FINAL REPORT FOR CONTRACT ENTITLED

THE DEVELOPMENT OF PREDICTORS AND COVARIATES FOR THE EVALUATION OF THE SOUTHWEST COOPERATIVE PROGRAM (SWCP) BIG SPRING AND SAN ANGELO, TEXAS

PHASE I: IDENTIFICATION AND SCREENING OF COVARIATE VARIABLES

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1.0 INTRODUCTION

Previous analyses by the Principal Investigators engaged in this proposal suggest that seeding in the Southwest Cooperative Program (SWCP) has been effective in increasing the rainfall in West Texas (Rosenfeld and Woodley, 1988 and Woodley and Rosenfeld, 1988). To be consistent with the SWCP conceptual model, which postulates that an effect of seeding will be evident first on the cell scale before it is evident in the experimental unit overall they focused first on the cells (Rosenfeld and Woodley, 1988). Two approaches were adopted in the cell analyses: 1) calculation of cell properties (i.e. height, maximum reflectivity, duration, volume rain rate and rain volume) from the tracking of individual, treated (AgI or simulated AgI) cells until they merged into other cells or splitted (i.e. the "short track" approach) and 2) calculation of cell properties from the tracking of individual, treated cells for their full life-cycles, determined objectively by the tracking programs (i.e. the "long track" approach). This analysis effort made use of only SWCP 1987 data, because the poorer quality of the SWCP 1986 data would not permit individual cell analyses.

Both cell analyses suggest an appreciable positive effect of AgI treatment on cell duration, maximum reflectivity, area, rain rate and rain volume. A smaller effect on maximum cell height is indicated. The largest apparent effect is on mean total cell rainfall and ranges from a minimum of 50% more rain volume for the "short track" approach to 146% more rain volume for the "long track" approach.

Further physical insight into the cell results was provided by the construction of time composites of the mean cell properties as a function of the approach (short or long track) and the treatment decision (AgI or simulated AgI). Composite time-height reflectivity profiles as a function of approach and treatment also were derived. Very small differences in mean cell properties were noted at the time of first treatment, indicating little initial natural bias. The S and NS plots diverged greatly, however, after treatment. The biggest contributor to the increased rainfall from the AgI-treated cells appears to come from increased cell area, followed by increased cell duration and a small (5% to 10%) increase in cell height. There was no effect on peak cell reflectivity.

Seeding apparently caused the rain of the convective cells to cover larger areas and for longer periods of time, without increases in their local maximum rain intensities. Some of these changes were promoted by echo merger, which occurred twice as often in AgI treated cells.

The next step in the investigation was examination of the 23 experimental units that were obtained in SWCP 1986 and 1987. Again, two approaches were adopted.

The first approach to the examination of the experimental units followed the design document, which calls for termination of rainfall calculations at the time declared in "real time" by the radar controller. This is an ideal analysis when the experimental units go through a simple cycle of growth, maturation and dissipation. When some of the echoes in the experimental units merge with other large echoes, however, this approach becomes somewhat subjective. Because the controller knew the treatment decision, one cannot totally eliminate the possibility that unintended bias could have influenced his decision on case termination.

The second approach to the analysis of the experimental units required that the rainfall calculations continue for as long as the unit is on the radar scope, regardless of whether it may have merged with other echoes. This approach is objective, but it has the disadvantage of allowing non-experimental echoes into the unit. This increases the natural precipitation "noise" and usually weakens the seeding signal.

The ratios of Seed (S) to No Seed (NS) rainfalls by half-hour interval and cumulatively generally exceed a factor of 1.20 for the two approaches employed in the analyses. The ratios are largest for mean cumulative rainfalls at 2.0 to 2.5 hours after the initial treatment. Ratios of median rainfalls suggest a somewhat larger potential effect of treatment.

Small samples are characteristically dominated by one or two large values, and this can affect the average values greatly and produce a misleading result. To be certain that this is not a serious problem for SWCP 1987, median rainfalls and ratios of median rainfalls were calculated. Because the median value is merely the middle value in an ordered listing of the data, medians are not affected by extreme values.

The median calculations suggest a somewhat larger positive effect of treatment in 1987, 1986 and 1986 and 1987 combined. This suggests that seeding affected the rainfall on most days and that the apparent effect does not depend on a single large rainfall event.

None of the rainfall results for the experimental units is statistically significant at the 10% level of significance using simple non-parametric Wilcoxon-Mann-Whitney testing procedures. The sample is still much to small to obtain strong P-value support for the results.

Two sensitivity tests, making use of 1987 radar data, suggest nevertheless that treatment may have been responsible for at least a portion of the observed S vs NS differences. The first sensitivity test involved repeating the rainfall caluculations for four radii (i.e. 15, 20, 30 and 35 km) from the initial treatment position in addition to the "standard" radius of 25 km. Both the mean and median calculations indicate that the ratios of seed to no seed rainfall are greater than one near the point of initial treatment early in the period of calculation and that the ratios increase further and move outward with time. Such a result is consistent with a positive effect of seeding.

The second sensitivity test focused on the areas within the experimental unit in which the cells received treatment. This "focused area" approach involved calculations for radii of 5, 7, 10, 15, 20, 25 and 35 km around each treatment position, providing eight separate analyses. The results also are consistent with a positive effect of AgI treatment on rainfall that begins on the cell scale and spreads into the overall experimental unit with time. The size of the apparent effect on this scale could be as large as 75%.

Based on all of the evidence, it appears likely that randomized AgI seeding increased the rainfall in the SWCP. The apparent effect begins on the scale of individual cells and spreads into the overall unit with time. The best estimates of the sizes of the apparent effects are over 100% on the cell scale, at least 50% on the focused area that contains the grouping of treated cells and at least 30% on the experimental units.

As in virtually all cloud seeding experiments with small samples, however, the natural rainfall variability in West Texas may be masking the true effect of seeding. The apparent effects of treatment on rainfall in West Texas are quite large and it is crucial to know whether these apparent effects are representative of the true rain enhancement potential in this region.

This proposal has taken the next step in the continuing investigations of the effect of seeding in West Texas by identifying and screening covariate variables that can be used in developing linear multiple regression equations to reduce the natural variability that is inherrent in these experiments. This was done for both the cells (the treatment units) and for the small mesoscale convective clusters (the experimental units). These "best" variables are now available for the development of the linear multiple regression equations for the evaluation of the effect of seeding in West Texas. This will be done in Phase II of this proposal.

2.0 Objectives of the Proposed Research (Phases I and II)

The objectives that are to be achieved in the six-month research effort are:

1. Identification of meteorological variables that are correlated with the rainfall from convective cells and from small mesoscale convective clusters (Phase I);
2. Identification of the best four to five predictor/covariate variables for cell and cluster rainfalls through a systematic screening process (Phase I);
3. Development of exploratory linear models for cell and cluster rainfalls (Phase II);
4. Evaluation of the effects of seeding in the SWCP on cell and cluster rainfalls using the exploratory linear models (Phase II).

The two objectives of Phase I have been accomplished and an evaluation of the effect of seeding on the individuals cells has been completed. In addition, a proposal for continuation of the SWCP effort within the context of the Texas-Israel Exchange has been written by the two Principal Investigators. This document has been provided under separate to the Texas Water Commission and to the Israeli government, and it will not be discussed in this Final Report.

Once it has been funded, the work under Phase II of the contract will be addressed in progress reports and in the final report.

3.0 FURTHER ANALYSES OF THE EFFECT OF SEEDING ON CONVECTIVE CELLS IN WEST TEXAS: THE USE OF "CONTROL" CELLS TO REDUCE THE NATURAL VARIABILITY

The effect of AgI seeding in SWCP 1987 on the properties of convective cells has been treated extensively by Rosenfeld and Woodley (1988) and a summary was presented in the introductory section of this Final Report. All of the evidence suggests that AgI seeding was effective in increasing the rainfall from the individual cells by over 100%.

The obvious question concerning these highly encouraging results is whether they are confounded by the natural rainfall variability. Even though the cell results appear to make sense scientifically, one cannot discount the possibility that the luck of the draw played a role in their generation. It is vital, therefore, to address this uncertainty.

The first approach in addressing the natural variability is a refinement of an analysis pioneered by Gagin et al (1986) that was used in the Florida Area Cumulus Experiment and made use of "control" cells in the environments of the AgI-treated and sand-treated cells. This approach is simple conceptually, but, as will be seen, care must be exercised to implement it properly.

The value of this approach is readily apparent. Assume that "control" cells can be identified in the environments of the S and NS cells on all days and that the linear correlation coefficient between the NS cells and the control cells is perfect (i.e. 1.00). Such a correlation would indicate that the control cells are perfect predictors of the rainfall to be expected from the NS cells. Similarly, in the absence of treatment effects, these control cells would be good predictors of the rainfall to be expected from the S cells as well. With this assumption in place, suppose, for example, that the ratio of the mean Seed (S) to No Seed (NS) cell rain volumes for a period of study is 2.00 (i.e. percentage rainfall increases of 100%). Suppose further that the ratio of rainfalls for the control cells is 2.00 as well. This would allow us to define the double ratio (DR):

$$DR = S/NS \div (\text{Control})_S/(\text{Control})_{NS} \qquad (1)$$

Substituting the values for the ratios in this hypothetical example, one obtains 2.00/2.00 = 1.00, which means that AgI seeding has had no effect whatsoever on the cell rainfalls even though the single ratio (SR) of S to NS cell rainfalls would suggest that the effect is 100% (i.e. a factor of 2.00). Accounting for the natural rainfall variability through the control cells has eliminated this hypothetical seeding effect.

Clearly this is an analysis worth pursuing. It must be shown, however, that it is possible to define "control cells" objectively and that these control cells are good predictors. Having accomplished this, the "control cells" can then be used to account for the natural variability in the SWCP cell analyses.

3.1 Defining the Control Cells

In defining the cells to be used as controls, several factors had to be considered. First, the propsective cells had to conform as much as possible to the selection criteria of the actual experimental cells that received S or NS treatment. Second, the control cells had to be separated from the S and NS cells by a minimum distance to ensure that the experimental cells did not contaminate those cells, which are to be used as controls (only a consideration for those experimental cells that received AgI treatment). Third, because of range biases in cell measurements that can result from the characteristics of the measurement radar, each set of control cells had to be as far from the radar as the experimental cells that resided within each experimental unit (i.e. the small mesoscale convective cluster).

The criteria for the selection of the control cells are the following:

a) The prospective cell has been tracked for at least two radar scans,

b) The cell is no more than 125 km from the radar at the time of its birth,

c) The prospective cell is never within 35 km of any treated cell,

d) The height of the prospective control cell must be at least 6.5 km on the second radar scan, and it must be taller on the second scan than on the first, but not more than 10 km,

e) The reflectivity of the prospective cell must be greater on the second radar scan than on the first,

f) The prospective control cells must reside in the 60-km wide annulus that is centered on the mean range of the treated cells for which the controls are being selected.

The last criterion is best understood by reference to Figure 1 in which the treated cells, the environmental cells and the control cells are plotted. Note that the three treated cells (either S or NS) are defined to have a 25 km region of effect around them, and that the environmental cells, which will be discussed at length later, are defined as those cells, which did not receive either S or NS treatment, that live in this region of effect. The cells which are to be used as controls are depicted schematically in the 60-km wide annulus. The center of the annulus is at the mean range of the treated cells from the radar. To be consistent with criterion c) above, the annular region in which the control cells can be selected ends at least 35 km from the treated cells. In essence, therefore, there is at least a 10 km buffer between the area of effect and the region that contains the control cells.

The problems that are inherrent to the radar measurement of cell properties account for the selection of control cells in an annular region at the mean range of the treated cells. Radar assessment of the properties of convective cells depend in large measure on the geometry of the radar beam and on the distance of the subject cells from the radar. Radars with narrow beams provide provide

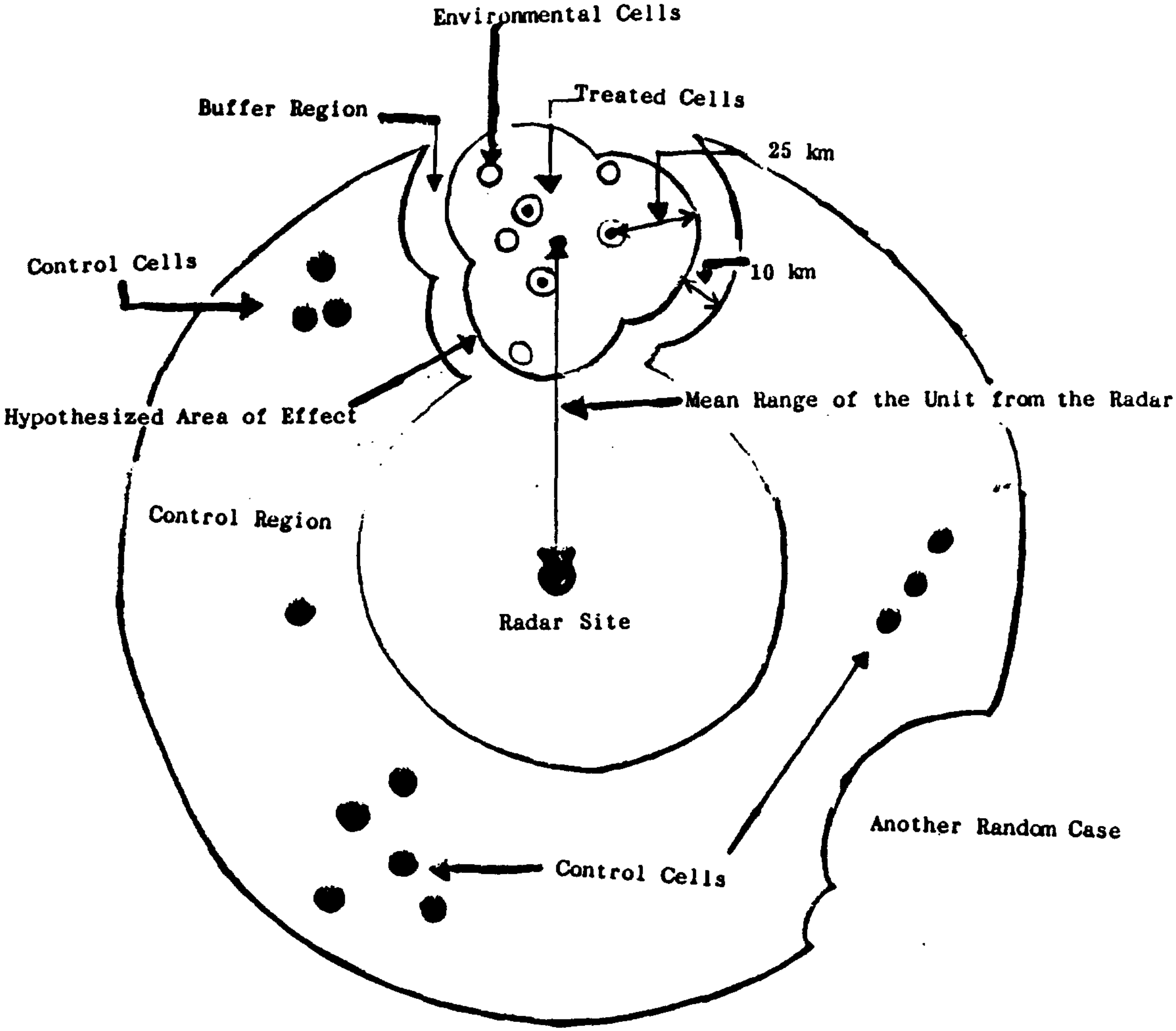

Figure 1 Diagram showing the analysis scheme for the cell analyses. The hypothesized area of effect contains the treated cells and the environmental cells. The control region contains the control cells. There is a 10 km buffer between the region of effect and the control region. No control cell can ever be within 35 km of of treated cell. The environmental cells can be as much as 25 km from a treated cell.

measurements with much greater resolution than radars with coarse beams. As range increases, however, all radar measurements are degraded, because the subject cell no longer fills the radar beam --- even for radars with narrow beams. What a radar measures, therefore, is dependent in part on the range of the subject cell from the radar.

Consequently, in selecting control cells it is important that they be in the same range interval as the treated cells for which they will serve as controls. This requirement will help ensure that the same radar inaccuracies apply to both the control and experimental cells and that any differences are real and not due to non-meteorological factors.

3.2 Results

A listing of the properties of the control cells that were obtained from the "short" tracking program for each of the 13 experimental units that were obtained in SWCP 1987 is provided in Table 1. The properties of the cells to be used as controls for the NS experimental units are listed at the top and those to be used as controls for the S experimental units are listed at the bottom of the table. The cell properties that correspond to each experimental unit represent means for the number (N) of control cells that were selected for that unit. The column headings have the following meaning:

1) HMAX is the maximum height (in km) of the cells during their lifetimes,

2) ZBMAX is the maximum reflectivity (in dBz) at cloud base of the cells during their lifetimes,

3) RVOLBAS is the rain volume (in $m^3 \times 10^3$) produced by the cells durign their lifetimes,

4) ABMAX is the maximum area (in km^2) of the cells during their lifetimes,

5) DUR is the duration (in minutes) of the cells,

6) RVRBMAX is the maximum rain-volume rate (in $m^3 hr^{-1} \times 10^3$) of the cells during their lifetimes,

7) Range refers to the mean range of the cells, and

8) N is the number of control cells for each day.

The last line in the top and bottom portions of Table 1 provides overall means for the sample. They are not averages of the means in the table. Consequently, the values in this line are dominated by the days that have the most cells.

Table 1

PROPERTIES OF THE CONTROL CELLS FOR SWCP 1987

For the NS Experimental Units

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
6/12	9.3	46.5	66.1	41.8	23.2	269.3	73	96
8/11	9.3	38.3	28.8	27.7	19.8	109.5	58	198
8/12	7.9	40.5	20.8	21.3	22.0	109.9	51	15
8/12	8.3	46.5	49.6	37.8	32.9	201.2	81	13
8/13	8.5	43.2	70.5	62.0	22.4	281.2	88	22
8/14	9.3	44.5	115.3	69.2	24.0	345.6	107	22
8/15	10.7	42.5	66.6	53.4	31.6	226.1	90	46
Means	9.3	41.6	48.9	38.0	22.8	184.4	70	412

For the S Experimental Units

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
7/13	8.0	35.3	15.3	38.8	15.0	71.2	70	67
8/10	8.9	46.5	55.5	47.1	24.1	262.9	105	11
8/11	9.5	41.3	70.1	59.4	27.2	234.3	101	112
8/11	9.2	38.1	22.0	21.9	18.0	92.9	49	142
8/13	8.2	43.6	61.4	54.1	21.1	255.7	81	27
8/14	9.5	40.3	46.7	28.9	17.6	174.0	54	57
Means	9.0	39.4	40.7	38.4	20.3	153.7	71	416

Upon examining Table 1, it becomes readily obvious why the assessment of the effects of AgI seeding is such a difficult proposition. Note the great variability in the properties of the control cells even within the same day. A factor of two variability is not at all unusual. Is it any wonder, therefore, that it is difficult to detect a seeding effect in view of this great variability? Only in accounting for this variability through predictors and covariates can there be any hope of evaluating a seeding experiment.

A listing of the calculated properties of the experimental cells from SWCP 1987 is provided in Tables 2 and 3 from the "short" track cell data and in Tables 4 and 5 for the "long" track data. The explanation of Table 1 applies to each of these tables, except the data in these tables are for the cells that were selected randomly either for AgI treatment (S) or for simulated AgI treatment (NS).

Table 3

PROPERTIES OF THE EXPERIMENTAL CELLS FOR SWCP 1987
(From the "Short" Track Data for Cells Receiving More Than 8 Flares)

For the NS Cells

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
6/12	9.0	58.5	80.2	44.3	41.0	389.9	80	1
8/11	10.9	48.4	94.1	47.7	27.3	353.9	62	7
8/12	8.6	37.7	30.1	27.7	22.3	99.5	55	6
8/12	6.4	43.2	13.5	25.1	29.0	55.0	75	2
8/13	10.4	41.3	76.9	50.8	6.7	465.9	87	3
8/14	13.0	52.4	205.4	97.1	40.0	636.0	117	4
8/15	11.1	53.6	74.7	70.3	35.0	411.5	96	3
Means	10.2	46.3	85.5	51.8	27.3	336.6	77	26

For the S Cells

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
7/13	6.2	35.4	5.9	29.6	15.0	34.7	83	1
8/10	7.5	36.4	66.9	39.8	18.3	228.0	106	3
8/11	10.1	47.4	268.2	85.0	38.7	574.7	110	6
8/11	12.4	55.8	91.2	80.7	25.0	581.3	49	2
8/13	8.2	47.1	143.9	78.3	28.7	469.0	88	7
8/14	15.6	48.5	77.6	40.2	30.5	295.8	59	2
Means	9.7	46.0	150.5	69.0	29.2	438.3	90	21

Table 4

PROPERTIES OF THE EXPERIMENTAL CELLS FOR SWCP 1987
(From the "Long" Track Data for Cells Receiving at Least One Flare)

For the NS Cells

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
6/12	7.7	52.1	41.1	28.6	36.3	192.8	83	7
8/11	11.7	50.5	154.0	64.6	47.8	443.0	61	8
8/12	8.5	51.8	57.9	42.8	47.6	202.0	51	8
8/12	7.2	44.5	22.2	30.6	38.7	93.6	75	3
8/13	10.9	48.2	155.6	90.9	29.5	651.2	96	11
8/14	15.6	53.3	258.5	139.6	54.0	923.6	119	5
8/15	9.7	45.7	45.8	55.8	42.1	225.5	97	7
Means	10.3	49.7	109.7	66.1	41.3	411.2	82	49

For the S Cells

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
7/13	6.7	41.3	12.0	29.2	23.3	68.6	83	3
8/10	9.1	47.1	110.6	72.9	59.3	372.0	110	7
8/11	10.9	51.1	387.8	112.6	69.3	759.3	114	10
8/11	10.5	48.8	80.3	61.3	50.7	387.9	43	7
8/13	9.5	43.6	333.0	77.5	48.3	754.4	86	13
8/14	15.9	55.8	456.5	84.2	85.5	984.1	55	6
Means	10.6	48.0	267.8	79.7	58.1	626.7	85	46

Table 5

PROPERTIES OF THE EXPERIMENTAL CELLS FOR SWCP 1987
(From the "Long" Track Data for Cells Receiving More Than 8 Flares)

For the NS Cells

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
6/12	8.3	58.7	53.6	28.4	44.7	248.4	87	3
8/11	11.8	50.2	161.2	62.8	43.7	442.4	61	7
8/12	8.7	52.5	64.1	44.4	51.1	222.7	53	7
8/12	6.5	43.2	14.2	25.1	34.0	55.0	75	2
8/13	13.1	56.0	199.7	92.1	21.7	934.9	89	3
8/14	16.9	59.0	322.1	166.1	62.5	1149.2	117	4
8/15	11.1	53.6	76.8	70.3	50.0	411.5	96	3
Means	11.1	53.3	133.9	70.2	45.9	487.8	77	29

For the S Cells

Date	HMAX	ZBMAX	RVOLBAS	ABMAX	DUR	RVRBMAX	RANGE	N
7/13	6.2	35.4	6.4	29.6	25.0	34.7	83	1
8/10	10.3	49.0	151.5	74.4	71.3	504.8	104	4
8/11	11.6	55.7	468.3	121.2	73.0	927.4	108	6
8/11	11.4	51.8	102.5	74.2	53.3	557.2	43	3
8/13	12.7	54.5	567.5	113.1	67.4	1284.2	90	7
8/14	15.7	53.4	412.0	78.8	89.3	844.6	56	3
Means	11.9	52.6	372.4	96.0	68.7	867.2	87	24

The first order of business after the basic data had been computed and complied was an investigation of whether the rain volumes from the control cells were correlated with the rain volumes from the cells within the NS experimental units. If no correlation exists, the use of such cells as controls could not be justified. The results are presented in Table 6.

