Final Report
On EAA Contract No. 01-68-PC with Woodley Weather Consultants for Services: ASSESSMENT OF THE EFFECT OF CLOUD SEEDING IN THE EDWARDS AQUIFER TARGET DURING THE 1999,2000 and 2001 SEASONS

Submitted to:
The Edwards Aquifer Authority
By:

Dr. William L. Woodley, Ph. D., C.C.M., President
Woodley Weather Consultants
11 White Fir Court
Littleton, Colorado 80127
Tel.: (303) 979-7946; Fax: (303) 973-3446
e-mail: Woodley@compuserve.com
with Participation of
Dr. Daniel Rosenfeld, Professor
Hebrew University of Jerusalem
Jerusalem, Israel 91904

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EXECUTIVE SUMMARY

This is the Final Report from Woodley Weather Consultants (WWC) to the Edwards Aquifer Authority (EAA) under Contract 01-68-PC between WWC and the EAA. The has entailed a comprehensive evaluation of project operations for the 1999, 2000 and 2001 seasons, including the seeding flights, record-keeping and data management procedures. WWC has also made an assessment of the effect of seeding in and downwind of the EAA target using a new, objective, comprehensive, computer-based method of evaluating operational cloud seeding programs. Finally, daily gauge vs. radar rainfall comparisons were made for the new EAA gauge network for the 2001 season. The results of all activities are reported herein.

The operational review determined that project documentation and data handling were good during the 1999, 2000 and 2001 seasons. The documentary work by project personnel was done both on-site and at the headquarters of Weather Modification, Inc. (WMI) in Fargo, North Dakota. The evaluation of project operations involved flights by the first author on the seeder aircraft to observe seeding operations and a detailed examination of the flight logs and other documentary data. Although a few problems were detected as discussed herein, they were eliminated quickly once they were brought to the attention of project personnel. The seeding flights fell short of ideal for several reasons. First, on some days there were too many suitable clouds to be reached by the two seeder aircraft. Second, there were a number of instances when the aircraft were scrambled too late for the seeding of suitable clouds. Third, the seeding should have been pursued more aggressively on some days both in terms of the number of seeding passes per flight and in terms of the number of seeding flights conducted on highly suitable seeding days. Despite these problems, it appears that there was enough seeding to justify a search for seeding effects under the contract.

WWC made a major breakthrough under the contract in its efforts to develop an objective and comprehensive method of evaluating the operational cloud seeding programs on an area basis in Texas. The new procedures have been applied to the Edwards Aquifer project for the 1999, 2000 and 2001 seasons and the results are documented in considerable detail herein.

A. The Analysis Method Developed by Drs. Woodley and Rosenfeld

The new method makes use of NEXRAD 15-minute mosaic reflectivity data for all of Texas to estimate rainfall for the analysis units, using the reflectivity (Z) vs. rainfall rate (R) relationship ($Z = 300R^{1.4}$), which was published by Woodley et al. (1975) and is standard practice for rain estimation by the National Weather Service. Each analysis unit is a circle that has a radius of 25 km (covering 1,964 km^2) around the point at which an echo first reaches 40 dBZ. A second unit is defined when another echo reaches 40 dBZ at least 25 km from the first unit. Thus, by design some units may overlap in order to make certain that no echo escapes analysis. Radar-estimated rainfalls are determined for all units going back in time from unit definition to the time echo first appeared in the unit and then forward in time until all echo disappeared from the unit. All units move at the direction and speed of radar echoes in and around the unit as determined by an objective computer algorithm.

After the units on each day have been defined, the position and seeding actions of all project aircraft in Texas as a function of time are superimposed onto the unit maps. A seeding unit is one in which some silver iodide (AgI) was expended, regardless of the method of delivery (i.e., flares near cloud top and/or flares and/or burners at cloud base). The remaining non-seed units are eligible to serve as controls for seeded units through a complicated objective match process as long as the prospective control was always at least 25 km from the perimeter of a defined seed unit. Matching is done using the actual first-seed time as the reference. Only non-seed units on days with actual seeding are eligible to serve as seed matches.

In order to be considered a match, the prospective control unit at the time of simulated seeding must satisfy the following criteria: 1) its rain-volume rate (RVR) is within 25% of the RVR of the seed unit, 2) its maximum reflectivity is within 5 dBZ of the maximum reflectivity within the seed unit, and 3) the correlation between prospective control and seed unit RVRs in the 75 minutes prior to first seeding must be ≥ 0.60. An individual non-seed unit can serve as a control for more than one seeded unit as long as it satisfies the match criteria. Matching of seed and control units can be done for any time period, ranging from the day on which the seed unit was defined to an entire season or seasons. When matching within the day, the match of the weather experienced by both the seed and control units is very good, but as many as half of the seed units cannot be matched due to a lack of suitable controls. When matching within the season or seasons, all seed units can be matched with controls many times (100 matches per seed unit is not unusual), but the weather of each control match may not be well matched with the weather experienced by the seed unit. This problem can be mitigated to some extent by partitioning the data by the Index of Coalescence Activity (ICA), which was calibrated by the AVHRR satellite inferences of cloud microstructure, and then matching within each ICA partition.

Although this match process is objective and comprehensive, even perfect matches do not guarantee that inadvertent selection bias, favoring the seed units, has been eliminated from the analyses. It is possible that a knowledgeable seeding pilot might recognize cloud characteristics (e.g., exceptionally hard towers, strong cloud organization, etc.) immediately prior to first seeding that are not readily quantified by the existing match criteria. In such instances, bias favoring the seed units is a possibility.

The main advantages of this new method of analysis are: 1) it is computer-automated, permitting the analysis of virtually all of the seeding events in each project, ranging from isolated clouds to massive thunderstorm clusters and lines, 2) it is objective and comprehensive, eliminating potential human bias during the analysis phase, 3) the size of the analysis unit (presently 1,964 km^2) can be changed as can the match criteria and the analysis can be redone with the new parameters, 4) it makes the analysis of all projects possible and facilitates comparisons among projects, and 5) it makes possible the inference of seeding effects as a function of area size, cloud structure, unit age and rain activity at the time of initial seeding, and the method whereby the nucleant was delivered to the clouds

B. Results of Analyses

The correlations of the RVR of the seed units with the average RVR for the matched control units are excellent. The linear correlation coefficient for the seasonal matches for the Edwards Aquifer program is 0.997. All seed units were matched for this time frame. The inferred seeding effect for the 10 hours after seeding is +12%. This estimate of seeding effect may be biased negatively against an effect of seeding, however, because most of the control units for use as matches come on the wettest days with strongly forced convective echo activity. Thus, there would be a disproportionate number of wet no-seed units available to serve as matches.

When matching within ± 12 hours of the initiation of the seed units, the apparent seeding effect is +55%. Only 63% (i.e., 192 of 305 units) of the seed units could be matched, casting some doubt on the overall estimate of seeding effect. In order for more units to be matched in this time frame, the match criteria would have to be relaxed. This would be counterproductive. Conversely, if the match criteria were made even more stringent, even fewer seed units would be matched in the ± 12 hour time frame. Thus, this restricted analysis may not provide a realistic estimate of overall seeding effect.

The most realistic assessment of seeding effect is provided by sample-weighting the results of matches within the ICA partitions. The apparent effect of seeding for the 1999, 2000 and 2001 seasons by 10 hours after initial seeding for the Edwards program is +21%. This increased rain amount corresponds to a volumetric rain increase of 923 acre-feet per analysis unit.

Further analysis provided additional insights into the effects of seeding. The apparent effect of seeding in the Edwards program appeared to depend on the age of the unit when it was first seeded. Units more than 2 hours old when first seeded showed no response to seeding (i.e., S/C = 1.02), while those less than an hour old when first seeded showed a strong positive response to seeding of +51% (i.e., S/C = 1.51). Because 66% of the units seeded in the Edwards program were old cloud systems, it seems likely that the overall apparent seeding effect is relatively small because too many of the clouds were seeded too late in their lifetimes. This may be due to the movement of old cloud systems into the target, or it may indicate that the project meteorologist was too cautious in scrambling the cloud seeding aircraft for treatment such that the seeding pilots were too late in initiating seeding in many of the cloud systems.

The temporal response to seeding is also of considerable interest. Plots of seeded and control rainfalls as a function of time indicate that the greatest response came about an hour after the initial seeding in the unit. Although the response diminished with time, it seemed to persist in many cases for up to 8 hours. If the units are moving, this means that the effect of seeding is not limited to the boundaries of the target but rather extends outside the target downwind. Thus, those living outside a seeding target in a region that is normally downwind of the seeding activity are benefiting from the enhanced rainfall without having to pay for it.

