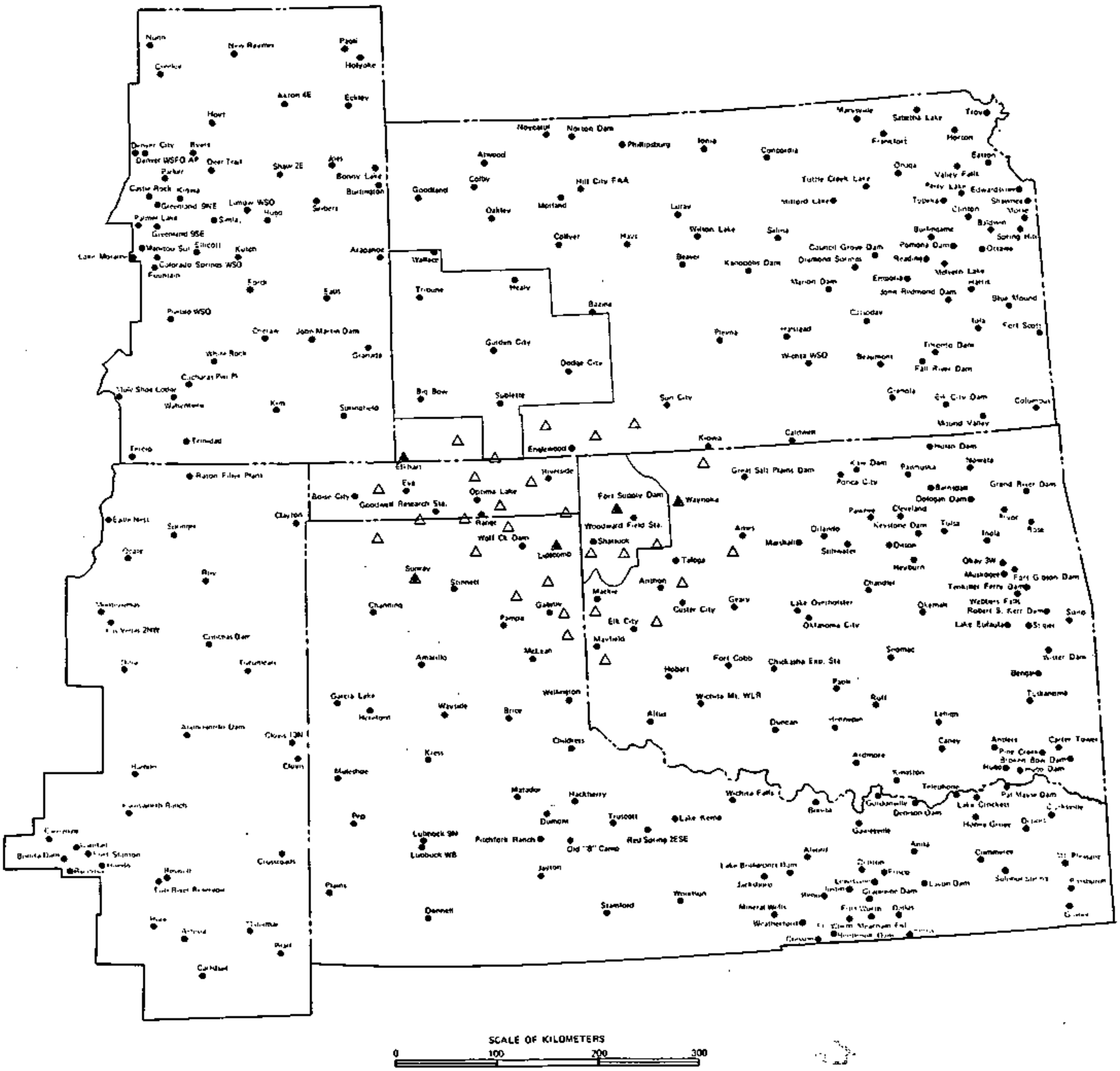


Fig. 3.1. NWS Raingage Networks.

half of the total rainfalls of frontal storms. However, squall zone, static front, and air mass storms appeared to receive little or no effect from the urban environment except for possible influence on squall zone storms imbedded in deep convective air masses (i.e., a mixing depth > 3000 m). Most of the excessive rainfall in the maximum-effect area occurred on days when the natural precipitation was moderate to heavy in intensity (i.e., when storms produced 25 mm or more of surface rainfall).

Given these relationships of rainfall patterns which were modified by a relatively large surface area, the present study attempted to determine if rainfall changes can be identified by the modification of weather systems during operational programs from much more localized sources (aircraft or ground generators). The procedures employed in the synoptic analyses consisted basically of three parts: (1) selection of the precise seeding days to be included in the analyses, (2) performing synoptic analysis on each day, and (3) computation of the rainfall distribution for various stratifications.

3.1.1 Selection of the seeded days

Due to both the large number of seeding days in each program and the time constraints of this study, not all seeded days were included in the evaluation. For MR, it was decided to use only those days seeded during the months of May, July, and August. June was excluded because the operations were geared mainly towards hail suppression. Days in May, July, and August that were seeded solely for hail suppression were also omitted from the synoptic analyses. A total of 163 seeding operations for which satisfactory operational and meteorological data were available were used in the synoptic evaluation.

In the OK study, seeded days selected for synoptic evaluation were taken from the months of May through August. By means of a random number generator, one-half of each month's total seeded days were chosen. During the summers of 1975-76 when both MR and OK projects were operated concurrently, the selection was based only on those days on which seeding occurred in OK but not in MR. This precaution was taken to preclude the chance of contamination from either projects because of their close geographical proximity. An initial total of seeded days in MR of 163 and in OK of 111 was used (Table 3.1).

Table 3.1. Monthly Totals of Seeding Days Evaluated within OK and MR.

Year	1972	1973	1974	1975		1976		1977	1978	1979
Project	OK	OK	OK	OK	MR	OK	MR	MR	MR	MR
May	3	3	9	3	10	2	8	18	8	10
June	9	8	9	2	0	4	0	0	0	0
July	9	10	5	2	15	2	10	11	11	8
Aug	10	7	11	2	10	1	10	13	11	10
Total	31	28	34	9	35	9	28	42	30	28

3.1.2 Synoptic analysis

Meteorological charts covering all seeding years were obtained from the National Climatic Center in Asheville, North Carolina to determine the synoptic type and storm motion for each seeded day. The data included surface charts for every 3 hours, upper air charts for every 12 hours, and radar charts at hourly intervals.

The method of synoptic evaluation in both projects was identical. The initial determination was to record the time during each day over which seeding actually occurred. In OK, this information was provided by the project personnel on a site by site basis. Seeding periods were defined as the time containing a continuous period of operation between the ignition of the first ground generator in the project area until the last one was extinguished. In MR, the information on seeding periods was provided by the Kansas Water Resources Board. Determination of the seeding periods had to be done from individual pilot reports for 1976 and 1977.

The synoptic summaries developed for each period ran from 3 hours prior to the start of seeding and continued until 3 hours after seeding ended. During the study of each day's synoptic charts, the most pertinent information was recorded for review later. In general, surface and upper air charts were reviewed first to locate the positions of controlling features such as fronts, troughs, etc., found in a close geographical location to the target. A sketch was made of the major surface features at both the time seeding began and ended (with a "mid-period" map included if seeding continued for more than 10 hours) across the general region of both MR and OK target areas (see Fig. 3.2 for an example). Wind speed and direction were tabulated from the surface, 850-, 700-, 500-, and 300-mb levels as in Table 3.2. Next, radar charts were studied with information tabulated concerning the coverage, continuity, movement, and severity (maximum height of echoes, existence of line structure and/or hail, etc.) of precipitating systems in the area. Copies of the radar charts at 2-hour intervals were also added to the summary of each seeded day. An example of a daily summary is shown in Table 3.3. A 16-point compass was used in recording wind direction in all charts.

After a review of all charts was completed, a determination of the synoptic type controlling each seeding period was performed. The guidelines used in formulating the synoptic divisions were basically those developed in the analysis of inadvertent weather modification effects around St. Louis during METROMEX (Changnon et al., 1977). Eight different synoptic stratifications were used. These were squall line, squall zone, frontal (cold, warm, and stationary), pre/post front, air mass, and low pressure. A general description of each synoptic type is given below.

Table 3.2. Example of Synoptic Tabulation Sheet.

Project: Oklahoma Year: 1973

Date/time	Surface dir	Surface spd	850 mb dir	850 mb spd	700 mb dir	700 mb spd	500 mb dir	500 mb spd	300 mb dir	300 mb spd	Mean dir	Mean spd
23 May/OOZ	NE	10	W	10	W	20	W	25	WSW	45	W	25
03Z	NE	5										
06Z	NNE	5										
09Z	N	5										
12Z	N	5	NW	5	NW	15	NW	25	SW	30	W	19
15Z	N	5										

Storm motion: W 25
Synoptic type: Squall line
Seeding period: 1900-0800 CDT (0000-1300Z), 22-23 May 1973
Plume wind: NE 5
Comments: A weak trough appeared at all levels over the study area. Surface charts showed a stationary cold front 75 and 150 miles south of the target.

Squall Line Storms. A nonfrontal group of thunderstorms accompanied by a trigger mechanism, usually a short wave trough. The convective activity associated with the storm system was intense, well-organized, and often times was arrayed in a narrow band or line of active thunderstorms.

Squall Zone Storms. A mesosystem of thunderstorms organized into an area or cluster and independent of a frontal zone. These storms, like squall lines, tended to move across large regions, and an upper-air impulse was usually discernible.

Frontal Storms. Precipitation formed within 120 km (75 mi) of a surface front (cold, static, or warm). There was no synoptic evidence that this precipitation was associated with a squall line or squall zone which, on occasion, moved 40 km (25 mi) or more ahead of the fronts.

Pre/Post Frontal Storms. Precipitation associated with a frontal structure but at a distance of 120 to 240 km (75 to 150 mi) ahead or behind a front.

Air Mass Storms. A shower or thunderstorm generated within an unstable air mass. No large scale or mesoscale synoptic causes were evident. The resulting convective activity was usually widely scattered to scattered and weak.

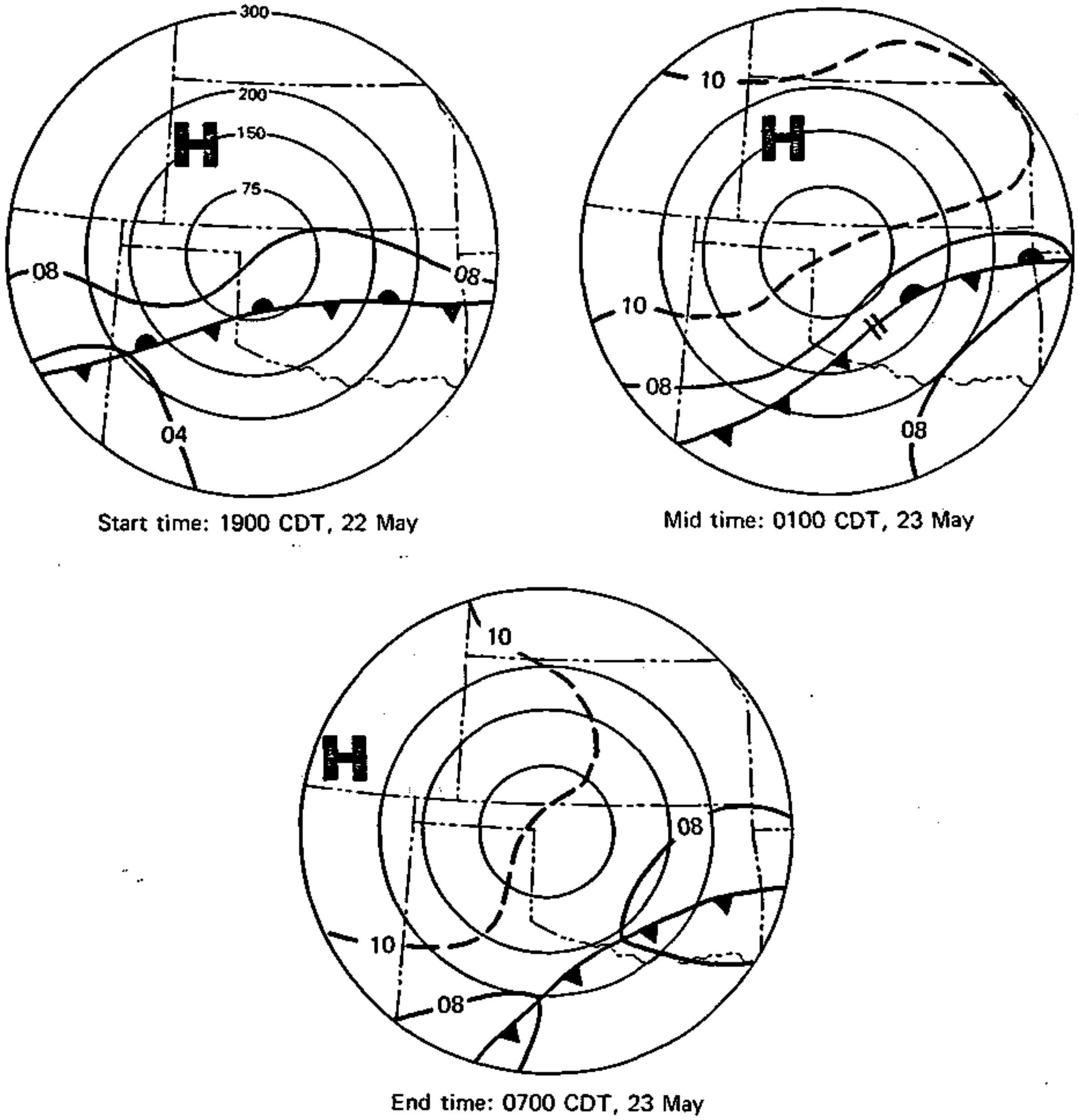


Fig. 3.2. Example of major surface synoptic features.

Table 3.3. Example of Radar Tabulation Sheet.*

Project: Oklahoma Year: 1973

Date /Time	Rain in Target	Echo Description[a]	Echo Motion	Echo Tops	Rain Types[b] RW	Rain Types[b] TRW	Comment
22 May							
2040Z		SA in eCO,neNM,wTX, scOK;BL in ecOK	W 30	450	M	M-H	
2240Z	Y	SA in seCO,wTX,and e 2/3 of OK	W 35	450	L	M-H	line forming in seCO to wTX
23 May							
0040Z	Y	BL in seCO to seTX; SA in sOK,ncTX	W 25	400		H	seeding started at 00Z
0240Z	Y	B-SL in swKS,wOK, cTX	W 20	360		M-H	area of shower surrounding line
0440Z	Y	S-BL in OK,ncTX	W 25	330		M-H	area of shower surrounding line
0640Z		BL in cOK to cTX	W 35	340	L	M-H	
0840Z		BA in eOK,SA on n target boarder	W 25	210	L	M-H	line in seOK
1040Z		BA in nOK	W 20	250	L	M	
1240Z		BA along e 2/3 of OK-KS border	W 20	230	L	M	seeding stopped at 13Z
1440Z		BA along e 2/3 of OK-KS border	W 20	250		M-H	
1640Z		BA in cOK,neOK	W 20	250	L-M	M	

*Time that echoes were observed over target: 2240-0540, 0740-1140.
Location of precipitation at 1200Z (0700 CDT); (observation for most raingage sites): 22 May: east-central CO, KS, TX Panhandle, north-central TX;
23 May: north-central & north-eastern OK, south-central and south-eastern KS.

[a] BA: broken area; BL: broken line; SA: scattered area; SL: scattered line; B-SL: broken to scattered line; S-BL: scattered to broke line; CO: Colorado; KA: Kansas; NM: New Mexico; OK: Oklahoma; TX: Texas; eCO means east Colorado, ncTX means north central Texas, etc.

[b] L: light; M: moderate; H: heavy

Low Pressure Storms. A cyclonic storm situation so close to the research area that it was not possible to associate the precipitation with a frontal or mesoscale weather structure. These systems are rare during the summer months.

In most cases, the target and its immediate surroundings were influenced by only one type of weather system during each period. However, due to both the size of the general area of interest (approximately 500 km across) and the length of some seeding periods (occasionally over 20 hours in OK), changes in synoptic type within several of the seeding periods were unavoidable. When this occurred, qualitative estimates of precipitation were made from the radar charts of the day to determine if one synoptic type appeared to provide most of the rainfall across both the target and outside-target comparison areas. If no type seemed to have a definite predominance of influence, the day was taken out of the analysis to be included later if other reasons dictated. It must be stressed here that in order for any multi-typed day to be included, the synoptic type over both areas had to be identical.

Synoptic stratification totals for each project are shown in Table 3.4. The results show a definite preference for air mass storms across both areas. Cold front, static front, and squall zone storms appeared to be closely divided, each with frequencies of between 15-20 percent. Squall line storms occurred less often but still accounted for about 10% of the total. Synoptic types that occurred less than 10% of the time were not investigated as an individual group due to their infrequent occurrence.

Storm motions were obtained primarily from echo movements reported on radar charts. Guidance came also from calculation of a mean wind over the target area of the upper-air level values. The stratified totals of storm motions can be seen in Table 3.4 also. West was the most predominant wind direction, occurring nearly one-fourth of the time in both projects. Not surprisingly, storm motion was from the northwest to south southwest over 90% of the time. The highly subjective nature of this analysis (as well as the hand plotting of radar echo motions through 1977 by NWS) can be seen in the peaking of directional preference in the primary directions (NW, W, and SW) compared to the secondary divisions (WNW, WSW, and SSW).

Table 3.4. Percentages of Synoptic Type, Storm Motion, and Plume Wind Stratifications within OK and MR.

	Stratification	OK	MR
Synoptic Type	Squall Line	10.8	10.4
	Squall Zone	14.4	20.2
	Cold Front	20.7	18.4
	Static Front	15.3	16.6
	Warm Front	0.9	0.6
	Pre/Post Front	4.5	7.4
	Air Mass	33.3	25.8
	Low Pressure	0	0.6
Storm Motion	NNE	0	1.2
	N	0.9	1.2
	NNW	2.7	3.7
	NW	12.6	17.2
	WNW	15.3	12.9
	W	27.9	20.9
	WSW	11.7	12.9
	SW	13.5	15.3
	SSW	7.2	14.1
	S	6.3	0.6
	SSE	0.9	0
	SE	0	0
	ESE	0.9	0
Plume Wind	SE	47.6	
	SW	23.2	N/A
	NW	2.4	
	NE	26.8	

Due to the use of ground-based generators as the seeding apparatus, an additional sorting of days was accomplished in the OK program according to the direction of motion of the low-level winds (i.e., the surface and 850-mb levels). Here, estimates of the so-called "plume" winds were calculated to give an indication of the initial flow of the seeding materials as it departed from the surface source. Direction estimates were made only to the closest quadrant (NE, SE, SW, or NW). It was believed that the variations in surface conditions would be too great to accurately estimate the plume winds to a closer degree.

As was done during the synoptic typing, if a significant change occurred in the storm motion direction during a seeding period, the case was first evaluated for precipitation production during each different motion period. If none predominated, then the case was removed from the analysis for the time being. Extreme care was taken when examining a switch in the plume wind since changes there nearly always resulted from frontal passages. More often than not, multi-plume cases were dropped. However, it was possible for a case to have been excluded from the analysis due to multi-types within the seeding period but included for analysis in the storm or plume motion stratifications.

It was decided that in the evaluation of both projects, seeding occurring in any part of the target would be assumed to affect the entire target. The target was considered an entity and was either seeded or not. No attempt was made in either project to divide the target into smaller regions pinpointing the areas where seeding actually occurred and relate these to precipitation. The sampling density (raingages, upper air observations, etc.) was not considered adequate for this purpose.

The day of each seeding period was taken to be the day seeding began. Quite often (especially in OK) seeding continued into the following day. This point is made to avoid confusion with the observation date of the precipitation, which almost always was the day following seeding.

3.1.3 Rainfall data

Hourly and daily rainfall totals in 1972-79 were used for the precipitation analyses. Boundaries were drawn to define a study area, which covered five states: Colorado, Kansas, New Mexico, Oklahoma, and Texas (Fig. 3.1). Specifically, the boundaries were the 97th and 105th meridians, 32.5°N. latitude, and portions of the northern state borders of Kansas and Colorado.

In the early stage of analysis, it was decided to use 24-hour rainfall totals to compare various stratified groups of storm motion and synoptic types. The period used for summing 24-hour rain started sometime in the morning and continued into the following day. The advantage of using this method was that since the seeding periods (as well as the precipitation) occurred mainly during the afternoon and early morning, rainfall sites with a morning observation time would almost always encompass all of the seeded precipitation from the previous day. Of course, unseeded rainfall would also be included and would damper the seeding effects. Nevertheless, it was believed that by averaging many cases within each stratification, the seeding effects, if present and substantial, would emerge.

An analytical problem encountered with this method was that the observation times of daily rainfall at NWS stations varied from state to state. In Kansas, Oklahoma, and Texas, 70 to 80% of all observation were taken at either 0700 or 0800 local time. In Colorado and New Mexico, however, the predominant observation time was in the late afternoon, thus the observations had to be discarded. This yielded poor spatial resolution for the region immediately upwind of the target areas, especially in MR. To alleviate this problem, additional NWS stations with hourly data were used to compute 24-hour rainfalls, ending at 0700 local time. This improved the stations spacing problem somewhat. Still, regardless of the depletion of useable sites in the western part of the area due to the differences in observation time, approximately 465 stations (depending on the year) out of 689 total sites were useable in the analysis.

Isohyetal maps showing total rainfall as well as gage-average rainfall were produced for each synoptic type, storm motion, and plume wind, if at least 10 cases were available for the stratification. Within a particular synoptic type or storm motion, only stations having more than one-half non-missing cases were plotted.

3.2 Muddy Road Aircraft Seeding Project

Hsu et al. (1981a) studied the results of the Muddy Road program, based on analyses of monthly and seasonal precipitation data, and concluded that statistically there was a non-significant reduction of rainfall in the target area during the seeded period. Fixed control areas located west (most commonly upwind) and east (usually downwind) of the target area were used in the evaluation. However, the use of monthly or seasonal data and fixed controls could lead to conservative results in evaluation, since seeding may produce different effects depending upon storm movement, types of synoptic weather conditions, precipitation intensity and other factors, as found in the METROMEX research (Changnon et al., 1977). Therefore, an investigation was undertaken to evaluate the Muddy Road rain enhancement program, based upon analyses of each seeding day, and stratifying the data according to various meteorological factors.

3.2.1 Analytical approach

Each seeded period was categorized according to storm motion, synoptic storm type, and storm intensity, as measured by areal mean rainfall for the 24-hour period during which cloud seeding occurred. Computation of areal mean rainfall was made from the observations of the NWS climatic network in which most of the gages are of the non-recording type; therefore, no finer division of the rainfall distribution could be made.

Varying control areas were used in the investigation, and these were made to conform closely with the size and shape of the target area. In each storm period, the designated control area was determined from the general motion of the storm system being seeded. This was done to minimize potential control contamination from the seeding material. The locations of the 7 control areas are shown in Fig. 3.3.