Table 6

CORRELATIONS BETWEEN MEANS OF CELL PROPERTIES OF
CONTROL CELLS AND THE NS CELLS IN SWCP 1987

	Cell Property					
No. of Expt. Units	RVOLBAS	ABMAX	ZBMAX	HMAX	RVRBMAX	DUR
7	0.66	0.75	0.21	0.46	0.51	0.50

It can be seen from Table 6 that the control cells are positively correlated on a unit-by-unit basis with the corresponding properties of the cells that were randomly selected for treatment but did not receive AgI (i.e. the NS cells). The correlation is strongest for RVOLBAS and ABMAX and weakest for ZBMAX. This indicates that the controls are, in fact, controls and that they can be used to account for some of the natural variability in the seeding expereiments.

Before the control cells could be used for evaluation of the SWCP cell experiments, the control values corresponding to each of the experimental units had to be weighted as a function of the number of treated cells in that unit. If this were not done, the overall control value for the S and NS units would have been dominated by the unit that had the most control cells. Thus, the control cells have the same weight and influence as the treated cells (either S or NS) that they are meant to represent.

Table 7 provides mean cell properties for the four categories for all treated cells (S or NS), regardless of the amount of treatment for the 13 experimental units (6 S and 7 NS) of SWCP 1987, where T refers to treated values and C refers to control values and the S and NS subscripts have the same meaning as before. Thus, C_{NS} is a control mean that corresponds to those 7 experimental units that did not receive AgI treatment. This table also provides the double ratios (DR) and single ratios (SR) as defined earlier. The significance levels were obtained by the Monte Carlo rerandomization technique with 3,000 iterations (see Gabriel and Feder, 1969).

Table 7

MEANS, SINGLE RATIOS AND DOUBLE RATIOS FOR THE VARIOUS CELL PROPERTIES
FOR THE 13 EXPERIMENTAL UNITS THAT WERE OBTAINED IN SWCP 1987.
The Significance Levels (SL in %) Were Obtained by 3,000 Rerandomizations of the Data.
The Cell Properties Were Calculated from the "Short" Track Analysis

							Rerandomizations SL (%)	
Cell Property	T_S	C_S	T_{NS}	C_{NS}	SR	DR	SR	DR
RVOLBAS (10^3 m^3)	94.6	52.1	63.0	57.5	1.50	1.66	15.8	5.9
ZBMAX (dBz)	37.4	41.7	42.0	42.6	0.89	0.91	87.6	81.1
HMAX (km)	8.5	8.9	9.0	9.0	0.95	0.96	67.9	64.4
AMAX (km^2)	48.1	45.5	46.4	45.0	1.04	1.02	42.2	43.7
RVRBMAX (10^3 m^3 h^{-1})	278.4	205.9	259.6	216.2	1.07	1.13	38.7	32.4
DUR (min)	21.4	21.6	23.7	24.2	0.90	1.01	67.7	48.7
N (no.of cells)	44	416	48	412				

The most important result in Table 7 is that accounting for some of the natural variability using the control cells increases the apparent effect of AgI treatment on the cell rainfall. Note that the SR is 1.50, but the DR is 1.66, and the corresponding significance levels are 15.8% and 5.9%, respectively. It is remarkable that the cell rainfall results are nearly significant statisticall with a total sample of only 13 experimental units.

The above analysis was repeated for those cells that received more than 8 flares (real or simulated). One reservation is applicable to this exercise. The control cells are the same as those identified earlier. It would have been better to add an additional selection criterion to identify only those control cells that would have qualified for more than 8 flares. Such cells would have been better controls for the treated cells that received more than 8 flares. We could not, however, figure out how to identify these cells objectively from the radar data, so we decided to stay with the initial control sample.

The short-track results for those cells receiving more than eight flares are provided in Table 8. With the exception of the duration, the DR values are somewhat less than the SR values and the significance levels are degraded slightly as well. The overall sample is about half what it was without partitioning.

Table 8

MEANS, SINGLE RATIOS AND DOUBLE RATIOS FOR THE VARIOUS CELL PROPERTIES
FOR THE 13 EXPERIMENTAL UNITS THAT WERE OBTAINED IN SWCP 1987.
The Significance Levels (SL in %) Were Obtained by 3,000 Rerandomizations of the Data.
The Cell Properties Were Calculated from the "Short" Track Analysis for Those Cells
Receiving More Than 8 Flares

							Rerandomizations SL (%)	
Cell Property	T_S	C_S	T_{NS}	C_{NS}	SR	DR	SR	DR
RVOLBAS (10^3 m^3)	150.5	55.7	85.5	52.5	1.76	1.66	15.4	9.2
ZBMAX (dBz)	46.1	42.1	46.3	41.8	0.99	0.99	52.6	55.8
HMAX (km)	9.7	8.9	10.2	9.0	0.94	0.95	67.6	69.0
AMAX (km^2)	69.0	48.4	51.8	40.9	1.33	1.12	14.8	22.3
RVRBMAX (10^3 m^3 h^{-1})	438.3	218.5	336.6	192.4	1.30	1.14	22.1	30.4
DUR (min)	29.2	22.4	27.3	23.8	1.07	1.14	36.7	22.4
N (no.of cells)	21	416	26	412				

Woodley and Rosenfeld (1988) have shown that AgI-treated cells were twice as likely to merge as their unseeded counterparts. In view of this tendency, the short-track analysis, which is terminated when a cell merges, may be somewhat misleading as to the true effect of AgI seeding. This is why the long-track analysis, which follows a cell beyond its merger as long as it can be identified objectively, was developed. As expected, this analysis did indeed suggest a larger effect of seeding (Rosenfeld and Woodley, 1988).

It was logical, therefore, to subject the long-track results to the same control-cell analysis that has been described for the short-track results. Before the results are presented, it should be noted that the properties of the control cells were calculated from the short-track program while the properties of the treated cells were calculated from the long-track program. It would have been better to have the properties of both the control and treated cells calculated from the long-track program, but his was not possible for the control cells. This should not affect the conclusions, however, since the analysis was applied equally to both the S and NS cells.

The results of the control analysis as applied to the calculated properties of the treated cells from the long-track program are shown in Table 9. The explanation of Table 7 applies equally well to Table 9.

Table 9

MEANS, SINGLE RATIOS AND DOUBLE RATIOS FOR THE VARIOUS CELL PROPERTIES FOR THE 13 EXPERIMENTAL UNITS THAT WERE OBTAINED IN SWCP 1987.
The Significance Levels (SL in %) Were Obtained by 3,000 Rerandomizations of the Data. The Cell Properties Were Calculated from the "Long" Track Analysis for Those Cells that Received at Least One Flare.

							Rerandomizations SL (%)	
Cell Property	T_S	C_S	T_{NS}	C_{NS}	SR	DR	SR	DR
RVOLBAS (10^3 m^3)	268.9	51.5	109.5	57.7	2.46	2.75	4.8	1.5
ZBMAX (dBz)	48.0	41.7	49.7	42.7	0.97	0.99	75.4	56.9
HMAX (km)	10.6	8.9	10.3	9.0	1.03	1.04	40.7	35.5
AMAX (km^2)	79.7	45.5	66.1	44.9	1.21	1.20	21.3	15.9
RVRBMAX (10^3 m^3 h^{-1})	626.7	204.7	411.3	217.3	1.52	1.62	9.5	5.2
DUR (min)	58.1	21.6	41.3	24.1	1.41	1.58	2.5	0.4
N (no.of cells)	46	416	49	412				

This analysis suggests a large and significant effect of AgI seeding, especially on cell duration, rain volume and rain-volume rate. By incorporating the control cells into the evaluation, the apparent effect of seeding on rainfall is increased to well over 100%. This increase is the result of larger cell areas, rain rates and durations.

The final presentation in the control analysis of the treated cells is found in Table 10 for those long-tracked experimental cells that received more than 8 flares. The apparent effect of AgI seeding is greater yet for this partition. There is no evidence whatsoever that the luck of the draw favored to the AgI cases. On the contrary, the control analysis suggests that the natural variability favored the NS cases. If this is indeed true, one is left with the conclusion that AgI seeding increased cell rainfall in West Texas by well over 100%.

Table 10
MEANS, SINGLE RATIOS AND DOUBLE RATIOS FOR THE VARIOUS CELL PROPERTIES
FOR THE 13 EXPERIMENTAL UNITS THAT WERE OBTAINED IN SWCP 1987.
The Significance Levels (SL in %) Were Obtained by 3,000 Rerandomizations of the Data.
The Cell Properties Were Calculated from the "Long" Track Analysis for Those
Cells that Received More Than 8 Flares.

							Rerandomizations SL (%)	
Cell Property	T_S	C_S	T_{NS}	C_{NS}	SR	DR	SR	DR
RVOLBAS (10^3 m^3)	375.1	53.9	133.6	52.3	2.81	2.72	3.8	1.5
ZBMAX (dBz)	52.6	42.1	53.3	42.0	0.99	0.99	62.0	60.4
HMAX (km)	11.9	8.9	11.1	9.0	1.08	1.08	29.8	26.9
AMAX (km^2)	96.0	46.4	70.2	40.2	1.37	1.18	15.0	14.6
RVRBMAX (10^3 m^3 h^{-1})	867.3	213.3	487.8	194.8	1.78	1.61	8.4	5.0
DUR (min)	68.7	22.0	45.9	23.7	1.50	1.61	0.6	0.2
N (no.of cells)	24	416	29	412				

The last analysis involved an evaluation of the effect of AgI treatment on the environmental cells, where an environmental cell is defined as a cell that did not receive direct treatment within 25 km of a treated cell (S or NS). The purpose of the analysis is to determine whether the effect of AgI seeding can be detected in cells in the near vicinity of the treated cells.

The analysis proceeded in the following steps:

a) Calculation of the properties of the environmental cells for the S and NS cases,

b) Computation of the single ratios of cell properties in S units to cell properties in NS units,

c) Incorporation of the control cells into the evaluation of the environmental cells in order to account for the natural variability.

The results are presented in Table 11.

Table 11

MEANS, SINGLE RATIOS AND DOUBLE RATIOS FOR THE VARIOUS CELL PROPERTIES FOR THE ENVIRONMENTAL CELLS WITHIN THE 13 EXPERIMENTAL UNITS THAT WERE OBTAINED IN SWCP 1987

The Significance Levels (SL in %) Were Obtained by 3,000 Rerandomizations of the Data.
The Cell Properties Were Calculated from the "Short" Track Analysis

							Rerandomizations SL (%)	
Cell Property	T_S	C_S	T_{NS}	C_{NS}	SR	DR	SR	DR
RVOLBAS (10^3 m^3)	67.4	53.6	44.2	52.3	1.52	1.49	42.3	34.7
ZBMAX (dBz)	40.1	41.3	43.3	41.8	0.93	0.94	79.1	67.6
HMAX (km)	9.6	9.0	9.4	9.0	1.02	1.03	38.5	34.7
AMAX (km^2)	39.7	44.3	39.4	41.5	1.01	0.94	47.7	57.2
RVRBMAX (10^3 m^3 h^{-1})	242.6	204.8	189.2	200.2	1.28	1.25	40.3	33.9
DUR (min)	20.7	21.0	22.0	22.3	0.94	1.00	58.4	49.0
N (no.of cells)	47	416	51	412				

The values of Table 11 suggest that AgI seeding in West Texas has enhanced the rainfall from the cells that are in the near environment of the directly treated cells. The SR values are smaller and less significant than those for the directly treated cells, as one would have expected if AgI seeding is actually affecting the rainfall. Incorporation of the control cells into the analysis decreases the apparent effect only slightly.

This result is consistent with the conceptual model that is guiding the SWCP experimentation, which predicts that AgI seeding will first enhance the directly treated cells, followed by increased convergence in the near vicinity of these cells, new cell growth and more rainfall from the larger cloud system. It is also consistent with the work of Rosenfeld, which indicates that cells growing within a clustered convective system will produce more rain volume than those in more isolated convective systems.

3.3 Conclusions

The conclusion is inescapable that AgI seeding has enhanced the rainfall from convective cells in West Texas. Incorporation of control cells into the cell analyses only serves to strengthen the case for seeding effects. The size of the apparent effect on cell rainfall is a minimum of 50% and it probably exceeds 100%. The latter is significant at the 5% level using rerandomization procedures. This is a remarkable result in view of the fact that the sample contains only 13 experimental units. It appears also that AgI seeding has enhanced the rainfall in the near vicinity of the directly treated cells, but the effect is smaller and much less significant.

The analyses must now focus on the experimental units for the identification and testing of predictors and covariates. This process began in May and it will be ended in July, which was the last month of the three-month contract. These predictors and covariates will then be incorporated into linear regression models for the evaluation of the experimental units.

4.0 IDENTIFICATION OF PREDICTORS AND COVARIATES FOR THE EXPERIMENTAL UNITS OF SWCP

4.1 The Data

A listing of some of the data for the experimental units of SWCP 1986 and 1987 that will be used in this study is provided in Table 12. Tabulations of the rainfalls for the experimental units in half-hour intervals and cumulatively by half-hour intervals are provided in Tables 13 and 14. Extrapolated rainfall values are identified with an asterisk (*). In addition, the cumulative rainfalls for the period from case qualification to termination for each of the 10 experimental units in 1986 and the 13 experimental units in 1987 are provided in the right-hand portion of Table 14. Woodley and Rosenfeld (1987), Rosenfeld and Woodley (1988) and Woodley and Rosenfeld (1988) discuss all aspects of SWCP 1986 and 1987, including how these rainfall values were derived.

Several varibles listed in Table 12 were covariate candidates in this study. These included:

a) the liquid water content and updraft at the time the experimental unit was qualified,

Table 12. SUMMARY OF SWCP 1986 and 1987 RANDOM CASES

Date	Acft.	Scntst	Time of Trmt Dec.	Lcn of Trmt	Qual. LWC	Pass Updrft	Trmt Dec.	# Flares*	# Trmt Passes	Time of 1st Trmt	Time of Last Trmt	Time Off Rdr.	Div at 1st Trmt	Cld Base Tdmp (°C)
								1986 DAYS						
5/29	Seed 1	WLW	1520	004°/47	2.62	500	NS	NA	NA	1526	NA	1610MO	-0.2	15.0
5/29	Seed 1	WLW	1654	285°/82	0.71	1,000	S	34 (32)	6	1701	1738	1800M	-3.2	15.0
6/17	Seed 1	WLW	1602	340°/62	1.68	1,000	S	64 (57)	8	1602	1726	1800D	+1.1	19.0
6/18	Seed 1	WLN	1450	236°/56	1.36	1,000	S	33 (29)	6	1456	1546	1527M	-0.3	19.0
6/19	Seed 1	WLW	1602	40°/78	0.90	1,000	NS	NA	NA	1606	NA	1737D	+2.4	18.0
6/20	Seed 1	WLW	1656	215°/10	1.30	1,000	S	7 (4)	2	1706	1709	1900D	+0.6	19.0
6/23	Seed 1	WLW	1651	320°/88	1.08	2,000	NS	NA	NA	1653	NA	1755MO	-4.0	16.0
7/11	Seed 1	JJ	1632	280°/78	0.80	1,200	NS	NA	NA	1654	NA	1820D	-1.1	14.0
7/20	Seed 1	JJ	1516	272°/39	1.30	1,000	NS	NA	NA	1521	NA	1721D	-0.5	9.0
7/20	Seed 1	JJ	1640	065°/48	1.10	1,000	S	65 (55)	9	1659	1816	2052D	-0.2	9.0
7/21	Seed 1	JJ	1346	277°/42	1.30	2,000	NS	NA	NA	1354	NA	1415D	+0.6	17.0
								1987 DAYS						
6/7	Seed 1	WLW	1621	251°/19	2.34	869	S	67 (64)	11	1629	1731	1903D	+7.0	15.5
6/7	Seed 2	JJ	1909	360°/48	1.20	1,300	NS	4 (0)	1	1937	1937	2043D	-0.5	15.5
6/12	Sedd 1	WLW	1345	270°/48	2.15	1,760	NS	56 (0)	9	1405	1508	1544M	-0.2	19.0
7/13	Seed 1	WLW	1257	315°/36	2.01	2,746	S	25 (25)	6	1302	1329	1530D	+9.5	16.0
8/10	Seed 1	WLW	1852	008°/29	2.61	3,278	S	85 (79)	11	1901	1954	2101D	-5.3	17.0
8/11	Seed 1	WLW	1442	307°/41	1.64	1,394	NS	138 (0)	15	1445	1600	1701D	-2.1	14.0
8/11	Seed 1	WLN	1619	264°/24	1.50	1,800	S	123(114)	15	1622	1802	1845M	+4.0	14.0
8/11	Seed 1	WLW	1846	292°/52	2.00	2,000	S	65 (52)	7	1851	1938	2045D	-11.8	11.5
8/12	Seed 1	JJ	1715	300°/45	2.44	2,158	NS	119 (0)	9	1718	1810	2013D	-9.6	17.0
8/12	Seed 1	JJ	1832	279°/52	1.97	1,257	NS	55 (0)	6	1835	1904	1952D	-4.6	17.0
8/13	Seed 1	WLW	1451	335°/42	2.23	1,674	NS	75 (0)	9	1458	1621	1731MO	-1.6	18.0
8/13	Seed 1	WLW	1615	268°/34	1.76	1,088	S	92 (84)	15	1625	1834	1900D	-7.0	18.0
8/14	Seed 1	JJ	1606	298°/43	1.25	2,724	S	100 (50)**	6**	1609	1700	1740M	-5.0	14.0
8/14	Seed 1	JJ	1843	355°/20	1.74	2,209	NS	62 (0)	7	1848	1923	1940M	-0.3	14.0
8/15	Seed 1	WLW	1843	262°/64	1.50	1,000	NS	100 (0)	11	1846	1933	2013D	+5.0	15.0

NOTES:

1. All times are CDT
2. Seed 1 is a turbo Aero Commander; Seed 2 is a Cessna 340
3. All VOR positions are magnetic (to convert to true add 9°) from the San Angelo radar
4. There are no LORAN positions from Seeder 2 (the Cessna 340 aircraft)
5. LWC is measured in gm/m^3 from JW instrumentation and updrafts in SWCP 1986 are measured in ft/min from a Ball variometer.
6. In "No Seed" cases in SWCP 1987 each "treated" tower is penetrated and the number of flares is simulated.
7. The convergence (or divergence) values have been interpolated to the location of the qualification pass from the hour calculation that is nearest in time to the time of the pass.
8. D = Expt. Unit dissipated; M = Expt. Unit merged with other echoes; MO = Center of Unit Moved Out of Research Area
9. * The first number in the flare column refers to the number of flares attempted and the second number is the number of flares actually fired. No flares are actually fired in No Seed (NS) cases. In SWCP 1986 no simulated seedings were attempted, and the flare column is not applicable (NA) for these cases.
10. ** 100 flares were attempted during 11 treatment passes, but only 50 flares were actually ejected on 6 treatment passes.

Table 13

RAIN VOLUME IN THE EXPERIMENTAL UNITS IN 1/2 HOUR INTERVALS ($m^3 x 10^3$)

			TIME INTERVAL RELATIVE TO QUALIFICATION (min.)				
1986		DATE	0-30	30-60	60-90	90-120	120-150
Case	- 1	May 29	38.2	3.8	490.6	1874.5	1979.4
	2	May 29	798.8	1307.9	3490.9	1702.6	0.0
	3	June 17	1316.6	1719.5	1078.9	55.9	0.0
	4	June 18	2041.0	1373.3	1375.3	1530.0*	10.0*
	- 5	June 19	462.6	379.5	403.1	241.6	0.0
	6	June 20	401.0	303.9	38.1	14.3	0.0
	- 7	June 23	1600.0	1403.8	927.9*	456.3*	51.3*
	- 8	July 11	627.1	244.5	3.5	0.0	0.0
	- 9	July 20	176.2	132.9	226.6	274.3	186.6
	10	July 20	436.5	288.9	389.6	1361.4*	380.6*
1987							
Case	- 3	June 12	73.7	25.1	0.0	0.0	0.0
	4	July 13	144.6	22.6	2.4	0.0	0.0
	5	Aug 10	429.4	362.3	102.4	3.2	0.1
	- 6	Aug 11	478.0	633.1	518.7	197.6	29.3
	7	Aug 11	301.7	705.7	608.7	1153.8	1105.9
	8	Aug 11	173.8	92.8	23.6	38.4	1.7
	- 9	Aug 12	312.8	405.6	66.9	5.8	0.4
	-10	Aug 12	45.0	19.3	0.4	0.0	0.0
	-11	Aug 13	1422.8	2537.5	3502.1	2856.1	1066.7
	12	Aug 13	25.1	421.3	1860.0	2077.9	1597.1
	13	Aug 14	1214.1	1597.8	1406.5	1444.0	2239.7
	-14	Aug 14	363.5	990.0	2379.9**	2610.0**	2610.0**
	-15	Aug 15	255.1	369.0	21.3	0.0	0.0

* Refers to extrapolated values based on the trends evident in the rainfall in the 10 minutes prior to termination of radar data.