The accuracy of the radar rainfall estimates relative to gauge measurements was determined for the 2001 season using 96 recording rain gauges operated by the EAA and other jurisdictions. The area averaged rainfall for the gauge network covering 11,796 km^2 was 10.11

in. and 6.49 in. in the period between May 4th and September 20th for the gauges and radar, respectively, giving a G/R ratio of 1.56. The G vs. R correlation was impressive at 0.922. These results suggest that the Z-R equation (i.e., $Z = 300R^{1.4}$), which performed well on a seasonal basis for the High Plains target in 1999 and 2002, underestimated the unit radar-estimated rain volumes by a factor of 1.56 or 56% in at least the 2001 season. Whether this applies to the 1999 and 2000 seasons is unknown, because G vs. R comparisons were not possible in this time period. A major plus is the finding that the errors relative to the rain gauges were fairly systematic, making it easy to adjust the larger-scale radar rainfall estimates to the gauge standard. The 2001 results did not come as a big surprise, because the Z-R relationship is known to underestimate rainfall from clouds with a maritime structure by as much as a factor of two. Considering the flow of tropical air from the Gulf of Mexico into the EAA target on some days, one would have expected the radar to underestimate the rainfall from clouds growing in that air mass.

Because the analysis involves S vs. C comparisons, it is unlikely that the radar vs. gauge differences affected the estimates of seeding effect, since the differences presumably applied to both the S and C samples. Assuming that the radar underestimated the rainfall by a factor of 1.56 for the 1999, 2000 and 2001 seasons, a conservative calculation of the benefit to cost ratio for the Edwards program is nearly 12 to 1. This ratio is based on 259 seeded units, an adjusted apparent rain increase of 923 acre-feet (i.e., 592 acre-feet x 1.56), an assumption that 75% of the enhanced rainfall reaches the ground, the value of an acre-foot of water is $100, and project costs of $1,517,100. This benefit to cost ratio may change with time depending on the suitability of the clouds for seeding, the competence of the project meteorologist and the expertise of the cloud seeding pilots. Comparable analyses are possible for all of the Texas seeding projects.

C. Assessment and Recommendations

In the Progress Report delivered by WWC to the EAA in January 2002, the following observations/recommendations were made:

"The results of the Edwards project to date warrant its continuation, although there is considerable room for improvement, particularly in initiating seeding at the time and place it will be most effective. The Edwards target seems too large for two seeding aircraft. Either the target size should be reduced or the number of seeding aircraft increased for maximum seeding effectiveness. If picking the former option, the seeding should be focused on the portion of the target where it will do the most good. With respect to the Edwards target this would appear to be in the recharge zone for the Edwards Aquifer in the western and northwestern portions of the target.

Additional recommendations, based on the analyses of the 1999 and 2000 seasons, are that the Edwards project should be more aggressive in the conduct of the seeding. More seeding should be done over longer time periods. Night seeding should be done, if it can be done safely and efficiently. Up to half the natural rainfall occurs at night during some months and it should not be ignored. More attention also should be focused on the project meteorologist and on the seeding pilots since project success begins with them. Continuity from one season to the next for these positions is highly desirable. Finally, project management should make a commitment to evaluate and document everything of consequence to ensure efficient seeding operations and high data quality."

Since then, the EAA governing board decided to continue its seeding program for the 2002 season by providing financial support to the South Texas and Southwest Texas operational seeding programs to seed the western portion of the EAA target, constituting the major recharge zone for the Edwards Aquifer. At this writing this transference of seeding responsibility appears to be going well. Even so, the observations made in January 2002 above still apply. The benefit to cost ratio after three seasons of cloud seeding of nearly 12 to 1, supports this action.

Upon considering this apparent benefit, the obvious recommendation is that the seeding program should continue, and the action for the 2002 season is consistent with this recommendation. It is not enough, however, to simply turn over the EAA seeding project to other entities without a commitment to stay involved in its conduct and evaluation.

The installation and activation in 2001 of the EAA recording rain gauge network was a major milestone for the seeding project and for the EAA overall, permitting documentation of systematic radar underestimation of the aquifer rainfalls by about 56%. Adjustment upward of the Edwards Aquifer radar rainfall estimates by 56% brought them into better agreement with rainfall estimates elsewhere in Texas. In addition, this adjustment facilitated a more realistic estimate of project benefits relative to its costs. This rain gauge network is now a major asset to the EAA and the resources needed to keep it in good working order should be expended.

Finally, it is recommended that the data generated by the EAA cloud seeding effort be used to relate radar-estimated, gauge-adjusted, target rainfalls to recharge of the Edwards Aquifer. This can be done in any time frame for areas of any size in the Edwards Aquifer. Knowing how the Aquifer responds to rainfall as a function of its intensity, duration, total amount, and location will make it possible to focus cloud seeding activities on the portions of the Aquifer that will be most beneficial. The development of rainfall vs. recharge relationships based on years of observations also will be valuable to the development of realistic hydrological models for the Edwards Aquifer.

1.0 INTRODUCTION

As of the 2001 summer season, ten cloud seeding projects for rain enhancement were in operation in Texas (Figure 1). One and perhaps two additional projects will be added in 2002. The history of the Texas operational cloud seeding programs is addressed in Appendix A, which was excerpted from the paper by Bomar et al., (1999). Dr. Woodley was its second author.

Everyone involved in these efforts agrees that the evaluation of seeding effectiveness in all the programs should have high priority. They understand that seeding efficacy must be demonstrated or the projects ultimately will end in disillusionment and controversy. Although considerable local and matching state funds have been expended to date to run these projects, very little state funding has been dedicated so far to their evaluation. The Texas Natural Resource Conservation Commission (TNRCC) did, however, provide "seed" funds via a competitive contract to Woodley Weather Consultants (WWC) for the development of new methods for the evaluation of non-randomized seeding projects. In addition, the TNRCC has awarded funds to the Texas Weather Modification Association (TWMA) for the development and use of assessment methods that make use of project TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting) radar data and assessment software. The monitoring responsibility for the WWC and TWMA contracts with the TNRCC was transferred to the Texas Department of Agriculture (TDA) in mid Fiscal Year 2001, and Mr. George Bomar, who had contract monitoring responsibility at the TNRCC, was transferred to the Texas Department of Licensing and Regulation (TDLR).

Two of the ten operational cloud seeding projects (i.e., High Plains and Edwards Aquifer) have expended project funds to evaluate their programs. Both analysis efforts were awarded to WWC via competitive contracts. This Progress Report provides an interim assessment of the Edwards Aquifer operational cloud seeding program for the 1999 and 2000 seasons by Woodley Weather Consultants (WWC) under Contract 01-68-PC with the Edwards Aquifer Authority (EAA). The work to date has involved a comprehensive evaluation of project operations, including the seeding flights, record-keeping and data management procedures and an assessment of the effect of seeding on rainfall in and downwind of the target using a new, objective, comprehensive, computer-based method of evaluating the operational cloud seeding programs in Texas.

2.0 EVALUATION OF PROJECT OPERATIONS

2.1 Documentation

Project success begins with careful documentation of all aspects of the program. Final documentation of the Edwards Aquifer program by private contractor Weather Modification, Inc. (WMI) of Fargo, North Dakota was very good for the 1999 and 2000 seasons. The same was found to be true for the High Plains cloud seeding program that had heavy WMI involvement. The credit for this circumstance must be shared by project personnel in Hondo, Texas and in Fargo, North Dakota. Regardless of where the credit should lie, it was possible to take the documentary CD-ROM for each season and recreate all aspects of project operations for each day. Not all of the Texas projects can say the same. The weather is documented textually and with a listing of key atmospheric parameters. What was done on each day and why is also documented in separate files. The flight information appears in yet another file that provides the cloud-pass and seeding information. Finally, GIF radar images at 10-min intervals round out the documentation. All of these products are in addition to the TITAN radar data that includes a temporal record of aircraft position and aircraft action.

The EAA activated its rain gauge network for the 2001 season. These data have been used for the gauge vs. radar rainfall comparisons that are reported in this Final Report. Mr. Jesse Mireles and other EAA personnel were responsible for recording and processing these rainfall data, and it appears that it was accomplished successfully.

2.2 Data Handling

It appears that all data in the EAA program was handled with the care it deserved, although some problems were detected during the assessment. The most serious problem was occasional inconsistencies in the flight data, especially mix-ups in recording the time of particular events. All times were supposed to be in Greenwich Mean Time (GMT), but some were erroneously recorded in Central Time. Although a simple error, it caused considerable confusion in some instances until the matter could be resolved. The lesson in all of this is that one cannot be too careful and too paranoid in the handling of project data. Checks and more checks on virtually a daily basis are needed when managing seeding projects and the data they generate.