The monthly normals for the target and each control areas are shown in Table 3.5. In most cases, the monthly normal in the target area exceeds that in the selected control areas. Because of a substantial climatic gradient in the preci-

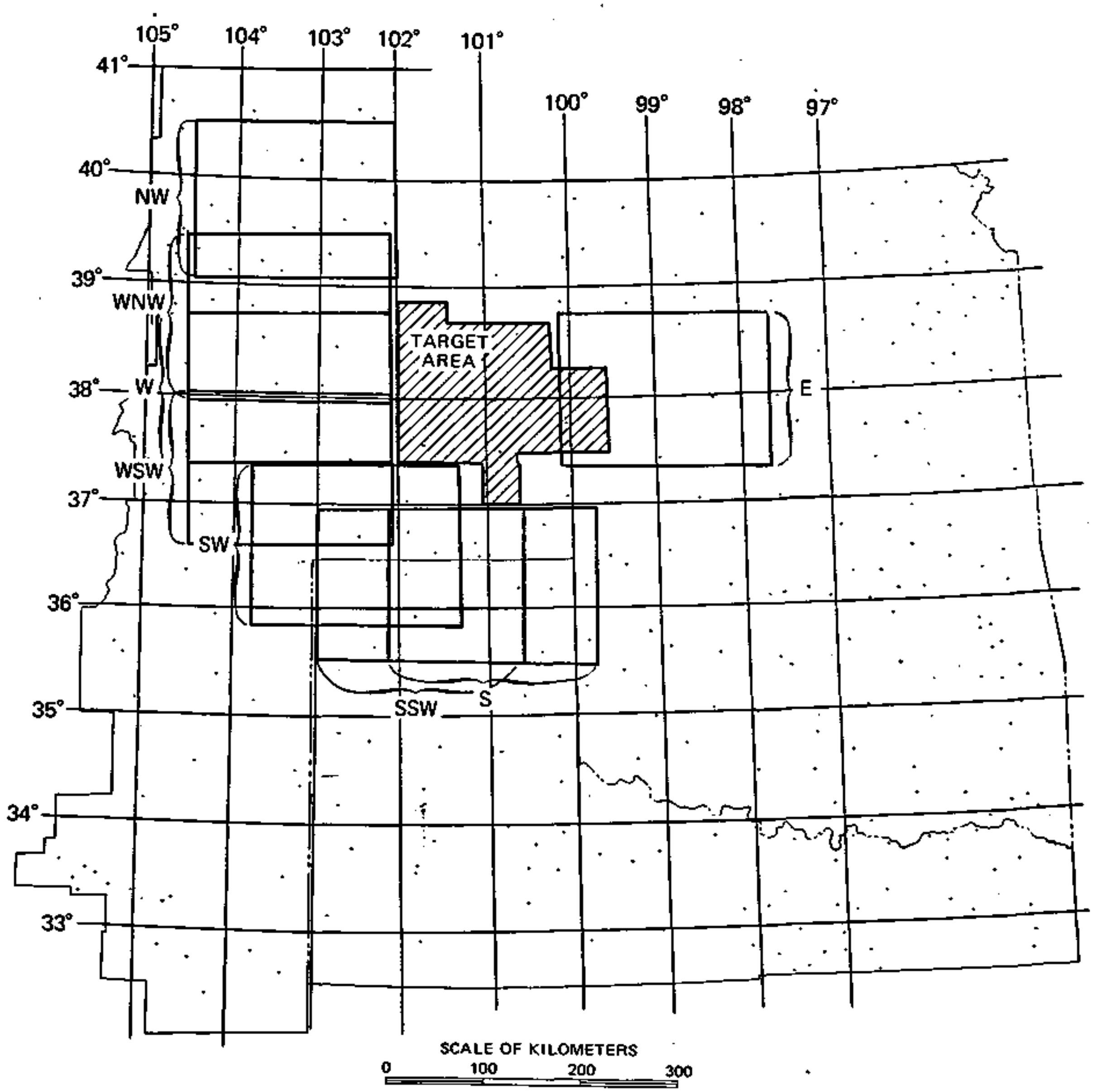


Fig. 3.3. Upwind Control Area, Muddy Road Project.

pitation distribution within the target and control areas, the storm period rainfall was adjusted, based on the 1941-1970 monthly NWS normals, for the target and control rainfalls to compensate for the differences.

Table 3.5. Climatic Rain Normal of Muddy Road Project Areas, 1941-1970 Average.

Areas	No. of Stations	May	June	July	Aug.	Sept.
Target	22	2.88	3.31	3.21	2.59	1.83
Control						
NW	8	2.77	2.56	2.57	1.98	1.29
WNW	8	2.12	1.79	2.23	2.02	1.17
W	7	2.09	1.75	2.18	2.06	1.33
WSW	3	2.24	1.91	2.22	2.23	1.58
SW	10	2.58	2.37	3.08	2.53	1.75
SSW	10	3.03	2.89	3.27	2.62	1.79
S	14	3.23	3.19	3.33	2.56	1.84

3.2.2 Results

Target-Contro1 Relations Grouped by Storm Motion. Table 3.6 summarizes the relationship found between storm motion and target-control differences. Mean rainfall is shown for the control areas and for the target area before and after adjustment for the climatic gradient. Also shown is the target/control ratio with and without the climatic adjustment. Overall, Table 3.6 shows that seeded storms system moving from the WNW, WSW, SW, and SSW produced more rainfall in the target (T) than in the control area (C). Similarly, storms moving from the NW and W had more rainfall in the control than in the target area. Combining all storm periods, the target received 25% more rainfall than the control before adjustment, but this decreased to 9% after adjusting for the natural climatic gradient. Omitting the W and NW storm movements, the adjusted T/C ratio is 1.43. For combined W and NW motions, the ratio is 0.72.

Table 3.6. Target-Control Relations in Storm Periods Stratified by Storm Motion, Muddy Road Project.

Storm Motion	N	C (mm)	Unadjusted T (mm)	Adjusted T (mm)	Tu/C	Ta/C
NW	29	61	56	47	0.92	0.77
WNW	20	31	60	45	1.94	1.45
W	34	154	142	108	0.92	0.70
WSW	21	41	71	60	1.73	1.46
SW	25	66	108	102	1.64	1.55
SSW	23	98	128	133	1.31	1.36
S	1	3	0	0	--	--
Total	153	454	565	495	1.24	1.09

Fig. 3.4 illustrates the type of isohyetal patterns obtained with the storm motion stratification. Fig. 3.4a shows the pattern with storms moving from the NW, along with the location of the target and control area. The adjusted target rainfall was approximately 23% less than the control rainfall with the NW storms. Fig. 3.4b shows the isohyetal pattern with storms moving from the WNW, in which the adjusted target rainfall was nearly 50% greater than in the control area.

Meteorologically, from perusal of the available data, there is no apparent reason for the wide range in T/C ratios among the storm movements. Similarly, topographic causes are not indicated from available information. If the differences are meteorological or topographically related, more detailed information would be required to reveal them.

The above findings suggest an overall increase in rainfall from the 5-year seeding program of approximately 9%, but the size of the overall T/C difference and its variability with storm motion indicate a possible seeding effect is not firmly established from the results presented here. Huff (1966) has shown how natural variability and gaging deficiencies can produce substantial area differences in summer rainfall measurements in the Midwest that may persist for several years. For example, summer rainfall differences on the order of 5% persisted

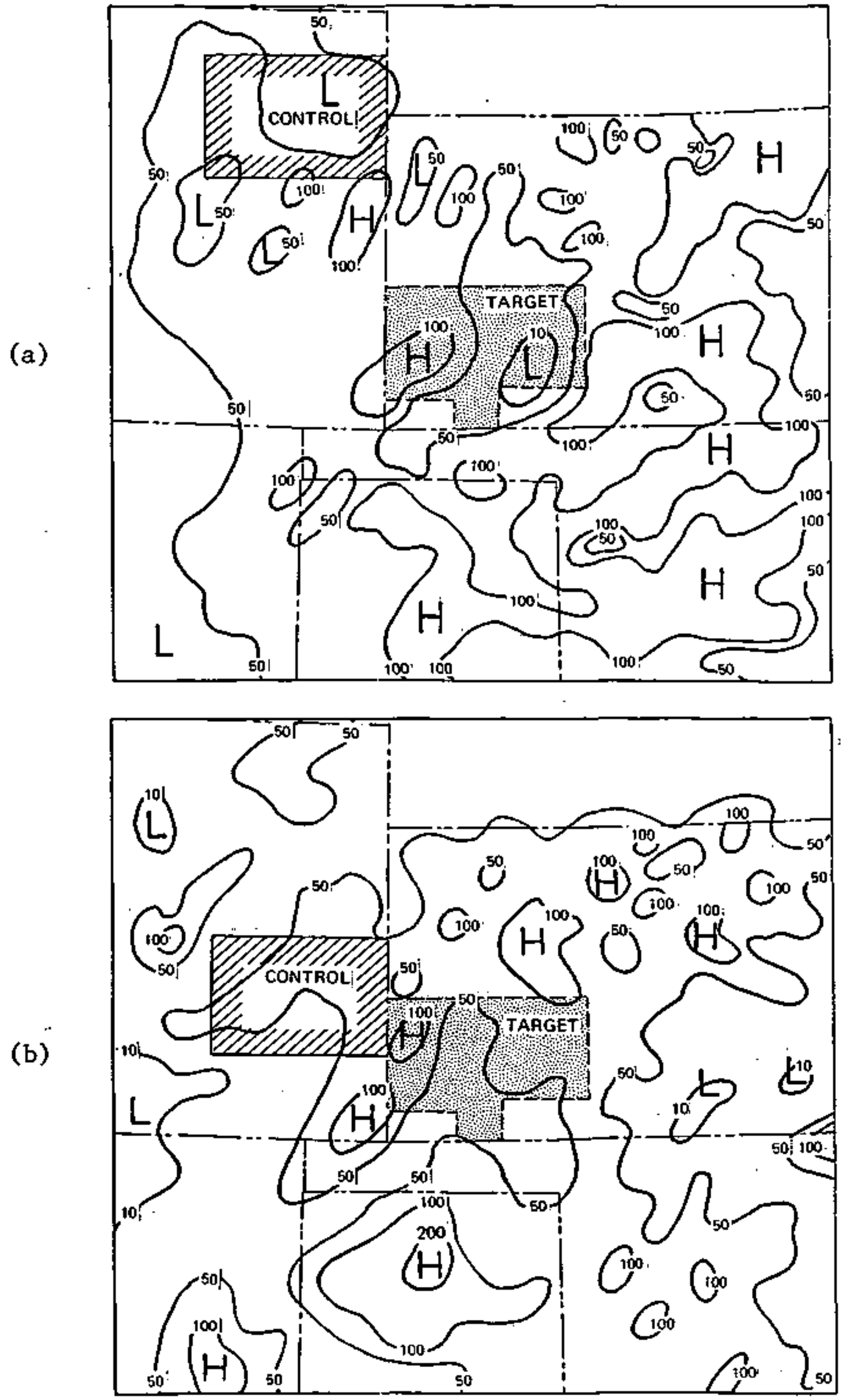


Fig. 3.4. Rainfall totals of a) NW storms, b) WM storms, Muddy Road Project.

over periods of 5 years in densely-gaged areas immediately adjacent to each other in Illinois. Thus, it is conceivable that the 9% difference averaged over 5 summers shown in Table 3.6, based on raingage stations located 15-25 miles apart in many cases, could conceivably be largely a product of natural variability and raingaging deficiencies.

Target-Control Relations Grouped by Synoptic Type. Target-Control relations resulting from stratification by synoptic storm type are summarized in Table 3.7. Results are shown only for those storm types for which 10 or more cases occurred. Air mass storms (AM) occurred most frequently and squall zones (SZ) produced the most rainfall. After adjustment for the climatic gradient, the two heaviest rain producers, squall zones and cold fronts (CF) showed less rainfall in the target than in the control areas. Control areas, as in Table 3.7, were determined by storm motion for each storm. Thus, each synoptic type includes various storm motions.

Combining all the storms in Table 3.7 (149), the adjusted T/C ratio is only 1.03. Thus, omitting only 4 storms, the T/C ratio was lowered from 1.09 in Table 3.6 to 1.03 in Table 3.7. This illustrates the strong effect that can be produced by omitting a very small percentage of the storm sample, and emphasizes further the reservation with which the relatively small T/C difference for the 5 summers must be treated. The target rainfall sample (566 mm) for the 5-year program represents only 51% of the normal rainfall for this period.

Fig. 3.5 shows typical patterns obtained when the data were stratified according to synoptic storm type. Fig. 3.5a shows the isohyetal pattern obtained with cold front storms in which the adjusted target rainfall for the 5-year sampling period was approximately 13% less than in the control areas. Except for SW of the target, the total rainfall was greater in the region immediately sur-

Table 3.7. Target-Control Relations in Storm Periods Stratified by Synoptic Storm Type, Muddy Road Project.

Synoptic Type	N	C (mm)	Unadjusted T (mm)	Adjusted T (mm)	Ratio Tu/C	Ratio Ta/C
Cold Front	29	123	128	107	1.04	0.87
Static Front	26	58	94	80	1.62	1.38
Post-Frontal	10	35	26	19	0.74	0.54
Squall Line	17	43	86	82	2.00	1.91
Squall Zone	31	154	138	122	0.90	0.79
Air Mass	36	17	35	33	2.06	1.94
Total	149	430	507	443	1.18	1.03

rounding the target. Fig. 3.5b shows the isohyetal pattern associated with static front storms, in which the target rainfall was nearly 40% greater than in the control areas used on conjunction with the target. The region lying immediately NW, W, and SW of the target shows substantially lighter rainfall than the target area. Target versus control increases were also sizable in the squall line and air mass cases.

Target-Contro1 Relations Grouped by Areal Mean Rainfall. An analysis was performed in which the target-control data were grouped according to the control mean rainfall. It was assumed that the control was unaffected by the seeding, and, therefore, provided a measure of the natural rainfall in the study area. The storms were grouped according to the following mean rainfall divisions: 7.5 mm or more, 5.0-7.4 mm, 2.5-4.9 mm, 1.25-2.4 mm, 0.25-1.24 mm, and 0.00 (no control rainfall on the seeding day). Results are shown in Table 3.8 in which values are presented for adjusted T-C and T/C for each mean rainfall group. The number of cases in each group is also indicated.

(a)

(b)

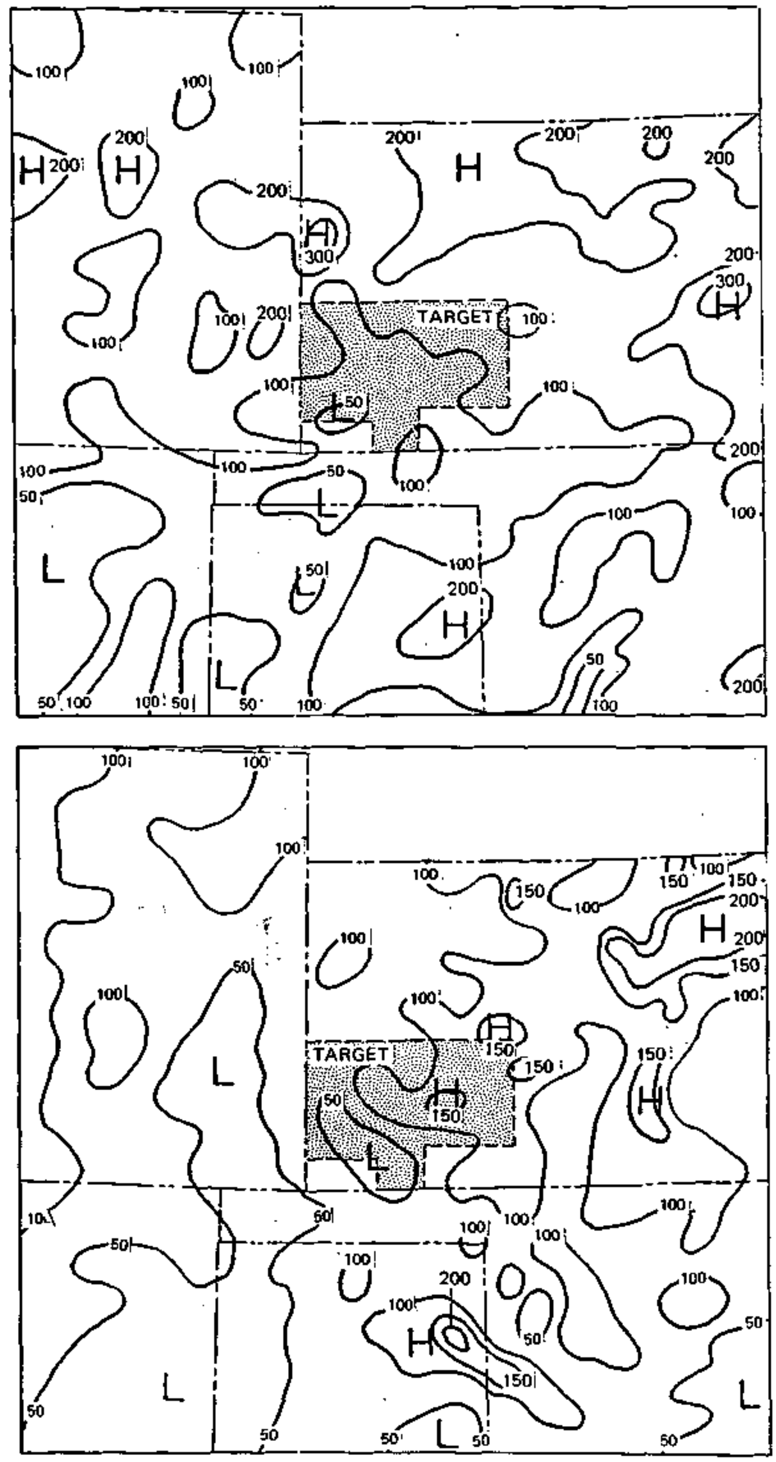


Fig. 3.5. Rainfall totals of a) cold front storms, b) static front storms, - Muddy Road Project.

Table 3.8. Relation Between Storm Period Mean Rainfall and Target-Control Differences, Muddy Road Project.

Control Area Mean(mm)	Number of Cases	Target-Control(mm)	Target/Control
< 0.25	41	54	---
0.25-1.24	41	78	4.68
1.25-2.49	19	39	2.20
2.50-4.99	16	11	1.24
5.00-7.49	20	-14	0.88
> 7.50	16	-124	0.44

The results in this table show a pronounced trend throughout the stratification; that is, there is a distinct decrease in the T/C ratio in progressing from relatively light to relatively heavy rainfall. T-C changes from a positive value for mean rainfalls up to 5 mm (0.20 inch) to a negative value for these exceeding 5 mm. The implication is that the seeding effect, if present, was concentrated in those storms producing only relatively light amounts naturally. Conversely, the table implies that the seeding was not effective or was suppressing the natural rainfall on the target in those storms producing moderate to heavy amounts. If Table 3.8 reflected seeding effects, then one would have to be careful to avoid seeding those storms capable of producing moderate to heavy amounts naturally. This could be a very difficult problem in seeding operations. The implications in Table 3.8 are opposite to those found in the METROMEX inadvertent weather research (Changnon et al., 1977) in which it was established that the inadvertent mechanisms were most productive in those storms producing heavy amounts naturally.

An analysis was made to investigate further those storms most responsible for the T-C and T/C values shown in Table 3.8. Results showed that the T/C ratio exceeded 1.00 in 41 of 112 storm periods (37%) in which control mean rainfall was 0.25 mm or more (measurable rainfall). The ratio was 1.00 in 8 cases (7%) and less than 1.00 in 63 storm periods (56%). Thus, if seeding was effective, the above statistics indicate it was not consistently so, since T/C exceeded 1.00 in less than 50% of the seeded storms.

Examination was made of the frequency with which the target exceeded the control mean rainfall, when seeding days were grouped into the mean rainfall categories of Table 3.8. Results showed that T exceeded C on 44% of the seeded days with the control mean ranging from 0.25 to 1.34 mm (very light rainfalls). This percentage gradually decreased to 12% on days with the control mean equal to or exceeding 7.5 mm (moderate rainfalls). These statistics support the findings presented in Table 3.8 and the implications of these findings. However, in all of the mean rainfall categories (with the exception of no rainfall days on the control) there were more seeding days on which the control exceeded the target rainfall than vice versa.

Analyses were made of those storms in which T/C did exceed 1.00. Rankings from high to low values of T-C showed that among the 10 highest (Table 3. 9), the range was from 8-26 mm (0.33-1.03 inches). The control mean rainfall ranged from 0.25-18 mm (0.01-0.69 inch). The control mean was less than 2 mm in 5 of the top 10 ranks, and was below 5 mm in 8 cases. Thus, the greatest differences were predominantly with light rainfall on the control. Storm movement was from the SSW in 4 storms and out of the SW quadrant in 7 cases. There was no common standout among the storm types. Thus, the T/C ratios tended to maximize with storms moving from the SSW to WSW in which light rainfall amounts were occurring naturally. Table 3.9 also indicates that the larger target excesses occurred most often in May (6) and, more specifically, in May 1977 when 5 of the 10 largest T-C differences were recorded. The distribution is less skewed when the top 25 ranks are considered. Among these, there were 10 cases in May, 7 in July, and 8 in August. The greatest negative differences (control-target) were recorded in July with 5 of the top 10 ranks of these cases. Among the 25 largest negative storm values, 13 occurred in May, 8 in July, and 4 in August.

Table 3.9. Ranking of Target-Control Differences When Target Exceeded Control Mean Rainfall, Muddy Road Project.

Rank	T-C(mm)	Control Mean(mm)	Storm Motion	Synoptic Type	Storm Date
1	26.2	1.8	SSW	Squall Line	5/18/77
2	21.8	0.5	SSW	Squall Zone	8/1/76
3	15.0	17.5	SSW	Warm Front	5/20/77
4	14.7	4.1	W	Pre-Frontal	5/12/75
5	13.7	7.4	W	Cold Front	8/10/77
6	12.2	1.0	SSW	Air Mass	5/24/77
7	9.6	0.3	WSW	Static Front	5/01/77
8	9.6	2.0	WSW	Squall Line	8/30/77
9	8.6	0.3	SW	Squall Line	5/14/77
10	8.4	4.8	WNW	Static Front	8/5/77

An examination of the 41 seeding days during which no rainfall occurred in the control area showed that rain did not occur on the target on 27 (65%) of these days. Total target rainfall on the 27 days was 54 mm (2.12 inches) which amounts to 11% of the adjusted target total. However, there were also 18 days on which the control recorded rainfall when the target had none. The total rainfall was 39 mm (1.55 inches) and this accounted for 7% of the control total for the 5 summers.

Adding the 27 storm periods with target rainfall when none occurred on the control, there was a total of 68 storm periods seeded. This is only 44% of the seeded storms which is a further indication that a consistent seeding-induced enhancement of the target rainfall was not being achieved during the 5-yr program.

Annual Target-Contro1 Relations. Analysis was made of the year-to-year variation in the targetcontrol differences. Results are summaried in Table 3.10 in which comparisons are made, based on the adjusted target rainfall. Table 3.10 shows that the target exceeded the control rainfall during 3 years. They were approximately equal in 1976, and the control exceeded the target rainfall in one year (1978). Omitting 1978, the T/C ratio increases from 1.09 to 1.23, which is a substantial difference and would strongly suggest seeding enhancement in the target area. However, examination of the 1978 data from a meteorological standpoint (storm motion, synoptic type, precipitation type) revealed no reason to eliminate 1978 from the 5-year sample. The control excess resulted from two storms producing heavy amounts in the control (21 and 26 mm) compared to light target amounts (2 and 6 mm) in these storms.

3.2.3 Summary of analyses

Analyses were made to evaluate the results of the Muddy Road rain enhancement program carried out in southwestern Kansas during the warm seasons of 1975-1979. Analyses were limited to the months of May, July, and August, since June seeding was primarily concentrated on hail suppression. A total of 163 seeding days for which satisfactory weather and operational data were available for the 15-county area were used in the evaluation. For analysis purposes, the seeding day data were stratified according to storm motion, synoptic storm type, and mean rainfall on the target and control areas.

Storm Motion. Initial stratification of the data was according to storm motion with grouping by 16 points of the compass. Results showed that the target rainfall exceeded the control precipitation by relatively large amounts (36% to 55%) when seeded storms moved from the SSW, SW, WSW, and WNW. Conversely, control exceeded target rainfall by substantial amounts (23% to 30%) when storms moved from the NW and W. Combining all storms, the target rainfall, adjusted for

Table 3.10. Annual Target-Control Relations for Muddy Road.

Year	Control Mean(mm)	Target Mean(mm)	T-C(mm)	T/C	Number of Storms
1975	85	93	8	1.09	32
1976	67	67	0	1.00	25
1977	152	202	50	1.33	41
1978	98	57	41	0.58	29
1979	52	76	24	1.46	26

the climatic gradient, exceeded the control rainfall by approximately 9% for the 5 years combined. Storms moved most frequently from the west, and the control exceeded the target rainfall by 30% in these storms during the 5 years. Omitting the westerly storms from the sample, the T/C ratio for the 5 years would increase from a relatively small value of 1.09 to a relatively high 1.29. However, at this time no reason for omitting the westerly storms from the sample has been determined from available meteorological data and topographic considerations. Except for WNW, the target excesses were concentrated in storms moving from the SW quadrant, and these would tend to have greater moisture content, and consequently, greater potential for rain production when integrated over a long period of time.