** The rainfall for this case was extrapolated through the 60-90 and 90-120 minute period. The rainfall for the 120-150 minute period was held constant from the previous 90-120 minute period.

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Table 14

CUMULATIVE RAIN VOLUME IN THE EXPERIMENTAL UNITS (m^3x10^3)

			Time Interval Relative to Qualification (min.)					Qualification to Case Termination	
1986		Date	0-30	0-60	0-90	0-120	0-150	Term. Reason	Rain Vol.
Case	- 1	May 29	38.2	42.0	532.6	2407.1	4386.5	moved out	4386.5
	2	May 29	798.8	2106.7	5597.6	7300.2	7300.2	merged	6535.9
	3	June 17	1316.6	3036.1	3036.1	4115.0	4170.9	dissipated	4170.9
	4	June 18	2041.0	3414.3	4789.6	6319.6*	6329.6*	merged	4789.6
	- 5	June 19	462.6	842.1	1245.2	1486.8	1486.8	dissipated	1486.8
	6	June 20	401.0	704.9	743.0	757.3	757.3	dissipated	757.3
	- 7	June 23	1600.0	3003.8	3931.7*	4388.0*	4439.3*	moved out	3003.8
	- 8	July 11	627.1	871.6	875.1	875.1	875.1	dissipated	875.1
	- 9	July 20	176.2	309.1	535.7	810.0	996.6	dissipated	996.6
	10	July 20	436.5	725.4	1115.0	2476.4*	2857.0*	merged	1547.3
1987									
Case	- 3	June 12	73.7	98.8	98.8	98.8	98.8	dissipated	98.8
	4	July 13	144.6	167.2	169.6	169.6	169.6	dissipated	169.6
	5	Aug 10	429.4	791.7	894.1	897.3	897.4	dissipated	897.4
	- 6	Aug 11	478.0	1111.1	1629.8	1827.4	1856.7	dissipated	1987.5
	7	Aug 11	301.7	1007.4	1616.1	2769.9	3875.8	merged	3663.1
	8	Aug 11	173.8	266.6	290.2	328.6	330.3	dissipated	330.3
	- 9	Aug 12	312.8	718.4	785.3	791.1	791.5	dissipated	791.5
	-10	Aug 12	45.0	64.3	64.7	64.7	64.7	dissipated	64.7
	-11	Aug 13	1422.8	3960.3	7462.4	10318.5	11385.2	moved out	11612.0
	12	Aug 13	25.1	446.4	2306.4	4384.3	5981.4	merged	6884.3
	13	Aug 14	1214.1	2811.9	4218.4	5662.4	7902.1	merged	4741.6
	-14	Aug 14	363.5	1353.5	3733.4*	6343.4*	8953.4*	merged	1353.5
	-15	Aug 15	255.1	624.1	645.4	645.4	645.4	dissipated	645.4

* Refers to extrapolated values based on the trends evident in the 10 minutes prior to termination of radar data.

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b) the number of flares (AgI or simulated AgI) that were expended in each unit,

c) the number of treatment passes made in each unit (1987 only),

d) the time of 1st treatment,

e) the duration of treatment,

f) the divergence value at the time and place that the unit was qualified,

g) the temperature at cloud base on each day of experimentation.

Most of these covariate candidates, with the exception of the divergence variable, are self-explanatory. Additional background on the divergence variable is provided in Appendix A.

In addition to the variables listed in Table 12, several others were derived for testing. These included:

a) the natural growth (Nat. Grwth) of a cloud tower (in km) having a 1 km radius as predicted by the Great Plains Cumulus Model using the 1200 GMT Midland sounding as input (the Del Rio sounding was used on August 11 and 13, 1987 when the Midland sounding was not available),

b) the rain volume in the 25-35 km annulus (Ann. Rain) around the experimental unit in the 30 min after initial treatment. The experimental unit has a radius of 25 km and the initial treatment takes place at the center of the unit, so contamination of the 25-35 km region in the 30 min after initial treatment is not believed to be a problem. This variable receives additional treatment in Appendix B.

c) the rain volume in the experimental unit in the 5 min prior to initial treatment (Prior Rain),

d) the difference in rain volume in the experimental unit between the rain in the 5 min immediately prior to treatment and the rain in the period 5 min earlier. This variable is called the Rain Trend.

e) the mean rain volume from the control cells (Cntrl Rain) that correspond to a particular experimental unit. This variable was discussed extensively earlier in this report, and the values were obtained from Table 1.

A listing of the values corresponding to each of these five covariate candidates for each of the experimental units is provided in Table 15. Note that 1986 values are not available for the annular rainfall and for the control cell rainfall. Note further that 4 of the 5 new covariate candidates are related to rainfall. This is in recognition of the old adage that the best predictor of rainfall is rainfall itself.

Table 15

LISTING OF ADDITIONAL COVARIATE CANDIDATES FOR SWCP EXPERIMENTAL UNITS
(The Natural Growth variable is in km; rain variables are in $m^3 \times 10^3$)

Date	Case #	Nat. Growth	Ann. Rain	Prior Rain	Rain Trend	Cntrl. Rain
5/29/86	-1	6.8	-	143.9	-140.3	-
5/29/86	2	6.8	-	301.3	+220.9	-
6/17/86	3	7.0	-	1902.4	+430.0	-
6/18/86	4	5.3	-	878.4	-154.1	-
6/19/86	-5	6.8	-	952.8	+124.0	-
6/20/86	6	1.9	-	1372.2	+168.1	-
6/23/86	-7	6.0	-	1752.0	+60.4	-
7/11/86	-8	13.0	-	407.3	+260.3	-
7/20/86	-9	8.0	-	138.0	-60.3	-
7/20/86	10	8.0	-	32.5	-4.9	-
6/12/87	-3	10.4	9.9	134.3	+59.5	66.1
7/13/87	4	9.5	34.7	518.2	-295.6	15.3
8/10/87	5	7.1	0.0	647.5	+387.1	55.5
8/11/87	-6	13.1	466.1	402.3	-43.9	28.8
8/11/87	7	13.1	302.1	68.1	+50.1	70.1
8/11/87	8	13.1	15.8	17.1	-17.3	22.0
8/12/87	-9	11.2	288.9	58.5	+3.0	20.8
8/12/87	-10	11.2	2.3	93.0	+11.0	49.6
8/13/87	-11	14.7	336.1	1091.0	+650.5	70.5
8/13/87	12	14.7	23.6	128.1	-77.4	61.4
8/14/87	13	10.4	20.6	1272.8	+132.7	46.7
8/14/87	-14	10.4	243.2	58.4	52.0	115.3
8/15/87	-15	11.3	58.8	34.7	34.0	66.6

In examining the entries in Table 15, one notices immediately the great variability in all the values. With this kind of variability in the potential covariate values, it is little wonder that the rainfall in the experimental unit itself is highly variable.

4.2 Results

The next step in the study was to determine how well the potential covariates are correlated with the rainfall in the experimental unit as a function of time. SPSS software and an IBC personal computer were used to calculate the correlations. The results are presented in Table 16 for the Seed (top) and No Seed cases. In instances in which only 1987 data are available, the correlations are obviously for 1987. The total sample includes 23 experimental units (11 Seed and 12 No Seed); the sample for 1987 includes 13 cases (6 Seed and 7 No Seed). Because of the limited sample, the results in Table 16 must be viewed cautiously. Only with a larger sample of days can one be certain of the results.

the correlation decays. The correlation actually improves with time for the control-cell rainfall, because this is a cell-lifetime variable with a period of calculation that is comparable to the period of calculation for the experimental units.

A second interesting feature of the results in Table 16 is the degrdation of the correlations for the Seed sample. The correlations for three of the four "first order" covariates are much less than for the No Seed sample, suggesting that AgI seeding may have disturbed or destroyed the natural relationship between the covariates and the subsequent rainfall. This, of course, is exactly what seeding should do, if it has been effective. In addition, more rain than is predicted by the covariate relationships should be the outcome of a successful seeding experiment. Whether this is the case for the SWCP must still be determined in the second phase of this research. At this point the results are highly encouraging.

Further examination of the correlations in Table 16 reveals other variables that might be useful as covariates. These include the updraft speed and liquid water content at the time the experimental unit was qualified, the temperature at cloud base and the model-predicted growth of an unseeded cloud tower having a radius of 1 km. These "second order" covariates are rather marginal, however, having decreased by nearly a factor of two over the "first order" covariates, and it is questionable whether they will enter into the predictive equations that will be derived during the second phase of the research.

When the three to five best covariates are combined into a single linear equation via multiple regression procedures, it is expected that the multiple regression coefficient will be on the order of 0.70. If this prediction is correct, it will mean that the equation will account for nearly 50% of the unexplained variance in the rainfall. Despite the small sample on which it is based, this equation will permit an assessment of the effect of seeding on the experimental units to be made with much more confidence than has been possible so far. It is important that this be accomplished well before final plans for SWCP 1989 have been completed.

5.0 CONCLUSIONS

All that was set forth as goals for the first phase of this six-month research program has been accomplished. In developing a means of identifying control cells objectively, it was learned that the large positive effects of AgI seeding on the cells are real and not due to chance. This is the most important result that has been obtained to date, because it is the cells which must be affected by seeding before one can expect to see an effect in the overall experimental unit.

In the screening and testing of potential covariates, four covariates have been identified, which have correlations with the experimental unit rainfall that equal or exceed 0.50. Although these covariate variables will themselves be correlated with each other, it is expected that a multiple correlation exceeding 0.70 will be achieved during stepwise regression procedures. This will permit an assessment of the effect of seeding on the small mesoscale convective clusters using linear regression models. This will be accomplished during the second phase of the research program.

Finally, a proposal to develop an exchange program in weather modification research between Texas and Israel was written by the two PIs with funding under this contract. This proposed effort has been approved for inclusion under the existing Texas-Israel Exchange, which had previously been limited to agricultural and irrigation studies. An intensive effort is now underway to obtain funding of this joint research effort. The proposal itself has been supplied under separate cover to the Texas Water Commission, the administrative office of the Texas-Israel Exchange, and to representatives in Israel.

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APPENDIX A

Relating Surface Moisture Convergence to Experimental Unit Rainfall

One of the first obvious steps in the study was a reexamination of the relationship between surface moisture convergence at the time and place an experimental unit was qualified and the subsequent rainfall in the unit. The question to be addressed by this exercise is whether surface convergence that has been calculated from observing stations on a rather coarse meso-synotpic scale provides any predictive information for rainfall on the smaller convective scale. Woodley, et al. (1987) had examined this question for the limited data from SWCP 1986 and first results suggested that surface moisture convergence might prove to be a valuable predictor variable for the experimental units.

During SWCP 1986 and 1987 hourly calculations of surface moisture convergence were made using an objective analysis scheme in conjunction with dewpoint and wind data from the standard meteorological observing stations surrounding the project area. The calculations determined surface moisture convergence values on a grid centered on Sterling City, Texas, the center of the project area. The calcuations were interpolated to grid points spaced 40 km apart on a map that encompassed the SWCP area.

On a subjective basis, the results from the moisture convergence calculations during SWCP 1986 had been quite promising. In most cases deep convection developed in association with areas of strong surface moisture convergence, and in many cases the observed convergence preceded the convection by as much as one hour. Severe convective events were virtually always associated with strong surface convergence. Furthermore, convective storms which propagated into areas of stronger convergence generally intensified and those which moved into divergent areas usually weakened. These overall results are similar to those reported in Florida.

The question to be addressed here is whether surface moisture convergence calculations have any predictive power for the weaker convective events that were selected for randomized treatment during SWCP 1986 and 1987. An affirmative answer would be immensely important to SWCP. Development of such a covariate would provide an objective means of evaluating the experiments; it would account for some of the natural variability that is inherrent in convective rainfall and it would decrease the number of cases needed to obtain statistical significance for the results.

A listing of the surface moisture convergence values nearest in space and time to the location and time of the initial treatment and the rainfalls for the hour following initial treatment for each experimental unit has been provided in Table A-1 and the appropriate rainfalls have been provided in Tables 2 and 3 of the main text. The convergence values were interpolated to the position of the initial treatment pass from the four surrounding grid points.

A plot of the 23 convergence (divergence) values on the abscissa versus cluster rain volume in the hour following initial treatment is shown in Figure A-1. The solid circles are Seed cases (AgI treatment) and the open circles are No Seed cases. No obvious relationship is evident in the scatter plot. The

Table 16

CORRELATION MATRIX
(Seed Cases)

Dep Vrbl.	ANN. RAIN	CLS RAIN	RAIN TREND	LWC	UPD	# FL	# PASSES	T. 1ST TRMT.	DUR. OF TRMT.	DIV.	TEMP. AT CLD BASE	MAF	CNC
C30	-0.11	0.58	0.17	-0.34	-0.24	-0.17	-0.36	-0.28	-0.13	0.06	0.35	-0.46	0.12
C60	0.03	0.61	0.31	-0.42	-0.26	-0.02	-0.26	-0.23	-0.01	0.03	0.34	-0.35	0.31
C90	0.01	0.26	0.19	-0.62	-0.35	-0.01	-0.13	-0.17	0.07	-0.12	0.24	-0.17	0.49
C120	0.10	0.16	0.12	-0.65	-0.43	0.09	0.02	-0.19	0.25	-0.13	0.18	-0.05	0.58
C150	0.12	0.12	0.08	-0.62	-0.33	0.27	0.13	-0.19	0.35	-0.17	0.11	0.11	0.57

CORRELATION MATRIX
(No Seed Caes)

Dep Vrbl.	ANN. RAIN	CLS RAIN	RAIN TREND	LWC	UPD	# FL	# PASSES	T. 1ST TRMT.	DUR. OF TRMT.	DIV.	TEMP. AT CLD BASE	MAF	CNC
C30	0.60	0.90	0.65	-0.29	0.40	-0.11	-0.10	-0.15	0.08	-0.16	0.19	0.08	0.12
C60	0.58	0.78	0.74	-0.10	0.46	0.05	0.07	-0.15	0.28	-0.13	0.22	0.23	0.24
C90	0.53	0.63	0.75	0.04	0.45	0.08	0.12	-0.14	0.34	-0.06	0.18	0.27	0.42
C120	0.49	0.50	0.69	0.17	0.38	0.04	0.08	-0.12	0.31	-0.01	0.14	0.24	0.52
C150	0.46	0.38	0.58	0.24	0.33	0.01	0.05	-0.08	0.25	0.03	0.09	0.18	0.61

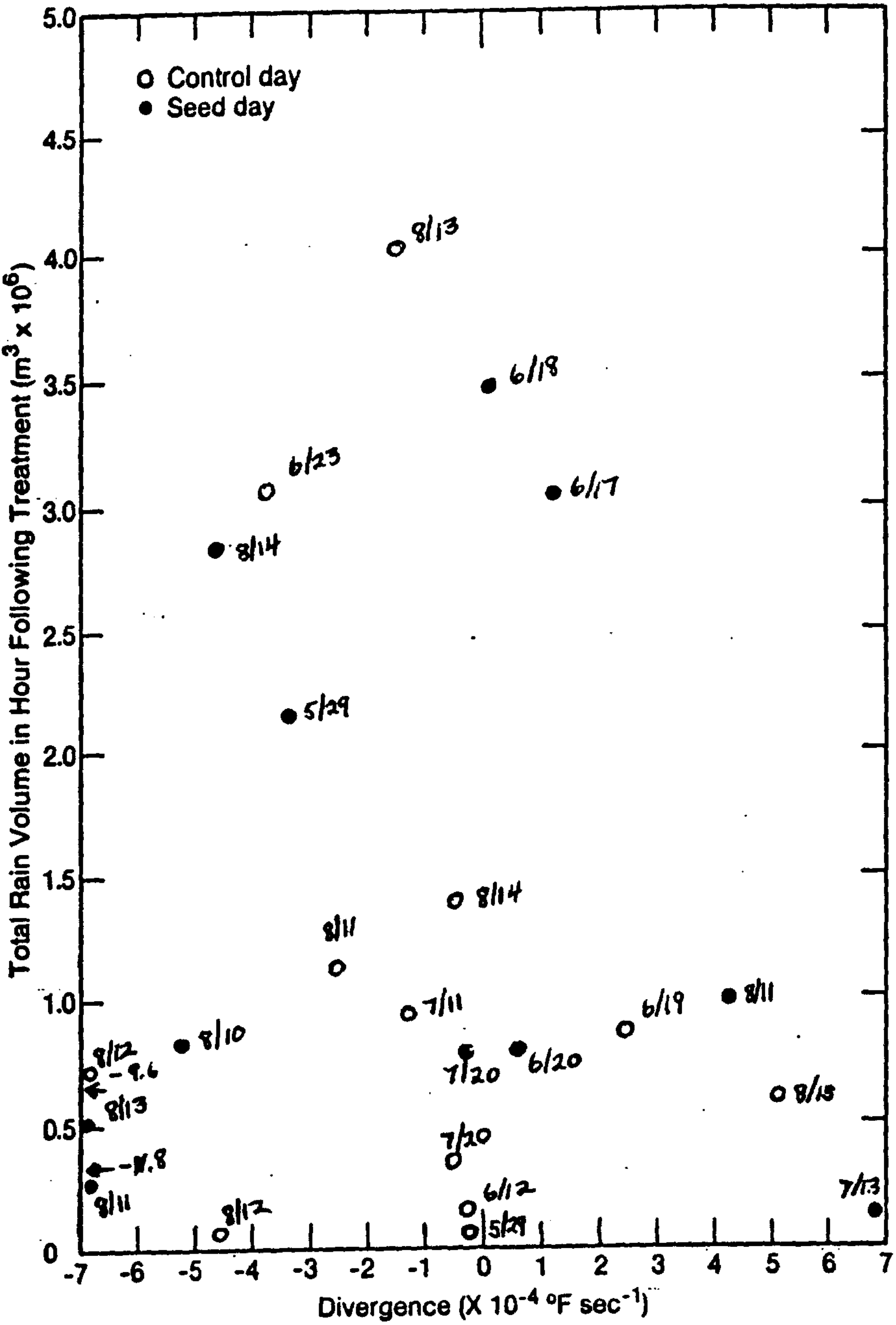


Figure A1 A plot of surface moisture convergence (units: 10-4 oF sec-1) at the location and near the time of initial treatment (real or simulated) versus the total rain volume (units: m3 x 106) produced by the convective cluster in the hour following initial treatment for 10 experimental units during SWCP 1986.

greatest total rainfalls for the cluster in the hour following treatment occurred when the surface moisture convergence was + 3 units either side of zero (0). For higher moisture convergences immediately prior to qualification of the unit, the subsequent hourly cluster rainfalls were much smaller.

This result is somewhat perplexing. One might have predicted a general increase in cluster rainfall as the surface moisture convergence increased. That this does not appear to be the case suggests that other factors such as the depth of the moist layer, atmospheric stability, and duration of the convergence are interactive with the instantaneous surface moisture convergence. For example, even with strong surface moisture convergence, no rainfall may result if the atmosphere is too dry above the earth's surface to sustain the convection.

In investigating the utility of the surface moisture convergence further, cumulative mean rainfalls were calculated in two ways as a function of the surface moisture convergence. First, the cumulative means were computed from the most convergent case to the most divergent case. Second, the cumulative means were calculated in reverse order, from the most divergent case to the most convergent case. In this exercise the cluster rainfalls in the 30 min immediately following unit qualification were used in the calculation. The results are presented in Table A-1.

If surface moisture convergence is related strongly to the 30-min subsequent rainfall, one would expect the cumulative means to reach a maximum in the most convergent portion of Table A-1. That this is not the case and the cumulative means reach a maximum in the middle portion of the convergence scale agrees with the results of Figure A-1. Again, this result suggests that if surface moisture convergence is to be used as a predictor variable, it will have to be combined with other variables such as an atmospheric moisture parameter. By itself, it does not appear that it will provide any predictive assistance.

Table A-1 CUMULATIVE MEAN RAINFALLS VERSUS MOISTURE CONVERGENCE

Date	Case #	Moist. Conv.	Rainfall (0-30 min)	Cumulative Mean Rainfall (Conv. to Div.)	Cumulative Mean Rainfall (Div. to Conv.)
8/11/87	8	-11.8	173.8	173.8	571.2
8/12/87	-9	-9.6	312.8	243.3	589.3
8/13/87	12	-7.0	25.1	89.5	602.4
8/10/87	5	-5.3	429.4	174.4	631.3
8/13/87	13	-5.0	1214.1	382.4	641.9
8/12/87	-10	-4.6	45.0	326.2	610.1
6/23/86	-7	-4.0	1600.0	508.1	643.4
5/29/86	2	-3.2	798.8	544.5	583.6
8/11/87	-6	-2.1	478.0	537.1	569.2
8/13/87	-11	-1.6	1422.8	625.7	575.8
7/11/86	-8	-1.1	627.1	625.8	510.6
7/20/86	-9	-0.5	176.2	588.3	500.9
6/18/86	4	-0.3	2041.0	700.1	530.4
8/14/87	-14	-0.3	363.5	676.0	379.4
7/20/86	10	-0.2	436.5	660.0	381.1
5/29/86	-1	-0.2	38.2	621.2	374.2
6/12/87	-3	-0.2	73.7	589.0	422.2
6/20/86	6	+0.6	401.0	578.5	480.3
6/17/86	3	+1.1	1316.6	617.4	496.1
6/19/86	-5	+2.4	462.6	609.6	291.0
8/11/87	7	+4.0	301.7	595.0	233.8
8/15/87	-15	+5.0	255.1	579.5	200.0
7/13/87	4	+9.5	144.6	560.6	144.6

Note: The cases are numbered by year. A minus (-) on the case number refers to a NS case
The units of the moisture convergence are 10^{-4} ^{o}F sec^{-1} and the rainfall units are 10^{3} m^{3}.