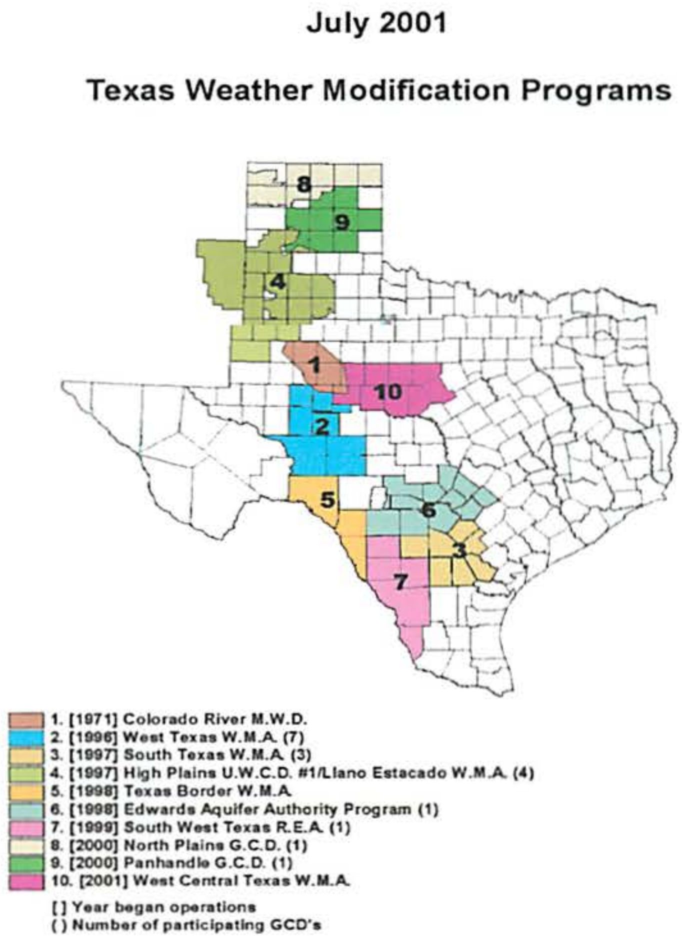


Figure 1. Location of the ten operational cloud seeding programs that were operative in Texas during the 2001 season.

2.3 Project Operations

The long-term future of the seeding projects in Texas will depend on evidence that seeding is increasing the rainfall as intended. Assuming that cloud seeding does in fact increase the rainfall, the success of a project in reaching its goal will depend on how well the seeding was conducted. This requires in-the-air training. Some had been done prior to the 2001 season.

During 1999 the first author spent time flying with the seeder pilots both in Lubbock and Hondo, Texas. The flights went quite well as the pilots learned aggressive seeding techniques, which involved many passes into suitable clouds such as those shown in Figure 2. Without exception the number of on-top seeding passes increased substantially relative to what had been common practice prior to the training flights. Unfortunately, the improved performance did not persist with time after the training flights. Pilot seeding performance remains a major weakness of most operational seeding projects.

During the course of flight training by this author there has been a discussion of the relative merits of on-top and base seeding. The critical factor in an operational seeding program is mapping a seeding strategy and then implementing it. In most cases, this is best done from on top, where the convective patterning can be discerned and the clouds most "ripe" for seeding intervention can be identified. This is especially true in the formative stages of the convective systems.

Figure 2. Picture of hard vigorous cloud towers at 1818 CDT on June 5, 2001 taken from 17,000 feet from "Cloud 2", the Cessna 340 seeder of the High Plains operational cloud seeding project. The clouds shown were typical on this day.

The visibility with base seeding is limited and it is more difficult to identify the best seeding targets and to deliver the nucleant when and where it is needed. The updrafts are typically spotty and weak and it is difficult to find and stay in them, especially if the base seeding is being done with silver iodide generators. Further there is greater uncertainty with base seeding that the nucleant is going to reach the supercooled portion of the cloud at the time and in the concentrations needed to affect the cloud and its rainfall.

As the cloud systems develop into larger better-organized cloud systems, however, base seeding becomes a viable option, sometimes more viable than top seeding. The updrafts of organized cloud systems are typically stronger and on a larger scale such that the aircraft has no difficulty finding the inflow and updraft regions. If the supercooled cloud towers are embedded in layer clouds produced by the convection, they cannot be reached from on top. Base seeding is the only option. The message is that an operational seeder aircraft should be equipped to do both on-top and base seeding. Rainfall cannot be increased unless many suitable clouds are reached by the seeding.

With this as background it is obvious that training is the key to a successful project and that the main obstacle to its success is the changeover in project personnel, especially pilots. Despite belief in some quarters to the contrary, cloud seeding is a complicated undertaking, requiring dedication and training. A seeding effect begins with the seeding pilots and, if they do not know what they are doing, it is foolish to expect to find an effect of seeding during later analysis. This applies to the Edwards Aquifer seeding program as well as all the rest of the Texas operational seeding projects. On balance, more things were done right than wrong in the conduct of seeding during the 1999, 2000, and 2001 seasons, but there were problems, as documented here.

The first author's main concern about the conduct of the Edwards Aquifer seeding program was the causal nature of project operations when he was on site at the Hondo, Texas field headquarters. The weather briefings typically were brief and superficial, the "scramble" of the seeding aircraft was often late, and it was rare that more than two total seeding flights were conducted per day. Finally, in depth debriefings of the seeding flights were rare. Such problems are not typical of WMI operations elsewhere, and it made the first author uneasy during the project assessment.

Cloud seeding was done at cloud top with ejectable flares on most days with supplemental seeding at cloud base with acetone silver iodide generators. Although there were a number of exceptions, top seeding typically was done first when the clouds were young and growing and this frequently was followed by base seeding in the inflow regions of the clouds that had matured into large convective systems, sometimes stretching across much of the target. A listing of flight and seeding activity is provided for the 1999, 2000 and 2001 seasons in Appendix B.

The number of seeding passes vs. the number of ejectable flares expended by aircraft for each day of seeding in the Edwards Aquifer target during the 1999 (blue), 2000 (red) and 2001 seasons is shown in Figure 3. There is a wealth of information in this figure. Although the capability exists on each seeder aircraft, no aircraft ejected more than 90 flares per day during the three seasons. The most intensive seeding activity appears to have taken place in 1999.

Although the number of flares expended is of interest, the main focus must be on the number of seeding passes, because only if many clouds are seeded can one expect to see an effect of seeding over the entire target. Although there were not too many seeding flights in the three seasons, those that did take place did a fairly good job in the number of on-top seeding passes. For example, there were 35 seeding flights on which 20 or more seeding passes were made during the three seasons. Upon examining the scatter plot in Figure 3, one can see that the seeding expenditures averaged about 2 flares per pass, which is less than the 5 flares per pass that were expended during the randomized seeding experiments in Thailand.

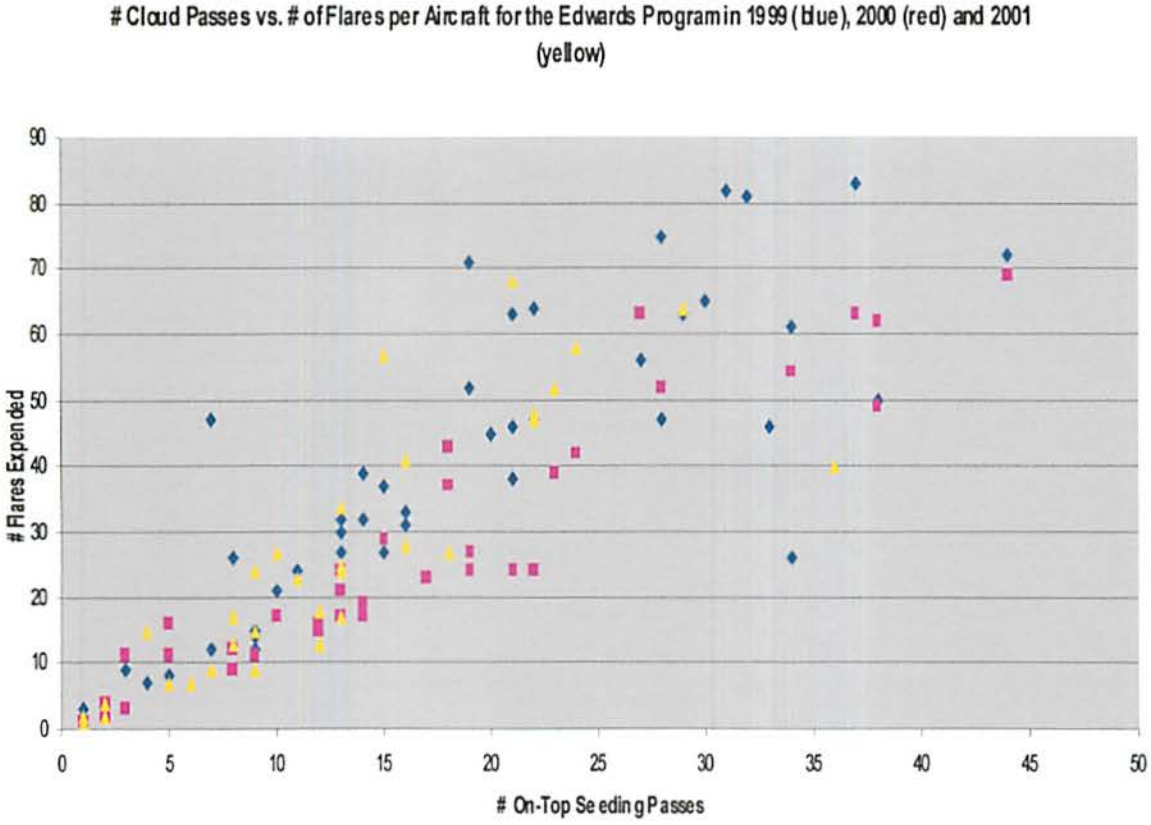


Figure 3. The number of seeding passes vs. the number of ejectable flares expended by aircraft for each day of seeding in the Edwards Aquifer target during the 1999 (blue), 2000 (red), and 2001 (yellow) seasons.