Synoptic Type. Stratification of the seeding day data according to synoptic storm types showed target rainfall excesses in squall line, stationary front, and air mass storms; while control exceeded target rainfall in cold fronts, squall zones, and post-frontal storms. Each synoptic group incorporates various storm motions, since the control for each seeding day was determined from the existing storm movement. Post-frontal storms tend to occur in atmospheric conditions in which precipitable water is below average and more stable conditions exist than in the pre-frontal atmosphere. Thus, post-frontal conditions would appear to be less favorable for seeding enhancement than the-pre-frontal atmosphere. Squall zones which were associated with greater control than target rainfall in the

Muddy Road program, were also found to be inactive in stimulating inadvertent mechanisms in the METROMEX research. However, cold fronts and squall lines were found to strongly affect the inadvertent processes in METROMEX, whereas cold fronts were associated with control area rainfall excesses in Muddy Road. In general, the synoptic stratifications provide no strong support for rain enhancement in the Muddy Road program. It would have been desirable to stratify the data by grouping each synoptic type into storm motion categories, but the sample size was not large enough to yield statistically reliable results with this double grouping.

Mean Rainfall. Stratification according to seeding-day mean rainfall in the target and control areas indicated that the target excesses were concentrated in those storms producing relatively light rainfall on the control area. For the 5 years combined, control area means less than 5 mm (0.2 inch) had target excesses that increased with decreasing control mean rainfall. Conversely, seeding days with rains of 5 mm or greater showed a control excess for the 5 years combined, and the excess increased with increasing mean rainfall. This finding indicates that if the seeding was enhancing rainfall, it was doing so mostly in light rainstorms. However, if seeding enhancement is accepted as a primary cause of the target excesses in light rainfalls, then the implication is that the seeding may have been suppressing rainfall in storms producing moderate to heavy amounts naturally. This is different from the METROMEX findings concerning inadvertent enhancement in urban areas, since urban increases were found to be most pronounced in relatively heavy storms.

Further study of the target-control differences on seeding days showed that the 10 largest target excesses occurred mostly on days with light rainfall in the designated control. Among the 10 maximum target excesses, six occurred with control means of 2 mm (0.08 inch) or less, and eight were associated with control means less than 5 mm (0.2 inch). The large differences were most often associated with storms moving from the SW quadrant, but with no dominant synoptic storm type.

Analyses of the frequency with which target rainfall exceeded control rainfall showed that the target exceeded the control amount on less than 50% of the seeding days. This indicates that if seeding was enhancing the target rainfall, it was not doing so consistently, since the control amounts exceeded the target amounts on 56% of the seeding days.

Analyses of target-control relations in individual years showed that target excess occurred in three years, no difference in one year, and a control excess took place in one year. Analysis of available data for the year with a control excess (1978) revealed no major differences in meteorological conditions that might account for it.

3.3 Oklahoma Ground Seeding Project

An operational program encompassing three counties in northwestern Oklaholma (Harper, Woodward, Ellis) was carried out during 1972-76 in an effort to increase the growing season (May-Sept.) precipitation. Ground generators were used as the seeding device. The spatial distribution of the generator sites and location of the target area are shown in Fig. 3.1. A total of 111 seeding periods from the 5-year period were analyzed. This represents approximately 45% of the 5-year total number of seeded days. These 111 storms were selected through the use of a random number generator. This analytical limitation was necessary to keep within personnel and budget limitations.

3.3.1 Analytical approach

As indicated in the section on synoptic analysis methods, each seeded storm period was categorized by synoptic storm type (cold front, warm front, etc.), by storm motion, and by low-level plume movement. The low-level plume winds provided some guidance in estimating where and when the seeding agent may have entered the cloud system of storms approaching the target area.

This problem is similar to that- involved in analysis of inadvertent weather modification effects on precipitation in and around large metropolitan areas where precise information on the relationship of the urban plume (heat, moisture, condensation and raindrop nuclei) with incoming storm systems is not normally available and very difficult to determine even with sophisticated meteorological measurements. Consequently, analytical techniques found most useful in the METROMEX research (Changnon et al., 1977) for evaluating inadvertent seeding effects were adopted in the OK study. Essentially, this consisted of comparing the target area rainfall with that in the surrounding areas, after stratifying the seeding days according to storm movement, low-level plume movement, and storm type, and adjusting the surface rainfall distribution by the natural climatic gradient in precipitation across the study area. Monthly rainfall normals for the study area are shown in Fig. 3.6. Relatively strong precipitation gradients with a general east-to-west decrease in rainfall occur in May and June. The gradient is much weaker in July and August.

In evaluating the results, several comparison areas were selected following the METROMEX approach. These are shown in Fig. 3.7. Areas labeled C1, C2, and C3 were used for comparison in evaluating seeding effects with storms moving from W, WNW, and WSW. These accounted for approximately 55% of the storms and 70% of the target mean rainfall. The three comparison areas have the same shape and size as the target. C1 is located immediately W of the Target, C2 immediately east of it, and C3 has a buffer zone of approximately 70 km (44 mi) between it and the target. Control comparison areas C4 and C5 were used in conjunction with storms moving from the SW, and C6 and C7 areas were used in evaluating seeding. effects with storms moving from the NW. The above five groups of storm movements incorporated 84% of the storms in the 111 storm sample and approximately 95% of the total rainfall recorded in the target area during the 111 storms.

After each storm period was stratified according to synoptic storm type, storm motion, and plume movement, the precipitation amounts at all NWS recording stations in the target and surrounding area were totaled, and an isohyetal map

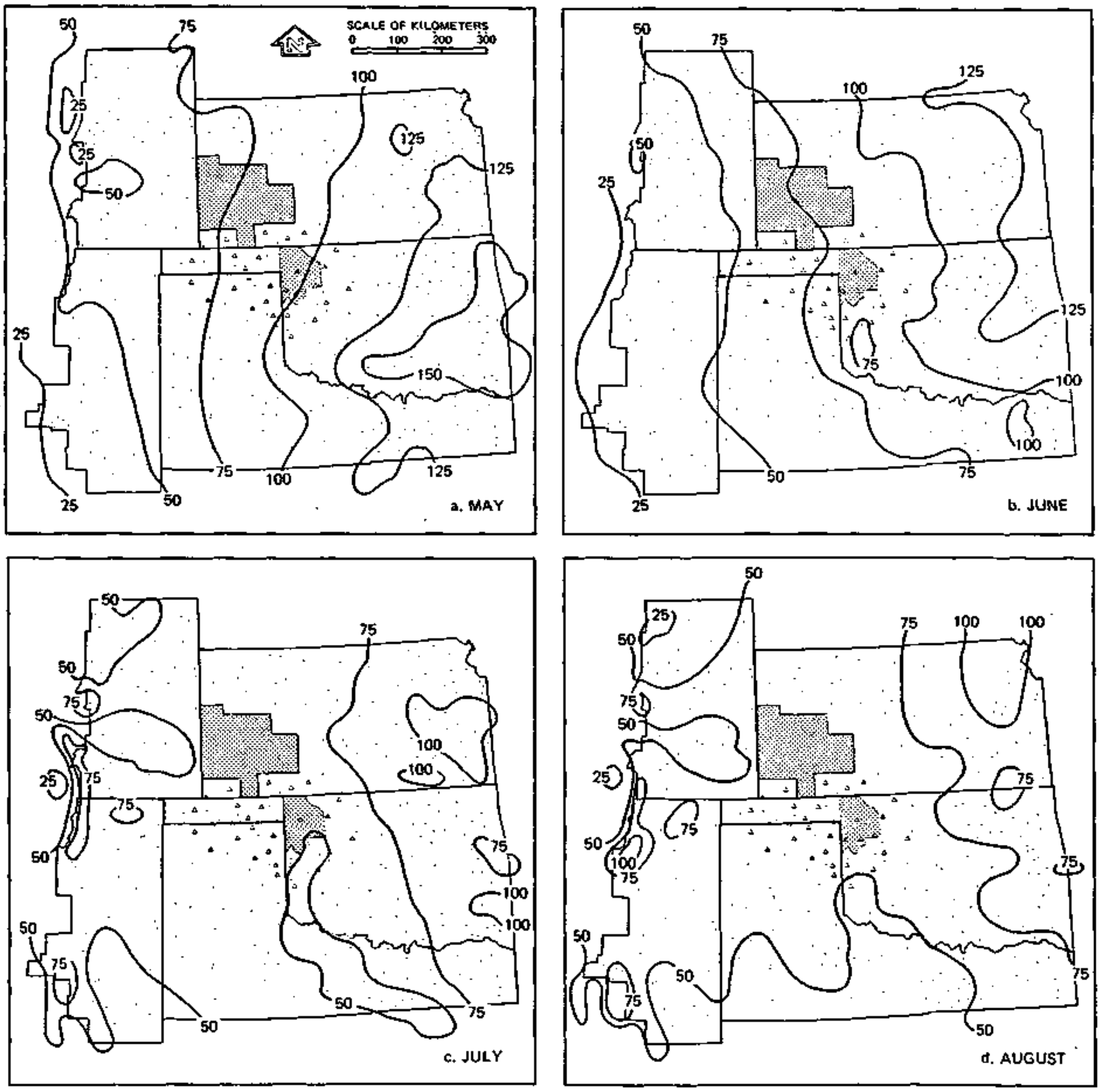


Fig. 3.6. Climatic Rainfall Normals.

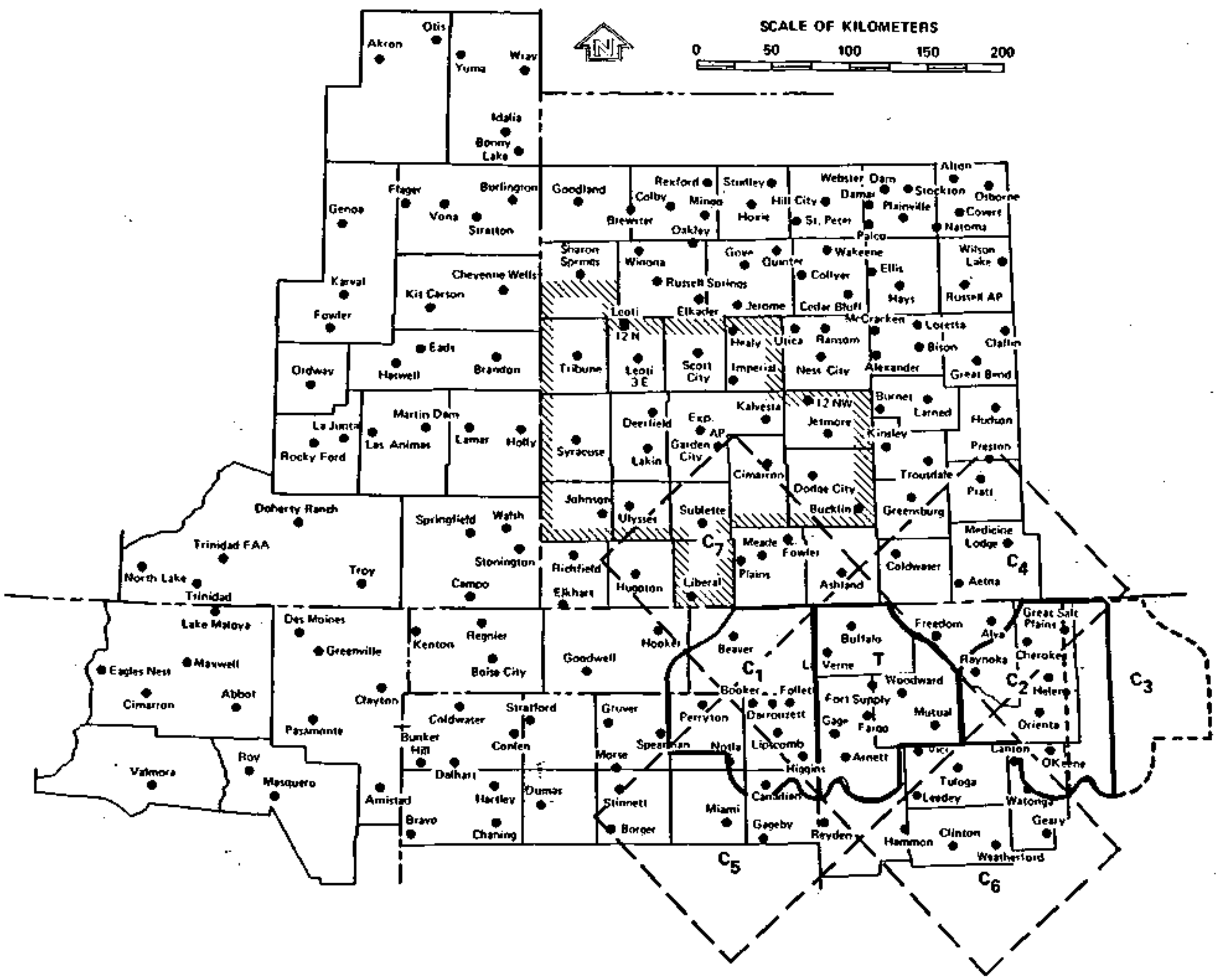


Fig. 3.7. Comparison Areas, Oklahoma Project.

drawn for each stratification. Maps for selected stratifications are shown in Figs. 3.8 to 3.16. The isohyetals are for total rainfall recorded from all storms sampled for a particular stratification.

Isohyetal patterns based on storm movement. Fig. 3.8 shows the rainfall distribution for 111 storms combined. The most noteworthy feature of the isohyetal pattern is a relatively strong high centered approximately 90 km (55 mi) east of the target area. Other highs are located equivalent distances SW, SE, and N of the target area. There is no indication of increased rainfall in the target area with respect to the surrounding area. The question raised in Fig. 3.8 (and which can not be definitively answered here) is whether the pronounced easterly high represents (1) natural rainfall variability during the sampling period, (2) a localized topographic-induced anomaly (for which there is no indication in the long-term mean rainfall pattern or local topographic features), or (3) a seeding-related anomaly resulting from a general miscalculation by the cloud seeding operations of the time-distance relationship between seeding release, cloud ingestion of seeding material, and seeding effect at the surface, at least in relation to the target.

The 4-month period (May-August) was divided into two parts, and the total rainfall distribution for May-June and July-August determined. The isohyetal patterns (not shown) indicate that the easterly high was present and quite pronounced in both 2-month periods. Values in the center of the high were 2 to 3 times the target average in both periods. The easterly high was the only outstanding feature of the two isohyetal patterns in and near the target area.

Fig. 3.9 shows the isohyetal pattern for the storms which moved from a westerly direction. If the easterly high of Fig. 3.7 was seeding-related, persistence of the easterly high would be expected with storms moving W to E. This persistence is indicated in Fig. 3.8. Further stratification of the W-E storms by low-level plume winds showed the easterly high was strongest with plumes moving from the SE. This is the primary inflow direction for convective precipi-

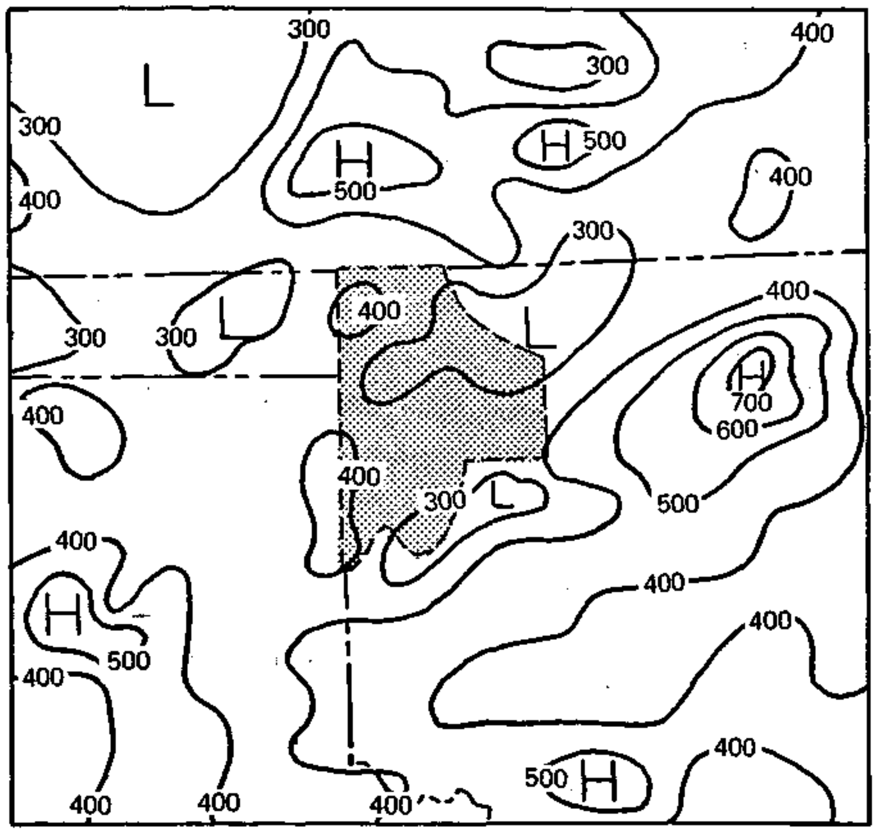


Fig. 3.8. Rainfall Totals of All Storms, Oklahoma Project.

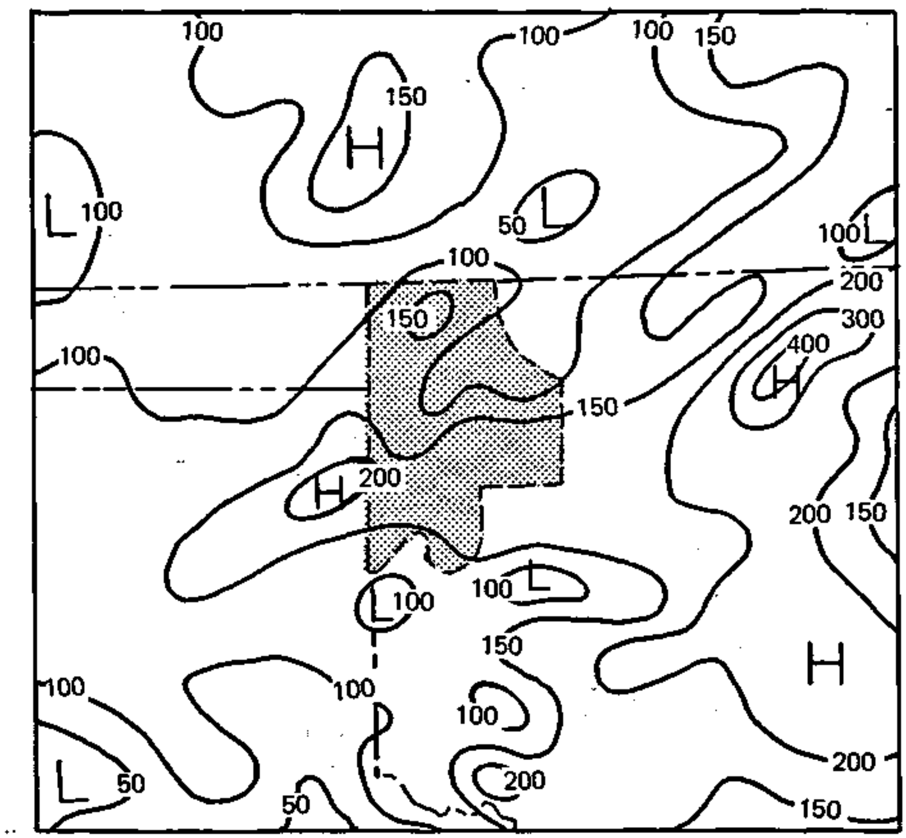


Fig. 3.9. Rainfall Totals of W Storms, Oklahoma Project.

tation cells moving from the west.

Fig. 3.10 illustrates the isohyetal pattern in storms moving from the SW. If seeding-induced, the easterly high would be expected to be relatively weak or non-existent, and any seeding-induced high should be most evident over the RE of the target. Fig. 3.10 shows no indication of the easterly high of Figs. 3.8 and 3.9. There is some indication of a relatively high rainfall area NE of the target area, but this high also may be an extension of a high rainfall area which was oriented NE-SW across central Kansas.

Fig. 3.11 shows the rainfall distribution in storms moving from the NW. Only 6% of the total sample rainfall on the target area occurred in this group of storms which included about 13% of the total number. Fig. 3.11 indicates some- hat heavier rainfall over the target area than in the comparison areas NW and SE of the target. The easterly high which was pronounced in the westerly storms of Fig. 3.9 is not present.

<u>Isohyetal patterns associated with synoptic storm types</u>. Among synoptic types, the greatest amount of rainfall during the 1972-1976 period occurred in conjunction with cold fronts. These fronts accounted for approximately 30% of the total rainfall on the target area. The isohyetal pattern of total rainfall from cold fronts is shown in Fig. 3.12. No strong evidence of a seeding effect on the target area is indicated. Rainfall volumes were similar in areas immediately west and east of the target. Volumes were substantially less south of the target, but considerably greater north and NE of it.

Fig. 3.13 shows the isohyetal pattern for storms associated with stationary fronts. These produced about 20% of the total target rainfall. Relatively light rainfall is indicated over the target area. The heaviest rainfall occurred east of the target (easterly high) where totals were 2 to 4 times greater than in the target area.

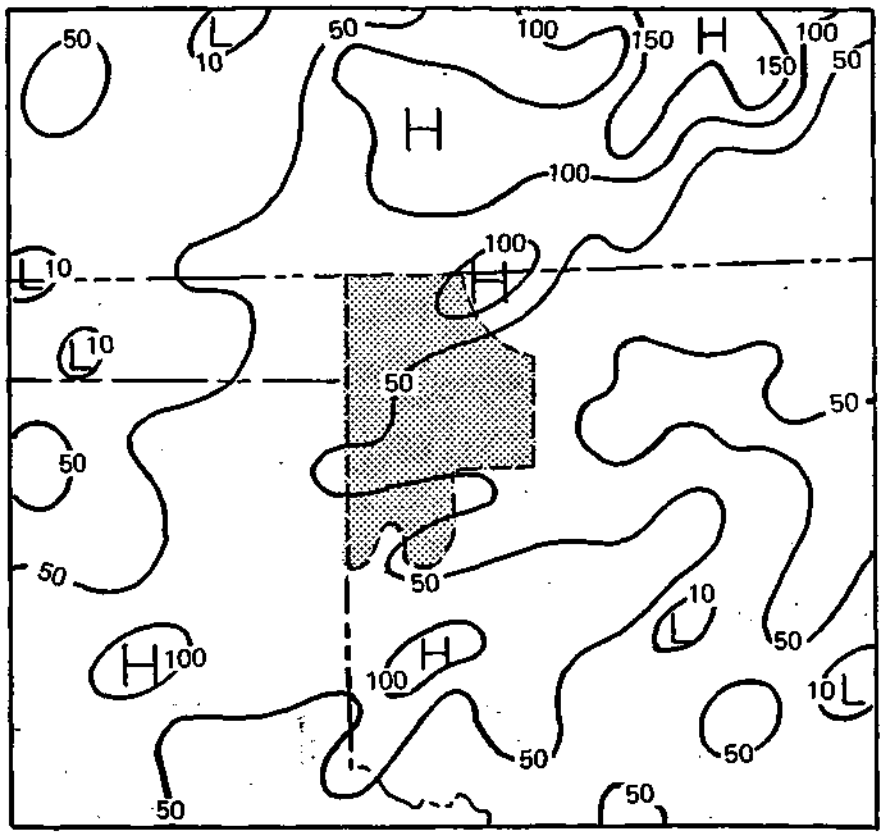


Fig. 3.10. Rainfall Totals of SW Storms, Oklahoma Project.