APPENDIX B

Rainfall Around the Unit as a Predictor of the Rainfall in the Unit

Since virtually the advent of cloud seeding studies, it has been recognized that the best predictor of rainfall is rainfall itself. It recognition of this fact, heavy emphasis was given to rainfall variables as predictors of rain-fall. A step in this direction was made by defining a new potential predictor variable, which is the rainfall in the annular region between 25 and 35 km, immediately outside the experimental unit (recall that the experimental unit has a fixed radius of 25 km), in the 30-minute period immediately following the qualification of the unit. This annular rainfall variable can then be tested as a covariate for the rainfall that actually occurs in the unit.

An immediate potential objection might well be that the rainfall in this annular region in the 30-minutes following unit qualification might have been contaminated by AgI seeding within the unit itself. This objection might have some merit, if and when, this variable is used to assess the effects of seeding. For now, however, there is no harm in examining the relationships. If no positive relationship exists, there is no point in pursuing the matter further.

A scatter plot of the annular rainfall around the experimental units in the 30-minute period immediately after unit qualificatin versus the unit rainfall in the 60-minute period after qualification for the SWCP 1987 cases is provided in Figure B-1 and a listing of the plotted data can be found in Table B-1. (The annular rainfalls have not yet been run for SWCP 1986; these will be included in subsequent reports if the data can be recovered.) Examination of scatter plot suggests a positive relationship between the two variables. The linear correlation is, in fact, 0.58.

This positive relationship is not surprising. Certainly, the rainfall around an experimental unit immediately after its qualification must give some indication as to how much rainfall will fall in the unit itself. If it did not, the prediction problem would be virtually intractable.

Table B-1

RAINFALL IN ANNULAR REGION (25-35 KM) AROUND THE EXPERIMENTAL UNIT IN THE 30-MINUTE PERIOD AFTER UNIT QUALIFICATION VERSUS RAINFALL IN THE EXPERIMENTAL UNIT IN THE 0-60 MINUTE PERIOD AFTER UNIT QUALIFICATION

(All rainfalls in $m^3 \times 10^3$)

Date	Case #	Unit Rainfall (0-60 minutes)	Rainfall in 25-35 km Annular Region (0-30 minutes)
6/12/87	-3	98.0	9.9
7/13/87	4	167.2	34.7
8/10/87	5	791.7	0.00
8/11/87	-6	1111.1	466.1
8/11/87	7	1007.4	302.1
8/11/87	8	266.6	15.8
8/12/87	-9	718.4	288.9
8/12/87	-10	64.3	2.3
8/13/87	-11	3960.3	336.1
8/13/87	12	446.4	23.6
8/14/87	13	2811.9	20.6
8/14/87	-14	1353.5	243.2
8/15/87	-15	624.1	58.8

CHARGES ON THE CONTRACT FOR JULY 1988

1. Salaries and Wages	
Principal Investigator (Woodley for 1 week)	$1,067
Secretarial Assistance	100
Total Salaries and Wages	1,167
Fringe Benefits (10% of salaries and wages)	117
Total Salaries, Wages and Fringe Benefits	$1,284
2. Consultant Services	
Dr. Danny Rosenfeld (2 weeks)	$1,154
3. Travel	0
4. Computer Time	0
5. Printing and Supplies	$50
6. Telephone	$42
7. Indirect Costs ($1,167 x 0.25)	$292
Total Amount Requested for July	$2,822
Plus retainage previously withheld	920.60
Total of FINAL PAYMENT	$3,742.60

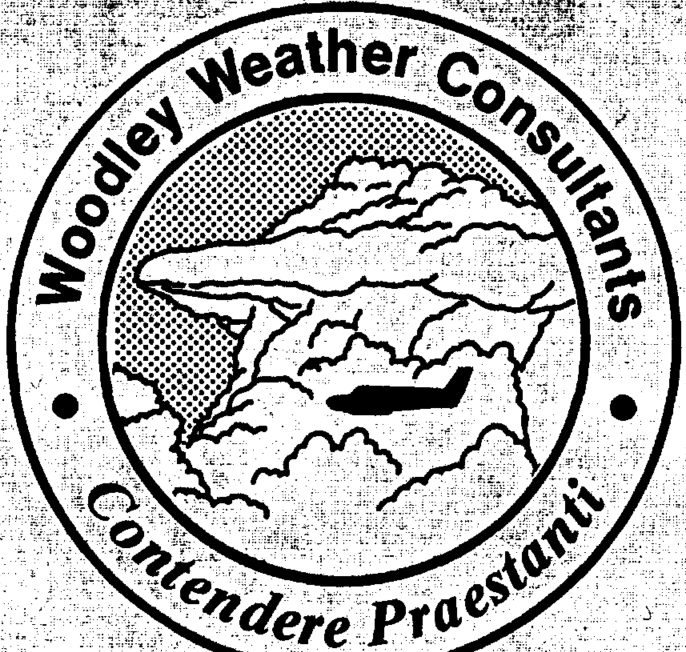
Amount Remaining on Contract: $15,000 - $7,336(May) - $4,852(June) - $2,822(July) = $0.00

Precipitation enhancement
through Cloud Seeding in
West Texas,

RESULTS OF OPERATIONAL SEEDING
OVER THE WATERSHED OF SAN ANGELO, TEXAS
MAY THROUGH SEPTEMBER, 1985-1989

BY

DR. WILLIAM L. WOODLEY, PRESIDENT
WOODLEY WEATHER CONSULTANTS



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by

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EXECUTIVE SUMMARY

This Report presents an assessment of five years of cloud seeding operations, conducted by under contract with the City of San Angelo, Texas, by North American Weather Consultants (1985 through 1988) and by Atmospherics, Inc. (1989). The period of operations was 15 April through 15 October in 1985 through 1989. The program was based on dynamic seeding concepts (e.g. Woodley, et al., 1982; Gagin, et al., 1986; Rosenfeld and Woodley, 1989) and had as its goals the replenishment of surface reservoirs, channel dams and surface aquifers and increased precipitation over the residential areas to reduce residential demand for municipal water. It was recognized that increased rainfall also would benefit the farming and ranching communities.

In conducting the seedings, all suitable clouds were to be treated with a silver iodide (AgI) nucleant while they were over the San Angelo watershed. Primary seeding emphasis was placed on clouds within 30 n.mi. of Twin Buttes and O.C. Fisher reservoirs that are located immediately southwest and northwest of the city, respectively.

Many of the seedings were at cloud top using droppable AgI flares. The number of flares used was a function of the suitability of a particular cloud system. Some of the seedings, particularly those at night, took place at cloud base, using either wing-tip AgI-acetone generators (1985 through 1988) or AgI flares affixed to racks on each wing (in 1989). Cloud-base seeding was the preferred mode of treatment, when large highly-organized cloud systems traversed the target area.

When conducting the "classical" mode of dynamic seeding, vigorous individual cloud towers, growing within the convective cells that make up all cloud systems, were seeded near their tops. Typical tops heights at seeding were 5.5 to 6.5 km and top temperatures were $-8^{o}C$ to $-12^{o}C$. The seeding devices were droppable flares that produced 20 gm of silver iodide (AgI) smoke during their 1.5 km free-fall through the upper portion of the cloud. An average of 2 to 3 flares were ejected per cloud tower in the updraft portions of the cloud pass. When the Johnson-Williams liquid water instrumentation aboard the aircraft was activated, the flare releases were made in regions in which there was coincidence of updraft and supercooled liquid water.

These operational seedings were done in the context of the conceptual model that guided the dynamic seeding experiments in the Florida Area Cumulus Experiment (FACE) (Woodley et. al., 1982) and is guiding the current experiments of the Southwest Cooperative Program (SWCP). The evaluation period for each year of operational seeding encompassed the five months May through September. April and October were not included in the analysis, because only half of these months had seeding (i.e. the last half of April and the first half of October). Because the official rainfalls for many of the stations used in the evaluation were reported only on a monthly basis, it would not have been possible to determine how much of the April and October rainfalls could be ascribed to the period of seeding.

During the 5-year program, the wettest May through September period, both within and outside the target area, occurred in 1986. The May through September periods in the remaining four years, ranked by decreasing wetness, were 1987, 1988, 1985 and 1989. The rainfalls in all years, except 1989, were above the May through September seasonal normals. It was dry in 1989, especially in the southwestern portion of the target and to its south and west.

During the program a total of 125 kgm of AgI were expended during the course of 2,315 separate seeding events. Most of the seedings took place within 30 n.mi. of San Angelo as intended, primarily to the west and southwest of the City.

Assessment of the effect of seeding made use of target-control regressions that had been derived from historical rainfall records. Historical monthly precipitation data were accumulated for long-term rainfall stations within the target and outside to the west and to the south. The period of record was 1960 through 1984 inclusive. Six control stations (Midland Airport, Penwell, McCamey, Bakersfield, Ozona and Sonora) and nine target stations (Garden City, Sterling City, Cope Ranch, Water Valley, Water Valley 10 NNE, Funk Ranch, San Angelo, Eldorado, and Mertzon and/or Mertzon 10 NE were used in the analysis. Potential control stations to the northwest and north of the San Angelo target were not used because of possible contamination by seeding during the Colorado River Municipal Water District operational seeding program, which was operative until 1988.

The analysis proceeded in the following steps:

1. A linear regression relationship between the average, seasonal (May through September) target and control rainfalls was derived. In a variation of this basic analysis, regression equations between mean seasonal control rainfall and the total seasonal rainfall for each target station were derived. This analysis produced ten separate equations, one for the overall target and one each for the nine target stations.

2. The regression equations were then used to evaluate the five years of seeding. The observed mean control rainfall for the six control stations was substituted into the regression equations, and the overall target rainfall and the rainfall for each station were predicted for each year.

3. The predicted rainfalls were compared to the observed rainfalls to obtain an estimate of the effect of seeding for each year. Combination of the yearly results provided an estimate of the effect of seeding for all five years.

The correlations between individual target stations and the mean control rainfall range between 0.58 and 0.84. The overall correlation between mean target and mean control rainfall is 0.77, indicating that this derived linear equation can be used to predict the yearly target rainfall in the absence of seeding.

The analysis suggests a positive effect of seeding (i.e. more rainfall) in each of the five years. The probability of this happening by chance is only 3%. In other words, there is a 97% likelihood that seeding was responsible for the apparent increases in rainfall.

The results of the analysis suggest an overall effect of seeding of about

+17% for the target for all years of operation. In addition, the area closest to San Angleo, where most of the seeding took place, had larger apparent seeding effects ranging between +27% and +42%. The mean increases in rainfall for this region, closest to the San Angelo reservoirs, average between 3 and 5 inches per season (May through September).

Sensitivity tests are an important component of any analysis. To test the sensitivity of the San Angelo results the following procedure was applied:

1. The 25-year base period (1960-1984) was divided into five 20-year blocks.

2. Linear regression equations relating control to target rainfalls were derived for the five 20-year base periods. With the derivation of each regression equation, the remaining 5-year period was set aside as a hypothetical period of seeding. As an example, the period 1965 through 1984 was used to derive the target vs. control relationship and the period 1960 through 1964 was set aside as a period of hypothetical seeding.

3. A seeding effect was then calculated for each 5-year period of hypothetical seeding and for the 5-year period (1985 through 1989) of actual seeding. The "seeding effects" were then compared.

The analysis reveals that in each 5-year period, the apparent effect of actual seeding for the years 1985 through 1989 exceeds the "effect" in each 5-year period of hypothetical seeding. In every instance the ratio of observed to predicted rainfall for the actual period of seeding is > 1, while only three of the five years is > 1 for the period of hypothetical seeding. The probability of of the seeded event happening by chance is only 3%. The magnitudes of the apparent positive seeding effects for the entire traget range from a minimum of + 14% to a maximum of +20%. These values bracket the point estimate of +17% that was obtained in the basic analysis.

This sensitivity analysis supports the interpretation that AgI seeding is responsible for the apparent increases of rainfall over the San Angelo watershed for the period 1985 through 1989. The magnitude of the seeding effect for the overall target likely ranges between 14% and 20%.

Upon assessing all of the evidence, we conclude that seeding has increased the rainfall over the San Angelo watershed. Among all of the evidence considered, we consider the following some of the more convincing:

1. In the statistical analysis an apparent positive seeding effect is evident in each of the five years of operational seeding. The probability of this happening by chance is 3%. The apparent overall area-wide effect is +17%.

2. The apparent effect of seeding is strongest over regions where most of the treatment took place during the 5-year program, especially near and to the west (upstream) of the reservoirs serving San Angelo. Effects in this region range between +27% and +42%.

3. The apparent effect of seeding is still evident after sensitivity testing.

4. The results of research in West Texas to date under auspices of the the Southwest Cooperative Program (SWCP) indicate that seeding in West Texas is effective in increasing the rainfall from individual convective cells by over 100% and that seeding promotes the merger of adjacent clouds, leading to larger and longer-lasting raining clouds. The results of the San Angelo operational program are consistent with the results of this research project.

5. Analysis of the 18-year operational cloud seeding program of the Colorado River Municipal Water District (CRMWD) by Jones (1985, 1988) indicates that seeding has increased the rainfall over their target by about 11%. This result also is consistent with the results of the San Angelo program.

A detailed analysis of the benefit to cost ratio of the San Angelo seeding program is beyond the scope of this report. It is possible, however, to make a "ballpark" estimate of this important parameter. Factors that should be considered in such an analysis are the cost of the program, the apparent increases in rainfall, what happens to the rainfall after it reaches the ground and the value of the increased water. The analysis herein suggests a benefit to cost ratio of at least 10 to 1 for the San Angelo Rain Enhancement Program, suggesting that the effort was highly cost effective.

The San Angelo Rain Enhancement Program appears to have accomplished its primary objective of increasing the water supply over the watershed serving San Angelo. The reservoir levels were higher at the conclusion of the 5-year effort than at the outset, and the analysis indicates that seeding played a significant role in the improved water levels.

1.0 INTRODUCTION

1.1 The Need for Water in Texas

Texas is a large state with a growing population and a diverse and viable economy. The State has a total land area of 693,233 km^2 (267,339 mi^2) and had a 1980 population of about 14.2 million people. The State's population is projected to grow to 17.8 million by 1990 and 20.9 million by the year 2000. It is a state that has long recognized the value of fresh water, as evidenced by its extensive water management programs, which include irrigation projects and conservation efforts.

Texas has a huge thirst for water. Approximately 2.37×10^{10} m^3 (19.2 million acre-feet) of Texas water (one acre-foot is 1,235 m^3 or 325,851 gallons) are used each year to meet the needs of households, industry, irrigation, steam-electric power generation, mining and livestock. Nearly 70 percent of the total water available each year, 1.62×10^{10} m^3 (13.1 million acre-feet), is consumed by farmers and ranchers for irrigation to produce food and fiber to meet the demands of both the State and the Nation. By the year 2000, it is projected that 2.75×10^{10} m^3 (22.3 million acre-feet) of water will be needed to meet the demands of the State, assuming that agricultural water use is held at 1.62×10^{10} m^3). Virtually all of this water is produced ultimately by precipitation and by pumping from ground storage. A map of the Texas average annual precipitation for the years 1950 through 1980 is provided in Figure 1. Annual precipitation increases from near 8.0 inches in the west to over 56 inches in the east.

Although Texas' supply of fresh water is usually sufficient to meet current needs, its areal distirbution does not correspond to the areas of greatest need. If additional water sources are not found in some regions of the State, serious water shortages will adversely affect the local economies. This is especially true in the fertile but semiarid Texas High Plains area where the Ogallala aquifer, the major source of municipal and irrigation water, is being exhausted. Currently, the Ogallala supplies irrigation water for 23,900 km^2 (5.9 million acres). At present annual use trends, however, it is estimated that by the year 2000 the Ogallala will be able to supply water to only 9,000 km^2 (2.2 million cres). Not only is water becoming more scarce, it is also becoming more xpensive to obtain, as the water table declines and energy costs to pump the ater continue to rise.

When droughts are factored into the Texas water equation, the potential for serious water problems is increased. The recent history of Texas drought has een addressed by Riggio *et al*., (1987), and it brings the importance of adequate recipitation into sharp focus. Riggio *et al*. note that at least one serious rought has plagued parts of Texas in every decade of the 20th century. The most atastrophic Texas drought was the state-wide dry spell that began in 1949 and nded in 1957. Wells ran dry, rivers stopped flowing and ranchers and farmers ruggled to survive during this drought.

Droughts of shorter durations and severity have plagued various areas of the ate since then. In the Edwards Plateau portion of the state that includes Tom een County and the City of San Angelo, other drought periods have included the ars 1933 & 1934, 1947 & 1948, 1962 through 1964, and 1982 through 1984. It was

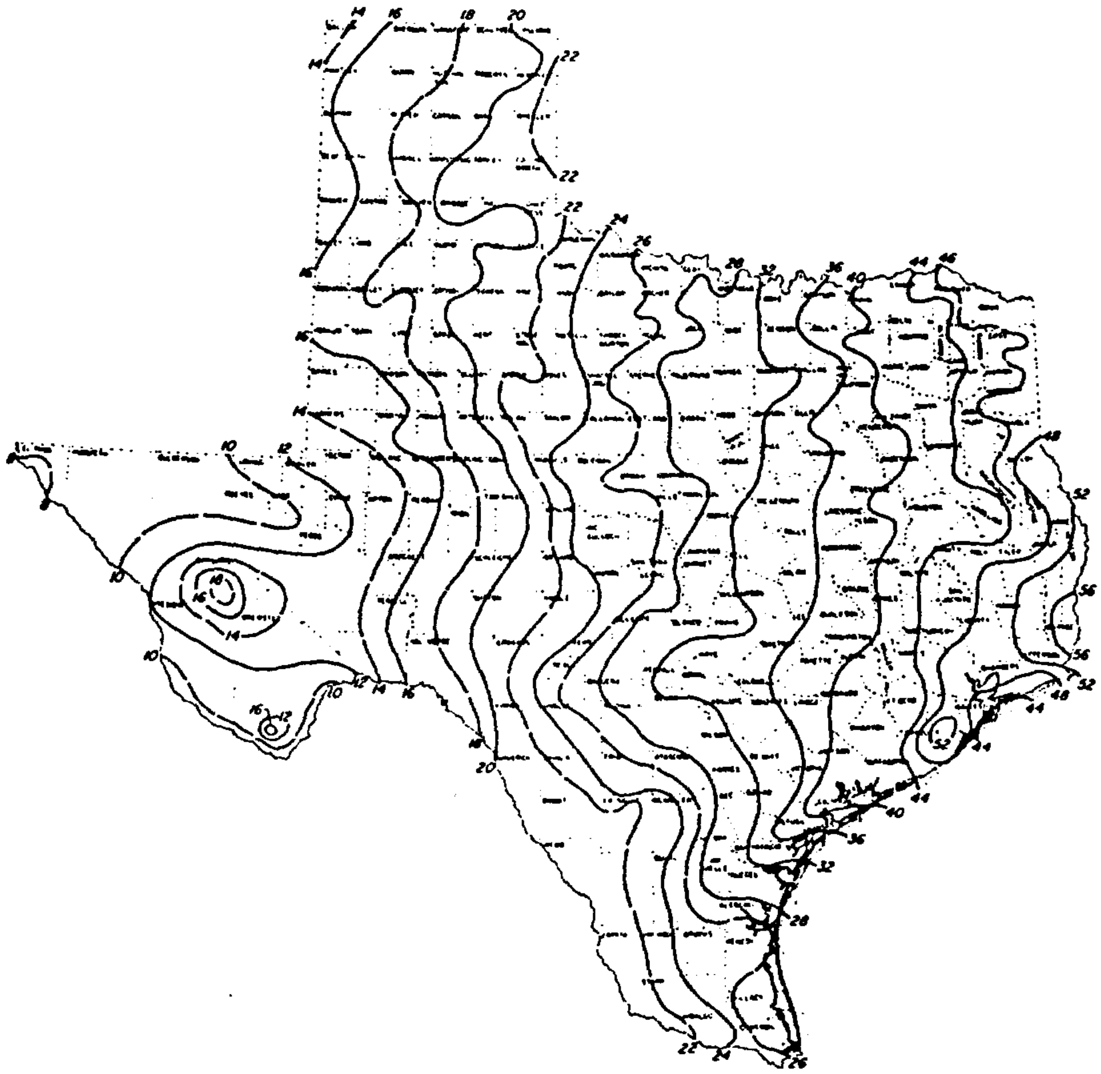

Figure 1
Mean Annual Precipitation
in Inches, 1951-1980
(From Riggio <u>et</u> <u>al</u>., 1987)

ry dry over the southern portion of the Edwards Plateau in 1989, including the ea just to the south of San Angelo. This is not a temporary aberration but the ginning of yet another drought period.

In order to meet the water needs of Texas, and specifically in the Texas gh Plains, additional and cost effective fresh-water supplies must be veloped. A potential technique for providing additional fresh water is to tap e moisture available in the atmosphere which does not fall as rain naturally. e value of this potential additional water has been demonstrated by exploratory udies of the Texas Department of Water Resources (Allaway *et al*., 1975; Lippke, 76; and Kengla *et al*., 1979). These studies indicate that cloud seeding in a ,000 km^2 (8.1 million acres) project area of the southern High Plains, yielding percent additional rainfall during the growing season, would result in an erall expansion in regional output of approximately \$3.68 million and a similar pansion in regional income of \$2.30 million.

Studies such as these, showing the value of increased water, explain why xas has a history of both meteorological research and cloud seeding efforts to hance the natural precipitation. The most relevant recent programs are the xas High Plains Experiment (HIPLEX), the operational seeding program of the lorado River Municipal Water District (CRMWD) and the research effort under the spices of the Southwest Cooperative Program (SWCP). These programs serve as e backdrop for the operational seeding program of the City of San Angelo that the focus of this paper.

1.2 Texas HIPLEX

Research into rainfall enhancement in Texas expanded rapidly during the 70's with the Texas High Plains Experiment or HIPLEX. The HIPLEX effort was nted by the Federal government in the U.S. High Plains, in cooperation with states of Kansas, Montana and Texas, to better understand the physical ocesses in growing-season convective clouds in this region and the response of ese clouds to seeding. This ambitious program of weather modification research s part of the U.S. Department of the Interior's "Project Skywater," which was signed to develop an effective technology for precipitation management to help plement the nation's fresh water supply needs.