A scatter-plot of the daily number of seeding passes vs. the number of flares ejected for the Edwards Aquifer target in 1999, 2000 and 2001 is given in Figure 4. Note that about half of the days with seeding had 20 or fewer seeding passes, and the worst year in this regard was 2001. Further, considering the size of the Edwards target, there appears to be too little top seeding for a target of this size. It must be noted, however, that base seeding with AgI acetone generators, producing about 2.5 grams of AgI per minute of operation, also was done on many days, especially when the cloud systems became too large or too embedded to reach by on-top seeding.

Before turning our attention to base seeding, it is interesting to compare the seeding performance in the Edwards program to that in the seeding program sponsored by the High Plains Underground Water Conservation District. This is done in Figure 5 by superimposing the contents of Figure 3 onto a plot of comparable information for the Edwards program. The plots also include data from the 2001 season. The number of seeding passes per aircraft appears comparable for the two programs, but the number of flares released per pass is a little greater for the High Plains program.

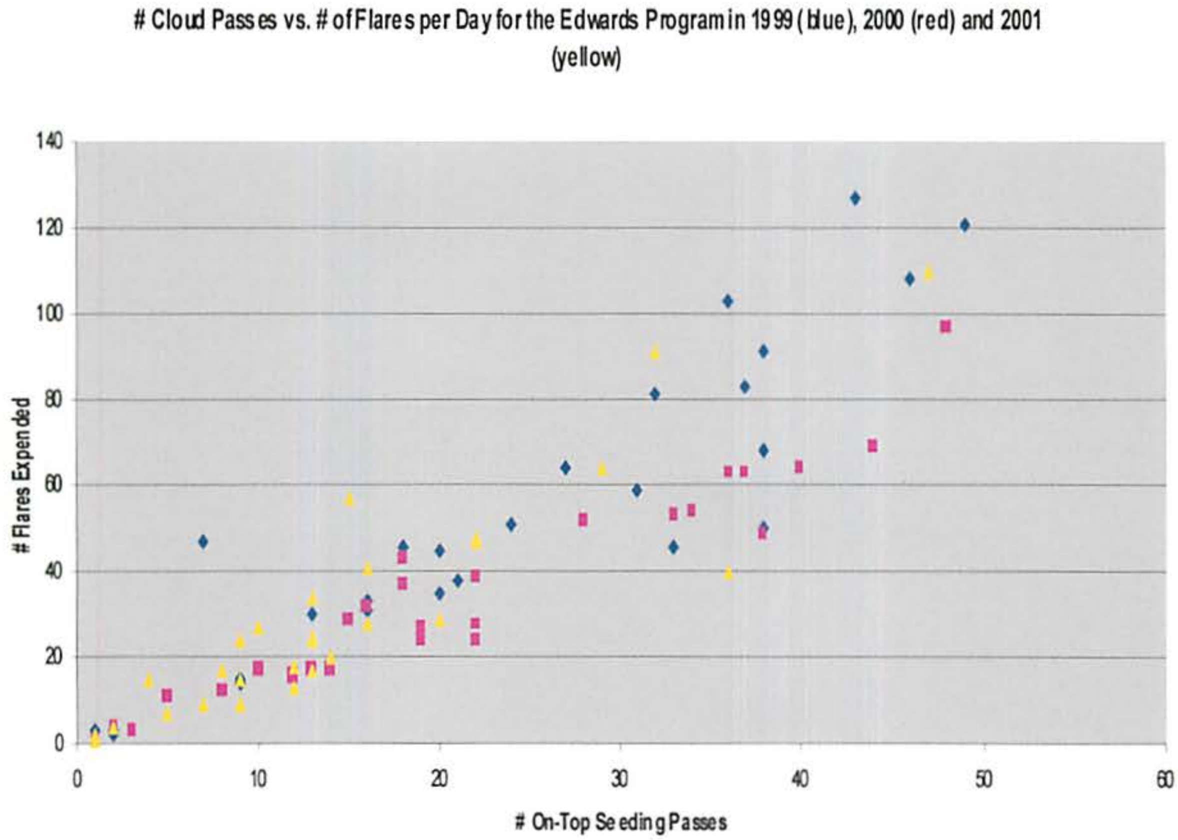


Figure 4. Daily number of seeding passes vs. the daily total number of flares ejected in the Edwards Aquifer target during the 1999 (blue), 2000 (red) and 2001 (yellow) seasons.

Both the High Plains and Edwards seeding programs in 1999 and 2000 did base seeding with silver iodide acetone generators in addition to the top seeding. A summary of the amount of silver iodide dispersed by top and base seeding in each program in these two seasons individually and combined is provided in Table 1. It can be seen that a greater percentage of the seeding in the Edwards Program was done at cloud top than at cloud base relative to the breakout for the High Plains Program. Even so, the High Plains Program released 74% of its silver iodide at cloud top for the two seasons combined. Thus, the emphasis was on top seeding in both programs.

More seeding (top plus base) was done in the High Plains Program than in the Edwards Aquifer Program in 1999 and 2000 combined (115.17 kg vs. 62.99 kg). If the sizes of the High Plains (44,755 km^2) and Edwards (22,658 km^2) targets are considered, however, there has been slightly less seeding per km^2 so far in the High Plains Program relative to the Edwards Program. The ratio of High Plains to Edwards target areas is 1.98 whereas the ratio of total of AgI released in the two targets in 1999 and 2000 was 1.83. Thus, the differences between the two programs have been small, especially so when one considers that differing weather in the two areas might account for a part or all of the differences in seeding output.