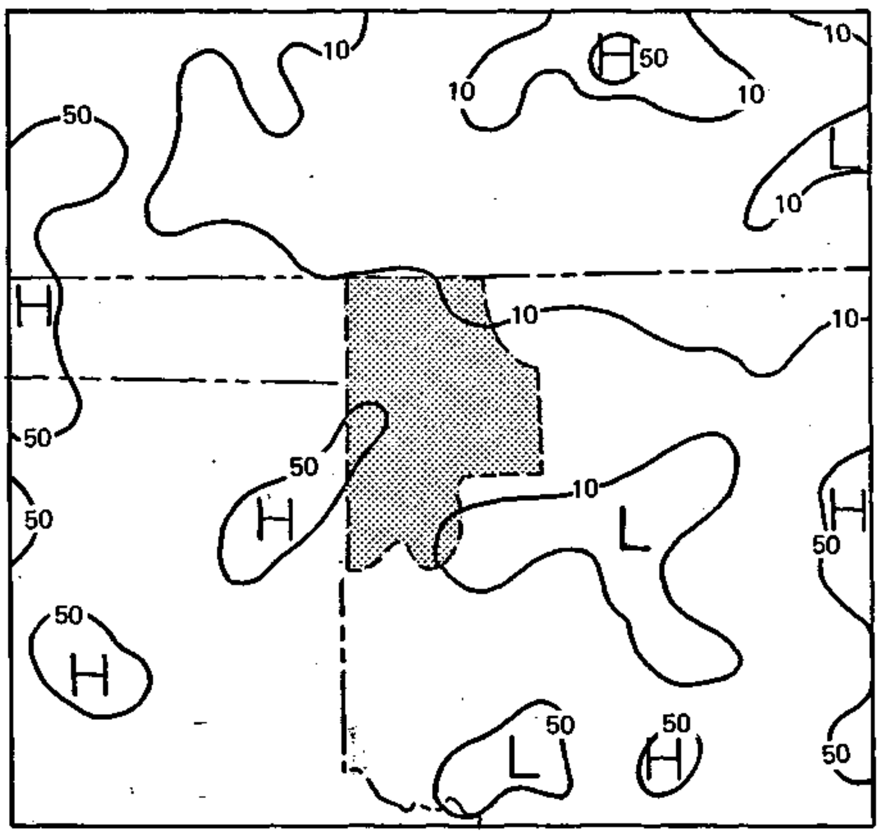


Fig. 3.11. Rainfall Totals of NW Storms, Oklahoma Project.

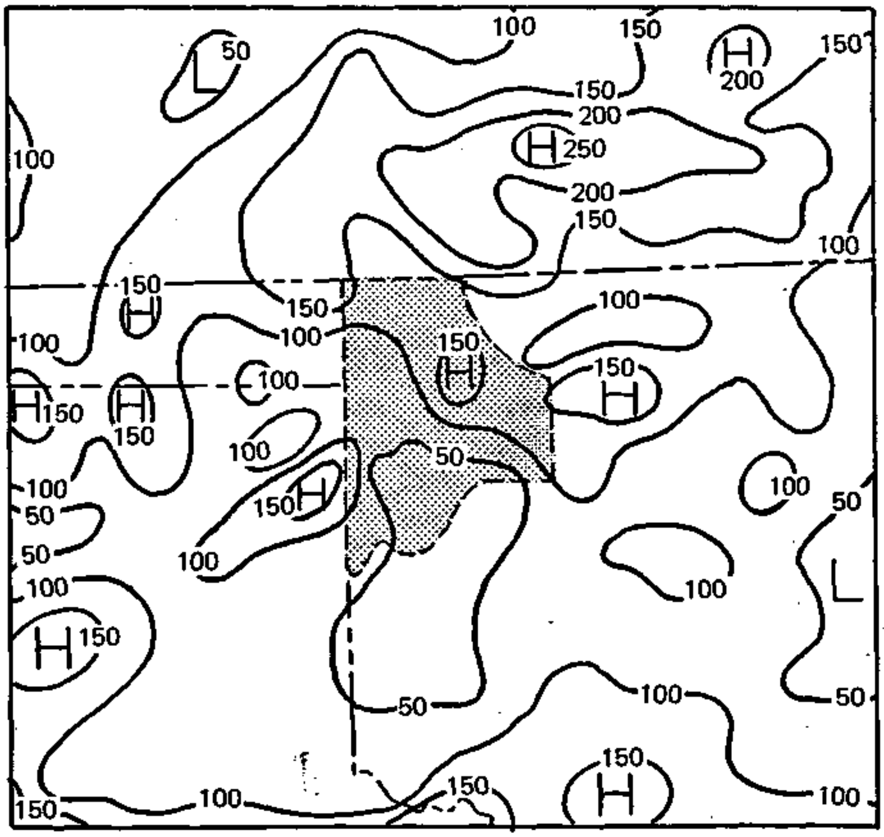


Fig. 3.12. Rainfall Totals of Cold Front Storms, Oklahoma Project.

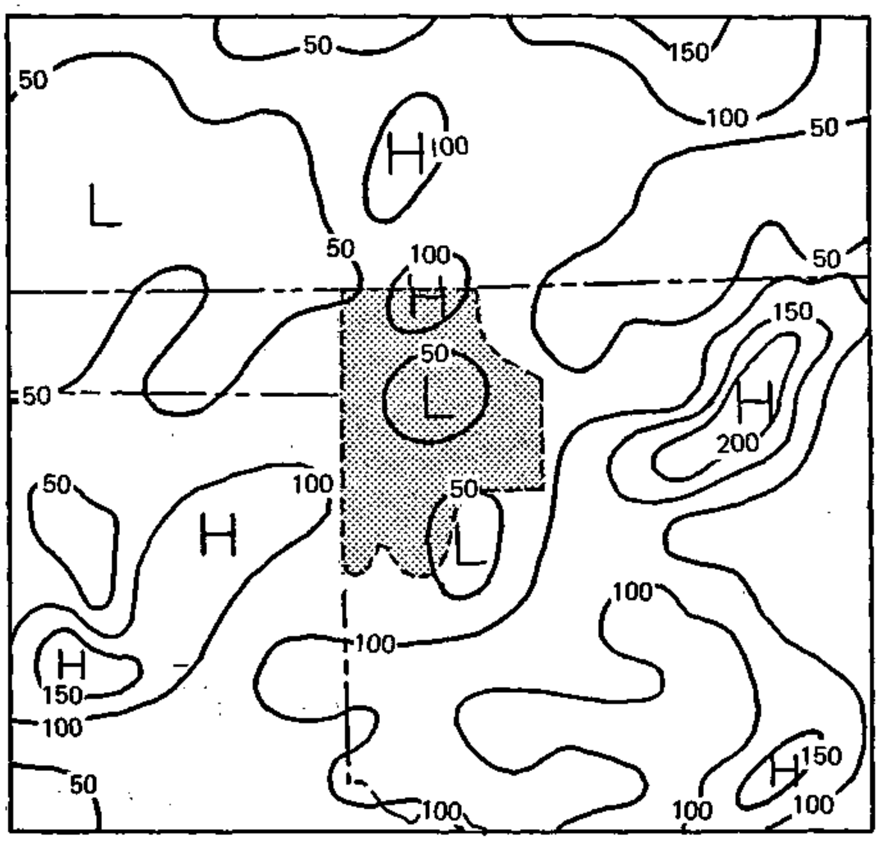


Fig. 3.13. Rainfall Totals of Stationary Front Storms, Oklahoma Project.

The isohyetal patterns for the other synoptic types (not shown) did not provide any strong evidence of seeding-induced rainfall increase on the target area. The pattern for squall line storms, which were associated with approximately 25% of the target rainfall, showed a flat gradient through the target area and to the W, E, and N of it. Heaviest rainfall was south of the target. In squall zone storms, numerous small highs and lows occurred. Values were similar over the target and immediately west and east of it. Air mass storms were the most frequent synoptic type, but produced the least rainfall of all the major storm types. The isohyetal pattern showed many small highs and lows, but provided no support for an increase in target rainfall from seeding activities.

Isohyetal patterns associated with low-Level plumes. Plume winds were from the SE quadrant in approximately 48% of the seeded storms, compared with 23% from the NW, 27% from the HE, and only 2% from the NW. Fig. 3.14 shows the total rainfall pattern for storms in which the low-level winds were from the SE quadrant. The pattern is quite similar to that with the total storm distribution of Fig. 3.8. Rainfall over the target area and immediately W and SW of it is relatively light compared with that in highs located farther E, SW, N, and NE of the target. The easterly high discussed previously is rather pronounced with values at its center approximately twice the target average. This could only be a seeding effect, however, if the surface location of the seeding effect was persistently in error with a strong bias for the error to maximize a considerable distance east of the target.

Storms associated with NE plumes (Fig. 3.15) show a relatively strong high SW of the target. Conceptually, this high could have been associated with seeding agent moving from the NE being swept into storm clouds SW of the target area. If so, the operational plan did not work satisfactorily, since rainfall volume over the target was less than 50% of that in the SW high. The easterly high was again present, and values at its center were 2 to 3 times greater than the target average. The target was in an area of relatively light rainfall that

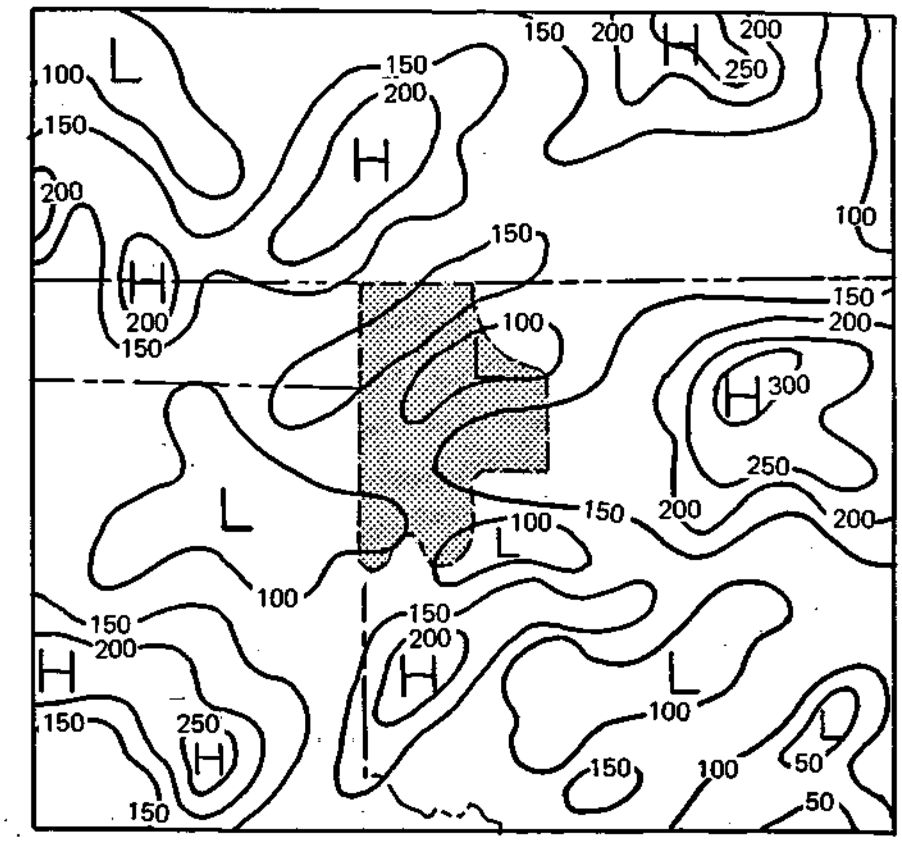


Fig. 3.14. Rainfall Totals of Storms with SE Low-Level Winds, Oklahoma Project.

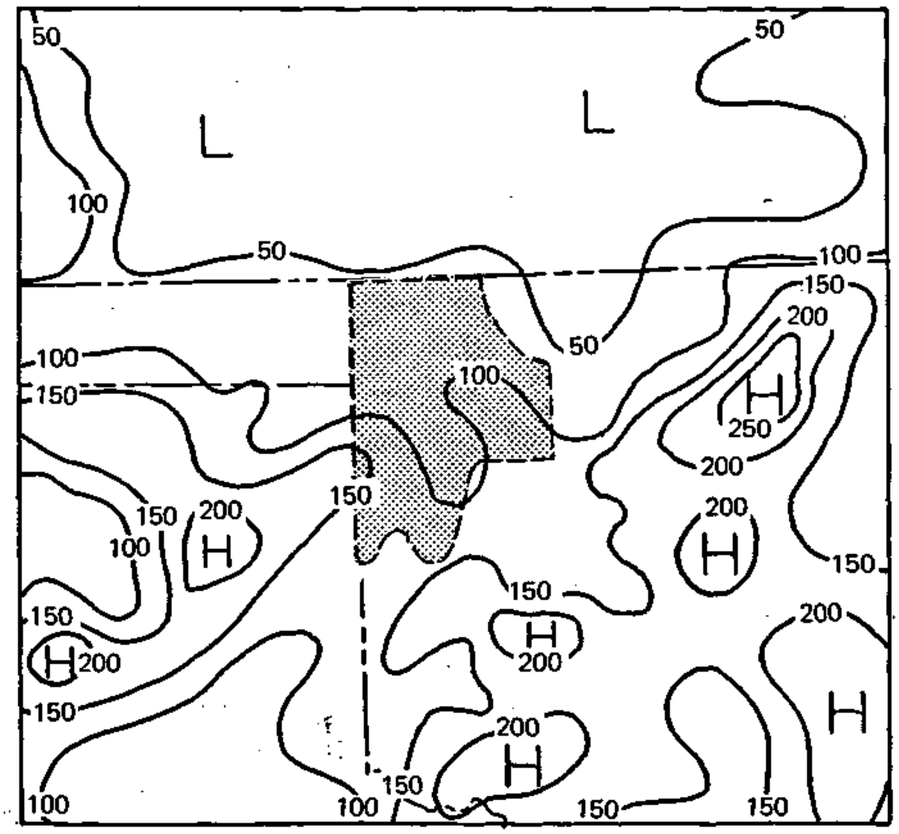


Fig. 3.15. Rainfall Totals of Storm with NE Low-Level Winds, Oklahoma Project.

extended N and NE into southern Kansas. However, one can not say with any strong degree of confidence that the pattern does not merely reflect natural spatial variability in the storm sample.

Reference to the isohyetal pattern with plume winds from the SW quadrant (not shown) provided no evidence of a seeding effect in the target area. The pattern was very flat within and adjacent to the target. NW plume winds occurred too infrequently to be included in the analyses.

Isohyetal patterns with storm movement-plume wind combinations. The data were further stratified to examine isohyetal patterns with various combinations of storm movement and low-level plume directions. This was done in a further effort to seek evidence of any seeding effect from the 1972-1976 operations. Thus, with storms moving from the SW and plume winds also from the SW, any seeding effect should occur over, NW, or SW of the target area. With W-E storm movement and SE plume winds, any seeding effect would be most likely to occur over the target or in an easterly or westerly direction from it, if the time-distance relationship between seeding agent release and cloud reaction to the seeding was in error.

The foregoing isohyetal analyses did little to clarify further the operational seeding effects. The easterly high was present with most combinations of SE and NE plumes and storms moving from the W, WNW, and WSW. This high was not indicated with combinations of SW plume with storms moving from the SW and NW. The easterly high was most pronounced with the combination of W-E movement and SE plume shown in Fig. 3.16. Values at the center of the high were approximately 3 times the target average. The number of cases in some of the storm movement-plume wind combinations was really too few to place a high degree of confidence in the representativeness of their isohyetal patterns.

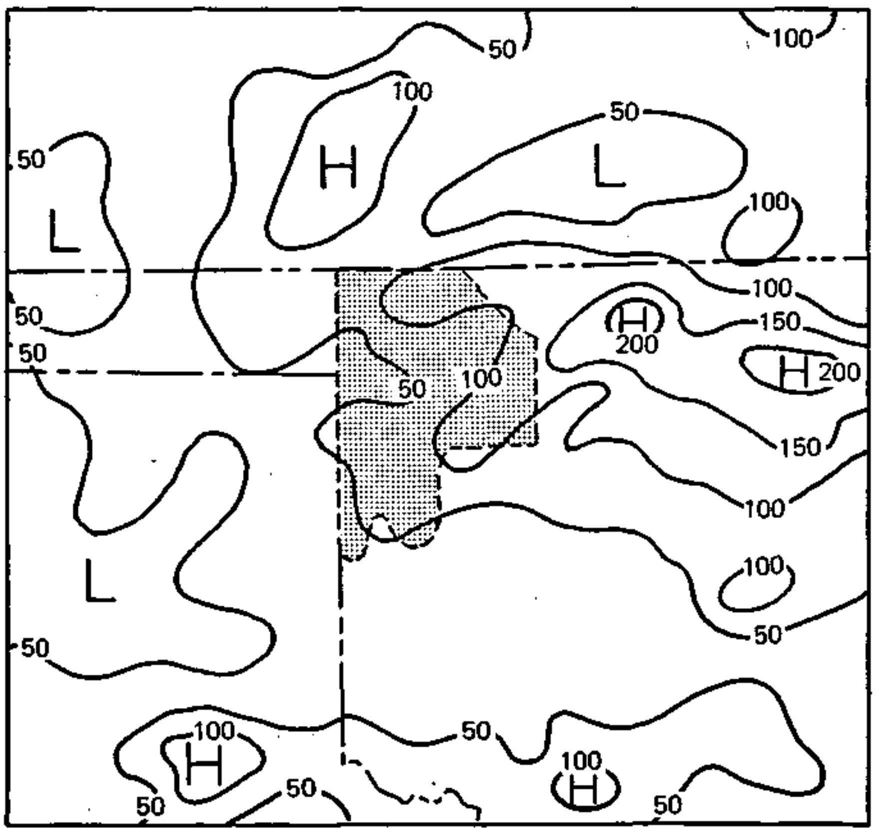


Fig. 3.16. Rainfall Totals of W Storms with SE Low-Level Winds, Oklahoma Project.

Target-contro1 comparisons. As indicated earlier, several areas adjacent to the target area were selected for rainfall comparisons with the target (Fig. 3.7). These "controls" or comparison areas were selected for use with storms moving from the W, WSW, WNW, SW, and NW. These movements include those storms with produced approximately 95% of the target mean rainfall in the 1972- 1976 seeding sample.

An overall summary of the analytical results is provided in Table 3.11. The target mean for total rainfall is indicated for various stratifications, along with the number of storm days in each category. Ratios of the target to comparison area means are shown for the appropriate comparison areas. Similarly, the percentage differences between target and comparison areas are indicated. Adjustments have been made in the target/control ratios and in the target-control differences for the natural rainfall gradient, based on the monthly normals shown in Fig. 3.6. As pointed out earlier in this section, C1 to C3 are selected comparison areas for storms moving from the W, WNW, and WSW, C4 and C5 were used with storms moving from the SW, and C6 and C7 are the comparison areas for storms moving from the NW (see Fig. 3.7 for locations).

For all storms combined, Table 3.11 shows that the comparison areas west and east of the target area received 10% to 23% more rainfall than the target. Since the objective of the seeding was to increase rainfall on the target area, the "all storm" rainfall comparisons indicate little, if any, success.

A similar conclusion is indicated by storms moving from the west for which the rainfall was 4% to 36% greater in the comparison than in the target areas. The largest differences were in the easterly comparison areas. The WSW storms produced more rainfall in the target than upwind of the target, but much less (percentagewise) than in the downwind (easterly) comparison areas. The WNW storms did show more rainfall over the target than downwind. Combining the three groups, Table 3.11 indicates little difference between the target and upwind comparison areas, but rainfall in the downwind comparison areas was 30% to 32%

greater than over the target.

Table 3.11 indicates that for storms moving from the NW showed the opposite trend; that is, the target rainfall was substantially greater (26%, 72%) than experienced in the comparison areas.

Table 3.11. Target-Control Comparisons in Oklahoma Project, 1972-1976 (adjusted for climatic gradient).

Storm Group	Target Mean (mm)	Target/Control Ratio C1	C2	C3		Target-Control Diff. (%) C1	C2	C3		N*
All storms	342	0.90	0.79	0.77		-10	-21	-23		111
May-June storms	206	1.13	0.77	0.74		+13	-23	-26		52
July-Aug. storms	136	0.69	0.82	0.81		-31	-18	-19		59
W-E Motion	136	0.96	0.71	0.65		-4	-29	-36		31
WSW-ENE	64	1.09	0.56	0.59		-8	-44	-41		13
WNW-ESE	41	0.95	1.18	1.24		-5	+18	+24		17
W+WSW+WNW	241	0.99	0.70	0.68		-1	-30	-32		61
		C4	C5	C6	C7	C4	C5	C6	C7	N*
SW-NE Motion	52	.69	.85	-	-	-29	-15	-	-	15
NW-SE Motion	31	-	-	1.72	1.26	-	-	+72	+26	14

*N Number of seeded days.

4. ASSESSMENT OF OPERATIONAL PROJECTS USING HISTORICAL DATA

Several commercial seeding projects were selected as being suitable for testing the statistical-physical evaluation techniques. They were chosen for two reasons: (1) the need to test various types of seeding operations, and (2) the availability of adequate data and operation information. Projects selected for testing included several small-scale projects and two large-scale projects. The small-scale projects were five airborne-seeding projects operated in Illinois during 1976-1980 and a hail suppression project in the Texas Panhandle area operated during 1970-1976. The large-scale projects selected were the one using ground-based generators in northwestern Oklahoma (1972-76) and a combined hail suppression/rain enhancement project in southwestern Kansas during 1975-1979 (the Muddy Road Project).

Large-area seeding projects have become common during the past few years (Hsu, 1981a) and will continue to be so in the future as a viable mean for managing water resources and reducing hail losses. However, evaluation of operational projects extending over 10,000 sq km or more produces complex spatial and temporal control problems relating to climatic homogeneity and temporal variability.

In evaluating the seeding effect of a weather modification operation, the response deemed caused by the seeding must be compared with other responses not affected by the seeding. For a randomized experiment, these other "responses" are usually those of the "unseeded" units in the target area during the operational period set aside randomly in the project design. However, in a non-randomized operation it is statistically undesirable to make such a similar comparison for two reasons: (1) there might exist natural rainfall excess in favor of the seeded units over unseeded units in the target area (Gabriel, 1979); and (2) there might exist a natural rainfall excess in favor of the selected seed units in the target over those in the neighboring control areas (Hsu el al., 1981a). An approach which accounts for these two "selection biases" has to be used to properly address the evaluation of non-randomized operations (WMAB, 1978; Hsu and Changnon, 1983b).

The approach presented here for evaluating non-randomized seeding operations uses a relatively long sampling unit as well as historical climatic data. A sampling unit as long as a month or a season lumps together the responses of both seed and unseed occasions. Use of such long units eliminates the first kind of bias and still allows for the detection of seeding effect, although their use might render the statistical test conservative (i.e., less powerful in detecting a seeding effect). Use of historical climatic data provides a partial answer to the second kind of bias by adjusting target values with control values. It is this issue of adjusting target values using historical data that our research has been focused on.

The use of a long sampling unit and historical climatic data therefore provides a solution for reducing potential biases in evaluating non-randomized projects. A critical question concerning such an approach is the temporal stationarity, i.e., whether the historical (unseed) target-control relationship holds in the seed period, had no seeding been done (Brownlee, 1967). Recent simulation studies (see a later chapter) have shown that in the worst possible scenario the significance values of the statistical tests using regression were twice as much as what would be expected. Thus, use of historical comparison would be appropriate if the critical value of the test is selected to correspond to half of the nominal significance level.

Data used in the evaluation consisted of rainfalls from the National Weather Service's Cooperative Raingage Network and the hail insurance data furnished by the Crop-Hail Insurance Actuarial Association.