The Texas HIPLEX Program was intended as a long term multi-phase research fort to develop a technology to augment West Texas summer rainfall. Due to deral funding cutbacks, however, Texas HIPLEX was limited to its initial phase 975 through 1980), which included the collection, processing and analysis of eorological data in order to better understand the cloud systems of West as. The data collected during the six summer field programs included surface upper-air observations, and cloud physics, radar, satellite and raingage a. Of most relevance to the San Angelo program, the HIPLEX studies revealed t the larger and better organized convective systems produce the bulk of the nfall in West Texas (Riggio *et al*., 1983; Matthews, 1983). This finding has obvious implication that operational seeding must act to stimulate these ger cloud systems if it is to be effective in augmenting regional rainfall.

1.3 The Operational Rain Enhancement Program of the Colorado River Municipal Water District (CRMWD)

The operational seeding program that is most relevant to the San Angelo effort is the convective cloud seeding program, sponsored by the Colorado River Municipal Water District (CRMWD) in Big Spring, Texas, which ran continuously from 1971 through 1988 (18 years). The twofold purpose of this program was to increase precipitation runoff for storage in the CRMWD reservoirs and to increase rainfall for use by agriculture. Seeding during this program was done primarily at cloud base using silver iodide (AgI) acetone generators.

In assessing the apparent effect of seeding in the CRMWD program, Jones (1985 and 1988) made use of the historical rainfall record (1936-1970) to calculate percent of normal rainfall at target and control stations. He also used these data to develop target-control regressions, which were used to predict rainfall in the seeded period (1971-1988). The predicted and observed target rainfalls were then compared. The percent-of-normal analysis indicates 30% above normal rainfall in the center of the target while the regression analysis suggests that seeding increased the rainfall about 11% in the target area.

A second analysis by Jones (1988) of the yields of unirrigated cotton in and around the target since seeding began in 1971 indicates increases of cotton production of 48% and 45% in the target and downwind of the target, respectively, while the increase in cotton production in the same time period in the counties upwind of the seeding was only 8%. If one assumes that rainfall has been the major control of cotton production over the entire region, this result might be interpreted as further evidence for seeding-induced rain increases.

1.4 The Southwest Cooperative Program (SWCP)

The Southwest Cooperative Program (SWCP) of Texas and Oklahoma is a joint effort to develop a scientifically sound and socially acceptable applied weather modification technology for increasing water supplies in this region. The sponsors of the Texas effort are the Texas Water Commission, the U.S. Bureau of Reclamation, the Colorado River Municipal Water District in Big Spring, Texas, and the City of San Angelo, Texas. Experimentation was conducted from a base in San Angleo, Texas during portions of the summers of 1986, 1987 and 1989.

The CORE component of the Texas SWCP is the statistically randomized seeding effort aimed at determining the potential of stimulating additional rainfall from clusters of convective clouds in West Texas through the application of "dynamic" seeding techniques to individual convective cells that make up the cloud system. All aspects of the SWCP through 1987 are addressed in the paper by Rosenfeld and Woodley (1989). Dynamic seeding is discussed in the next section.

The SWCP experiments have been conducted in accordance with the SWCP Design Document (Jurica and Woodley, 1985) and SWCP Operations Plans (Jurica et al., 1987) over the area between San Angelo and Big Spring in West Texas. In every case, the experimental unit was the small multiple-cell convective system within a circle having a radius of 25 km and centered at the location of the convective cell which qualified the unit for treatment. The treatment decisions were randomized on a unit-by-unit basis and all suitable convective cells within the unit received the same treatment -- silver iodide (AgI) in the case of a seed (S) decision or simulated AgI in the case of a no seed (NS) decision.

During the actual randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical top heights of 5.5 to 6.5 km and top temperatures -8°C to -12°C). The seeding devices were droppable flares that produced 20 gm of AgI smoke during their 1 km free-fall through the upper portion of the cloud. Between 1 and 10 flares normally were ejected during a seeding pass, but more were ejected in a few instances in especially vigorous clouds. The flare ejection button was pressed approximately every second while the cloud liquid water reading was greater than 0.5 g/m^3 <u>and</u> the updraft exceeded 1,000 ft/min. In the simulated seeding passes no flares were actually ejected when the button was pressed, but the event was still recorded in the aircraft data system.

In the SWCP design, therefore, the treatment units are the convective cells which contained cloud towers that met the liquid water and updraft requirements. It is the cell that receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells.

The inferred seeding effects were to be interpreted in the context of the conceptual model that has guided the dynamic seeding experiments in the Florida Area Cumulus Experiment (FACE) (Woodley et. al., 1982) and in the SWCP of West Texas. A discussion of this conceptual model and the results of the SWCP to date are presented by Rosenfeld and Woodley (1989). A brief summary is presented in section 3.4.

2.0 THE SCIENTIFIC BASIS FOR CLOUD SEEDING IN WEST TEXAS

One major general premise of cloud seeding is that the introduction of ice nuclei into a nuclei-deficient supercooled cloud will improve its precipitation efficiency, leading to more precipitation. Relatively small numbers of ice nuclei (1 to 10 per liter) are thought to be needed to improve precipitation efficiency. This approach to seeding has been called "static" because the seeding concept is to add small concentrations of ice nuclei to clouds, whose precipitation efficiency has been degraded by a deficiency of such nuclei. The nucleated ice crystals will then grow in size by diffusion and deposition until they fall from the cloud as precipitation. The release of fusion heat during the gradual glaciation process is thought to be comparatively small and unimportant. An excellent discussion of the "static" approach to seeding is provided in a review paper by Silverman (1986).

A second premise of cloud seeding is that massive glaciation of a supercooled cloud will lead to substantial releases of the latent heat of fusion, leading to increased cloud buoyancy and greater cloud growth. These larger clouds will last longer and process more water, leading to more precipitation on the ground. This approach is commonly called "dynamic seeding", because the intention is to invigorate the cloud's internal circulations to promote larger clouds. Orville (1986) provides a comprehensive discussion of the "dynamic" approach to cloud seeding.

A complication for both approaches to cloud seeding is the tendency for secondary ice production in supercooled clouds with base temperatures warmer than about 10°C (see Hallet and Mossop, 1974; Mossop, 1976; Mossop, 1978a, 1978b; Vardiman, 1978 and Mossop, 1985). In warm-based clouds, the coalescence of water drops is a dominant precipitation-forming mechanism. When these precipitation-sized water drops are carried to the supercooled portion of the cloud, a few of them freeze, releasing ice splinters in the freezing process. Silverman (1986) points out that other factors, such as liquid water content, cloud droplet concentration, cloud depth, and updraft speed are also important factors in this secondary ice production. The major determining factor, however, apparently is cloud base temperature. Johnson (1982) indicates that +10°C is the critical cloud-base temperature threshold for natural ice multiplication.

Artificial nucleation may not be necessary in clouds with an active coalescence process. It may be counterproductive in some cases, because the cloud may already contain enough natural ice for maximum precipitation efficiency. This may be a greater problem for the "static" approach to cloud seeding than for the "dynamic" approach. Large effects of dynamic seeding have been shown in both Florida (Simpson and Woodley, 1971; Gagin et al., 1986) and Texas (Rosenfeld and Woodley, 1989), and in virtually every instance the seeded clouds had base temperatures > +10°C.

Both the "static" and "dynamic" approaches likely are relevant to the clouds of West Texas. The static seeding approach may work best on cold-based cumuli and on highly organized convective systems, while the dynamic seeding approach vill be most applicable to warmer-based convective clouds that have not yet eveloped massive stature. In most cases, the response of a cloud to seeding is mixture of both static and dynamic effects. Which effect dominates probably epends on the initial conditions of the cloud and environment when seeding is nitiated and on the amount of nucleant introduced into the cloud.

.0 DESIGN AND CONDUCT OF THE SAN ANGELO RAIN ENHANCEMENT PROGRAM

3.1 Background

During the latter stages of the 1982-1984 drought that affected San Angelo, he City Council and Manager of the City investigated the potential of cloud eeding for mitigating the drought over the city's watershed. Aware of the esults of the long-term CRMWD program and of continuing progress in cloud eeding research, the Council issued a solicitation for a qualified weather dification contractor on November 8, 1984. North American Weather Consultants AWC) answered this solicitation and was selected to conduct the operational oud seeding program through the summer of 1988. Atmsopherics, Inc., conducted e program in 1989. Annual reports on the seeding operations have been prepared Girdzus and Griffith, (1986); Griffith and Girdzus, (1987); Risch and iffith, (1988); Girdzus and Griffith, (1989); and Woodley et al.(1989).

The San Angelo program was based initially on dynamic seeding concepts and results from Florida (Woodley, et al., 1982; Gagin, et al., 1986). Later positive research results for West Texas (Rosenfeld and Woodley, 1989), obtained during the course of the Southwest Cooperative Program (SWCP), provided additional justification for the operational seeding effort. In both the SWCP and the CRMWD efforts, however, it appeared that "static" seeding effects might have been operative as well to increase the precipitation. "Static" and "dynamic" seeding concepts are discussed in sections 2.3 and 3.4.

3.2 Objectives

The San Angelo rain enhancement program was designed to use state-of-the-art aircraft, radar and instrumentation systems to recognize and act upon seeding opportunities for rain enhancement over the target area shown in Figure 2. The primary objective of the program was the enhancement of rainfall over the watershed that feeds San Angelo's two main reservoirs, Twin Buttes to the southwest and O.C. Fisher to the northwest of the city. Seedings were to be concentrated in suitable clouds within 30 n.mi of these reservoirs to increase runoff in streams and channel dams supplying the reservoirs and to increase precipitation directly into the reservoirs themselves. Seedings at greater radii were approved in instances when the seeded cloud systems were expected to move toward the storage reservoirs. In meeting the primary objective, recharge of the area's shallow aquifers would be accomplished as well. A secondary objective of the program was to increase the rainfall in residential areas in order to decrease the demand for municipal water.

The program sponsors understood clearly that cloud seeding in West Texas would not "break" droughts, but that it likely would be effective in augmenting the rainfall during periods of natural rainfall. Whether this has been the case during the five-year seeding program is the focus of this paper.

3.3 Facilities and Their Use

The San Angelo rain enhancement program made use of twin-engine, turbocharged aircraft, silver iodide (AgI) pyrotechnic flares and solution-burning seeding generators, C-band operational radars, and raingages. All randomized seedings were conducted over the target area in Figure 2.

Aircraft

The primary function of the aircraft was to accomplish the seeding of suitable convective clouds using fixed or droppable 20-gm silver iodide pyrotechnics. The base of aircraft operations was Mathis Field in San Angelo, Texas. The cloud seeding aircraft were a Cessna 340 (in 1985, 1987 and 1988), a Beechcraft Duke (in 1986) and a Cessna 421 (in 1989).

All seeder aircraft had weather radar and seeding systems. The former was used primarily to ensure the safety of the aircraft and crew during seeding penetrations and the latter were used to carry out either on-top or cloud-base seedings of convective clouds. Under the belly or tail sections, the seeder aircraft carried flare racks that held up to 200 20-gm silver iodide pyrotechnic flares (TB-1 formulation). These flares normally burn for about 45 sec and fall up to 4,500 ft when ejected at altitudes of 20,000 ft in still air. In addition,

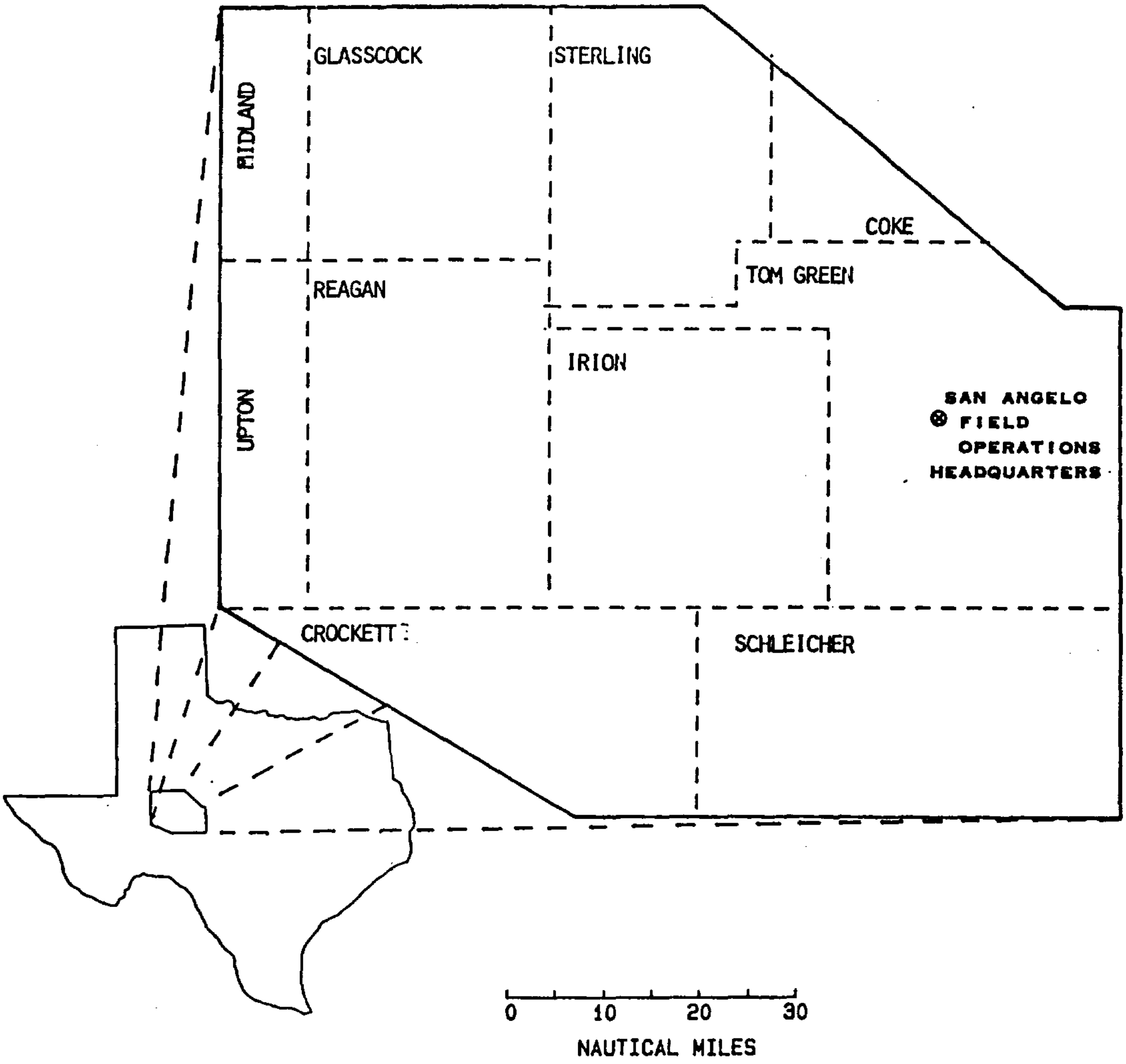

Figure 2 The target area for the San Angelo Rain Enhancement Program

the seeder aircraft had either wing-tip, AgI-acetone generators (1985 through 1988) or AgI flares affixed to racks on each wing (in 1989). Each generator usually produced about 2 gms of AgI per minute of operation, while the fixed flares produced about 3 gms of AgI per minute for each 20-gm flare that was burned. Total burn time for each fixed flare was about 6 minutes.

Radar

The San Angelo operational radar was a C-band Enterprise system in all years. In 1985 through 1988 the radar was an Enterprise WR-100-2 and in 1989 it was an Enterprise WR-100-5. In some years the radars had L-band aircraft transponder display capability which was used for coordination of the seeding flights. The radars were located at Mathis Field near San Angelo, Texas at 31° 21.5' N and 100° 29.7'W. The airport elevation is 1916'.

The radar operator was charged with assessing echo top height, reflectivity values and echo patterning. Operation of this radar system was usually manual. During the course of operations, PPI scope paper overlays were prepared at 15-30 min intervals, showing echo positions, top heights, reflectivities and motion. As the seeder aircraft climbed to altitude, the radar operator closely observed the field of echoes to determine cell vigor, organization and lifetime. This information was radioed to the aircrew to assist with the selection of suitable seeding targets. During operations the radar operator monitored the weather-data system for NWS severe storm warnings specific to the echoes being worked by the aircraft and assessed any severe echo development via direct radar measurements.

Raingages

Rainfall information for this study was obtained from long-term raingage sites that included Garden City, Sterling City, Cope Ranch, Funk Ranch, Water Valley, Water Valley 10NNE, San Angelo, Mertzon, Mertzon 10NE, Eldorado and Ozona. It should be noted that the Eldorado gage site was 11 mi. NW of the city through June of 1981 and 2 mi. SE of the City from September 1981 to the present. The Mertzon site ceased operation in 1987, whereas the Mertzon 10NE site began its operation in 1977. These stations figure prominently in the assessment of seeding effects. The gage observations are discussed extensively later in this report.

3.4 Seeding Methods and Their Rationale

In conducting the seedings, all suitable clouds were to be treated with a silver iodide (AgI) nucleant while they were over the watershed shown in Figure 2. Primary seeding emphasis was placed on clouds within 30 n.mi. of Twin Buttes and O.C. Fisher reservoirs located immediately southwest and northwest of the city, respectively.

Many of the seedings were at cloud top using droppable AgI flares. The number of flares used was a function of the suitability of a particular cloud system. The basic rationale for this approach to seeding is presented in section 2.4 and is discussed further in this section. Some of the seedings, particularly those at night, took place at cloud base, using either wing-tip AgI-acetone generators (1985 through 1988) or AgI flares affixed to racks on each wing (in

1989). The AgI-acetone generators produced more effective nuclei per gram of AgI at -10°C, averaging between 10^{14} and 10^{15} nuclei per gram of nucleant, than the droppable or fixed flares, which averaged between 10^{12} and 10^{13} effective nuclei per gram of nucleant. Cloud-base seeding was the preferred mode of treatment, when large highly-organized cloud systems traversed the target area.

3.4.1 Seeding Near the Tops of Growing Cumulus Towers

When conducting the "classical" mode of dynamic seeding, individual cloud towers, growing within the convective cells that make up all cloud systems, were seeded near their tops. Typical top heights were 5.5 to 6.5 km and top temperatures were -8°C to -12°C. The seeding devices were droppable flares that produced 20 gm of silver iodide (AgI) smoke during their 1 km free-fall through the upper portion of the cloud. An average of 2 to 3 flares were ejected per cloud tower in the updraft portions of the cloud pass. When a Johnson-Williams liquid water instrument aboard the aircraft was activated, the flare releases were made in regions in which there was coincidence of updraft <u>and</u> supercooled liquid water.

These operational seedings were done in the context of the conceptual model that guided the dynamic seeding experiments in the Florida Area Cumulus Experiment (FACE) (Woodley et. al., 1982) and is guiding the current experiments of the Southwest Cooperative Program. Ideally, according to the <u>initial</u> steps in this conceptual model, the seeding should produce more rain from individual cells and groups of cells through the following steps:

1. Intensive AgI-seeding of the updraft portion of a vigorous supercooled cloud tower rapidly converts the supercooled water to ice.

2. The released latent heat due to freezing and deposition increases the buoyancy of the cloud tower, increases the updraft and causes the cloud to grow taller.

3. The cloud tower produces more rainfall by virtue of its greater height.

4. Enhancement of the rainfall from the treated convective elements, leading to enhanced water loading which, in conjunction with increased entrainment of drier environmental air into the cloud, invigorates the downdrafts. The enhanced downdrafts interact with the subcloud ambient winds to increase convergence and trigger more neighboring cloud growth. Some of these new clouds will in turn produce precipitation, resulting in the expansion of the cloud system. This effect is often referred to as the "areal effect".

This conceptual model is backed by the observations that taller convective cells precipitate more. Observations of natural convective rain clouds in Florida (Gagin et. al., 1985) indicate that an increase of cell top height by 20% nearly doubles its rain production. If a seeding-induced enlarged cloud behaves as a natural cloud reaching to the same top height, the rainfall of the treated cloud will be increased accordingly. It should be noted that the "areal effect" is conditioned on a significant primary effect of the seeding on the individually-treated convective cells.

A review of the status of seeding from dynamic effects as of 1986 has been provided by Orville (1986). A recent paper by Rosenfeld and Woodley (1989) indicates that AgI seeding of convective cells in West Texas was effective in increasing the areas, durations and rain volumes of the cells. The radar-estimated rainfall volume at the bases of the AgI-treated cells was more than double the rain volume from the cells that received simulated treatment. This result is significant at the 3% significance level using re-randomization procedures. The apparent effect of seeding and its significance increases slightly when control cells are incorporated into the analysis. The effect of treatment on maximum cell height, as measured by radar, generally averaged less than 5%.

In moving from the cell scale to the larger scales, it was found that cell merger occurred twice as often in the AgI-treated cases. Merging was most pronounced for cells treated early in their lifetimes with 9 or more AgI flares. The merger results are highly significant.

Given that seeding produces a large effect on the convective cells of West Texas, the next question is how this effect spreads to the larger scales during the operational seedings. It is expected that cell mergers, leading to larger and more clustered areas of precipitation, play a major role in this transfer. The strong evidence for increased merging of the seeded cells in West Texas supports this speculation, as do the results of other investigators. It has been well documented, for example, that the merger of convective cells or elements can affect the future development of a cloud mass, leading to taller, larger and more intense convective systems that produce more rainfall (Simpson and Woodley, 1971; Lemon, 1976; Houze and Cheng, 1977; and Wescott, 1977).

Because vigorous cell mergers usually take place in regions of strong convergence of moist air beneath the clouds, one is left with the suspicion that seeding enhances the surface convergence. How this takes place is still a matter for conjecture, but the most likely process is enhanced downdrafts following seeding as postulated by Simpson (1980) and modeled later by Tao and Simpson (1988). Uncertainties such as this are the reason for continuation of research programs, such as the Southwest Cooperative Program (SWCP).