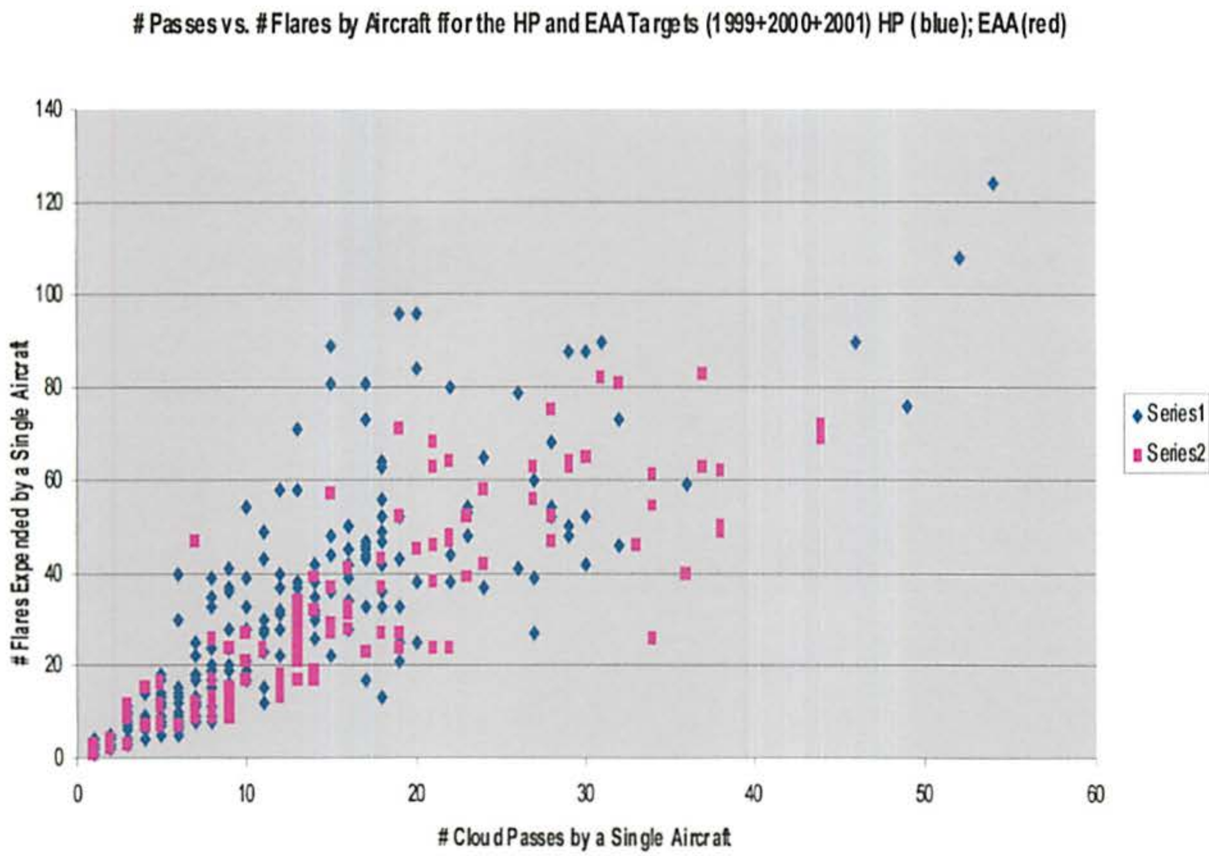


Figure 5. The number of seeding passes vs. the number of ejectable flares expended by aircraft for each day of seeding in the High Plains (blue) and Edwards Aquifer (red) targets during the combined 1999 and 2000 seasons.

Table 1
Amount of Silver Iodide (in kg) Dispersed at Cloud Base and at Cloud Top in the High Plains and the Edwards Aquifer Seeding Programs in 1999 and 2000
(The Percent of Total Expenditure Appears in Parentheses)

	High Plains Program		Edwards Aquifer Program	
Season	Amount at Cloud Top (% of total)	Amount at Cloud Base (% of total)	Amount at Cloud Top (% of total)	Amount at Cloud Base (% of total)
1999	37.58 (70%)	16.31 (30%)	36.53 (98%)	0.92 (2%)
2000	47.54 (78%)	13.74 (22%)	19.30 (76%)	6.23 (24%)
1999 & 2000 Combined	85.12 (74%)	30.05 (26%)	55.83 (89%)	7.15 (11%)

It is also of interest to look at the seasonal expenditure of AgI in bar-graph format as shown in Figure 6 to which the 2001 season has been added. Note that the expenditure in the High Plains program increased each season from 1999 to 2001, while the reverse was true in the Edwards program. The latter could be due to poorer weather each year and/or to the decision-making of the project meteorologist. In both programs the seasonal expenditure of AgI is quite small when spread out over the entire target area. For example, the maximum expenditure so far in the Edwards program gave 1.65 g km^{-2} in 1999 and 1.48 g km^{-2} in the High Plains program.

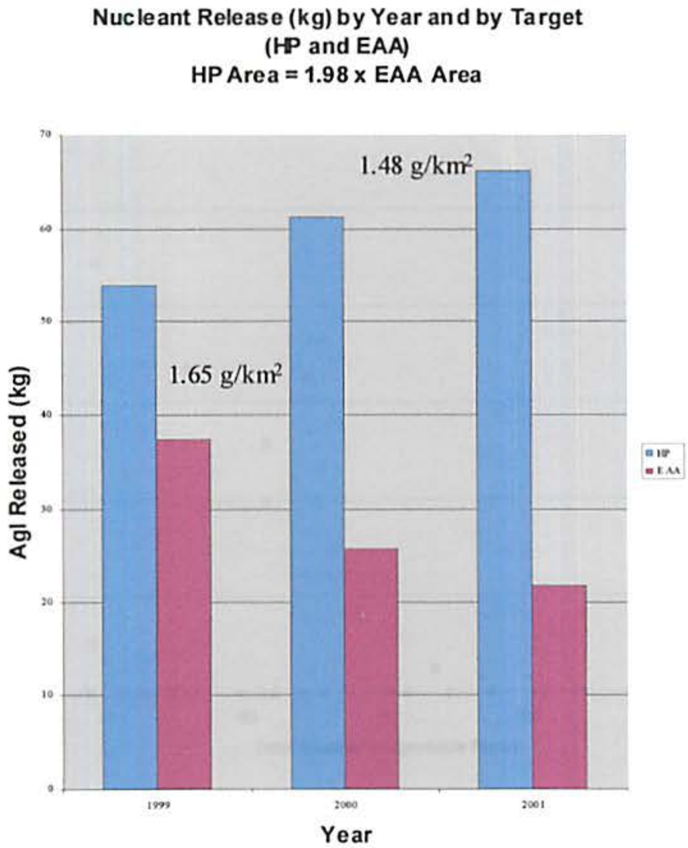
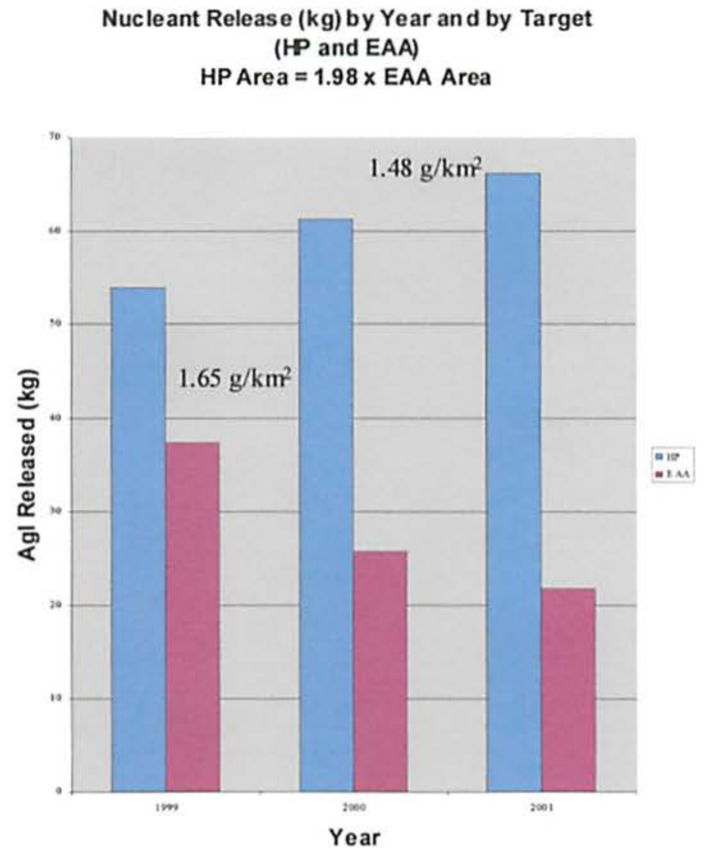


Figure 6. Documentation of the release of AgI nucleant (in kg) by season in the Edwards and High Plains targets.

Still more can be learned about cloud seeding in the Edwards program by studying a scatter plot relating the number of flares ejected vs. the minutes of burner time on each day of seeding (Figure 7). The scatter is enormous. In 1999 and 2001 most of the seeding was done near cloud top, while in 2000 there was a mix of top and base seeding.



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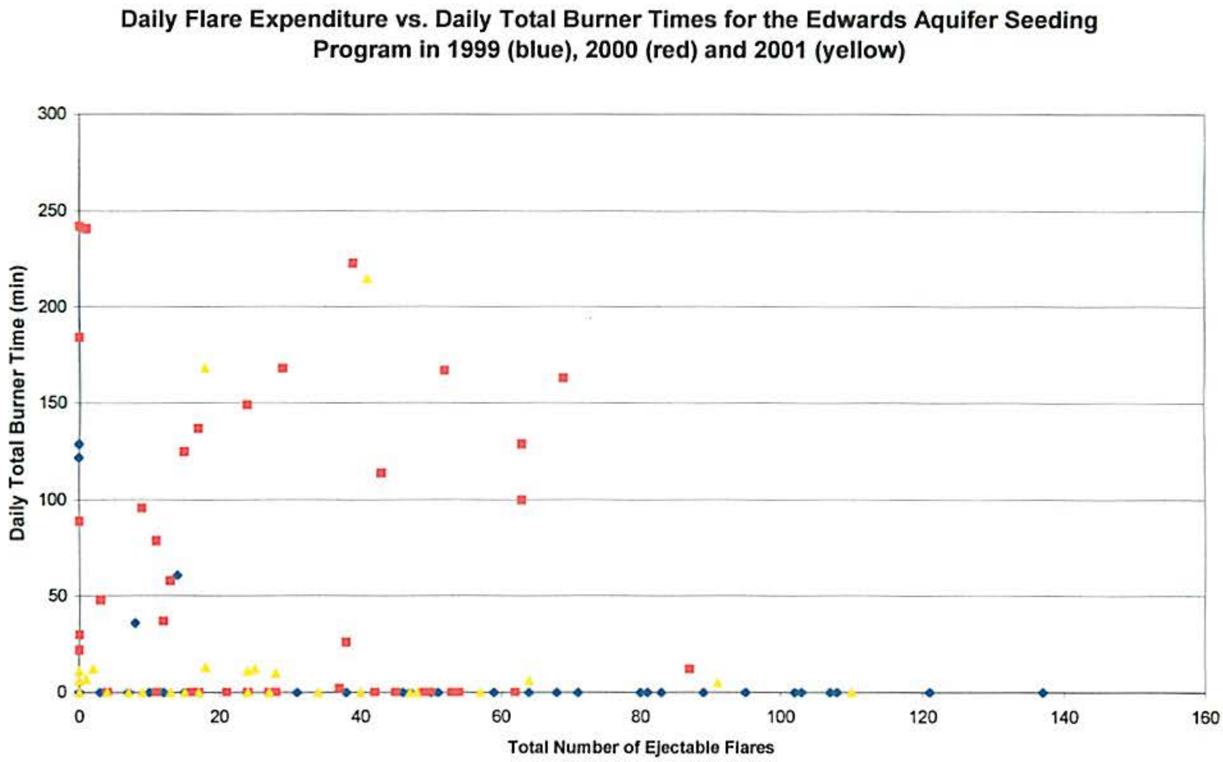