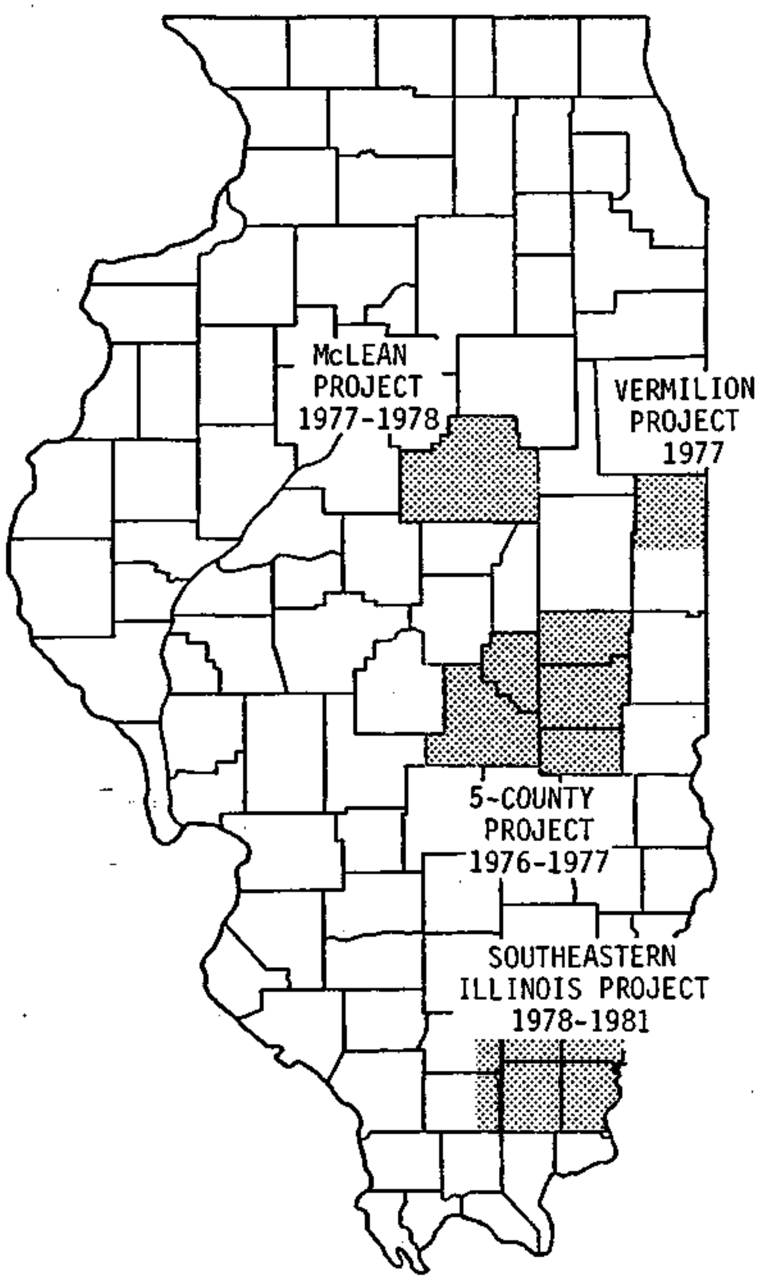


Fig. 4.1. Illinois weather modification projects during 1976-1980.

4.1 Illinois Projects

Several short-duration operation seeding projects were conducted in Illinois during 1976-1980 (Fig. 4.1). The evaluation of the these Illinois projects showed mixed outcomes (Table 4.1). Some indicated rainfall increases under seeding, other indicated decreases. Except for the 1979 result which was significant at 10% level, none of the projects were clearly significant. In the 1979 evaluation, PCR[1] yielded a smaller P-value than MREG or DR (Changnon and Hsu, 1981), as might be expected from the Kansas and ILL-EC simulation findings. The radar echo results were also mixed.

Table 4.1. General Conclusion of 5 Illinois Operational Projects.

Year	Target Rainfall	Target Radar Echoes
1976	not studied	+
1977	0 to weak +	poor data
1978	-	-
1979	+	not studied
1980	0 to weak +	poor data

Overall, these projects do not provide clear evidence of seeding effects. In all instances, regardless of the apparent increases or decreases in rainfall or echoes in the target areas, the 1-year (2-month duration) projects were too short to draw any conclusions that have statistical or physical significance when taken alone.

4.2 Texas Panhandle Bail Suppression Project

The hail suppression programs in the Texas Panhandle were carried out in a relatively small area in 1970-1976. Aircraft was used in the seeding. The target consisted of Hale, Lamb and part of Castro counties (Fig. 4.2). A summary of the project operations can be found in a report by Henderson and Munn (1973).

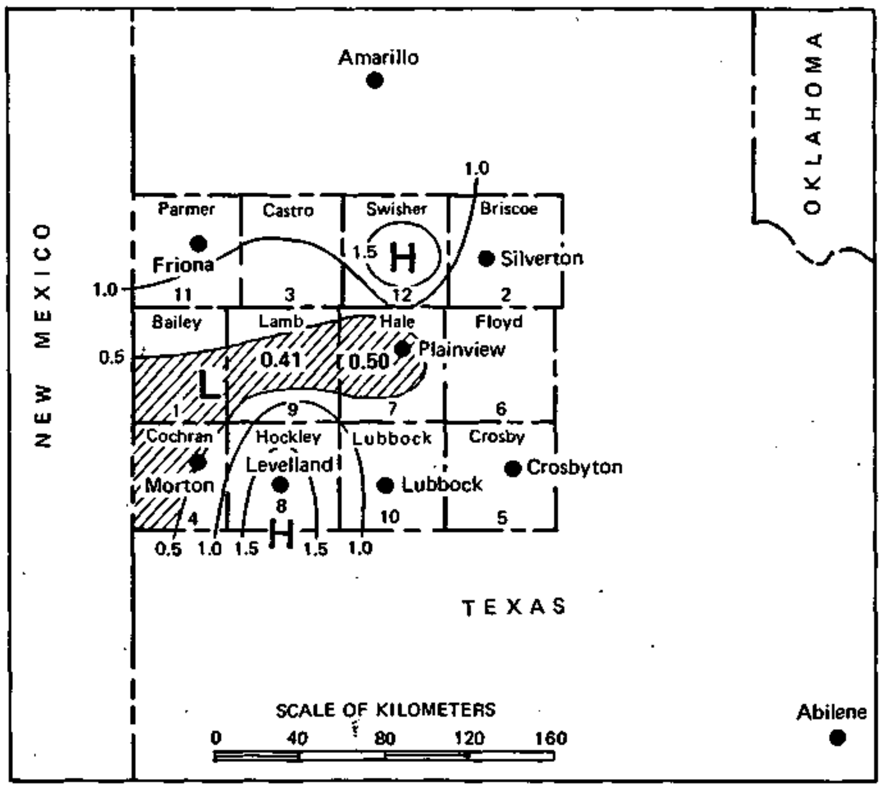


Fig. 4.2. Ratio of Seeded vs Historical L/C Values.

Hail insurance data, furnished by the Crop-Hail Insurance Actuarial Association, were used in the evaluation. Yearly loss-cost (L/C) ratio, defined as 100 x hail damages / insurance liability, was calculated for the 1970-1976 seeding period and the 1948-1969 historical period. Surrounding counties were selected as areal controls (Fig. 4.2) and their L/C values were also calculated.

Ratios of 1970-1976 average L/C value to 1948-1969 average L/C value were computed for each county (Fig. 4.2). Nine out of the 12 counties had ratios less than 1.0. A zone of minimum ratios occurred over the target and extended into the SW corner of the study area. Two counties, one to the north (Swisher) and one to the south (Hockley) of the target, experienced 50% more crop hail loss/cost in the seeding period than in the historical period, with both ratios greater than 1.5. This is a crude indication of possible hail reduction in the target area.

A number of exploratory analyses were applied to this data when appropriate. Fig. 4.3 is a rather informative plot displaying the identical information as that of Fig. 4.2 but in a different way. This plot reveals that, historically, the target counties (7, 9 and 3) were experiencing more hail damage (larger L/C value) than the other counties. It also demonstrates clearly that, in the target, the seeded L/C values were considerably smaller than their historical L/C values. Only two counties (1 and 4), both to the west of the target, had smaller such ratios.

A stem and leaves display of the yearly L/C values is shown in Table 4.2 for target average, all controls average, and high-liability controls average (namely, counties (5, 8, 10) that had high insurance liability during the 1948-1969 historical period). Clearly, the seeded values in the target distribution all lie at the lower spectrum of the display, while the corresponding control values are spread out over the entire range, with wider range for the high-liability controls. It is interesting that the target had a larger range (maximum - minimum) than the two control averages. It is remarkable that the seeding

Table 4.2. Stem and Leaves Display, Texas Panhandle Hail Suppression Project. (1947-1969 historical, 1970-1976 seeded)

Target	Stem	All Controls	High Liab. C.
68	0.	94	
64 *	1.		21
06,51	2.	19,91	89
49	3.	14,66,68	04,17,55
05,23,77,81,84,86	4.	11,84,85	34
26,40	5.		10,23,31,68,79
	6.	15,16,23,60	15,31,89,99
09,48,93	7.	22,34,54,78,95	57,62,63
38,46,79	8.	06,44,57	28
	9.	25,31,57	38,89,93
23	10.	13,75	
18,77	11.	13,90	34,37,46,68
40,68	12.		
	13.	62	47
	14.		33,49
90,92	15.	47	
49	16.		
19	17.		
	18.		
	19.		
	20.		
18	21.		
	22.		73
	23.		
	24.		
	25.		
	26.		
40	27.		

* Values in 1970-1976 were underlined.

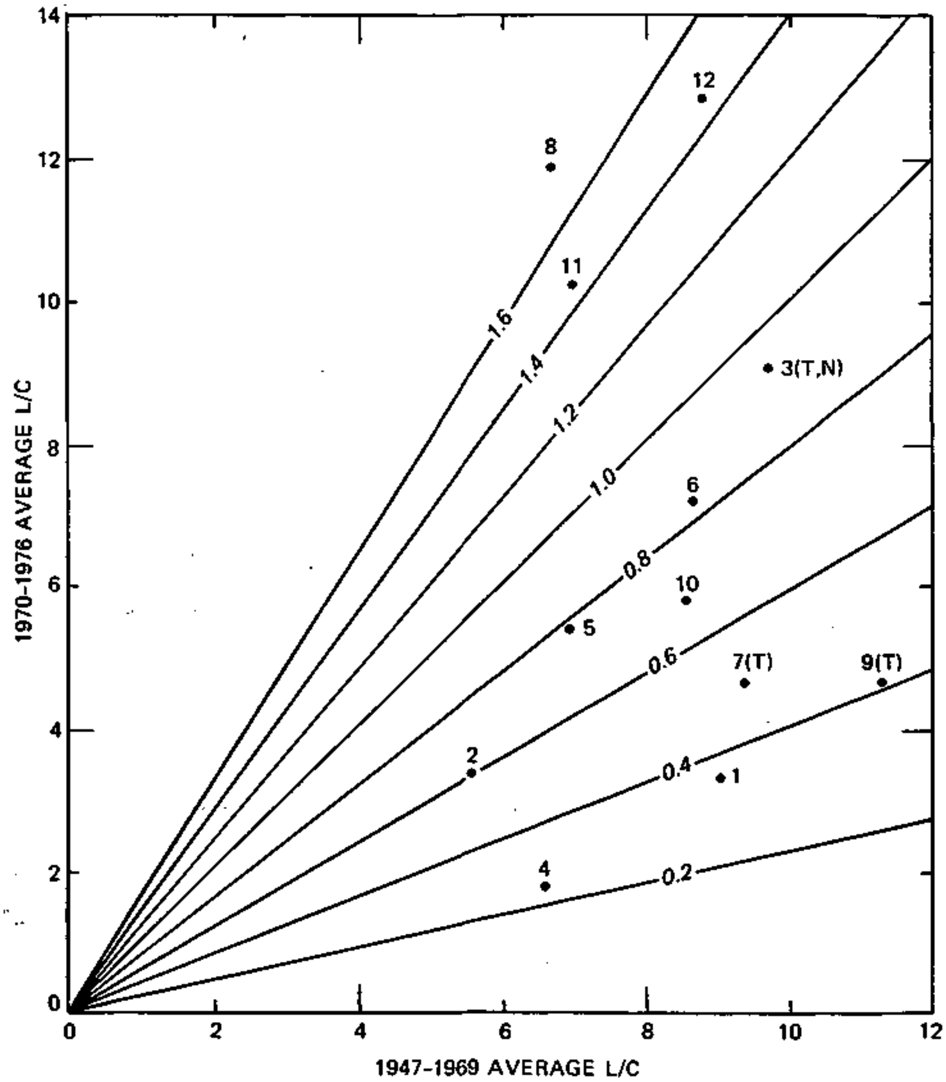


Fig. 4.3. Seeded vs Historical L/C Values, Texas Panhandle Project.

L/C values, as appeared in the two control averages' distributions, were rather random and not quite as extreme (i.e., all in the lower end) as the targets.

A time series plot of ratios of averaged target L/C over averaged control L/C values is shown in Fig. 4.4. A striking similarity is revealed between the 1956-1965 and 1966-1976 periods. Both periods experienced a sharp downward trend in the target/control ratios. Nevertheless, most ratios in the seeding period were less than 1.0 and were close to the overall minimum (1965) of such ratios, the only exception was 1970's. The reduction of seeded hail loss-cost values in the target area thus appeared to be not entirely caused by natural variability.

Box plots summarizing the ensembles of ratios of target average L/C value over control average L/C value are shown in Fig. 4.5, for the seeded and historical periods and for all controls as well as high liability controls. Median, mean, lower quartile (Q_1, the 25th percentage point), upper quartile (Q3, the 75th percentage point), minimum, and maximum of the distributions are shown in the plots. Notches in the plot represent the 95% confidence interval of the median (when the upper confidence point is higher than Q3, the notch is folded). The width of the box plot reflects the number of observations used, the larger the number of observations used the wider the box. The box plots clearly illustrate that, for both all controls and high liability controls, the confidence interval of the median in either of the 1970-1976 box plots is entirely below those in the 1948-1969 box plot. What this means is that, at 5% level, the median in the seeding period is significantly lower than the corresponding historical value. Results from using the high liability controls yield more convincing differences than using all controls, though the distributions are more skewed. Thus, these box plots effectively demonstrated that the difference between the seeded and historical distributions was significant.

Another informative display of this data set is shown in Fig. 4.6, in which each yearly L/C value is represented by a face plot. Value of each county is represented by one part of the face in the following order: eye size (1), pupil

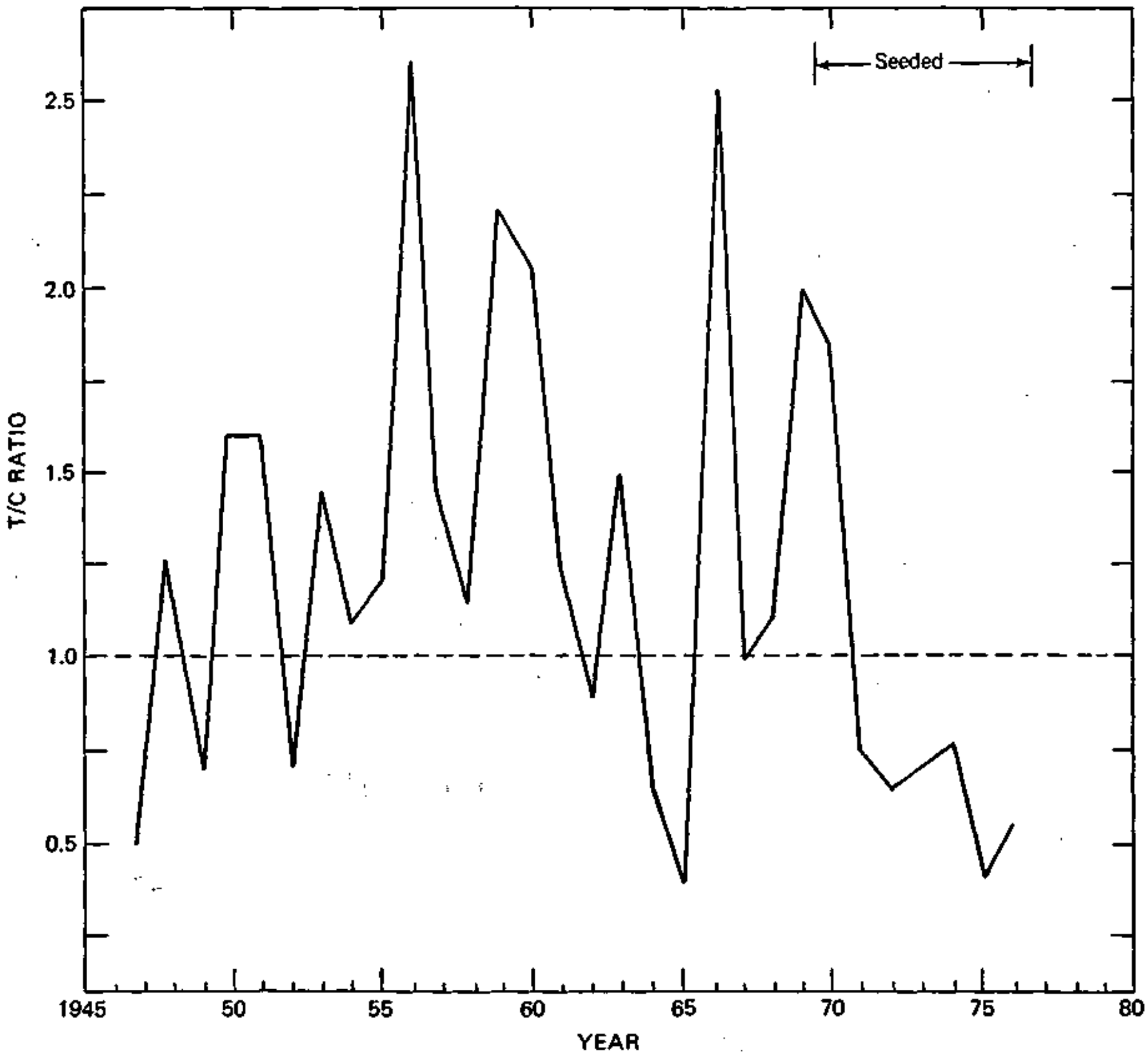


Fig. 4.4. Ratio of Target vs Control L/C Values, Texas Panhandle Project.

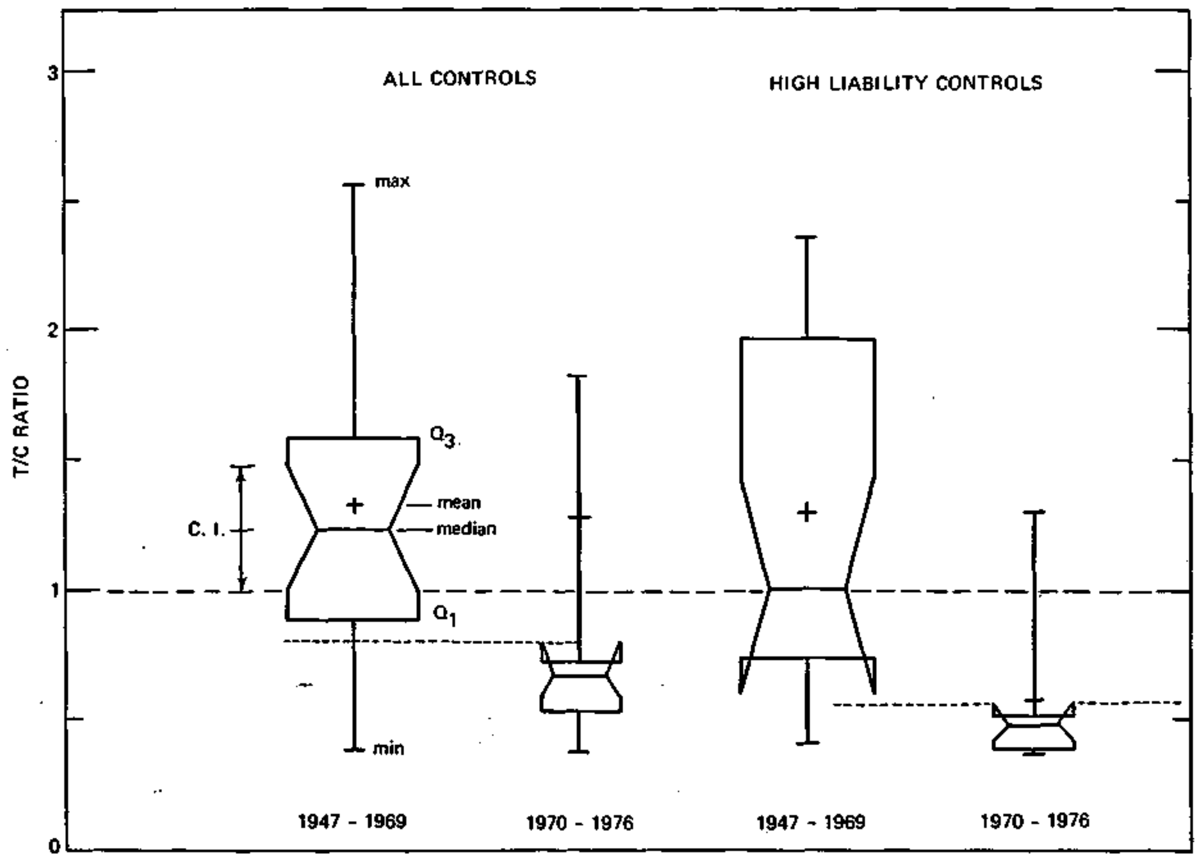


Fig. 4.5. Box Plots, Texas Panhandle Project.

size (2), pupil position (3), eye slant (4), horizontal eye position (5), vertical eye position (6), curvature of eyebrow (7), density of eyebrow (8), horizontal eyebrow position (9), vertical eyebrow position (10), upper hair line (11), and lower hair line (12) (see Flury and Riedwyl (1981) for details). Of particular interest are the 2 target counties, 7 and 9. Changes in these 2 parts of the face indicate the degree of differences in L/C values over the years. The other parts of the face serve as contrasts for assessing the significance of changes in the target values. These face plots are particularly useful in illustrating contrast between certain variables, for example target vs control. Detailed discussion on the face plot can be found in Flury and and Riedwyl (1981) and others. They are included here as an exploratory tool for potential use in evaluation.

Most of the above techniques/displays employ a certain kind of averaging method. They are quite apt for summarizing the data; however, the important information of temporal/spatial variability is often left out. The techniques we discussed earlier in the simulation studies can alleviate this problem and were applied to the Texas data. A summary of the results is shown in Table 4.3. The evaluation using target-control comparison and historical data revealed that a reduction of 48% in L/C, significant at 1% level, was found in the entire target area (DR, 9 or 10 control areas, in Table 4.3). The results by DR were slightly more favorable than those of MREG, PCR[1], or PCR[3], as expected in the Montana hail suppression simulation studies for small target area.