Despite its apparent value in augmenting rainfall, dynamic seeding may not always be the appropriate seeding approach in West Texas. When additional cloud-growth potential is low and the natural clouds are expected to be very tall, dynamic seeding may actually decrease precipitation. The large number of additional nuclei, injected near cloud top, may make the natural precipitation process less efficient. This is especially likely when the cloud bases are relatively high and cold (i.e. $< +10^{\circ}C$) and the water contents at seeding level are rather low (i.e. < 1 gm/m^3). Introduction of high concentrations of ice nuclei into such conditions may result in local "overseeding" whereby there are too many nuclei for the available water content. On the other hand, cloud-base seeding under these conditions may be effective in improving precipitation efficiency, if the natural ice crystal concentrations are relatively low (i.e. $<$ 1 per liter).

3.4.2 Seeding at Cloud Base

Seeding at cloud base in updraft regions is another proven method of seeding clouds. Targeting and timing of the nucleant into the supercooled region is more uncertain with cloud-base seeding than with ontop seeding, because of the distance between the seeding and the desired region of nucleation. On the other hand, tests have shown that the nucleant does reach the supercooled region of the cloud in most circumstances. Spiraling in the updraft while seeding at cloud base also ensures a steady stream of nucleant moving up through the cloud. This is important when doing static seeding to improve the efficiency of the precipitation process.

An important question is whether cloud-base seeding can be used to produce rapid glaciation, increased buoyancy and additional growth of the treated clouds. Such effects should be possible when the nucleant plume is carried rapidly upward from cloud base into the supercooled region of the cloud, where glaciation can take place before natural ice processes can become operative. Although targeting of the nucleant into the appropriate supercooled cloud region is certainly more difficult with base seeding, the higher yields of nuclei from the AgI-acetone generators may still make dynamic effects possible, even if a large fraction of the nuclei generated at cloud base never finds its way into the most seedable region high in the cloud.

Upon interviewing individuals in the private meteorological firms that acutally conducted the seeding in the San Angelo project, there was a general belief that base-seeding likely produced dynamic effects in the treated clouds. There is no proof, of course, since no program in Texas has demonstrated such effects with this mode of seeding. One has to admit, however, that base-seeding for dynamic effects should be possible in Texas under the right circumstances.

In summary, it must be noted that the seeding approach is not a matter of whim. What is done depends on the weather conditions. When the cloud bases are high and cold, base-seeding is probably the appropriate seeding approach. The cloud precipitation-forming mechanism is normally quite inefficient under these conditions, and the addition of a few ice nuclei per liter should result in the formation of ice crystals that will grow to precipitation size. On other days under more "tropical" conditions with high dewpoints, the cloud bases are low and warm. Such clouds may precipitate before they reach the -10°C level, as a result of an active coalescence process. There is, however, opportunity for the stimulation of the dynamics of such clouds, leading to larger and longer-lasting rain systems.

On some days, when the cloud bases are neither distinctly cold nor warm, either approach may work for the production of additional rainfall. In truth, however, exactly how the seeding works to stimulate more rain under these circumstances is not understood. This is the reason that cloud seeding research in West Texas must continue in parallel with the operational seeding efforts. Only in doing so can additional progress be made in the development of an effective cloud seeding technology for the state.

3.5 Weather During the Program

During the 5-year program, the wettest May through September period, both within and outside the target area, occurred in 1986. The May through September periods in the remaining four years, ranked by decreasing wetness, were 1987, 1988, 1985 and 1989. The rainfalls in all years, except 1989, were above the May through September seasonal normals. It was dry in 1989, especially in the southwestern portion of the target and to the south and west of the target.

3.6 Seeding Operations

A summary of seeding operations for the five-year operational program is presented in Table 1. The number of seeding days and the number of seeding flights are not correlated with the total rainfall. For example, 1989 ranked #2 in the number of seed days, #1 in the number of seeding flights, and #1 in the amount of seeding agent expended. It ranked last, however, in total rainfall. Seeding activity alone does not guarantee high rainfall totals.

Table 1

SUMMARY OF SEEDING OPERATIONS
May through September
1985 through 1989

Year	# Seed Days	# Seeding Flights	Amt. AgI (kgm)
1985	31	39	18.0
1986	26	35	31.4
1987	34	37	28.3
1988	27	35	9.4
1989	33	50	37.9
Totals:	151	196	125.1

A plot of each seeding event in the May through September period since the program began in 1985 is provided in Figure 3, where a seeding event is defined as the activation of at least one ejectable or end-buring flare. Examination of Figure 3 reveals that most of the 2,315 plotted seeding events took place within 30 n.mi of San Angelo, primarily to the west and southwest. In a later section it will be noted that the highest incidence of seeding coincides with the region of highest apparent seeding effect. This is as it should be if, indeed, AgI treatment is responsible for the increased rainfall.

WEATHER MODIFICATION PROGRAM - CITY OF SAN ANGELO

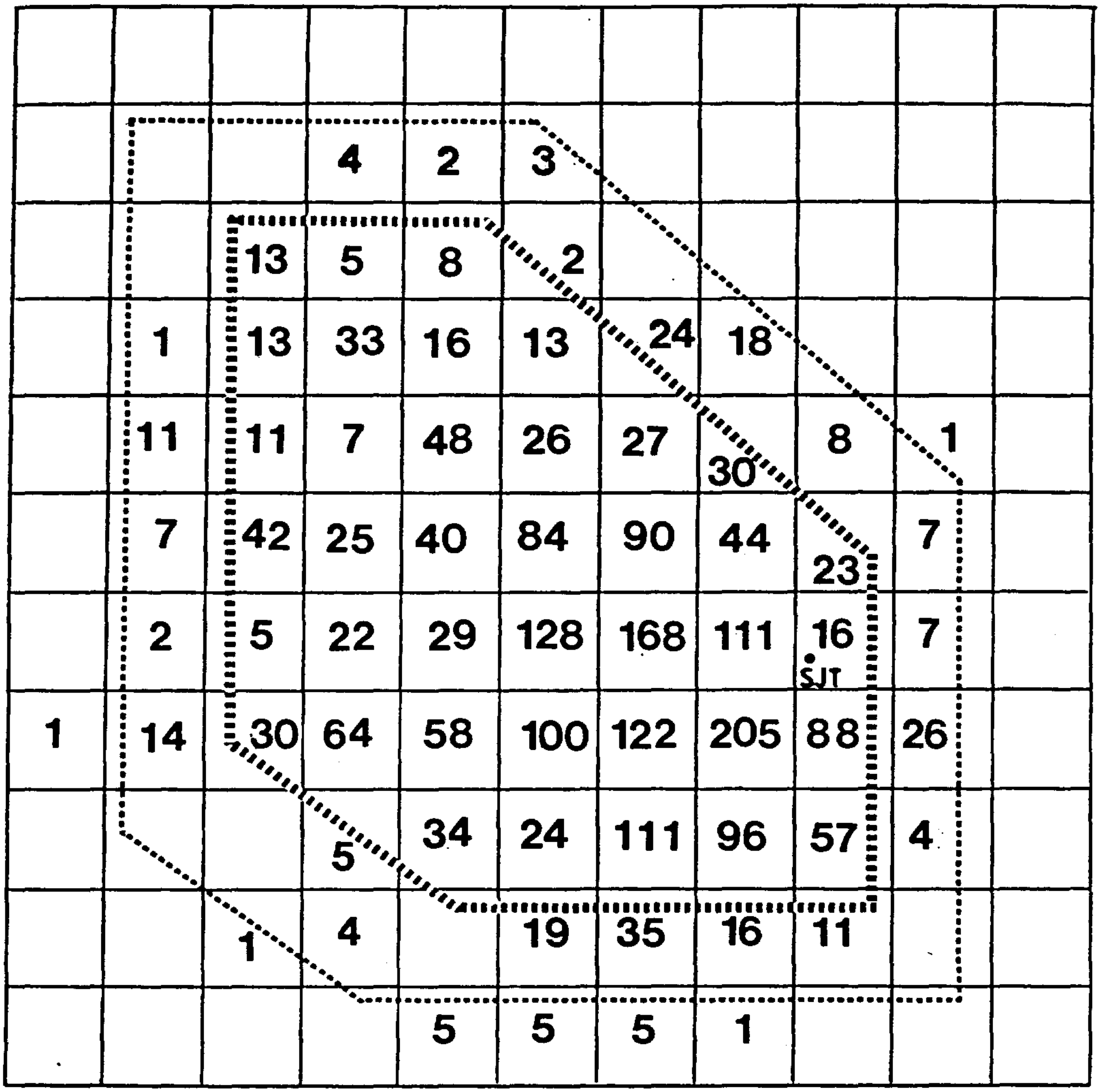

Figure 3 Location of seeding events during the San Angelo Rain Enhancement Program (May through September 1985 through 1989). A seeding event is defined as the activation of at least one flare or the ignition of the AgI-acetone generator. In the latter instance, the generator burn time was divided into 6-minutes segments and a seeding location was determined for each 6-minute time segment. The outer figure is the operational area for the program while the inner area is the target. Each grid square is 10x10 n.mi. San Angelo (SJT) is identified in the extreme eastern portion of the target.

4.0 ASSESSMENT OF THE EFFECT OF SEEDING

4.1 Approach

Evaluating the effect of seeding in an operational seeding program is essential if the effort is to have long-term credibility. Unfortunately, this is not an easy proposition. The treatment has not been done on a random basis, and there are no control days to serve as an objective basis of comparision for the days that have been seeded. It is possible, however, to make an assessment of the effect of seeding, using target-control regressions that have been derived from historical rainfall records. Flueck (1976) outlines this procedure and discusses its advantages and its limitations. The basic requirements are that the target and control rainfalls be correlated, that the rainfall at the control stations not be contaminated by the seeding in the target and that the derived relationship between the control and target stations is valid for the period of seeding.

Our approach to the assessment of seeding effects is similar --- at least initially --- to that of Girdzus and Griffith (1989). Historical monthly precipitation data were accumulated for long-term rainfall stations within the target and outside to the west and to the south. The period of record was 1960 through 1984 inclusive. These stations are shown in Figure 4. Six control stations (Midland Airport, Penwell, McCamey, Bakersfield, Ozona and Sonora) and nine target stations (Garden City, Sterling City, Cope Ranch, Water Valley, Water Valley 10 NE, Funk Ranch, San Angelo, Eldorado (11 NW and 2 SE), and Mertzon and/or Mertzon 10 NE were used in the analysis. Sheffield, Texas, was considered as a control station, but its record had too many gaps to permit its use.

Having selected the target and control stations, the analysis proceeded along the following steps:

1. A linear regression relationship between the average, seasonal (May through September) target and control rainfalls was derived. In a variation of this basic analysis, regression equations between mean seasonal control rainfall and the total seasonal rainfall for each target station were derived.

2. The regression equations were then used to evaluate the five years of seeding. The observed mean May-September rainfall for the six control stations was substituted into the regression equations, and the overall target rainfall and the rainfall for each station was predicted.

3. The predicted rainfalls were compared to the observed rainfalls to obtain an estimate of the effect of seeding. This was done for each year and for all five years of the program.

This analysis is only as good as the input data; the quality of the raingage records had to be addressed before any analyses could begin. All rainfall observations, except for those from the Mertzon 10 NE station, were provided by the National Climate Data Center in Asheville, North Carolina. Overall, the station record is fairly complete, but missing records were a problem for some stations. Table 2 lists the data availability for the target and control stations for the base period (1960 through 1984) and for the project period (1985 through 1989). It is based on the number of station-months that had to be edited. Each station-month requiring any intervention, whether one day or the entire month, is noted.

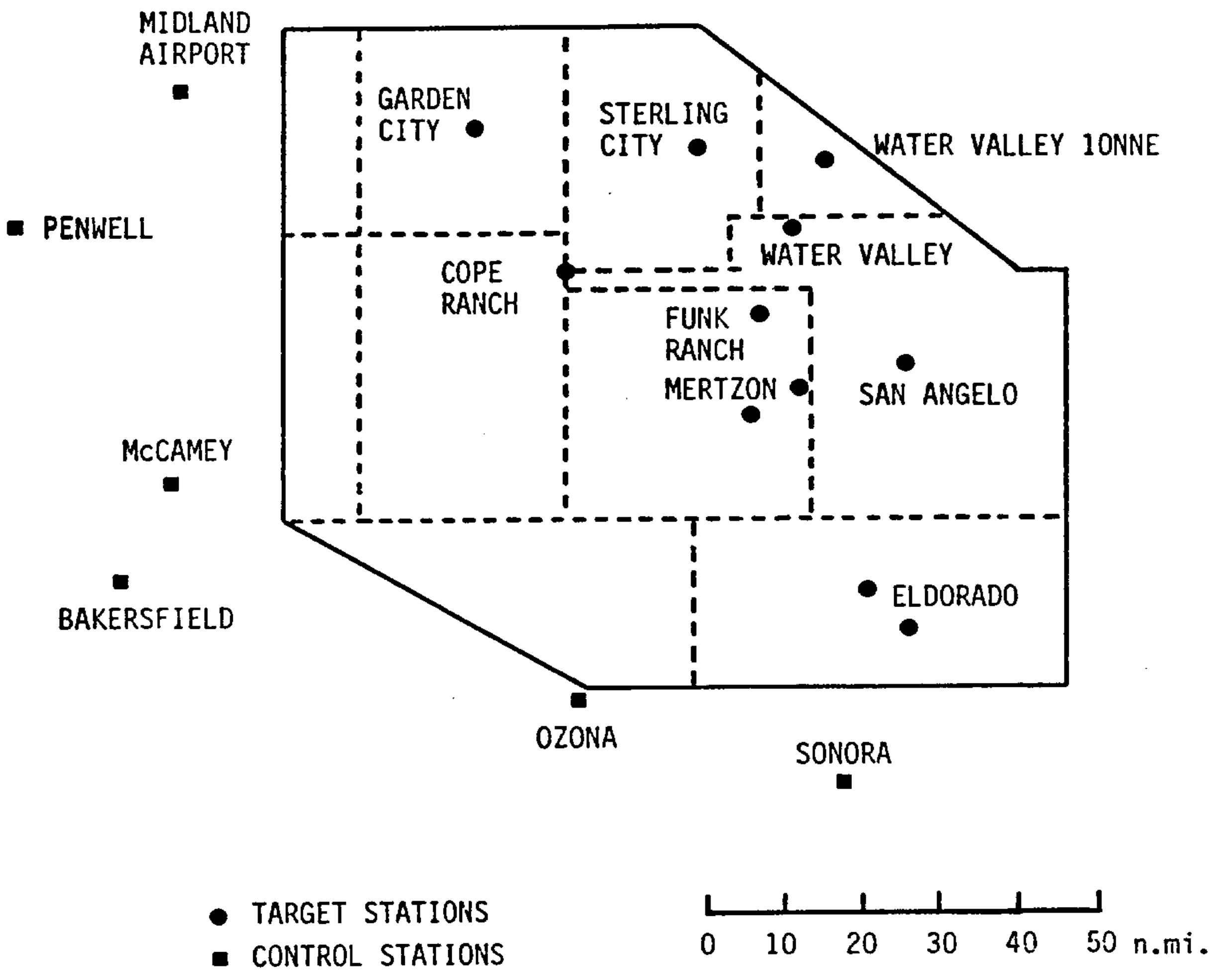

Figure 4 Map showing the location of the target and control stations used in the analysis. Two stations (i.e. Mertzon and Eldorado) have multiple sites. This is addressed in the text.

Study of Table 2 reveals that four stations (San Angelo, Water Valley, Cope Ranch and Midland) had a perfect record. With the exception of Sheffield (and perhaps Mertzon), the interpolations for missing data were minimal for the other stations. Sheffield was dropped from consideration because of large gaps in its record. Mertzon appeared to be acceptable. All of the editing necessary to complete the study with the remaining stations is documented in Appendix A.

In the cases of Eldorado and Mertzon, the gage sites at each location changed during the report period. Eldorado had no overlapping record for its two sites. The records for Mertzon and Mertzon 10NE, however, overlapped from 1977 through 1986. It was possible, therefore, to determine the relationship between the two stations. The results, which are presented in Appendix B, indicate that the rain measurements at the new Mertzon site (i.e. Mertzon 10NE) are low relative to the old site. Use of the new site for a portion of the treatment period will tend to underestimate the apparent effect of seeding. The alternative is to use the regression relationship of Appendix B to adjust the readings at the new site to the old. In view of the uncertainties involved, we decided to pursue a conservative course of action and to make no adjustments.

TABLE 2
NUMBER OF STATION-MONTHS* EDITING NECESSARY PRIOR TO REGRESSION ANALYSIS

Stn	Base Period (1960-1984; 130 months)	Project Period (1985-1989; 25 months)
	Control Stations	
Midland	0	0
Penwell	6	0
McCamey	1	0
Bakersfield	1	0
Sheffield	17	2
Ozona	3	0
Sonora	0	3
	Target Stations	
Garden City	1	0
Sterling City	4	5
Water Vly	0	0
Water Vly 10NNE	4	1
Cope Ranch	0	0
Funk Ranch	3	0
San Angelo	0	0
Mertzon	9	1 (record ends in 1987)
Mertzon 10 NE	-	0 (1987 through 1989)
Eldorado**	2	0

* A station is said to have one station-month of editing, if the record for only one day or as many as all days for that month was (were) missing.

** The record for Eldorado included Eldorado 11NW from 1960 through most of 1981 and Eldorado 2SE from September 1981 through the project period.

A listing of the data used for this preliminary analysis of seeding effect appears in Table 3, which appears on the next page. These are the input data for the regressions to be discussed in the next section. Documentation of all data editing and interpolations is presented in Appendix A.

4.2 Results

A listing of the regression equations relating target to control rainfalls and the resulting correlation coefficients is presented in Table 4. Note that the correlations range from a maximum of 0.84 to a minimum of 0.58. The overall target vs control correlation is 0.77. A complete correlation matrix among all stations can be found in Appendix C.

It must be emphasized that no search was made to find the "best" stations or "best grouping of stations" for this analysis. Such a search must have a physical basis, and we could find no physical reason to modify our initial selection of stations. In truth, we have used all of the candidate control stations that had a long-term rainfall record. In the case of the target stations, we used all stations within the target that had a complete or nearly complete record for the period of analysis.

TABLE 4

REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS
RELATING TARGET TO CONTROL RAINFALLS
FOR THE SAN ANGELO RAIN ENHANCEMENT PROGRAM
(Period of Record 1960 through 1984)

	Correlation Coefficient	Equation
Control vs Target	0.77	$T_R = 3.67 + 0.814C_R$
Control vs Garden City	0.65	$G_R = 3.83 + 0.738C_R$
Control vs Sterling City	0.64	$S_R = 4.32 + 0.774C_R$
Control vs Cope Ranch	0.66	$C_R = 4.03 + 0.735C_R$
Control vs Water Valley	0.63	$(WV)_R = 4.19 + 0.826C_R$
Control vs Water Valley 10NNE	0.60	$(WV^*)_R = 4.64 + 0.806C_R$
Control vs Funk Ranch	0.67	$F_R = 3.75 + 0.817C_R$
Control vs San Angelo	0.63	$(SA)_R = 2.70 + 0.832C_R$
Control vs Mertzon	0.58	$M_R = 4.51 + 0.734C_R$
Control vs Eldorado	0.84	$E_R = 1.05 + 1.067C_R$

11.52

TABLE 3

THE SAN ANGELO RAIN ENHANCEMENT PROGRAM

MAY TO SEPTEMBER YEARLY RAINFALLS FOR TARGET AND CONTROL STATIONS

	Control Stations							Target Stations									
								Pre-Treatment Period									
Yr	MAF	Pnwll	McCmy	Bkrsfld	Ozona	Sonora	Mean	Grdn Cty	Strlng Cty	Wtr Vly	Wtr Vly 10NNE	Cope Rnch	Fnk Rnch	SJT	Eldrdo	Mrtzon	Mean
60	7.81	7.86	8.21	6.90	7.09	5.13	7.17	8.17	6.53	6.20	5.43	6.21	7.19	5.24	5.23	4.98	6.14
61	15.65	5.21	5.65	3.82	13.98	11.97	9.38	17.33	16.42	12.01	18.45	12.21	16.52	13.23	17.84	17.77	15.75
62	10.81	9.74	5.55	6.66	4.94	12.43	8.36	9.45	8.35	4.91	4.66	6.83	6.87	5.40	9.00	6.16	6.85
63	8.03	7.15	6.17	6.66	6.55	8.47	7.17	8.70	8.88	7.75	9.97	10.20	8.91	9.37	7.87	9.52	9.02
64	5.55	3.83	12.23	5.67	9.17	16.29	8.79	9.78	13.58	8.53	8.34	9.38	7.47	5.19	9.19	8.51	8.88
65	8.01	6.95	8.35	6.08	9.34	9.57	8.05	10.75	14.73	11.09	14.89	14.40	9.91	9.82	7.86	8.05	11.28
66	12.60	8.18	8.33	11.12	12.72	10.21	10.53	6.53	11.70	13.13	11.76	11.52	15.72	10.42	14.68	11.82	11.92
67	5.13	8.27	6.74	6.90	7.39	12.26	7.78	10.96	13.93	13.13	12.48	16.01	13.47	13.55	12.52	13.42	13.28
68	10.48	8.67	11.29	9.82	12.26	10.33	10.48	11.07	9.04	9.96	9.85	5.91	12.02	11.60	10.33	9.41	9.91
69	8.55	5.47	7.41	8.08	10.92	8.26	8.12	12.00	15.86	15.23	11.80	7.12	14.48	12.78	10.34	9.56	12.13
70	4.27	5.03	8.65	10.66	6.19	8.73	7.26	9.02	6.38	7.07	9.63	8.07	8.11	6.97	9.81	7.94	8.11
71	10.45	11.16	7.06	9.16	22.75	18.73	13.22	14.01	15.84	19.19	19.90	11.01	17.12	16.70	16.77	22.13	16.96
72	8.33	11.44	11.15	11.14	19.62	20.99	13.78	14.84	17.22	16.06	20.38	14.64	16.20	18.23	13.65	14.69	16.21
73	5.02	6.31	5.42	10.37	10.69	11.23	8.17	6.53	6.95	12.03	13.62	7.72	15.00	9.82	11.11	9.65	10.27
74	11.94	12.11	18.38	29.73	20.83	23.30	19.38	13.26	16.41	18.20	20.80	17.41	19.24	15.01	22.12	17.62	17.79
75	18.34	13.26	11.13	11.70	9.48	14.10	13.00	16.39	15.50	15.21	13.91	15.87	11.76	12.87	10.96	12.35	13.87
76	8.87	8.90	11.37	16.94	17.10	24.08	14.54	16.80	14.74	14.60	12.52	18.17	12.33	11.76	19.38	12.41	14.75
77	2.27	4.39	4.79	3.94	5.85	7.03	4.71	6.95	7.01	10.28	10.06	10.49	6.22	3.78	6.29	5.11	7.36
78	11.66	10.06	15.70	15.29	9.10	15.94	12.96	9.35	12.70	13.79	11.17	14.19	8.10	9.33	15.37	10.27	11.59
79	9.42	7.23	5.85	7.31	8.96	8.77	7.92	12.49	6.85	9.24	9.83	12.54	10.48	6.36	9.36	7.54	9.41
80	14.07	13.30	10.29	8.56	11.94	14.00	12.03	19.05	17.43	22.58	17.42	14.15	20.01	22.49	13.07	17.20	18.16
81	8.08	5.39	7.01	7.29	10.61	13.95	8.72	9.27	11.75	11.56	11.50	11.91	9.42	13.30	7.80	16.14	11.41
82	9.95	7.58	2.73	7.47	6.88	8.56	7.20	10.30	14.89	17.83	18.08	10.76	9.18	11.08	8.26	16.11	12.96
83	1.74	2.15	1.72	2.05	5.01	6.13	3.13	2.19	5.84	7.43	7.84	5.28	5.34	5.45	5.97	8.81	6.02
84	10.73	11.43	8.03	7.63	5.53	6.06	8.24	7.59	5.28	6.12	5.31	5.31	8.77	7.21	7.57	11.83	7.22
								Treatment Period									
85	8.08	7.29	10.00	7.20	15.63	11.98	10.03	13.58	11.82	9.70	9.51	10.70	12.39	12.54	12.02	22.08	12.70
86	19.49	17.36	12.88	7.07	13.88	18.67	14.89	13.90	17.88	20.26	28.65	31.34	15.92	21.35	15.65	18.00	20.33
87	9.32	12.49	9.99	15.00	13.50	15.03	12.56	11.02	16.05	20.30	21.51	10.40	14.37	20.51	17.63	13.29*	16.12
88	16.49	10.83	7.88	8.41	15.30	13.92	12.14	18.13	15.79	13.35	12.78	14.11	12.57	10.79	15.26	24.49*	15.25
89	5.87	6.65	5.29	5.91	3.39	3.95	5.18	10.14	7.70	13.19	13.51	3.67	7.33	9.84	7.70	11.19*	9.36

* The gage totals for 1988 through 1989 are from Mertzon 10NE (see Appendix A for details)

The equations of Table 4 were used to predict the overall target rainfalls and the rainfall at each target station for each of the five years of seeding operation. The results in terms of ratios of observed to predicted rainfalls are presented in Table 5 and in terms of differences between observed and predicted rainfalls (units: inches) are presented in Table 6. If seeding has increased the rainfall during the program, there should be a preponderance of ratios and differences > 1. That they do, in fact, exceed 1 does not of itself prove the effectiveness of seeding in increasing rainfall. It is, however, a big step in that direction.