Figure 7. Daily flare expenditure vs. the daily total burner times for the Edwards Aquifer seeding program in 1999 (blue), 2000 (red) and 2001 (yellow).

The number of seeding missions per day is also of considerable interest. A frequency plot for the 1999, 2000 and 2001 seasons is provided in Figure 8. In all years the majority of days with seeding had only one seeding flight (i.e., 21 days in 1999, 19 days in 2000 and 19 days in 2001). Many days had two seeding flights per day (12 in 1999, 17 in 2000 and 7 in 2001), but there were very few days with three or more seeding flights on a given day. It would have been desirable to have more multiple seeding operations in each year, but it is not known whether more would have been warranted based on the weather conditions in the target. Only in being there could one have known for sure. Therefore, although the seeding was far from ideal in the Edwards program, it appears that enough seeding was done to warrant a search for seeding effects.

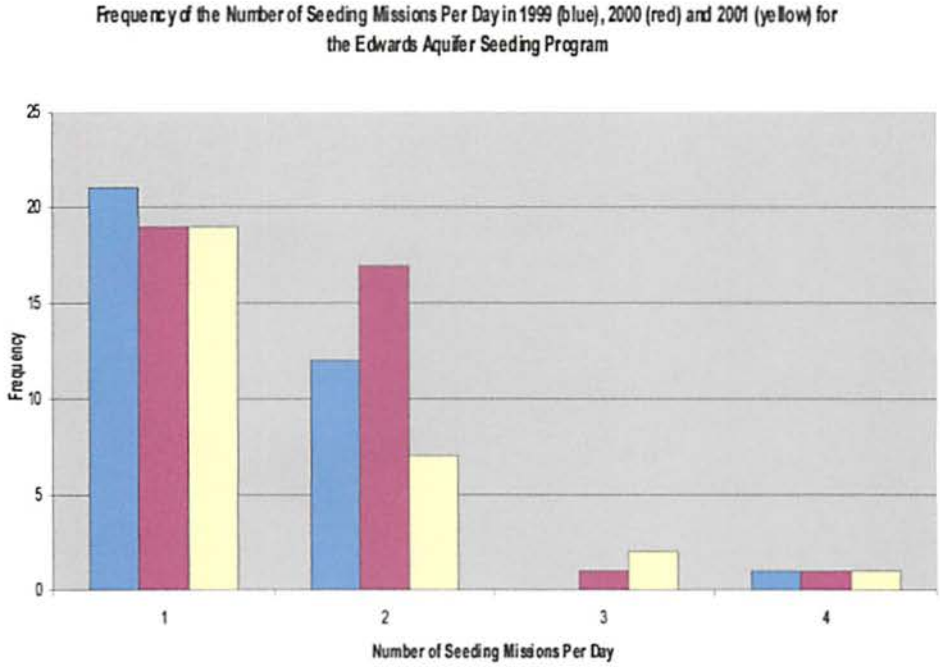


Figure 8. Frequency of the number of seeding missions per day in the Edwards Aquifer Program in 1999 (blue), in 2000 (red), and in 2001 (yellow).

2.4 Conclusions

A careful examination of the documentation for the Edwards cloud seeding program in the 1999, 2000 and 2001 seasons provide the basis for a search for an effect of seeding, especially if that search is limited to clouds that are known to have been seeded. Based on past research results, it is expected that an effect of seeding in such clouds will be detected in the Edwards target. Whether enough clouds were treated to produce a detectable effect over the entire target is doubtful. The challenge in detecting an area-wide effect of seeding in the Texas seeding targets in view of the natural rainfall background can be appreciated readily by examining the total April through September Texas radar-estimated rainfall (in mm) in 1999 and 2000 (see Figures 9 and 10) and the summation for the two seasons (Figure 11). The rainfall, which was estimated using the NEXRAD mosaic to be discussed in Section 3.0, was rather light in both years, especially in 2000, showing an increase from west to east and from south to north within the state.

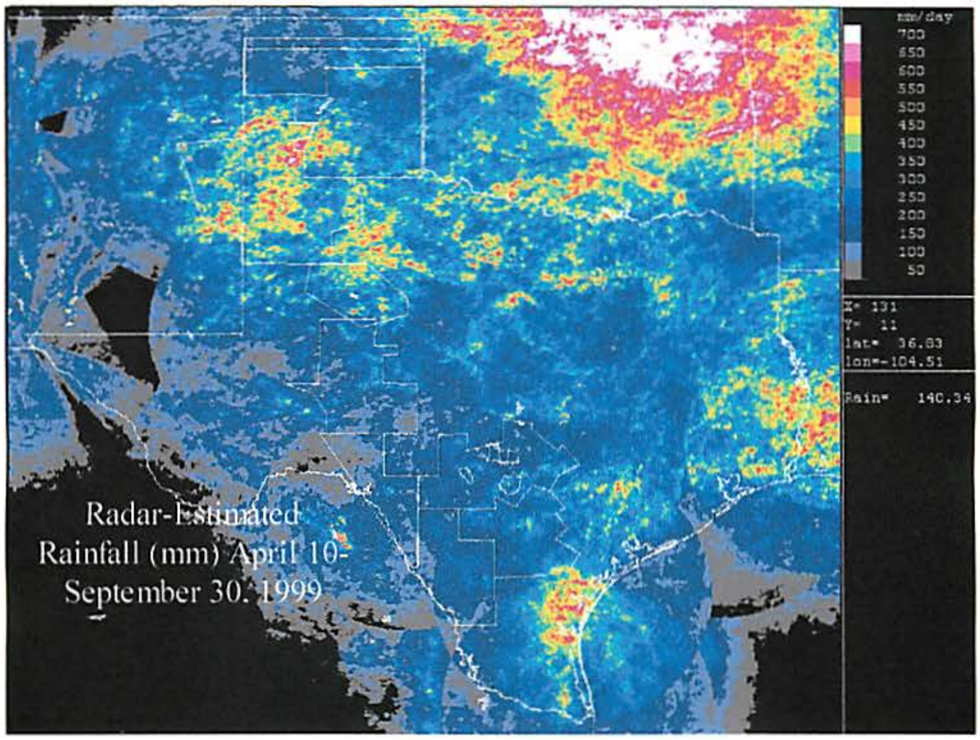


Figure 9. The radar-estimated rainfall (mm) for Texas in the period April 10 through September 30, 1999. The scale at the upper right relates the colors to rain amounts. The 9 seeding targets operative in 2000 are as shown.