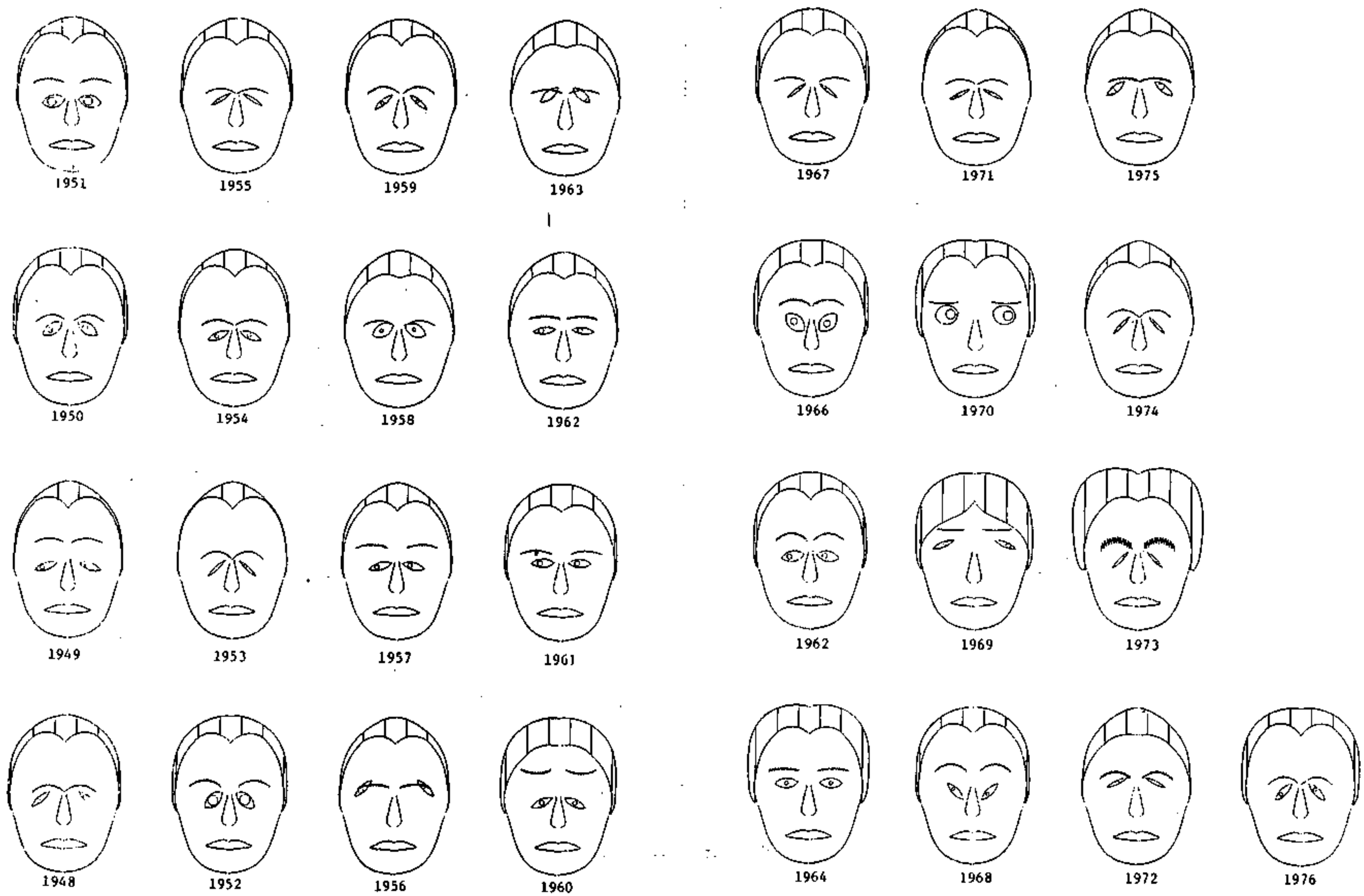


Fig. 4.6. Face Plot, Texas Panhandle Project.

Table 4.3. Statistics and 1-Sided Permutational P-value, Texas Panhandle Project, Hail Loss-Cost Values.*

Target	MREG	PCR[1]	PCR[3]	PR
		Using 9 Control Areas		
Lamb	-2.88 (.28)	-6.18 (.03)	-4.49 (.11)	.48 (.02)
Hale	-6.37 (.05)	-4.29 (.04)	-4.79 (.02)	.57 (.02)
Avg	-4.62 (.10)	-5.23 (.01)	-4.64 (.04)	.52 (.01)
		Using 10 Control Areas		
Lamb	-2.46 (.29)	-5.99 (.02)	-4.41 (.11)	.47 (.01)
Hale	-6.03 (.07)	-4.08 (.05)	-4.76 (.02)	.57 (.03)
Avg	-4.24 (.11)	-5.03 (.02)	-4.58 (.03)	.52 (.01)

*The total number of controls was 9 or 10 depending on whether Castro county was included or not.

4.3 Muddy Road Project

The Muddy Road project was conducted in southwestern Kansas and encompassed a target area varying between 12 to 15 counties over the years studied (Fig. 4.7). The project was intended for both rainfall enhancement and hail suppression in the warm season of April to September. Due to different agricutural needs, the main focus of the seeding operations were: rain in April, rain/hail in May, hail in June, rain/hail in July, rain in August and September, respectively. The project began in 1975 and continues to the present. The 1975-1979 operations were selected for evaluation. A description of the project and a summary of the seeding operations can be found in a report by Kostecki (1978).

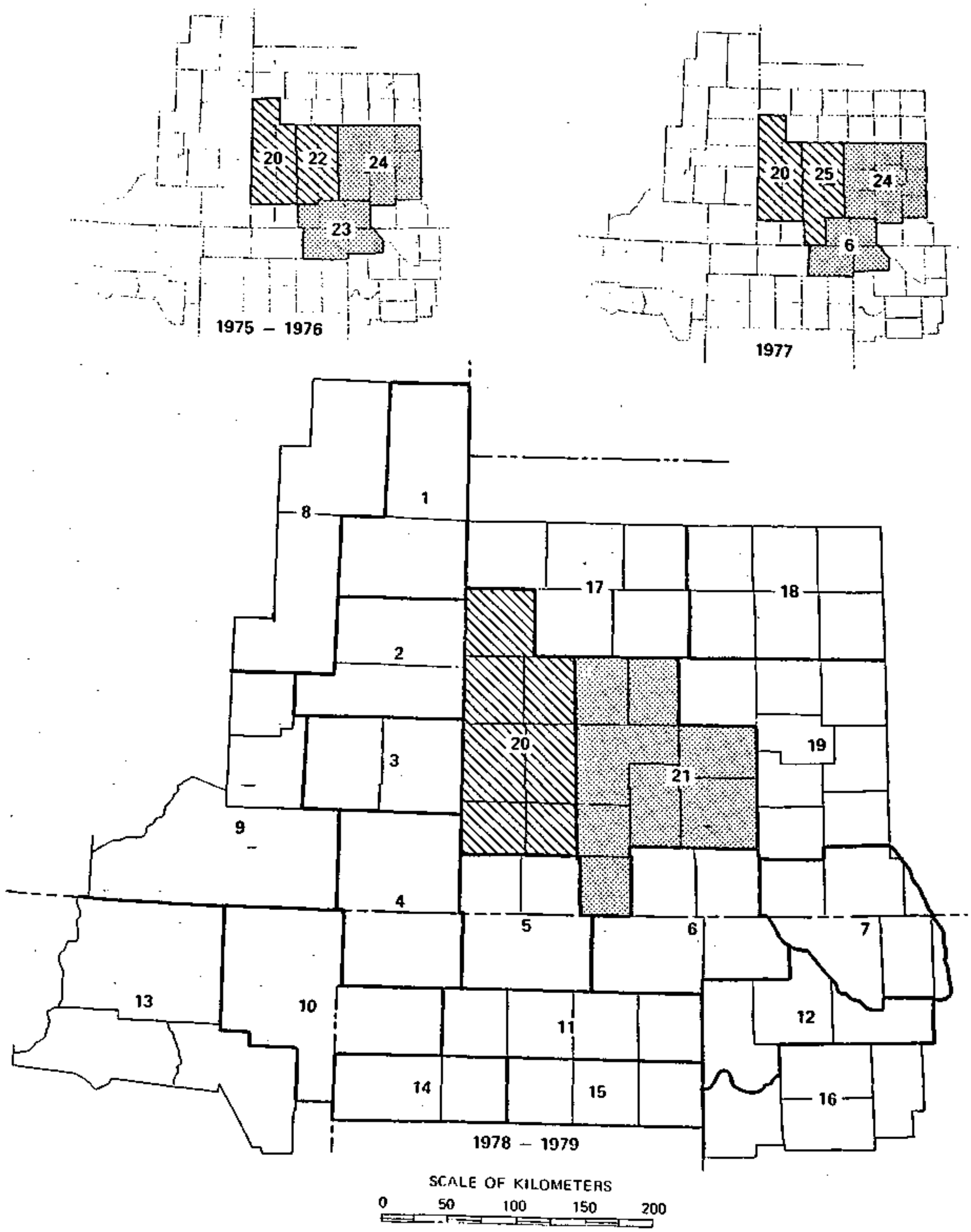


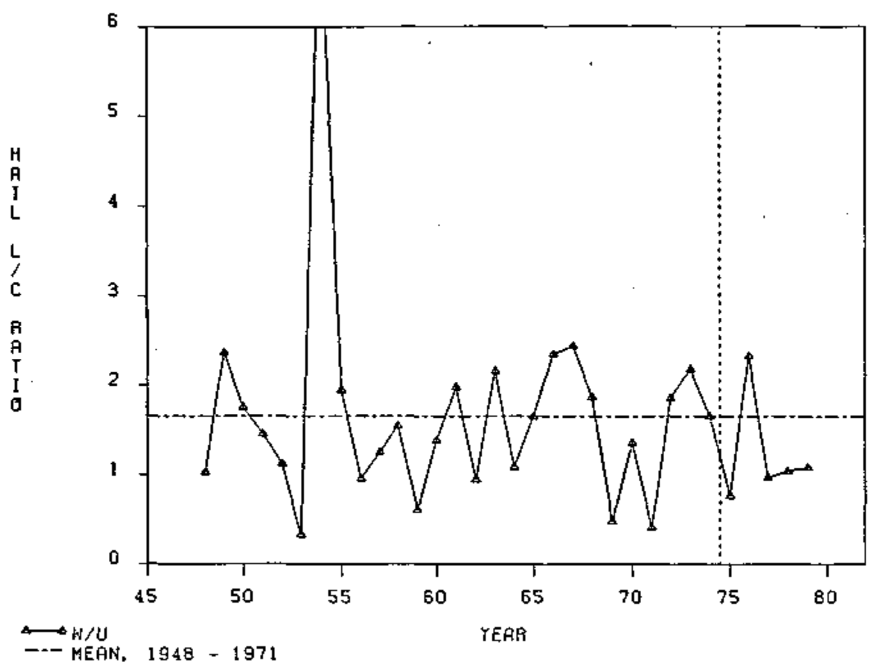
Fig. 4. 7. Muddy Road Project Area.

Two sets of data were employed in the evaluation: (1) monthly and seasonal rainfalls, with data from 1931-1971 used as historical controls, and (2) annual hail insurance loss-cost ratios (L/C), defined as 100 x hail damage / insurance liability, with data from 1948-1971 used as historical controls. The (historical) years of 1972-1974 were not included in the study mainly to avoid the possibility of contamination due to other cloud seeding activities carried out to the south of the MR target areas during this period.

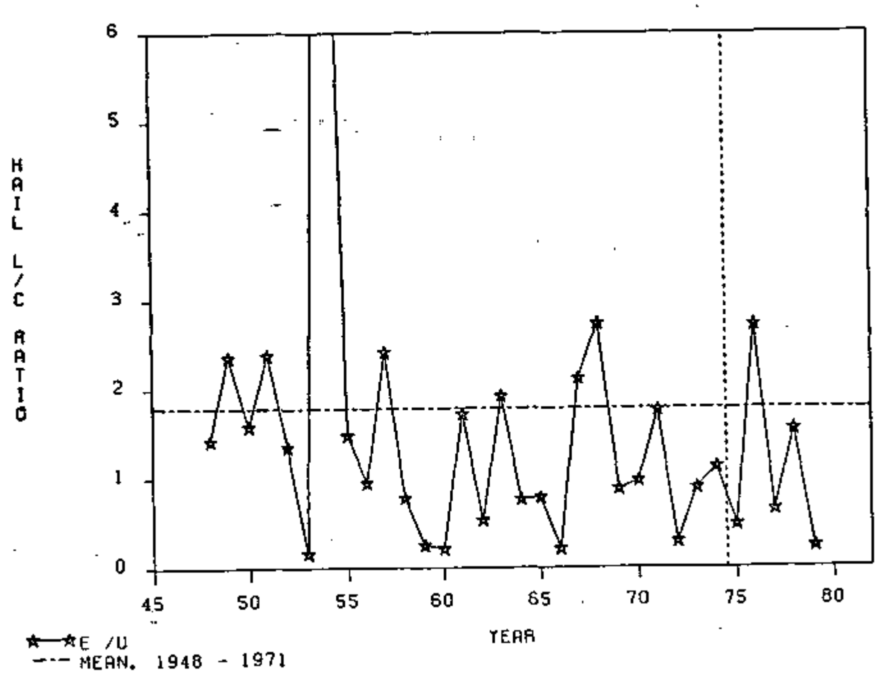
To discern possible geographical differences in seeding effects, the target was divided into a west (W) and an east (E) sub-targets. Controls having size similar to the sub-targets were selected from the neighboring counties and grouped into near-upwind (N-U), mid-upwind (M-U), far-upwind (F-U), and downwind (D) controls (Fig. 4.7). The N-U control consisted of areas 1, 2, 3, 4, 5, 6, and 7; the M-U control consisted of areas 8, 9, 10, 11, and 12; the F-U control consisted of areas 13, 14, 15, and 16; and the D control consists of areas 17, 18 and 19.

4.3.1 Evaluation of the hail suppression

Ratios of seeded average L/C (1975-1979) to historical average L/C (1948-1971) had shown that the ratios in the target were all less than 1.0 except two small areas in the northwestern and southeastern corners, where they were between 1.0 and 2.0 (see Fig. 4.2 in Hsu et al (1981a)). Fig. 4.8a shows a plot of ratios of the west sub-target L/C to the N-U L/C. No noticeable trend existed. Most ratios were larger than 1.0. The ratio in 1954 was considerably more than the others, and thus might render the mean 1948-1971 ratio (shown in the plot as the dashed line) unrealistically high. However, four out of five seed years experienced ratios well below the historical mean and were very close to the minimum. Thus, the reduction appeared to be real. Similar plot for the east sub-target (E/U) is shown in Fig. 4.8b. No trend was indicated. The 1954 ratio was also high. Four out of 5 ratios were below historical mean, though only 3 appeared to be real.



(a)



(b)

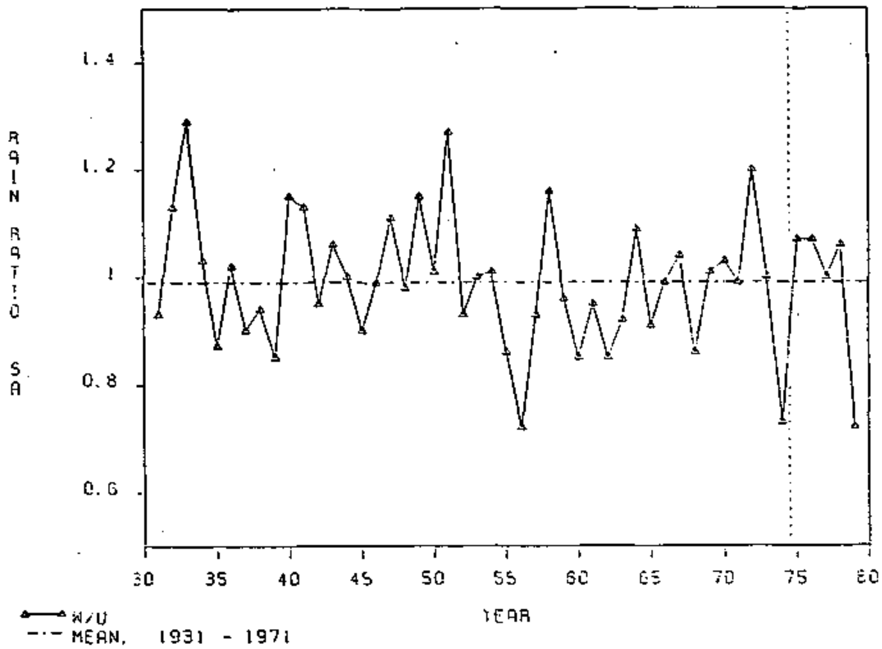
Fig. 4.8. Ratio of Target vs Control Bail L/C Values, Muddy Road Vroject.

Overall, the evaluation of the hail suppression of the Muddy Road project indicated that there was a general reduction of annual hail loss-cost values in the target area. The reduction of 39% in the eastern portion of the target area was significant at 6% level, but the reduction in the western sub-target was not significant. This evaluation, which involved a relatively large target for 5 seeded years, suggested that PCR is a more sensitive evaluation technique than MREG or other techniques, as might be expected from the Montana simulation studies.

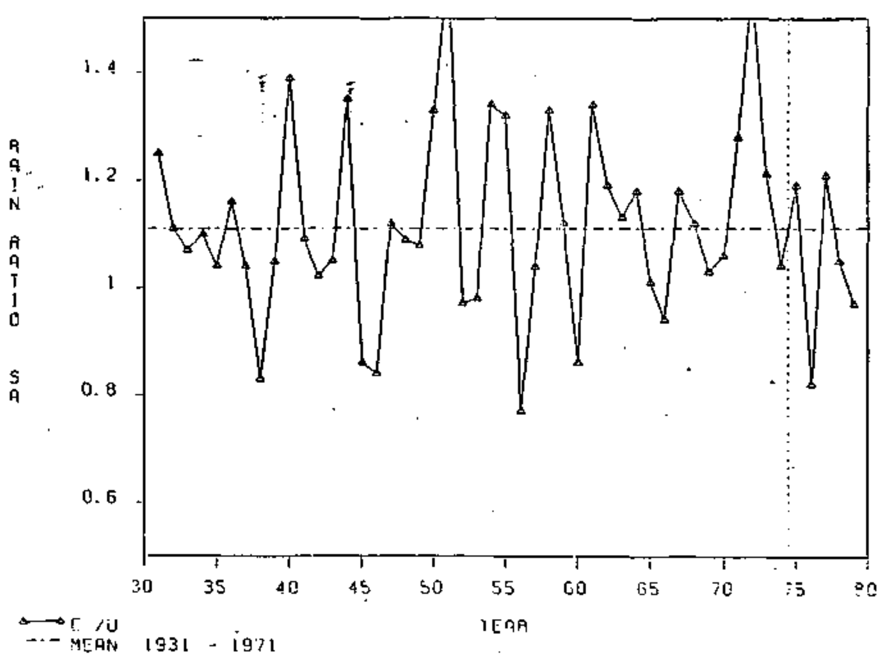
4.3.2 Evaluation of the rainfall enhancement

Seasonal rainfall was computed as the mean of May-August monthly rains. Ratios of average seed seasonal rains (1975-1979) to average historical seasonal rains (1931-1971) show that most of the ratios in the target area were above 1.0 (Fig. 4.3 in Hsu et al (1981a)). The ratios in the eastern part of the target were higher than those in the western part. Fig. 4.9a shows plot of ratios of the west sub-target seasonal rain to N-U controls seasonal rain. No noticeable trend existed. Most ratios were near 1.0. The 1931-1971 mean (shown in the plot as the dashed line) was very close to 1.0. Three out of 5 seed years had ratios slightly above the historical mean; while one ratio (1979) was very close to the minimum. Similar plot for the east sub-target is shown in Fig. 4.9b. No trend was indicated. The variability in this plot was noticeably larger than that in Fig. 4.8b. Two years (1949 and 1971) had high ratios, and thus rendered the historical mean larger than 1.0. Only two (1975 and 1977) out of 5 ratios in . seeded years were above the historical mean, and one (1976) was very close to the minimum.

The evaluation of the the rainfall of the Muddy Road project indicated that there was a non-significant rain decrease in the target when the entire season



(a)



(b)

Fig. 4.9. Ratio of Target vs Control Seasonal Rainfall, Muddy Road Project.

was used as sampling unit (Hsu, et al., 1981a). The results of all the techniques used were essentially identical. Furthermore, the findings of monthly rainfalls indicated that there was a significant target rain excess in the east sub-target area in April and August (see Table 4.3 in Hsu et al (1981a)), the months designated for rain enhancement, significant rain decrease in May (rain/hail) and non-significant decrease in September (rain).

4.4 Oklahoma Project

The Oklahoma program encompassed a target area of 3 counties - Harper, Woodward, and Ellis (Fig. 4.10). It was carried out to increase the growing season (May-September) precipitation in 1972-1976. Monthly and seasonal rainfalls from 1935-1971 were used as historical controls. Rainfall data from Kansas, Oklahoma, and Texas were used to form 8 areal controls with size similar to the target's (Fig. 4.10). The climatic monthly rainfall normals in the area indicate that there existed relatively strong precipitation gradients in May and June, with a general east-to-west decrease, and much weaker gradients in July and August.

Ratios of 1972-1976 seasonal rainfalls to historical seasonal rainfalls show that most of the study area received less rain during the seeding period than the historical period (Fig. 4.11). The differences among ratios were small, however. There was a general NW-SE gradient of rainfall ratios. The region of minimum ratios (<0.9) ran from southwest to northeast, peaking in the target area. The eastern portion of the target had higher rainfall ratios than the western portion. The highest ratios in the entire study area occurred in Kansas, north of the target. Similarly, ratios for the months of May-September are shown in Fig. 4.12. Rainfall ratios in the target were less than 1.0 in May, June and July, but were more than 1.0 in August and September. The target ratios in August were larger than the surrounding controls' except in the southwestern corner. However, in all other months the target ratios were less than the controls'.

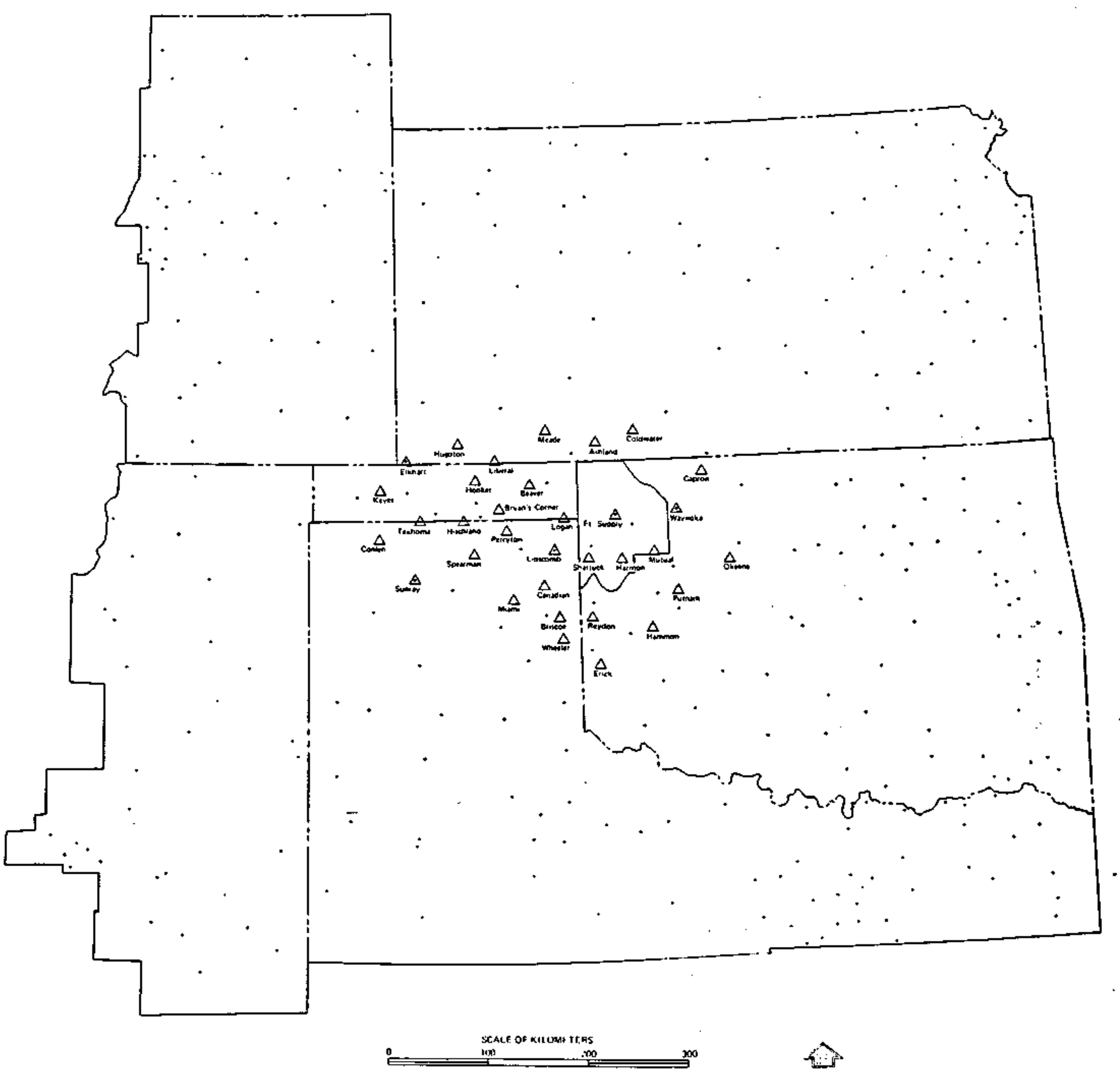


Fig. 4.10. Generators Location, Oklahoma Project.