TABLE 5

RATIOS OF OBSERVED TO PREDICTED RAINFALLS FOR TARGET STATIONS
BY YEAR AND FOR ALL FIVE YEARS OF OPERATIONAL SEEDING

Station	1985	1986	1987	1988	1989	All Years
Grdn Cty	1.21	0.94	0.84	1.42	1.33	1.12
Strlng Cty	0.98	1.13	1.14	1.15	0.93	1.07
Wtr Vly	0.78	1.23	1.39	0.94	1.56	1.16
Wtr Vly 10NNE	0.75	1.72	1.46	0.89	1.53	1.28
Cope Ranch	0.94	2.09	0.78	1.09	0.47	1.16
Funk Ranch	1.04	1.00	1.03	0.92	0.92	0.99
San Angelo	1.14	1.41	1.56	0.84	1.40	1.27
Mertzon	1.86	1.17	0.97	1.82	1.35	1.42
Eldorado	1.02	0.92	1.22	1.09	1.17	1.07
Target	1.07	1.29	1.16	1.13	1.19	1.17

TABLE 6

DIFFERENCES BETWEEN OBSERVED AND PREDICTED RAINFALLS FOR TARGET STATIONS
BY YEAR AND FOR ALL FIVE YEARS OF OPERATIONAL SEEDING
(Units are inches)

Station	1985	1986	1987	1988	1989	All Years (avg.value)
Grdn Cty	2.35	-0.92	-2.08	5.34	2.49	1.43
Strlng Cty	-0.25	2.05	2.02	2.09	-0.62	0.93
Wtr Vly	-2.77	3.77	5.74	-0.87	4.72	2.12
Wtr Vly 10NNE	-3.21	12.01	6.75	-1.64	4.69	3.77
Cope Ranch	-0.70	16.37	-2.86	1.16	-4.17	2.96
Funk Ranch	0.45	0.00	0.36	-1.10	-0.65	-0.18
San Angelo	1.50	6.26	7.36	-2.01	2.83	3.19
Mertzon	10.21	2.56	-0.44	11.07	2.88	5.26
Eldorado	0.27	-1.29	3.18	1.26	1.12	0.91
Target Average	0.87	4.54	2.23	1.70	1.47	2.16

The real challenge is interpreting the results of Tables 5 and 6. The regression equations for individual stations have correlations that range between 0.84 and 0.58, so they are not perfect predictors of target rainfalls. It would be a mistake, therefore, to interpret the results of Tables 5 and 6 as proving that seeding either increased or decreased the rainfall at a particular station in a particular year.

Overall impressions, however, may have validity. Approaching the results in this way, one notes immediately that there is a preponderance of ratios and differences > 1 in both tables. This is especially true for the stations closest to San Angleo (i.e. San Angelo and Mertzon), where most of the seedings took place (see Figure 3), and for all years combined. The overall target variable has ratios and differences > 1 for all 5 years of operation. Assessment of the significance of this result is possible if one views the result for a particular year as a random event, much like the flip of a coin. The probability that a particular year will have a target ratio or a rainfall difference > 1 is 1/2 or 50%. This is the same probability of obtaining "heads" (or "tails") upon a single flip of the coin. The probability of two years in a row > 1 is 25%. Finally, the probability that 5 years in a row will be > 1 is about 3% (i.e. $(0.5)^5$). Thus, there are 3 chances in 100 that the results for the San Angelo operational seeding program are due to chance and a 97% probability that they are due to seeding intervention.

Figure 5 shows a "scatter plot" of the seasonal (May through September) target and control values that went into the base period regression. In addition, the points for the five seeded seasons have been added to the plot (i.e. the larger dark circles). Note that all five points lie above the base-period regression line. Further, there is no obvious relationship between the size of the effect and the amount of control rainfall. This is in contrast to the results for the CRMWD effort (see Jones, 1985 and 1988) in which the effect of treatment seemed to increase with an increase in the control rainfall.

These results certainly suggest an overall effect of seeding of about +17% for the target for all years of operation. In addition, the area closest to San Angleo had apparent overall effects ranging between 27% and 42%. The mean increases in rain amount for this region closest to the San Angelo reservoirs average between 3 and 5 inches per season (May through September).

Plots of the all-years results of Tables 5 and 6 are provided in Figures 6a and 6b. The obvious "clinker" in the results are the ratio and rain-difference values for Funk Ranch. No effect, either positive or negative, is indicated at this site, even though the stations around it suggest appreciable effects of seeding. We have no explanation for the results for this station at this time. It certainly is an anomaly, but such anomalies are not ususual for this type of analysis.

4.3 Sensitivity Tests

Sensitivity tests are an important component of any analysis. To test the sensitivity of the San Angelo results the following procedure was applied:

1. The 25-year base period (1960-1984) was divided into five 5-year blocks.

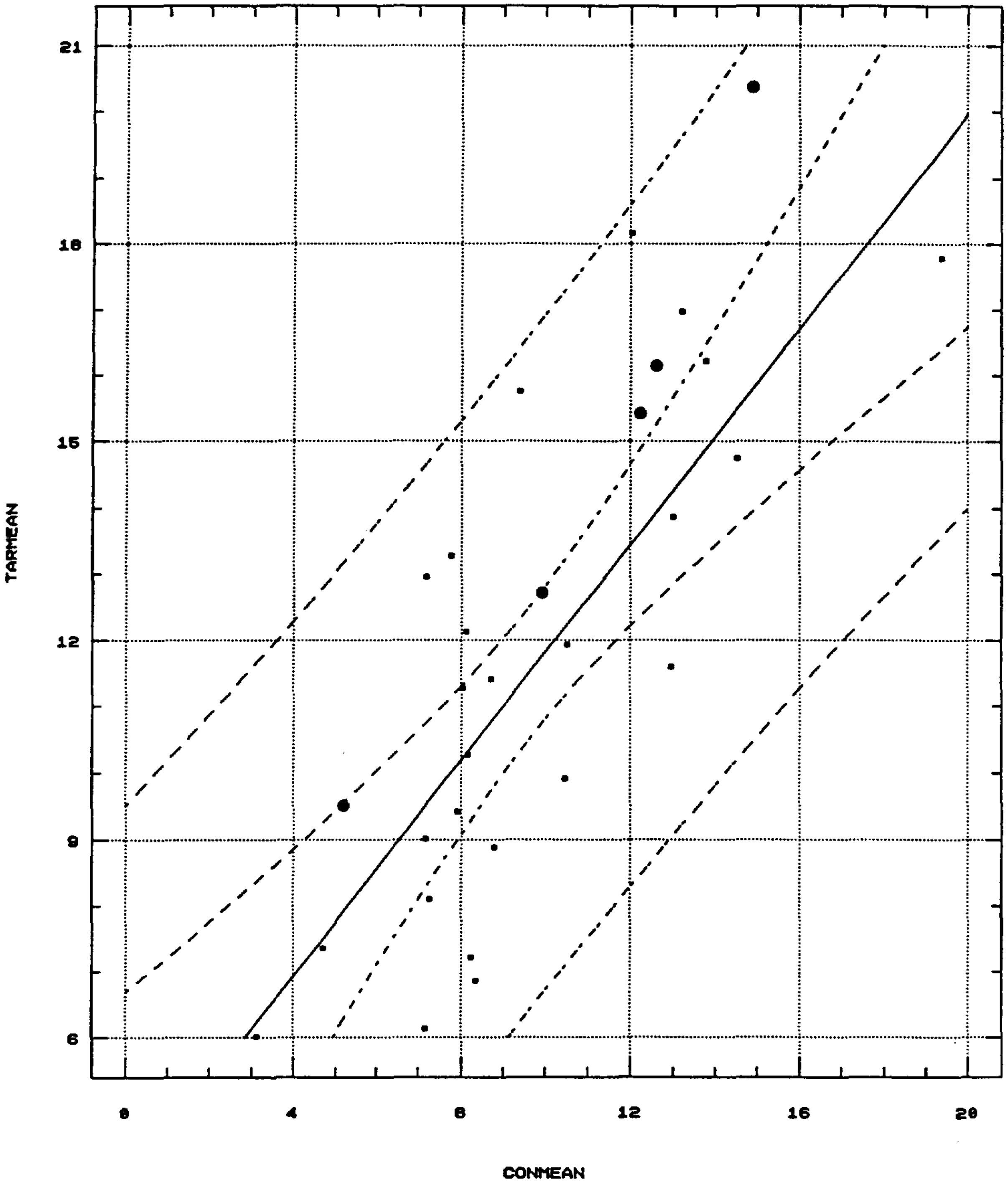

Figure 5 Scatter plot between the seasonal (May through September) mean control and mean target rainfalls for the base period 1960 through 1984. The solid line is the least-squares best fit. The dashed lines are 90% and 95% confidence intervals. The values for the five seeded seasons are plotted as large black dots.

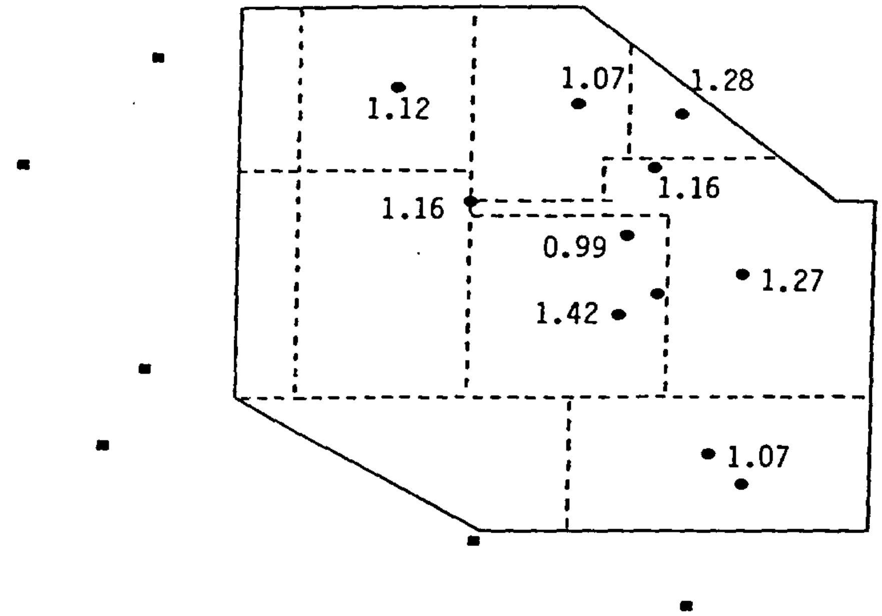

Figure 6a Ratios of observed to predicted rainfalls for target stations for all five years of operational seeding.

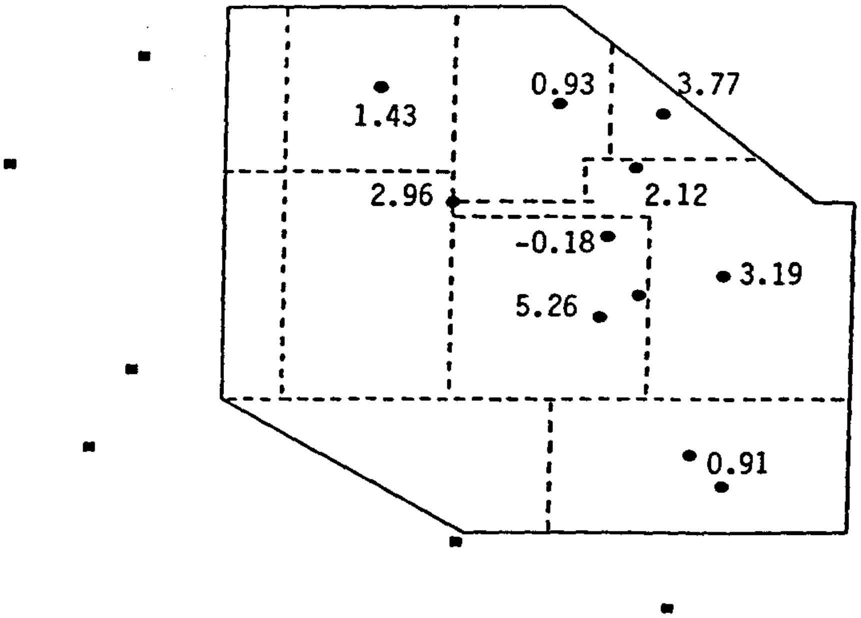

Figure 6b Differences between mean observed and mean predicted seasonal rainfalls for the target stations. The values are in inches.

2. Linear regression equations relating control to target rainfalls were derived for the five 20-year base periods. With the derivation of each regression equation, a 5-year period was set aside as a hypothetical period of seeding. As an example, the period 1965 through 1984 was used to derive the target vs. control relationship and the period 1960 through 1964 was set aside as a period of hypothetical seeding.

3. A seeding effect was then calculated for each 5-year period of hypothetical seeding and for the 5-year period (1985 through 1989) of actual seeding. The "seeding effects" were then compared.

If seeding indeed has been responsible for increased rainfall, one would expect the apparent seeding effect to be evident in each of the five sensitivity tests. Further, one would expect the apparent effect in the period of actual seeding, to be greater than the "effect" for each 5-year period of hypothetical seeding. These expectations are realized as is obvious by examining the presentation in Table 7.

TABLE 7

APPARENT SEEDING EFFECTS[1] IN PERIODS OF ACTUAL AND HYPOTHETICAL SEEDING

Base Period	Regression Equation	Hypothetical Seed Period	Seeding Effect	Actual Seed Period	Seeding Effect
1965-1984	$Y = 4.52 + 0.754X$ $r = 0.805$	1960-1964	0.87	1985-1989	1.15
1960-1964 + 1970-1984	$Y = 3.03 + 0.862X$ $r = 0.804$	1965-1969	1.09	1985-1989	1.18
1960-1969 + 1975-1984	$Y = 3.79 + 0.797X$ $r = 0.656$	1970-1974	1.02	1985-1989	1.18
1960-1974 + 1980-1984	$Y = 3.32 + 0.876X$ $r = 0.753$	1975-1979	0.90	1985-1989	1.14
1960-1979	$Y = 3.66 + 0.788X$ $r = 0.784$	1980-1984	1.13	1985-1989	1.20
1960-1984	$Y = 3.67 + 0.814X$ $r = 0.765$	---------	----	1985-1989	1.17

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[1] The seeding effect is defined as the ratio of observed to predicted rainfall for particular period of real or hypothetical seeding.

Note that in each 5-year period, the apparent effect of actual seeding for the years 1985 through 1989 exceeds the "effect" in each 5-year period of hypothetical seeding. In every instance the ratio of observed to predicted rainfall for the actual period of seeding is > 1, while only three of the five years is > 1 for the period of hypothetical seeding.

The "effect" of hypothetical seeding in the period 1980 through 1984 presents the biggest challenge to the period of actual seeding with a ratio of observed to predicted rainfall of 1.13 as compared to 1.20 for the actual seeding period. A year-by-year closer look produced ratios of observed to predicted rainfalls for the period of hypothetical seeding of 1.30, 1.08. 1.39, 0.98, and 0.71. The ratios for the actual period of seeding are 1.10, 1.32, 1.20, 1.15 and 1.21. Again, all of the yearly ratios are > 1 for the actual seeding period, whereas only three of the five yearly ratios are > 1 for the period of hypothetical seeding. As discussed earlier in the text, the probability of obtaining ratios > 1 five years in a row is only about 3%, suggesting that seeding might have been responsible for the apparent effect. On the other hand, the probability of obtaining three of five ratios > 1, as is the case for the 5-year period of hypothetical seeding, is about 13%.

This sensitivity analysis supports the interpretation that AgI seeding is responsible for the apparent increases of rainfall over the San Angelo watershed for the period 1985 through 1989. It does not, however, prove that is the case. Only by evaluating all of the evidence might one be justified in reaching such a conclusion.

5.0 DISCUSSION

Given that seeding has increased the rainfall over the San Angelo watershed, the question becomes how the increases were produced. A good start to answering this question are the research results presented by Rosenfeld and Woodley (1989), which show that seeding doubled the rainfall from individual convective cells (i.e. increases of over 100%. Because convective cells are the building blocks of all convective weather systems, there is every reason to expect that an effect that begins on the scale of the building block of a rain system will be manifested on the scale of the system itself.

It must be pointed out, however, that Rosenfeld and Woodley (1989) were not able to explain completely how the cell rain increases were produced in West Texas. It did not appear to be the "classic" dynamic-seeding response whereby the AgI-treated cell first grew explosively in the vertical before expanding laterally. Although the seeded cells were slightly taller (5 to 10%) in the mean than those cells that did not receive treatment, vertical growth of the cells was not the dominant response. Expansion and merger of the seeded cells appear to have been more important. How this took place is not known at this time.

Rosenfeld and Woodley (1989) noted several other apparent effects of seeding that are of relevance to the interpretation of the San Angelo operational seeding effort. Their seeded cells showed at least two growth pulses during their lifetimes, while those that were not seeded typically pulsed only once. This means that the seeded cells lasted longer than the unseeded cells. This suggests that dynamic effects were operative.

On the other hand, there was a stronger "bright band" phenomenon near the freezing level in the AgI treated cells. This suggests more snow crystals with slower fall velocities in the seeded clouds relative to the unseeded clouds. This implies that static effects were operative in the seeded cells as well.

Based on the Rosenfeld and Woodley (1989) study, therefore, it seems likely that the response of the treated clouds in the San Angelo program was a mixture of static and dynamic effects. This makes sense, and it may explain why apparent seeding effects were evident in 1988 when most of the seeding was done at cloud base. Such seeding is normally used to produce static effects, although, as discussed earlier, one could certainly make the case that the high-output seeding generators used by North American Weather Consultants in 1988 may have produced dynamic effects as well. When conducting base seeding in regions of strong updraft, it is likely that fairly high concentrations (i.e. $> 100\ l^{-1}$) of nuclei were carried upward in the strong updraft cores. Such concentrations of nuclei might have produced the rapid glaciation thought necessary for dynamic effects.

Without supporting physical measurements, one must be content with the circumstantial evidence for increased rainfall in the San Angelo program. Although this evidence is strong, it is not conclusive. The apparent positive effects in each of the five years of the program certainly suggest an effect of seeding. That the area of greatest apparent effect nearly coincides with the region that received the most seeding is a strong indicator of seeding effects. Finally, the finding that seeding effects are indicated after sensitivity testing also supports an interpretation of positive seeding effects in the San Angelo program.

More research is needed under the auspices of the Southwest Cooperative Program (SWCP) to resolve these important uncertainties. In the current austere funding situation it is not clear when such studies will be funded. In the interim, the results of the San Angelo Rain Enhancement Program appear to justify continued use of this cloud seeding technology to enhance rainfall in West Texas. If the increases in rainfall are indeed on the order of 3 to 5 inches per season over the San Angelo watershed to the immediate west and southwest of the city, it would be foolish not to continue the seeding program.

The benefit to cost ratio of such an effort should be enormous. The cost of the current seeding program has averaged about $200,000 per year while the increase in water volume over the half-circle having a radius of 30 n.mi. to the west of San Angelo is on the order of 300,000 acre-feet (assuming an increase of about 3 inches over the area). Even if an acre-foot of water were worth only about $10, the benefit to cost ratio would exceed 10 to 1. Much of this increased water supply does not, however, reach the reservoirs serving San Angelo. Some of it undoubtedly goes to groundwater, to evaporation and to greening the rangeland and watering the trees within the watershed. Exactly what happens to the apparent increases in rainfall from seeding is beyond the scope of this study. It is certainly worthy of further study.