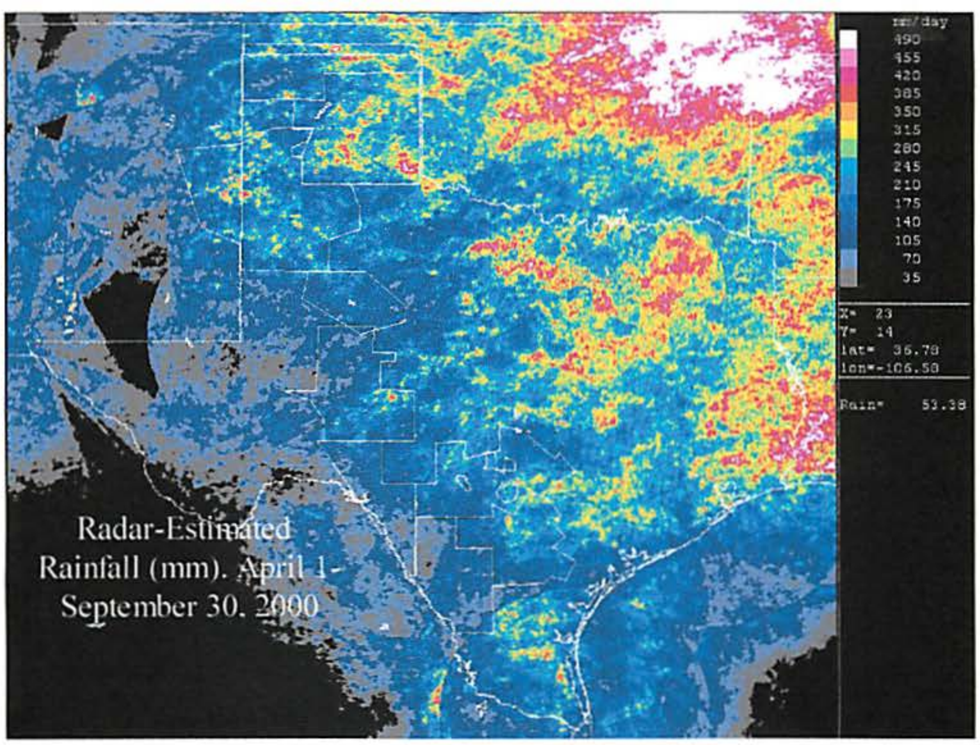


Figure 10. As in Figure 9, but for the period April 1 through September 30, 2000.

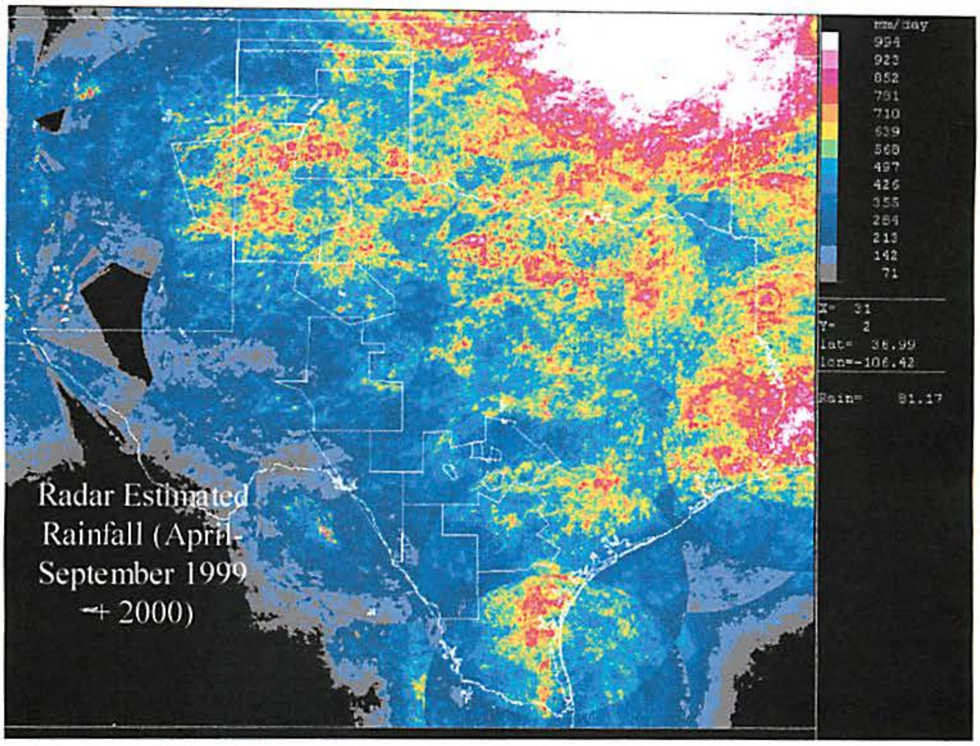


Figure 11. The summation of the seasonal totals in 1999 and 2000.

Although the seeding record justifies an intensive search for an effect of seeding in the Edwards target, the seeding fell well short of optimum on some days. There were times when there was too much convection within the target to be treated by the available seeder aircraft and other times when both seeder aircraft should have been scrambled to work target clouds. In addition, the on-top seeding should have been more aggressive on many days. Most of the shortcomings can be attributed to the rotation of seeding pilots through the seeding program. Without pilot continuity such problems are bound to exist.

2.5 Operational recommendations

As in any endeavor, there is room for improvement in the Edwards Aquifer seeding program. The recommendations and their rationale that will lead to project improvement are provided below. These recommendations are predicated on the EAA retaining operational control of its cloud seeding effort in 2002.

Train the pilots in seeding procedures and strive to maintain pilot continuity

The review of seeding procedures in 1999, 2000 and 2001 suggests that the seeder pilots need additional training in aggressive seeding procedures. The number of on-top cloud passes per flight was on average about half of what it should have been on most days. Cloud quality should not be sacrificed, however, in order to increase the number of treatment passes. The pilots need only be better trained in recognizing seeding opportunities and in mapping a strategy to reach them in order to reach this goal. On most days WMI put a co-pilot on the seeder aircraft to assist with flight and seeding duties. This is highly commendable. This permitted the training of a larger pilot base for future seeding flights. This will be important if additional aircraft are added to the seeding fleet at a later date and more pilots are needed.

Install a video camera on one of the seeder aircraft

The installation of a forward-looking video camera on at least one of the Edwards seeder aircraft for the purposes of flight documentation and for later critique and training would be a valuable addition to the program. Once the pilot(s) can get over the feeling that "Big Brother" is watching, they will come to the view that the camera greatly enhances project operations. There is no substitute for project documentation and the most important initial activity is cloud seeding. Only if it is being done right can one expect to increase the rainfall.

Forward-looking video cameras on aircraft are routine on most research and some operational aircraft. Recommendations on the best cameras and on their installation can be obtained, for example, from Weather Modification, Inc. in Fargo, North Dakota.

Improve seeding procedures

Seeding procedures can be improved through the following steps:

a) Select the seeding method for the conditions, b) Determine from the project meteorologist the flight level for on-top seeding, c) Choose on-top seeding for the formative stages of convection, d) Choose base seeding when the convective systems become better organized with strong inflows, e) Focus on clustered convection and avoid isolated clouds, f) Strive for many treatment passes to increase the chances of "secondary" seeding, g) Do over-the-top seeding whenever possible, h) Preferentially seed broad cloud towers instead of the narrow ones, i) Concentrate on upshear, "feeder" clouds for the seeding rather than those downshear, j) conduct multiple aircraft seeding operations on the same large cloud system in coordination with the FAA, and k) Be aggressive in the conduct of the seeding and maximize the number of seeding passes through highly suitable clouds.

Increase the number of seeder aircraft and the loads they can carry

Two seeder aircraft are not enough for the Edwards target. Project management is already aware of this reality. At least three seeder aircraft likely will be required on some days in order to do the seeding properly. Thus, an additional aircraft should be leased or purchased for project operations. An alternative would be to decrease the size of the target, retain the existing two seeder aircraft and concentrate on the portions of the target where aquifer recharge takes place. Regardless of the number of aircraft, all should be able to eject a minimum of 204 flares and be equipped for seeding at cloud base either with acetone generators or will burn-in-place flares. The existing two WMI aircraft are so equipped.

Co-locate project operations whenever possible

Typically, the efficiency of project operations and the morale of its personnel are enhanced when all project operations can be located at the same site. This has been possible in all years so far in the Edwards Aquifer Program. Because of a hangar fire at the Hondo airport in 2001, it now appears that the seeder aircraft will have to be hangared in Castroville to the east of Hondo, if WMI is retained for the 2002 season. The pilots may also take up residence there, resulting in their separation from the project meteorologist and radar, which will remain at the Hondo airport. Fortunately, Hondo and Castroville are only about 17 miles separate, so face-to-face interactions among the pilots and meteorologist should still be possible, and it should be encouraged.

Be dedicated to project documentation

The Edwards program did a good job through the 2001 season in documenting all aspects of its operations and providing the information on CD-ROM at the end of the program. Few projects were doing as well.

The buck has to stop with somebody in most human endeavors. In the Edwards project that individual was Bobby Bader, who was a good choice to oversee project operations given his interest and background. Much of the documentary work must, however, be done by the project meteorologist. On a day-to-day basis it is the project meteorologist who makes things happen in a seeding project. For this reason, the EAA and WMI should make certain that a well-qualified individual takes the position with the program, regardless of whether it is run by WMI or whether another organization assumes operational control.