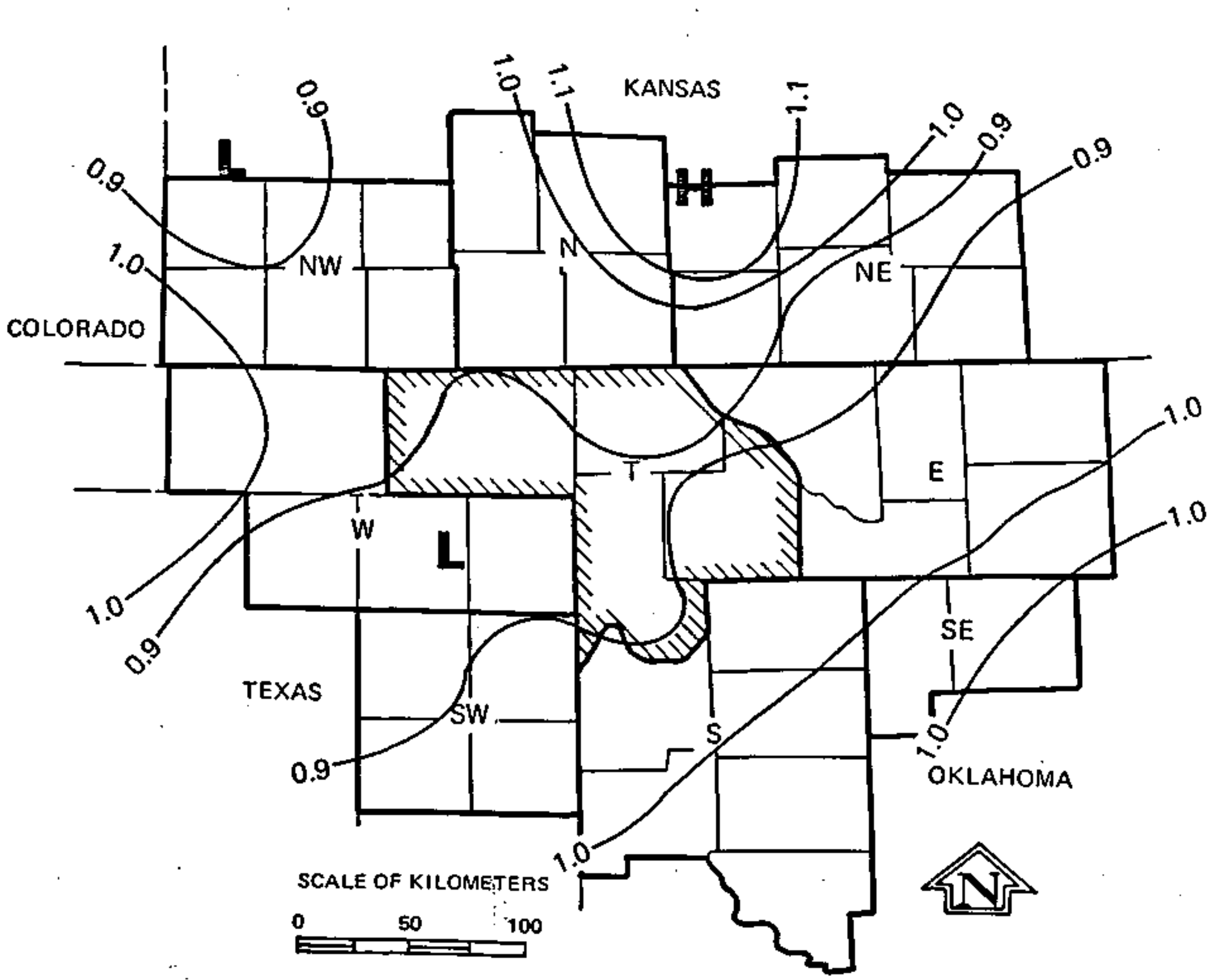


Fig. 4.11. Ratio of Seeded vs Historical Seasonal Rainfalls, Oklahoma Project.

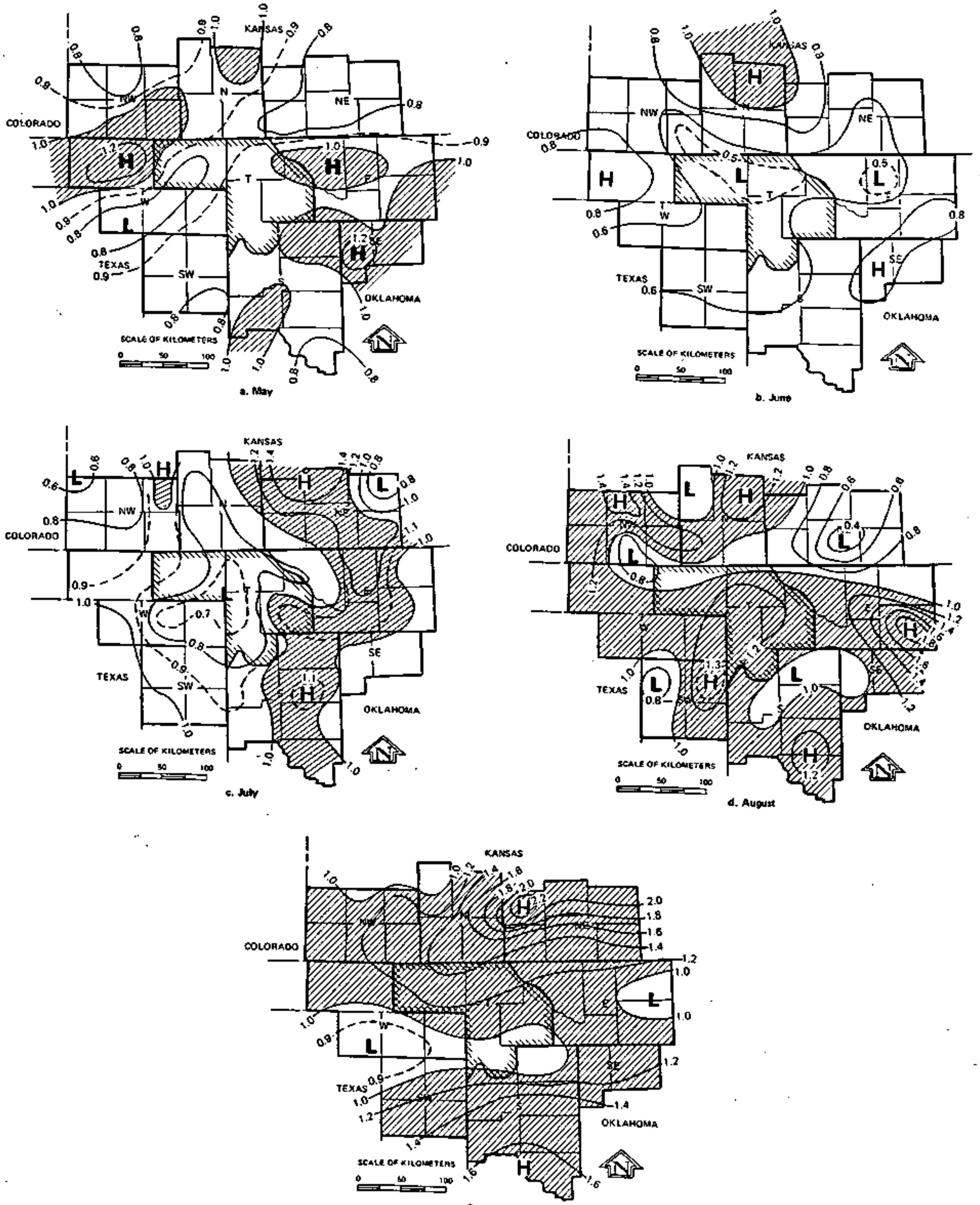


Fig. 4.12. Rainfall of Seeded vs Historical Monthly Rainfalls, Oklahoma Project.

The techniques of multiple regression (MREG) and principal component regressions with 1 (PCR[1]) or 3 components (PCR[3]) were applied to the seasonal and monthly rains using the 8 areal controls (Fig. 4.10) and the 1935-1971 historical controls. The mean differences between the estimated and observed seeded values, and their permutational significances are shown in Table 4.4. All the estimated mean differences were not statistically significant. There was a minor seasonal rainfall deficiency in the target than what would be expected. For the monthly rainfalls, most estimated rain differences were small and statistically non-significant. The biggest target rainfall excess, 0.66 cm, occurred in August when using All controls and PCR[1]. The largest decreases, all greater than 1 cm, occurred in June. Generally, the technique of PCR[1] indicated more increases or fewer decreases of target rainfalls than did MREG in June and August, but the opposite in May and July.

The evaluation of the Oklahoma ground-based project (1972-76) indicated that there was a non-significant 5% rain decrease in the target area when the summer season was used as sampling unit (Table 4.4).

Table 4.4. Mean Difference and 1-Sided P-value, Northwestern Oklahoma Project, Monthly Rainfall (in cm).

Month	MREG	PCR[1]	PCR[3]
	All Controls		
May	-.10	-.18	-.30
	(.54)	(.56)	(.63)
June	-1.78	-1.30	-1.42
	(.96)	(.91)	(.92)
July	.08	-.30	-.15
	(.50)	(.68)	(.61)
August	.25	.66	.36
	(.50)	(.24)	(.38)
September	-.64	-.66	-.79
	(.78)	(.80)	(.88)
Seasonal	.03	-.25	-.25
Average	(.47)	(.71)	(.71)
	West Controls Only		
May	.20	.00	.03
	(.39)	(.48)	(.42)
June	-1.37	-1.27	-1.50
	(.87)	(.84)	(.87)
July	.53	.03	.25
	(.27)	(.51)	(.37)
August	.23	.36	.25
	(.47)	(.38)	(.46)
September	.00	.05	-.36
	(.49)	(.44)	(.62)
Seasonal	-.13	-.18	-.13
Average	(.56)	(.60)	(.54)

Finally, results of the evaluation of all the selected operational seeding projects are summarized in Table 4.5, which shows various elements of the projects evaluated, the most sensitive technique found in the evaluation process, and the corresponding P-value. Generally, if the project evaluated had a positive seeding effect, then the P-values of various statistical techniques used in these project evaluations were in good agreement with the the findings of the simulation studies. Namely, the technique which yields the most significant P-value in the project evaluation is the one found to have highest or near highest power in the simulation studies. On the other hand, if none of the techniques revealed any positive seeding effect in the project evaluation, then the results were equivocal. The technique with smallest P-value in the project evaluation may be the highest-powered one in the simulation studies. This was to be expected, since all the techniques studied in the simulation studies were designed to be used as one-sided tests. They may be sensitive in detecting positive treatment effect (alternative hypothesis), but they are not necessarily good in accepting no positive effect (null hypothesis).

Table 4.5 Summary of Project Evaluation Testing.

Project	Type	Seeded Period	Target Area Size (sq km)	Sampling Unit	Statistical Technique	Estimated Seeding Effect	P-value(1)
Illinois	rain						
McLean	County	1977	3000	day	DR[2]	+13%	-
McLean	County	1978	3000	day	DR[2]	-26%	-
SE	Ill.	1979	3300	45-day	PCR[1]	+39%	.10
SE	Ill.	1980	3300	48-day	PCR[1]	+4%	.42
Muddy Road	rain	1975-1979	27000	season	PCR[1]	-18%	.81
				day	ratio[3,4]	+14%	-
	hail	same					
			15600(5)	year	PCR[3]	-39%	.06
Texas	hail	1970-1976	3200	year	DR	-48%	.01
Oklahoma	rain	1972-1976	15500	season	PCR[3]	-5%	.54
				day	ratio[3,4]	-10%	-

(1) when no re-randomization was carried out in the evaluation, it was denoted by "-".
(2) no compatible historical data were used in the evaluation.
(3) only control areas west of the target were used.
(4) adjusted by climatic gradient between the target and controls.
(5) result is for the eastern half of the target; no significant reduction was found in the western half.

5. METEOROLOGICAL COVARIATES

Based upon recommendations of the 1977 OSET advisory panel, an investigation was made of the use of meteorological covariates or predictor variables (PV) for (1) establishing operational criteria and (2) assisting in the evaluation of seeding results. Funding limited this effort to the study of potential surface covariates, and to one study area without validation testing. (We continued, however, to develop a set of physically "strong" variables that would most likely have predictive power when used with independent data.)

The initial goals for predictor variable research were established within the perspective of our experience in covariate research as part of the HIPLEX design project (Achtemeier et al., 1977; Schickedanz and Sun, 1977). Studies by Achtemeier (1980; 1981) revealed substantial spatial variations in the correlations between predictors and rainfall over distances of several hundred kilometers.

The OSET predictor-variable study was based on the METROMEX (Changnon et al, 1977) raingage network located near St. Louis, Missouri, and containing 255 raingages for June-August 1971-1975. Forty-eight surface stations provided meteorological data which were analyzed onto a 252-point mesh covering an area of 700,000 sq km. Twenty-four predictor variable fields were calculated from the gridded meteorological data (Achtemeier, 1981). Since the number of points per field (252) times the number of meteorological fields (24) gives a total number of 6048 PVs, some means had to be used to reduce the number of PVs and the problem of multiplicity (Gabriel, 1979). It was therefore required that some clearly defined physical link exist between the PVs and rainfall. Some criteria to establish the physical connection were:

1. The 24 fields were all determined to have dynamical or thermodynamical connections with weather systems that produce rain.

2. The PVs were calculated only for the area where a direct relationship with rainfall would most likely exist.

3. Within the area of the analysis, the signs, locations, and shapes of the correlation coefficient patterns would have to conform with expectations derived from meteorological "experience".

4. The physical explanations for the patterns would be simple to avoid the possibility of a multiplicity of physical explanations.

5. The physical explanation for any correlation coefficient pattern would have to be consistent with the physical explanations put forth for the other predictor variables.

The first step in reducing the number of PVs for the analysis was to eliminate every other row and column from the analysis grids. This step reduced the grid size from 252 points to 63 points and the number of PVs from 6048 to 1512 without much loss in power because the neighboring points were usually highly intercorrelated. Then the predictor variable fields were classed according to the 3-hr time interval from the time the rain began over the METROMEX network. These point PVs (PV(PT)) were then used in the studies of prediction and evaluation.

Rainfall values observed over the METROMEX raingage network were used as response variables and the covariates (24 meteorological fields, each computed at 63 grid points) were used as independent variables in simulation studies for testing whether the inclusion of the covariates could improve the power of the techniques in evaluating cloud seeding. There were 180 rainstorms which passed over this sub-area during this period. A storm was defined as a period of rain over the network with gaps not exceeding 6 hours.

The raingage network area was divided into 12 sectors with a buffer in the center. The sector downwind to the movement of each storm was designated as "target" and the opposite 3 upwind sectors as "controls". Rainfall averages were calculated for these sub-areas and used in the study. A subset of 132 storms during the 5- year period were used in the study, which satisfied the condition that rainfall average in the target and in any one of the 3 controls must be greater than or equal to 2.54 mm.

The meteorological covariates were screened by using C_p as the criterion (Hsu, 1978) to reduce the multicolinearity problem in the regression. For each meteorological field, at first, either a few point-covariates (PV(PT)) or a few principal components (PV(PC)) were obtained, then those retained were pooled and used as independent variables in the regression (first-stage screening in Table 5.1). This pooled set of covariates was screened again to reduce the number of covariates even further, again using C_p as the criterion (second-stage screening). Results of the simulations are summarized in Table 5.1.

The analyses indicate that the most powerful method of combining these meteorological covariates was to summarize them into 8 "fields" corresponding to 8 principal components. Such summarization increased the power of the resulting tests considerably over the use of MREG on the unsummarized covariate data. It was found that the evaluation by means of meteorological covariates alone was barely better than the evaluation using upwind area rain, but use of these covariates in addition to upwind areal rain did increase the power of the resulting test appreciably — by as much as .10 (i.e., from a power of about 0.440 to 0.540 for assumed seeding effect of 30%). However, the extensive screening involved in this selection process introduces a higher order of multiplicity and makes the validity of the findings uncertain. Cross-validation on other data is therefore highly desirable.

Table 5.1. Powers at 5% Nominal Significance Levels of the Multiple Regression, Using Averaged Difference (D) as Statistics, Storm Rainfall Totals as Response Variable (500 Runs in the Simulation).

		1st-Stage Screening		2nd-Stage Screening		
Change	No PV	45PV(PT)	16PV(PC)	11PV(PT)	8PV(PC)	8PV(PT)
			Without Upwind Rain Data			
1.1	-	.100	.138	.134	.130	.132
1.2	-	.136	.300	.238	.296	.236
1.3	-	.208	.452	.392	.484	.370
1.4	-	.330	.582	.516	.624	.498
A	-	.100	.058	.322	.404	.284
E	-	.186	.150	.576	.690	.564
C	-	.014	.002	.038	.042	.038
M	-	.170	.378	.274	.350	.272
			With Upwind Rain Data (Control Area)			
1.1	.156	.118	.158	.158	.158	.130
1.2	.286	.198	.308	.340	.328	.304
1.3	.440	.298	.488	.514	.540	.476
1.4	.604	.482	.638	.668	.690	.626
A	.374	.252	.412	.434	.436	.408
E	.690	.522	.710	.758	.772	.710
C	.050	.052	.048	.056	.040	.048
M	.336	.222	.350	.380	.382	.342

*Abbreviations:

PV(PC) : using principal component as predictor variables
PV(PT) : using point-value as predictor variables
No PV : no predictor variables were used

For change models A, E, C, M, see Hsu *et al.* (1981a).

6. ISRAELI EXPERIMENTS TESTING

For further testing of the statistical techniques, the results of the two Israeli experiments were studied. The Israeli I (1961-1967) experiment used a randomized cross-over design (Gagin and Neumann, 1974). Two areas, North and Center, were alternately seeded on suitable days; another two areas, Buffer and South, were used as controls (Figure 6.1). Buffer was located between North and Center, and South was located south of Center. In the present testing, only one target was compared at one time with one control.

The Israeli II (1969-1975) experiment was a randomized confirmatory experiment (Gagin and Neumann, 1981). It used a single target — the area designated as North — and one control — an area west of the target (Figure 6.2). The north target was subdivided into 8 sub-areas, some of which comprised the "catchment area" that was originally chosen as the primary target of the seeding operations. For the present study, the sub-areas were grouped into three sub-targets — North-West, North-Center, and North-East.

Power transformations to make the rain distributions closer to normal were undertaken for both Israeli I and II experiments by using an exploratory method (Emerson and Stoto, 1981). The exponents of transformation derived are shown in Tables 6.1 and 6.2. For seeded rainfall, the transformation used was that derived from the non-seed observations.

The results for Israeli I experiment is summarized in Table 6.3. (1) There was a clear positive seeding effect in the North-Buffer comparison, as confirmed by all the techniques. (2) There appeared to be a positive effect in the Center-South comparison, as indicated by all the techniques except those using sums of rank powers (SRP). Interestingly, the differences between the P-values yielded by the techniques MREG, DR, 2REG were minor. (3) No clear positive seeding effects were evident in the North-South and Center-Buffer comparisons. None of

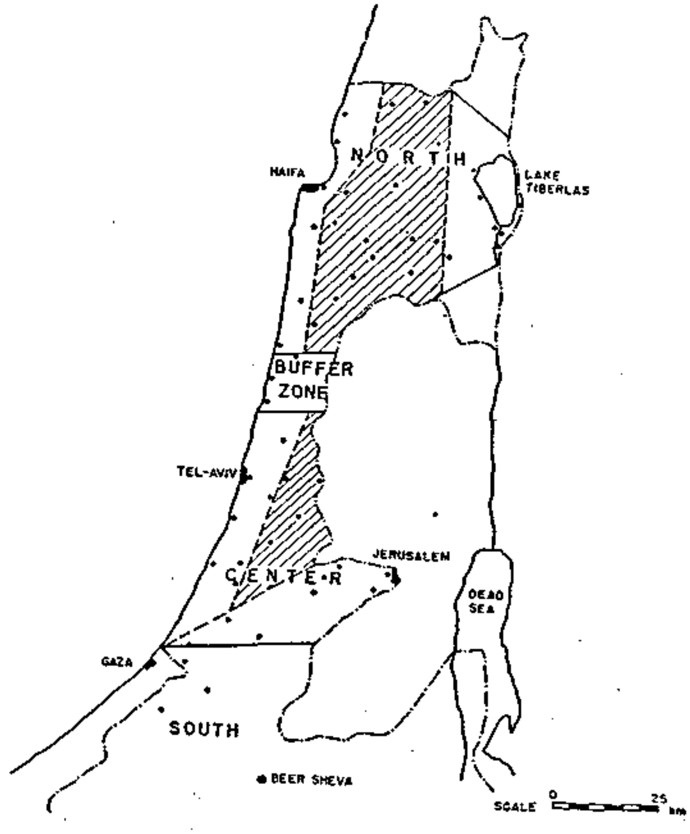


Fig. 6.1. Experimental Areas and the Interior Areas (shaded), Dots Indicate Raingages, Israeli I Experiment.

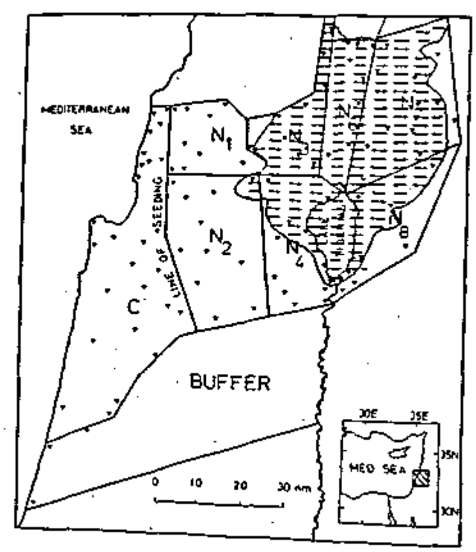


Fig. 6.2. Areas and Subareas of the Israeli II Experiment. (The hatched area defines the catchment, and triangles denote location of rainfall measuring stations.)

Table 6.1 Exponents for Power Transformations and Number of Days, Israeli I.

	North Seeded	Center Seeded	All
North Target	.453 (196)	.321 (174)	.361 (370)
Center Target	.282 (196)	.242 (169)	.306 (365)
Buffer Control	.469 (192)	.308 (169)	.396 (361)
South Control	.397 (146)	.333 (132)	.361 (278)

Table 6.2 Exponents for Power Transformations and Number of Days, Israeli II.

	Seed	No Seed	All
North Target	.346 (203)	.319 (175)	.345 (378)
Catchment Target	.361 (200)	.329 (170)	.380 (370)
N - W Target	.443 (194)	.443 (168)	.451 (362)
N - C Target	.397 (200)	.379 (172)	.389 (372)
N - E Target	.487 (190)	.418 (160)	.360 (350)
Control	.468 (200)	.362 (171)	.418 (371)

Table 6.3 Statistics and 1-Sided Permutational P-value, Israeli I Experiment, Rain.

Target	Control	MREG	DR	DD	SRP A_1	SRP A_2	SRP A_3	SRP C_2	SRP C_3	2REG
					Untransformed					
North	South	.97	1.03	.61	.51	.34	.25	.00	.00	.88
		(.20)	(.41)	(.32)	(.28)	(.34)	(.35)	(.21)	(.19)	(.19)
	Buffer	1.93	1.35	2.40	.53	.37	.28	.01	.00	2.74
		(.01)	(.01)	(.01)	(.01)	(.02)	(.04)	(.04)	(.08)	(.01)
Center	South	1.39	1.28	1.59	.50	.33	.24	-.00	-.00	1.64
		(.05)	(.05)	(.04)	(.44)	(.47)	(.52)	(.47)	(.52)	(.06)
	Buffer	.49	.99	.21	.49	.33	.24	-.00	-.00	.43
		(.29)	(.57)	(.61)	(.75)	(.71)	(.66)	(.68)	(.64)	(.35)
					Transformed					
North	South	.07	1.02	.04	.51	.34	.25	.00	-.00	.80
		(.20)	(.39)	(.34)	(.31)	(.36)	(.37)	(.25)	(.23)	(.20)
	Buffer	.13	1.11	.18	.53	.36	.27	.01	.00	2.65
		(.01)	(.01)	(.01)	(.03)	(.04)	(.07)	(.05)	(.09)	(.01)
Center	South	.04	1.05	.05	.49	.35	.24	-.01	.00	.69
		(.26)	(.24)	(.21)	(.63)	(.60)	(.59)	(.71)	(.70)	(.25)
	Buffer	-.02	.96	-.08	.49	.32	.24	-.00	-.00	-.48
		(.69)	(.82)	(.83)	(.80)	(.75)	(.68)	(.70)	(.64)	(.70)

* Abbreviations:

MREG = multiple regression; DR=double ratio;
DD = double differences; SRP= sum of powers of ranks test;
2REG = two regressions.