6.0 CONCLUSIONS

Upon assessing all of the evidence, we conclude that seeding has increased the rainfall over the San Angelo watershed. Among all the factors considered, we consider the following most convincing:

1. In the statistical analysis an apparent positive seeding effect is evident in each of the five years of operational seeding. The probability of this happening by chance is 3%. The apparent overall area-wide effect is +17%.

2. The apparent effect of seeding is strongest over regions where most of the treatment took place during the 5-year program, especially near and to the west (upstream) of the reservoirs serving San Angelo.

3. The apparent effect of seeding is still evident after sensitivity testing.

4. The results of research to date within the context of the Southwest Cooperative Program (SWCP) indicate that seeding in West Texas is effective in increasing the rainfall from individual convective cells by over 100% and that seeding promotes the merger of adjacent clouds, leading to larger and longer-lasting raining clouds. There is good reason to expect, therefore, that seeding will produce operational increases in rainfall.

5. Analysis of the 18-year operational cloud seeding program of the Colorado River Municipal Water District (CRMWD) indicates that seeding has increased the rainfall by about 11%. This result is consistent with the results of the San Angelo program.

The overall apparent effect of seeding (May through September) for the five years of seeding operation is +17%. This result has high statistical significance. In the area closest to the storage reservoirs the apparent effect of seeding ranges between 27% and 42%, amounting to 3 to 5 inches of additional rainfall per year of operation.

7.0 ACKNOWLEDGEMENTS

This report is dedicated to Mr. Stephen Brown, Manager of the City of San Angelo, whose vision and perseverance made this program possible. The results of this 5-year seeding effort indicate that his faith has been well-founded.

We thank also Mr. Art Talamantes, Meteorologist In Charge of the San Angelo Office of the National Weather Service, for his help and that of his forecasters (Jim Boyd, Bud Canfield, Jim Maxwell and Matt Sena). Whenever data and/or a forecast consultation was needed, they were there to help.

We also want to acknowledge that some of the analyses pursued in this report are based on initial analyses by Messrs. Girdzus, Griffith and Risch of North American Weather Consultants that were presented in their 4-year series of contract reports to the City of San Angelo. These contract reports are cited in the reference section of this report. We also appreciate the encouragement offered by Tom Henderson, President of Atmospherics, Inc., during the course of this study.

In addition, we recognize the efforts of Richard Jackson with the San Angelo raingage network. His efforts were valuable in evaluating the program, as is obvious when reading this report.

Finally, we thank Mr. George Bomar for his critique of this report. His comments were most helpful during its revision phase.

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APPENDIX A

DOCUMENTATION OF STATION DATA EDITING PRIOR TO REGRESSION ANALYSIS

This Appendix provides documentation of the editing and interpolations that were necessary to fill in gaps in the station rainfall records for the base period (1960 through 1984) and for the period of seeding operation (1985 through 1989). The records for four stations (Midland, Cope Ranch, Water Valley and San Angelo) are complete and required no data interpolations.

MIDLAND

The station record for Midland is complete for the period 1960 through 1989.

PENWELL

1. A total of 30 days were missing from August and September 1963. The missing records were estimated by summing the rainfall totals for the missing days at Midland and at Bakersfield and then using these summed values to interpolate a value for Penwell for the missing days. This summed interpolated value (1.18 in.) was then added to the existing observations at Penwell for August and September 1963 to provide totals for the two months. Five-month totals (i.e. May through September) were then calculated.

2. The record for September 10 through 30, 1965 was missing. As in 1. above, the records for Midland and Bakersfield were used to obtain the summed interpolated rainfall (0.67 in.) for Penwell for the missing days.

3. The record for September 9 through 30, 1966 was missing. The protocol described in 2. above was used to obtain an interpolated value of 0.69 in. for the missing period.

4. The records for August and September 1971 were missing. The monthly records for Midland and Bakersfield were used to interpolate the missing total (5.74 in.) for Penwell.

MCCAMEY

1. The record for July 1980 was missing. The missing monthly value was interpolated from the July 1980 values for Midland and Bakersfield. The interpolated value was 0.06 in.

BAKERSFIELD

1. The record for May 1971 and all but the last 4 days of June 1971 were missing for Bakersfield. The monthly records for McCamey and Sheffield (except for the last 4 days of June) were used to interpolate a value of 2.25 in.

OZONA

1. The record for the period 1 July through 8 August 1978 is missing for Ozona.

Sheffield and Sonora were used to interpolate a summed rainfall value for the missing period. The interpolated value is 1.21 in.

2. The record for May 1983 was missing. As in 1. above, Sheffield and Sonora were used to interpolate the missing monthly value. The interpolated value is 1.81 in.

SONORA

1. The period from 18 through 31 August 1985 is missing. The record for Ozona and for Humble Pump was used to interpolate the rainfall for the missing period. The interpolated rainfall is 0.17 in.

2. The period from 8 through 14 September 1987 is missing. The record for Ozona and Humble Pump was used to interpolate the rainfall for the missing period. The interpolated rainfall is 0.33 in.

3. The following periods are missing in 1988: 15 through 19 May, 3 June and 25 through 28 June, and September 16. Humble Pump and Ozona were used to interpolate the missing values.

GARDEN CITY

1. July 1982 is missing from the record for Garden City. The records for Midland and Sterling City for July 1982 were used to interpolate a value of Garden City. The interpolated value is 1.80 inches.

STERLING CITY

1. September 1963 is missing from the Sterling City record. The records for Garden City and Water Valley for September 1963 were used to interpolate a value of 0 in. for Sterling City.

2. May 1961 is missing from the Sterling City record. The records for Garden City and Water Valley were used to interpolate a value of 2.88 in. for May 1961 for Sterling City.

3. Fifteen days are missing from the September 1963 record for Sterling City. The records for Garden City and Water Valley were used to interpolate values for the missing days. The interpolated value is 0.36 in.

4. Two days in August 1984 are missing from the Sterling City record. Readings from Garden City and Water Valley were used to interpolate values for the missing days. The missing values are 0.

5. The record for May through September 1986 for Sterling City is missing. The readins for these months for Garden City and Water Valley were used to obtain a May through September value for Sterling City. The interpolated value is 17.88 in.

WATER VALLEY

The station record for Water Valley is complete for the period 1960 through 1989.

WATER VALLEY 10NNE

1. Fourteen days are missing from the July 1962 record for Water Valley 10NNE. The records for Water Valley and Robert Lee were used to interpolate values for the missing 14 days. The summed interpolated value is 0.63 in.

2. The record for June and July 1964 is missing from the record for Water Valley 10NNE. The records for Water Valley and Robert Lee were used to interpolate values for the missing two months. The summed interpolated value is 1.04 in.

3. The record for September 1965 is missing from the record for Water Valley 10NNE. The records for Water Valley and Robert Lee were used to interpolate a value for the missing month. The interpolated value is 1.78 in.

4. The record for September 1970 is missing from the record for Water Valley 10NNE. The records for Water Valley and Robert Lee were used to interpolate a value for th missing month. The interpolated value is 2.87 in.

5. June 17, 1985, is missing from the record for Water Valley 10NNE. The records for Water Valley and Robert Lee were used to interpolate a value of 0.65 in. for the missing day.

COPE RANCH

The station record for Cope Ranch is complete for the period 1960 through 1989.

FUNK RANCH

1. The record for May 1966 is missing from the record for Funk Ranch. The records for Cope Ranch and San Angelo were used to interpolate a value of 1.65 in. for the missing month.

2. The record for August 1971 is missing from the record for Funk Ranch. The records for Cope Ranch and San Angelo were used to interpolate a value of 6.14 in. for the missing month.

3. The record for July 1975 is missing from the record for Funk Ranch. The records for Cope Ranch and San Angelo were used to interpolate a value of 2.21 in. for the missing month.

SAN ANGELO

The station record for San Angelo is complete for the period 1960 through 1989.

MERTZON

1. Twenty-eight days are missing from July and August 1963. The records for Funk Ranch and for Eldorado 11NW were used to interpolate values for the missing days. The interpolated value is 1.92 in.

2. The record for Mertzon for July 1965 is missing. The records for Funk Ranch and for Eldorado 11 NW were used to interpolate a value of 5.63 in. for the missing record.

3. The record for Mertzon for August 1969 and one day in September 1969 are missing. The records for Funk Ranch and for Eldorado 11 NW were used to interpolate a value of 5.38 in. for the missing records.

4. The record for Mertzon for September 1970 is missing. The records for Funk Ranch and for Eldorado 11 NW were used to interpolate a value of 3.00 in. for the missing record.

5. The records for Mertzon for May and June 1971 are missing. The records for Funk Ranch and for Eldorado 11 NW were used to interpolate a value of 3.71 in. for the missing records.

6. The record for Mertzon for August 1972 is missing. The records for Funk Ranch and for Eldorado 11 NW were used to interpolate a value of 4.57 in. for the missing record.

7. The record for Mertzon for 5 days in June 1975 is missing. The records for Funk Ranch and for Eldorado 11 NW were used to interpolate a value of 0.27 in. for the missing record.

8. The record for Mertzon for 15 days in July 1983 is missing. The records for Funk Ranch and for Eldorado 2SE were used to interpolate a value of 0.05 in. for the missing record.

9. The record for Mertzon for 18 days in July and September 1984 is missing. The records for Funk Ranch and for Eldorado 2SE were used to interpolate a value of 4.06 in. for the missing period.

10. The record for Mertzon in June, July and September 1987 is missing. A second Mertzon station that is 10 mi. NE of Mertzon was used as an estimator of the rainfalls for the missing months.

11. The Mertzon station record was intermittent in 1987. The original Mertzon record was used for May and September 1987, and Mertzon 10NE was used for June, July and August of that year. Mertzon 10NE was used as an estimator of the Mertzon rainfalls in May through September in 1988 and 1989. A regression analysis that relates the Mertzon and Mertzon 10NE stations to one another is presented in Appendix B. According to the regression, use of the Mertzon 10NE station as an estimator of the Mertzon rainfall will tend to underestimate its rainfall. This, in turn, will tend to underestimte the apparent effect of seeding at this station.

ELDORADO 11NW and 2SE

1. The record for Eldorado 11NW ends after June 1981 and the new Eldorado station (i.e. Eldorado 2SE) was not yet in operation. The records for July and August 1981 at Ozona and Menard were used to interpolate a value of 3.41 in. for the missing Eldorado record. In September 1981 and thereafter, the new Eldorado station (Eldorado 2SE) was used for the Eldorado rainfall record.

2. In August and September 1989, Eldorado 2SE was not in operation. The readings from a project station installed in Eldorado proper were used for the missing months.

APPENDIX B

COMPARISON OF SEASONAL RAINFALL RECORDS FOR THE MERTZON SITES

This section describes the relationship between the rainfall records at two sites maintained near Mertzon, Texas, which were used in analyzing the operational seeding program conducted for the City of San Angelo from 1985 through 1989. Mertzon is located in a high priority portion of the overall project target area, about 30 mi. southwest of San Angelo and its reservoirs. Thus, it is an important site to the analysis.

The original Mertzon site record, dating from 1941, provided stable and fairly complete rainfall records for the pre-project (base) period used in the analysis. Unfortunately, its record ends on August 31, 1987, when the cooperative observer left the area. This circumstance jeapordized the analysis, since the seeded period included 1985 through 1989. However, investigation revealed that another individual, a now-retired FAA employee, has maintained quality rainfall records since 1977 at a site approximately 10 miles northeast of the original site. After some discussion with the "new" observer regarding the raingage type and its exposure, observation intervals and data logging procedures, as well as data completeness and availability, it was determined that the records would be suitable for use in the analysis.

Because of the interest in using the new records to preserve the continuity of the Mertzon record and because of the distance between the sites, the relationship between the sites had to be determined. Fortunately, the sites' periods of record overlap from 1977 through August 1987, allowing a quantative comparison. A simple linear regression was run using the two sites' data, employing season total values (May-September) from 1977-1984. Because seeding began over the watershed in 1985, the overlapping Mertzon records from 1985 through 1987 were not used in the comparisions to avoid the possibility of seeding contamination.

The comparison shows that the sites' seasonal data were reasonably well correlated ($r = 0.78$), but that the new site's values are consistently lower than those from the original site. The regression analysis yielded the equation $Y \text{ (orig)} = 1.66 + 1.091X \text{ (new)}$. As an example of the indicated difference according to the regression equation, a seasonal rainfall of 10 in. at the new site would correspond to an amount of 12.57 in. at the original.

As is discussed in the main text, the decision was made to adopt a conservative approach in combining the sites' records, using the new site's values with no adjustment, when the readings from the old site are no longer available. This obviously has the effect of reducing the apparent seeding effect at Mertzon. The relationship is documented here, so that others may apply it in their own assessments if desired.

APPENDIX C

CORRELATION MATRIX FOR BASE-PERIOD RECORDS

Sample Correlations

	YEAR	MIDLAND	PENWELL	McCAMEY	BKRSFLD	OZONA	SONORA	CONMEAN	GRDNCTY	STRLCTY	WTRVLYY	WV1ONNE	COPE	FUNK	SJT	ELDRDO	MERTZON	TARME
YEAR	1.0000 (25) .0000	-.0511 (25) .8084	.1418 (25) .4989	-.0533 (25) .8002	.1293 (25) .5378	-.0447 (25) .8322	.0389 (25) .8534	.0339 (25) .8720	-.0569 (25) .7872	-.0815 (25) .6984	.2929 (25) .1554	.1022 (25) .6270	.1051 (25) .6172	-.0547 (25) .7951	.1225 (25) .5596	-.0504 (25) .8110	.2378 (25) .2523	.08 (2 .68
MIDLAND	-.0511 (25) .8084	1.0000 (25) .0000	.6910 (25) .0001	.3823 (25) .0593	.3233 (25) .1150	.3492 (25) .0871	.2945 (25) .1530	.5985 (25) .0016	.6556 (25) .0004	.5138 (25) .0086	.4294 (25) .0322	.3624 (25) .0750	.3658 (25) .0721	.4960 (25) .0117	.4973 (25) .0114	.4733 (25) .0169	.4783 (25) .0156	.55 (2 .00
PENWELL	.1418 (25) .4989	.6910 (25) .0001	1.0000 (25) .0000	.5360 (25) .0057	.5414 (25) .0052	.4365 (25) .0291	.4743 (25) .0166	.7358 (25) .0000	.5676 (25) .0031	.4104 (25) .0416	.5143 (25) .0085	.3674 (25) .0708	.4403 (25) .0276	.5157 (25) .0083	.5904 (25) .0019	.4544 (25) .0225	.4466 (25) .0252	.55 (2 .00
McCAMEY	-.0533 (25) .8002	.3823 (25) .0593	.5360 (25) .0057	1.0000 (25) .0000	.7932 (25) .0000	.4923 (25) .0124	.6624 (25) .0003	.8209 (25) .0000	.4005 (25) .0473	.4125 (25) .0404	.3226 (25) .1158	.2450 (25) .2378	.4906 (25) .0128	.3462 (25) .0900	.3235 (25) .1147	.5864 (25) .0021	.1781 (25) .3944	.42 (2 .03
BKRSFLD	.1293 (25) .5378	.3233 (25) .1150	.5414 (25) .0052	.7932 (25) .0000	1.0000 (25) .0000	.5839 (25) .0022	.6846 (25) .0002	.8546 (25) .0000	.3085 (25) .1335	.3389 (25) .0975	.4383 (25) .0284	.4034 (25) .0456	.5297 (25) .0065	.4645 (25) .0193	.3467 (25) .0895	.7222 (25) .0000	.3200 (25) .1189	.50 (2 .01
OZONA	-.0447 (25) .8322	.3492 (25) .0871	.4365 (25) .0291	.4923 (25) .0124	.5839 (25) .0022	1.0000 (25) .0000	.7938 (25) .0000	.8084 (25) .0000	.5888 (25) .0020	.6519 (25) .0004	.6672 (25) .0003	.7537 (25) .0000	.5085 (25) .0094	.7793 (25) .0000	.6903 (25) .0001	.8059 (25) .0000	.6961 (25) .0001	.80 (2 .00
SONORA	.0389 (25) .8534	.2945 (25) .1530	.4743 (25) .0166	.6624 (25) .0003	.6846 (25) .0002	.7938 (25) .0000	1.0000 (25) .0000	.8631 (25) .0000	.5945 (25) .0017	.6589 (25) .0003	.5671 (25) .0031	.5778 (25) .0025	.7026 (25) .0001	.5270 (25) .0068	.5583 (25) .0037	.8021 (25) .0000	.5572 (25) .0038	.71 (2 .00
CONMEAN	.0339 (25) .8720	.5985 (25) .0016	.7358 (25) .0000	.8209 (25) .0000	.8546 (25) .0000	.8084 (25) .0000	.8631 (25) .0000	1.0000 (25) .0000	.6481 (25) .0005	.6402 (25) .0006	.6295 (25) .0007	.5959 (25) .0017	.6569 (25) .0004	.6700 (25) .0002	.6329 (25) .0007	.8430 (25) .0000	.5764 (25) .0026	.76 (2 .00
GRDNCTY	-.0569 (25) .7872	.6556 (25) .0004	.5676 (25) .0031	.4005 (25) .0473	.3085 (25) .1335	.5888 (25) .0020	.5945 (25) .0017	.6481 (25) .0005	1.0000 (25) .0000	.7557 (25) .0000	.6411 (25) .0006	.6170 (25) .0010	.6380 (25) .0006	.6497 (25) .0004	.7230 (25) .0000	.6009 (25) .0015	.5629 (25) .0034	.80 (2 .00
STRLCTY	-.0815 (25) .6984	.5138 (25) .0086	.4104 (25) .0416	.4125 (25) .0404	.3389 (25) .0975	.6519 (25) .0004	.6589 (25) .0003	.6402 (25) .0006	.7557 (25) .0000	1.0000 (25) .0000	.8168 (25) .0000	.7936 (25) .0000	.6937 (25) .0001	.6694 (25) .0003	.7844 (25) .0000	.6318 (25) .0007	.6915 (25) .0001	.89 (2 .00
WTRVLYY	.2929 (25) .1554	.4294 (25) .0322	.5143 (25) .0085	.3226 (25) .1158	.4383 (25) .0284	.6672 (25) .0003	.5671 (25) .0031	.6295 (25) .0007	.6411 (25) .0006	.8168 (25) .0000	1.0000 (25) .0000	.8537 (25) .0000	.6247 (25) .0008	.7703 (25) .0000	.8531 (25) .0000	.6160 (25) .0010	.7563 (25) .0000	.90 (2 .00
WVIONNE	.1022 (25) .6270	.3624 (25) .0750	.3674 (25) .0708	.2450 (25) .2378	.4034 (25) .0456	.7537 (25) .0000	.5778 (25) .0025	.5959 (25) .0017	.6170 (25) .0010	.7936 (25) .0000	.8537 (25) .0000	1.0000 (25) .0000	.6296 (25) .0007	.7724 (25) .0000	.7938 (25) .0000	.6530 (25) .0004	.7927 (25) .0000	.90 (2 .00
COPE	.1051 (25) .6172	.3658 (25) .0721	.4403 (25) .0276	.4906 (25) .0128	.5297 (25) .0065	.5085 (25) .0094	.7026 (25) .0001	.6569 (25) .0004	.6380 (25) .0006	.6937 (25) .0001	.6247 (25) .0008	.6296 (25) .0007	1.0000 (25) .0000	.4736 (25) .0168	.5416 (25) .0052	.6488 (25) .0005	.4626 (25) .0199	.73 (2 .00
FUNK	-.0547 (25) .7951	.4960 (25) .0117	.5157 (25) .0083	.3462 (25) .0900	.4645 (25) .0193	.7793 (25) .0000	.5270 (25) .0068	.6700 (25) .0002	.6497 (25) .0004	.6694 (25) .0003	.7703 (25) .0000	.7724 (25) .0000	.4736 (25) .0168	1.0000 (25) .0000	.8550 (25) .0000	.7426 (25) .0000	.7161 (25) .0001	.87 (2 .00
SJT	.1225 (25) .5596	.4973 (25) .0114	.5904 (25) .0019	.3235 (25) .1147	.3467 (25) .0895	.6903 (25) .0001	.5583 (25) .0037	.6329 (25) .0007	.7230 (25) .0000	.7844 (25) .0000	.8531 (25) .0000	.7938 (25) .0000	.5416 (25) .0052	.8550 (25) .0000	1.0000 (25) .0000	.5863 (25) .0021	.8111 (25) .0000	.90 (2 .00
ELDRDO	-.0504 (25) .8110	.4733 (25) .0169	.4544 (25) .0225	.5864 (25) .0021	.7222 (25) .0000	.8059 (25) .0000	.8021 (25) .0000	.8430 (25) .0000	.6009 (25) .0015	.6318 (25) .0007	.6160 (25) .0010	.6530 (25) .0004	.6488 (25) .0005	.7426 (25) .0000	.5863 (25) .0021	1.0000 (25) .0000	.6422 (25) .0005	.79 (2 .00
MERTZON	.2378 (25) .2523	.4783 (25) .0156	.4466 (25) .0252	.1781 (25) .3944	.3200 (25) .1189	.6961 (25) .0001	.5572 (25) .0038	.5764 (25) .0026	.5629 (25) .0034	.6915 (25) .0001	.7563 (25) .0000	.7927 (25) .0000	.4626 (25) .0199	.7161 (25) .0001	.8111 (25) .0000	.6422 (25) .0005	1.0000 (25) .0000	.84 (2 .00
TARMEAN	.0852 (25) .6856	.5535 (25) .0041	.5598 (25) .0036	.4256 (25) .0339	.5037 (25) .0103	.8029 (25) .0000	.7195 (25) .0001	.7658 (25) .0000	.8006 (25) .0000	.8901 (25) .0000	.9081 (25) .0000	.9050 (25) .0000	.7374 (25) .0000	.8702 (25) .0000	.9094 (25) .0000	.7967 (25) .0000	.8449 (25) .0000	1.00 (2 .00

Coefficient (sample size) significance level