Table 6.4 Statistics and 1-Sided Permutational P-value, Israeli II Experiment, Rain.*

Target	MREG	DR	DD	SRP A_1	SRP A_2	SRP A_3	SRP C_2	SRP C_3	2REG
				Untransformed					
Catchment	1.38	1.18	1.32	.52	.35	.27	.01	.00	2.21
	(.02)	(.02)	(.02)	(.15)	(.14)	(.14)	(.15)	(.19)	(.02)
North	1.02	1.13	.98	.52	.35	.26	.01	.00	2.04
	(.03)	(.03)	(.03)	(.16)	(.18)	(.20)	(.17)	(.18)	(.03)
N - W	.56	1.07	.56	.52	.35	.26	.01	.00	1.60
	(.06)	(.06)	(.06)	(.16)	(.18)	(.22)	(.20)	(.24)	(.06)
N - C	1.30	1.18	1.24	.52	.35	.27	.01	.00	2.33
	(.01)	(.01)	(.01)	(.10)	(.10)	(.12)	(.12)	(.15)	(.01)
N - E	1.34	1.14	1.30	.52	.35	.27	.01	.00	1.55 .
	(.05)	(.08)	(.06)	(.12)	(.14)	(.17)	(.13)	(.16)	(.05)
				Transformed					
Catchment	.11	1.07	.10	.51	.35	.26	.00	.00	2.22
	(.01)	(.02)	(.08)	(.20)	(.22)	(.24)	(.19)	(.21)	(.01)
North	.08	1.05	.07	.51	.34	.26	.00	.00	2.17
	(.01)	(.05)	(.15)	(.20)	(.24)	(.27)	(.23)	(.26)	(.01)
N - W	.08	1.04	.08	.52	.35	.26	.00	.00	1.76
	(.04)	(.04)	(.05)	(.14)	(.15)	(.18)	(.17)	(.23)	(.04)
N - C	.13	1.07	.12	.52	.35	.26	.01	.00	2.35
	(.01)	(.01)	(.02)	(.14)	(.15)	(.18)	(.14)	(.18)	(.01)
N - E	.15	1.08	.15	.52	.35	.27	.01	.00	1.73
	(.04)	(.04)	(.04)	(.12)	(.14)	(.18)	(.13)	(.16)	(.04)

*Abbreviations:
MREG = multiple regression; DR=double ratio;
DD = double differences; SRP= sum of powers of ranks test;
2REG = two regressions.

the statistical techniques showed any such effects.

For the Israeli II experiment, the analyses confirmed a general positive seeding effect, with a slightly more significant effect in the Catchment area. (This effect was revealed by all the statistical techniques except SRP. The differences between the P-values due to MREG, DR, and 2REG were again minor.)

Both of the Israeli experiments employed a 24-hour period of rain as a sampling unit. The sampling unit used in the OSET simulation studies closest to it was the 48-hour unit in the ILL-48 simulation, in which MREG was found to be the most powerful technique. The present tests ("untransformed" in Tables 6.3 and 6.4) revealed that <u>when</u> the seeding results were significant (P-value less than or equal to .10), MREG (which here is the same as PCR[1] because there was only one control) was the most sensitive technique, followed by DR. On the other hand, the inability of SRP to reveal a significant seeding effect in the testings led to the speculation that the two Israeli experiments may have produced constant multiplicative seeding changes of rainfall rather than varying effects which depend on the magnitude of natural rain. (This was inferred <u>indirectly</u> from the findings of the ILL-ST simulation, in which SPR was found to be the most powerful technique when employing models of varying seeding-induced changes.)

The same statistical techniques described above were applied to the transformed data. The results (Tables 6.3 and 6.4), however, did not show any improvement (decrease) of P-values for the Israeli I experiment, and were mixed for the Israeli II experiment. Thus, the use of power transformation dose not seem to lead to an improvement in the power of the evaluation techniques used.

7. MISCELLAHEOUS TOPICS

A number of issues relevant to the evaluation of cloud seeding projects are discussed here. They include (1) a discussion of validity of use of historical data in evaluation, (2) a listing of potential biases in the entire evaluation procedures, and (3) methods of combining several tests of significance.

7.1 Validation of Historical Comparison

Analyses of cloud seeding operations often compare precipitation during operations with precipitation during preceding historical periods. (For references see Hsu, 1981a). For example, rainfall at Santa Clara during 10 years of seeding operations after 1954 has been compared with the rainfall of 10 preceding years (Dennis and Kriege, 1966). Such comparisons implicitly involve the assumption that the difference, if any, between the pre-operational and operational periods reflects mainly the effect of seeding. Though it is acknowledged that random year-to-year variability may also result in differences between periods, tests of significance are used in an attempt to separate the 'true' difference from the random ones, and the former is ascribed to the effect of cloud seeding. This study has been concerned with the validity of such statistical analyses.

Problems of Comparison. It considered the assumptions underlying them and examined precipitation data with a view of verifying the appropriateness of these assumptions. Failing such verification, this study then examined the robustness of standard statistical analyses against the existing divergences from these assumptions. That should indicate what confidence, if any, one may place in historical precipitation data in evaluating cloud seeding operations.

The present study was not concerned with biases, however important these may be (see for example, Gabriel, 1979), but with the separate questions of whether comparisons of operational with historical periods may validly use standard statistical techniques. Such techniques are usually derived from a series of assumptions, including one which postulates that the observations are based on independent and identically distributed (IID) variables on which the effect of seeding, if any, is superimposed or added. In the present context, this would mean that annual amounts of natural, i.e., unseeded, precipitation were IID. But that surely does not fit known facts exactly. Some persistence and serial dependence of precipitation is known to exist, as are trends over short periods of years. Does the untruth of these assumptions then invalidate the use of standard statistical techniques?

One of the major conclusions of the statistical testing was the need to use historical data, i.e., data collected prior to the seeded period, as a basis for comparison of operational seeding data. Variations in historical data were therefore studied to ensure the validity of using temporal comparisons (seeded period data versus historical data). A total of 62 precipitation stations with long records provided sets of 2k (k=3,5,7,10,20) successive years (all unseeded, of course). These sets were analyzed as though the first k years were historical controls for the second k "operational" years.

A number of statistical test were then applied to these "pseudo- experiments" of k-vs-k years (without simulating any "seeding effect"), and the distribution of the resulting P-values was compared to the uniform distribution on (0,1) which should have been obtained had rainfall on successive years been independent and identically distributed. It was found that for small k, the P-values were indeed close to uniform. But for larger k, i.e., longer pseudo-experiments, there were more small P-values than expected from the uniform distribution. For k=20, the proportion of tests significant at level alpha rose to about twice alpha, instead of the expected alpha.

In conclusion, operational-vs-historical comparisons must be used with caution, perhaps by doubling the calculated P-value before assessing significance.

7.2 Possible Biases in Evaluation

One of the important issues in assessing effects of an operational cloud seeding project is how to deal with the potential biases in the evaluation. In a broader sense, these would include problems of weak or bad design, bad data, intentional and unintentional deviations in executing the operations plan, and most importantly, non-objective approach used in the evaluation process. In the following, we will first list these biases, then try to find ways to deal with them, if possible.

The problem of "bad draw" in a randomized project has been discussed by several authors (Keiburger and Chin, 1969; Williams et al., 1972; Gelhaus, 1973; Gelhaus et al., 1974; Super and Heimbach, 1974; Braham, 1979; Cook and Eolschuh, 1979; Summers et al., 1979). The term "unbalanced randomization" also has the same meaning. What the problem points to is that the randomization plan used had a very small probability of being selected, which should not be selected theoretically but was actually selected. The problem was observed in the evaluation of the Whitetop Project, Grand River Project, Bridger Range Project (in Montana), and recently the FACE-2 Project. Unfortunately, they were found a posteriori. No actions were built into the experimental design to handle them. As for operational projects, no randomization is usually employed in the design, thus there is no problem of bad draw. However, depending on the evaluation and data used, similar (but not identical) problems could occur.

To assess the effect of cloud seeding, the response values (rain, for example) of the target area in the seeding period are compared to some other similar but non-seeded values. If one views this as a plan of "pseudo-randomization" selected from a set of randomization plans, then it is possible that what had occurred is a bad draw. This is a delicate view and it is beyond the scope of this report to give a more detailed discussion. But the possibility is there. For example, if seeding were to be done in "very dry" years, and the rain values were to be compared with rain of preceding "not too dry" seasons, it could be argued that the problem of "bad draw" had actually happened. For in this case, it would be rather difficult to prove that small to moderate rain increases were caused by seeding if historical data were used. Therefore, from the statistical evaluation point of view, this design problem is usually not as big an issue in the operational project as in the randomized project.

Data problems have been recognized in several evaluations of weather modification projects (Lovell, 1972; Simpson and Eden, 1974). These and other difficulties are listed below:

1. General data problems

   1 poor instrumentation exposure
   2 poor instrumentation calibration
   3 error in observation/measurement technique
   4 change of observation technique
   5 change of observation location
   6 error in data transmission
   7 insufficient data collection

2. Problems associated with seeding operation

   1 equipment/instrument failure
   2 short of (seeding-related) material
   3 change of observers/operators
   4 change of seeding schedule
   5 change in decision tree
   6 inconsistency in identifying seeding opportunity
   7 subjective selection of seeding units

3. Potential biases in evaluation

   1 definition of target areas
   2 selection of control area(s)
   3 change of control area(s)
   4 change of response variables
   5 selection of inappropriate data subset
   6 selection of inappropriate historical data
   7 stratification
   8 assigning precipitation to wrong sampling unit
   9 a posteriori definition of sampling unit
   10 subjective allocation of precipitation to seeding
   11 problem of multiplicity
   12 wrong application of statistical test

The listings are not exhaustive. They are based on extensive literature reviews as well as considerable first-hand experience in dealing with weather modification over many years.

Most of the data problems can be prevented by a careful project design and by strict adherence to the design plan in project execution (Huff and Changnon, 1980). Problems associated with seeding operations are harder to alleviate, for some of the problems may occur unconsciously and may not be noticed until the end of the project. Problems associated with evaluation can be alleviated by a good project design and by following the "a priori" principle, namely, spelling out every detail involved in the evaluation before launching the actual analyses.

7.3 Combining Several Tests of Significance

The importance of combining significance levels obtained from several independent short-term seeding projects (1 to 3 years duration), so as to maximize the scientific information they provide individually, has long been recognized. For example, Godson (1956) discussed the combination of seeding results from different areas and time periods when using multiple regression.

Before employing such an approach, a few critical issues need to be addressed. It is reasonable to assume that projects to be considered for combination will be conducted under the influence of similar weather conditions, in similar geographic areas, using similar sets of operational criteria, and being seeded over a relatively short time span. On the other hand, it is apparent that different projects may provide different amounts of information. One project might last longer than another, or have a larger target area. Questions that need answering include (1) what information should be considered in combining projects, (2) how the projects can be combined, (3) how to compensate for the significance level if different statistical techniques were used in evaluating individual projects, and (4) what method of combining projects is to be used.

Statistically, the problem of combining independent tests of significance has been discussed by a number of writers, including Fisher (1932), Birnbaum (1954), Oosterhoff (1969), Koziol and Perlman (1978), Littell and Louv (1981) and Scholz (1981). A method for combining non-independent 1-sided tests was presented by Brown (1975).

Generally, the available methods fall into the following 8 kinds: (1) Tippet's method (1931), (2) Fisher's method, (3) sum of P-values, (4) inverse normal score (Liptak, 1958), (5) inverse chi-square method, (6) inverse logistic method (Mudholkar and George, 1979), (7) likelihood ratio test, and (8) others. None of the methods is optimal in all cases, and each may yield a most powerful test against some particular alternative hypothesis (Birnbaum, 1954; Scholz, 1981).

Fisher's method is the most popular and is appropriate when all the tests to be combined can be weighted equally. Recent study (Marden, 1983) has shown that Tippet's method, Fisher's method, and likelihood ratio test are optimal (admissible) under more circumstances than the other methods — sum of P-values, inverse normal score, inverse chi-square, or inverse logistic methods.

By using the union-intersection principle (Morrison, 1976), Scholz (1981) proposed a method that automatically selects a weighting function such that the combined P-value is most significant. He showed that the method is more powerful than Fisher's whenever at least one of the P-values is very close to zero.

The approach discussed here has high potential of obtaining as much information content as possible from existing data and measurements of seeding operations. More research is needed to decide how the combining methods can be applied to weather modification correctly and unbiasedly in avoiding the problem of multiplicity, without losing information.

8. SUMMARY

This research has attempted to study techniques for evaluating operational cloud seeding by using historical precipitation (or hail damage) data for areas considered as "target" on which seeding effects were simulated. It also used concomitant observations on neighboring control areas to adjust for spatial gradients and temporal variability of the response variables. We have studied and compared multiple regression (MREG), two simple regressions (2REG), principal component regression (PCR), double ratio (DR), sum of rank power tests (SRP), multi-response permutation procedures (MRPP) and ratio-difference (RD). These techniques either were used in evaluating past seeding operations, or were developed in this project. Each of these techniques compared the simulated "seeded" precipitation (or hail damage) on the "target" with the remaining un-seeded data, and used the neighboring control observations for adjustment. The techniques were compared in terms of their power to detect the seeding effects that were simulated.

Findings of the simulation revealed that the principal component regression technique is generally the most powerful or next to the most powerful technique when assuming constant multiplicative seeding effects. With monthly or summer rains as sampling unit, a single principal component was sufficient to attain such power. For 48-hour rainfall data, three principal components were needed. For annual hail data, three principal components were also needed to achieve higher power. This is consistent with the fact that the natural variability of hail or rainfall with shorter sampling unit is generally higher than that of rainfall with longer sampling unit, so more components are needed to retain a similar level of information (i.e., percent of total variance explained by the components retained).

In the case of using seasonal average as sampling unit, if the assumed seeding effect was small (10%), then MRPP was the most powerful among all the techniques studied. If the assumed effect was greater than 10%, other techniques were more powerful than MRPP. It appeared that MRPP is best suited for use in detecting small multiplicative change of seeding effects.

Though PCR was consistently the most powerful technique, occasionally, its power was lower than that of MREG or DR. Indeed, for short sampling units (storm or 48-hour), MREG seemed to be the most powerful; and for the hail project with a small target over 6 seeding years, DR was the most powerful. For variable seeding effects (used only in the storm simulation), the most powerful tests were SRP, namely, A_1 (the 2-sample Wilcoxon test) or C_2. When evaluating operational seeding projects, it is recommended to use long sampling unit to avoid biases in the selection of seeding occasions and to use historical data for proper comparison. Thus, from the operational evaluation point of view, the technique of principal component regression provides the most powerful and less-biased evaluation method.

It is not at present clear why these power differentials should have been found, but they seem to point to the advantage of using PCR for longer period units and MREG for shorter units if one assumes constant seeding effects. On the other hand, if the effects of seeding may be variable, one would do better to opt for simple non-parametric techniques.

A number of past seeding projects of the commercial type were selected for testing of the statistical-physical techniques developed. They included several small-scale rainfall enhancement projects in Illinois, and a hail suppression project carried out in the Texas Panhandle, a large-scale combined hail suppression/rain enhancement project in southwestern Kansas (the Muddy Road Project), and a ground-based project in northwestern Oklahoma.

The evaluation of the Illinois projects conducted in 1977-1980 showed mixed outcomes. Some indicated rainfall increases under seeding, other indicated decreases. Except for the 1979 result which was significant at 10% level, none of the projects were clearly significant. Overall, these projects do not provide clear evidence of seeding effects. In all instances, regardless of the apparent increases or decreases in rainfall or echoes in the target areas, the 1-year (2-month duration) projects were too short to draw any conclusions that have statistical or physical significance when taken alone.

The evaluation of the hail suppression programs in the Texas Panhandle used a number of exploratory analyses as well as using a target-control comparison with historical data. The findings indicated that a reduction of 48% in hail loss-cost values, significant at 1% level, was found in the entire target area.

The evaluation of the hail suppression phase of the Muddy Road project indicated that, by using historical data and target-control comparisons, there was in general a reduction of annual hail loss-cost values in the target area during the 1975-1979 seeding period. The 39% decrease of hail loss/cost values in the eastern portion of the target area was statistically significant at the 6% level; however, the decrease of L/C values in the western portion was not as significant. Ratios of seeded average L/C (1975-1979) to historical average L/C (1948-1971) had shown that the ratios in the target were all less than 1.0, except two small areas in the northwestern and southeastern corner, where they were between 1.0 and 2.0. This evaluation, which involved a relatively large target for 5 seeded years, suggested that PCR is a more sensitive evaluation technique than MREG or other techniques, as might be expected from the Montana simulation studies.

The evaluation of the rainfall of the Muddy Road project indicated that, by using historical data, there was a non-significant rain decrease in the target area when the entire season was used as the sampling unit. The results of all the techniques used were essentially identical. Uses of monthly rainfalls indicated that there was a significant target rain excess in the east sub-target area in April and August, the months designated in the project for rain enhancement, a significant rain decrease in May (rain/hail) and a non-significant decrease in

September (rain).

Further evaluation of the rainfall enhancement phase of the Muddy Road program, based upon a detailed and rather comprehensive analysis performed on daily rainfall data utilizing moving upwind areal controls and synoptic weather information, indicated that the effect of rain enhancement for the 5 years combined was relatively small or non-existent. There was some evidence from the mean rainfall distributions that rain enhancement may have been successful when seeding was performed on days producing only light natural rainfall. The target total rainfall for the 5 years exceeded the control total by 9%; however, the difference appears to be too small to provide firm support for seeding-induced increases. The natural variability in warm season rainfall and the errors inherent in determining mean rainfall from the NWS raingage network could conceivably produce all or part of the 9% variation between target and control. Of course, these factors could also cause underestimates of a seeding effect. Furthermore, the fact that the control exceeded the target rainfall on 56% of the 153 seeding days indicates lack of consistent success.

The results based on daily rainfall data and synoptic information did not differ greatly from those based on monthly/seasonal rainfall and fixed controls, which indicated no rainfall increase from the 5-year program. Implications for future cloud seeding in this area would be to focus on synoptic weather systems moving from the SW and predicted to produce light (greater than 5 mm) daily rainfall.

In evaluating the Oklahoma project, ratios of 1972-1976 period to historical period, using seasonal rainfalls, indicated that most of the study area received less rain during the seeding period than during the historical period. The differences among ratios were small, however. The eastern portion of the target had higher rainfall ratios than the western portion. Monthwise. rainfall ratios in the target were less than 1.0 in May, June and July, but were more than 1.0 in August and September. The target ratios in August were larger than the surrounding controls' except for the southwestern corner. However, in all other months the target ratios were less than those of the controls.

If historical data and target-control comparisons were used for evaluation, all the estimated mean differences were not statistically significant. There was a non-significant 5% seasonal rainfall deficiency in the target compared with what would be expected. When using monthly rainfall, the differences were small and statistically non-significant. The biggest target rainfall excess (0.66 cm) occurred in August. The largest decreases, all greater than 1 cm, occurred in June. In general, the technique of PCR[1] indicated more increases or fewer decreases of target rainfalls than did MREG in June and August, but the opposite in May and July.

When using daily rainfall data and synoptic weather information, the most pronounced feature of the isohyetal patterns for the various stratifications was a high in the rainfall distribution centered approximately 90 km east of the target area foT all seeded storms combined. The easterly high was also pronounced in the same general area in storms moving from the west, storms associated with stationary fronts, storms in which the low-level winds (plume winds) were from the SE and NE quadrants, and for storms moving from the west with SE plume winds; however, it was not evident in storms moving from the SW and NW quadrants and in storms with SW plume winds. In the majority of the stratifications, the target area recorded relatively light rainfall compared with most of the surrounding region. This indicates that the overall seeding effect (if any) may have been one of suppressing rather than increasing the natural rainfall on the target. However, it is not possible to prove this supposition unequivocally with the available data and the high degree of natural variability found in warm season rainfall in this region. Differences between the total rainfall in the target area and the easterly high center were considerably greater than indicated by the normal climatic gradient in the area of interest. This suggests the possibility of a downwind seeding-induced high resulting from errors in estimating the time-distance relationship between seeding agent release at the ground and cloud reaction to the seeding input. Again, data are inadequate to evaluate conclusively this possibility. The presence of the easterly high with NE or SE plume winds does not suggest a logical connection and suggests at least a portion of total rainfall high there was due to random choice. Furthermore, results of a target-control analysis using daily rainfalls adjusted by climatic normals indicated little evidence of increased rainfall from seeding in the target area.

As a summary of the evaluation of all the selected operational seeding projects, it is noted that if the project evaluated had a positive seeding effect, then the P-values of various statistical techniques used in these project evaluations were in good agreement with the the findings of the simulation studies. Namely, the technique which yields the most significant P-value in the project evaluations is the one found to have highest or near highest power in the simulation studies. On the other hand, if none of the techniques revealed any positive seeding effect in the project evaluation, then the results were equivocal. The technique with smallest P-value in the project evaluation may not be the highest-powered one in the simulation studies. This was to be expected, since all the techniques studied in the simulation studies were designed to be used as one-sided tests. They may be sensitive in detecting positive treatment effect (alternative hypothesis), but they are not necessarily good in accepting no positive effect (null hypothesis).

The study on integration of surface meteorological covariates into evaluation techniques indicated that the best method of combining the enormous number of covariates was to summarize them into 8 "fields" corresponding to 8 principal components. Such summarization increased the power of the resulting tests considerably over that with the use of MREG alone on the unsummarized covariate data. It was found that the evaluation by means of meteorological covariates alone was little better than the evaluation using upwind area rain, but use of these covariates in addition to upwind areal rain increased the power of the resulting test by as much as .10. However, the extensive screening involved in this selection process introduces a higher order of multiplicity and makes the validity of the findings uncertain. Cross-validation on other data is therefore highly desirable.

For further testing of the statistical techniques, the results of the two Israeli experiments were studied. The results for Israeli I experiment revealed that (1) there was a clear positive seeding effect in the North-Buffer comparison, as confirmed by all the techniques used. (2) There appeared to be a positive effect in the Center-South comparison, as indicated by all the techniques except those using sums of rank powers (SRP). Interestingly, the differences between the P-values yielded by the techniques MREG, DR, 2REG were minor. (3) No clear positive seeding effects were evident in the North-South and Center-Buffer comparisons. None of the statistical techniques showed any such effects.

For the Israeli II experiment, the analyses confirmed a general positive seeding effect in the target, with a slightly more significant effect in the Catchment area. This effect was revealed by all the statistical techniques except SRP. The differences between the P-values due to MREG, DR, and 2REG were again minor. Power transformations to make the rain distributions closer to normal were undertaken for both Israeli I and II experiments by using an exploratory method. The same statistical techniques described above were applied to the transformed data. The results, however, did not show any improvement (decrease) of P-values for the Israeli I experiment, and were mixed for the Israeli II experiment. Thus, the use of power transformation does not seem to lead to an improvement in the power of the evaluation techniques used.

Finally, three relevant issues in the evaluation of operational projects were studied. The issue of using historical data in evaluation is an important one. In simulation studies, it was found that for shorter-duration projects the P-values were indeed close to uniform, the expected distribution. But for longer-duration projects, there were more small P-values than expected from the uniform distribution; under some circumstances, the proportion of tests significant at level alpha rose to about twice alpha, instead of the expected alpha. Thus, use of historical comparison would be appropriate if, for no other reason than as a safe-guard, the critical value of the test is selected to correspond to half of the usual nominal significance level.

Potential biases which might affect the outcome of evaluation were listed and discussed. Statistical methods for combining several tests of significance were presented, although more study is needed for such applications to be feasible for the evaluation of weather modification.

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