3.0 DEVELOPMENT OF THE NEW ANALYSIS METHOD BY WWC

3.1 The TITAN Analysis Option

All of the Texas cloud seeding projects make use of WSR-74C (C-band) radars in conjunction with Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN) hardware and software. The basic radar displays echoes on the Plan Position Indicator (PPI) scope, which gives a horizontal cross section as the radar sweeps through each 360° revolution at a fixed elevation angle. The raw-log radar signals are processed by a Digital Video Integrator and Processor (DVIP), which permits the contouring of echoes as a function of their intensity. In addition, Sensitivity Time Control (STC) circuitry makes corrections for the loss of radar sensitivity with range. The basic radar can also display a vertical cross section of an echo by scanning the antenna vertically with no antenna rotation.

Because all project radars employ TITAN, it is important to take a critical look at this system for evaluation of seeding effects. In the TITAN system a PC computer serves as the radar data acquisition system (RDAS), which is interfaced with each radar operating in a volume-scan mode. Under the control of RDAS the radar normally will complete a series of 360° sweeps at increasing elevation angles in 4 to 5 minutes. The raw data stream is fed into RDAS where it is processed and then exported to a TITAN Linux workstation that runs TITAN. Here the data are converted to Cartesian coordinates and saved as MDV files, which are viewable through the RVIEW program.

The TITAN system has been a boon to projects that traditionally have made extensive use of radars in the conduct and evaluation of seeding operations. TITAN permits the radar operator to examine the three-dimensional structure of echoing clouds in real time. Individual echoes and groups of echoes can be tracked and their development and motion projected in time. Calculated parameters available in real time include the radar-estimated rainfall, echo heights, CAPPI slices, storm time-height profiles, histories of echo volume, area, precipitation flux, mass and vertically-integrated liquid (VIL). When these are combined with aircraft tracking, TITAN becomes a valuable tool for cloud seeding projects.

The ability to identify and track echoes and calculate their properties with time makes TITAN a potential tool for the evaluation of cloud seeding experiments. In projects employing randomization, the treatment decision is determined from a randomized sequence and the evaluation of the effect of seeding is made by comparing the rainfall from the seeded and control clouds. Rosenfeld and Woodley (1993) and Woodley and Rosenfeld (1996) did essentially this, using software written by Rosenfeld (1987), for the series of Texas cloud seeding experiments. Dixon and Weiner (1993) wrote what ultimately became the TITAN software for the series of South African experiments, initially for the glaciogenic seeding experiments (Mather et al., 1996) and later for their hygroscopic seeding experiments (Mather et al., 1997). The original TITAN software was revised further for the evaluation of the hygroscopic seeding experiments in Mexico (Bruintjes et al., 2001). Such evaluations are fairly straightforward.

The challenge comes in evaluating cloud seeding projects that are not able to employ randomization and select control clouds objectively. Without such controls there can be no evaluation. The developers of TITAN have come up with a limited new approach for the evaluation of operational (non-randomized) cloud seeding projects. A concise statement of the approach, excerpted from page 2 of the TITAN Analysis Software Guide (2000, TITAN Documentation, Volume 4), is provided below:

> "The most pressing dilemma with semi-operational and operational seeding work is to obtain a set of control storms (that do not have mock decision times) in an objective manner without introducing bias into the analysis. A novel way of achieving this was to use the tracking algorithms time-of-track origin as the point of reference instead of the decision time. Storms are then matched based on their behaviour from time-of-origin to time t. Of course, the longer this time interval is made the more complicated the storm dynamics become. Small discrete storm units early in their lifetimes can become large messy storm complexes. That is why this method of analysis is only effective and suitable for storms that were seeded early on in their lifetimes where the origin storm has retained a strong sense of its own identity. Therefore type "A" storms are defined as those that were seeded within the first 30 minutes from time-of-origin. From this it can be appreciated that many storms cannot be analyzed using this method. This is however the subset of storms where it is most likely for a seeding response (if there is one) to be detected."

A critique of the TITAN analysis approach and software must begin with its tracking methodology, which is very different from that developed by Rosenfeld (1987). The Rosenfeld method tracks peaks in echo reflectivity relative to their surroundings. In practice tracking can be done for echo intensities as low as 12 dBZ. As tracking begins the echo is assigned a number, which it retains until a change in its status is brought about by a merger and/or split with other echoes. At that point the echo mass receives a new tracking number. Under favorable circumstances, the long-tracking version of the Rosenfeld software can follow an echo mass for two hours or longer. In principle, therefore, a treated (seeded or non-seeded) echo can be tracked from the time of seeding or before. In the latter instance the Rosenfeld methodology provides a pre-treatment history of the echo that might be used in an assessment of natural pre-treatment biases.

When there is no randomization, as in the operational seeding programs of Texas, the Rosenfeld method can be used to identify objectively mock controls for comparison with the seeded clouds. There is no interest in doing so, however, since randomized cloud seeding programs have already established that the rainfall from individual clouds can be enhanced by glaciogenic seeding by about +75% for clouds that are microphysically-continental in structure. The real interest must be in area rainfall from clusters of clouds, if the operational programs are to demonstrate the efficacy of seeding. However, neither the current Rosenfeld method nor the TITAN system can handle cloud clusters and identify matching controls.

Echo tracking with the TITAN software begins with the assignment of a tracking number when an echo reaches a pre-set threshold, which was 39 dBZ for the Texas seeding programs through the 2001 season. This pre-set threshold presents several potential problems. With the TITAN tracking system an echo does not exist before reaching the tracking threshold, and an echo seeded in this time period has no pre-treatment history. Further, even after an echo reaches the tracking threshold, its presentation in height and area also is truncated at this threshold. Thus, if an effect of seeding is to decrease the maximum reflectivity and spread it out over larger areas, it will not be detected by TITAN tracking at a high threshold reflectivity.

It must also be noted that TITAN assigns numbers to all tracked echoes. The first is the "complex" number that identifies the family of echoes to which a given echo belongs. This might be viewed as the echo's last name. The second number is the "simple" track number, which might be viewed as the echo's first name. An echo's simple track number can change by virtue of merger or split, but its last name never changes. Although this protocol sounds reasonable upon first thought, it creates big problems for understanding the effects of seeding because of the way the tracking is done. This is illustrated later in this section.

The TITAN software was designed for the evaluation of the effects of seeding on simple individual echoes. Ideally, this should be done for echoes that retain their simple track numbers. The analysis reference point for the matching of seed and non-seed echoes is their time of origin, that is, the time they reached the pre-set threshold. This is objective in that it is not necessary to define a mock seeding for the control echoes, but it adds noise to the analysis in cases when the seeded echoes were treated before they reached their tracking threshold. Noise is also introduced into the analysis when seeding took place in an echo long after its time of origin. This explains why in the cited passage above it is recommended that the analyses be limited to echoes that were treated within 30 minutes of their time of origin.

Even if this is done, there are still problems. The actual matching of echoes is made normally on the basis of precipitation flux from the time of origin onward. In cases when the seeding takes place before the time of echo origin, this means that the match is made for seeded clouds based on their precipitation flux after seeding had already begun. This is obviously a serious problem, especially so if the seeding took place in an echo long before its time of origin, because the matching parameter has been contaminated by the seeding. Strictly speaking, this analysis is valid only for those cases in which seeding takes place after the echo's time of origin.

Yet another potential problem for the "simple" analysis of "A" units is the quality of the seed and control matches. If the matches are made for a particular radar site within a given day of seeding, it is possible that all of the "good" clouds will have been seeded, leaving only rejected clouds in the pool from which controls will be selected by the TITAN software. In this instance, it may be necessary to resort to "handicapping" to boost the precipitation flux from the potential control so it better matches the seeded echo. It may be difficult to do this objectively. An alternative would be to reject the "match" based on an objective criterion or to augment the control pool by including other days in the analysis.

Despite these problems, it may still be possible to obtain some insights into the effects of seeding on individual storms that retain their simple identification. The validity of the insights will depend on the quality of the echo matches. Given a large sample and good matches, it may be possible estimate the effects of seeding as a function of the amount of nucleant injected into the clouds, how it was delivered (i.e., at cloud base or from on top) and as a function of the microphysical structure of the clouds at seeding.

The documentation of the TITAN analysis software recommends that TITAN software not be used for the assessment of the effect of seeding on echo clusters, and for good reason. Such an analysis would have to be done on the basis of the echoes' complex name. Because of the peculiarities of the TITAN tracking software, this would present a major problem. In accomplishing the tracking, TITAN incorporates echoes into families before they are physically interactive with one another. Such echo families can be identified by their same complex name even though they have different simple names.

This creates problems for cluster evaluation. An example will make this point. Suppose an echo with complex ID 100 and simple ID 205 persists for an hour before losing its simple designation by merging with other echoes. When this happens, the merged echo receives another simple ID even though its complex designation (i.e., 100) is unchanged. Logically, analysis of the effect of seeding should follow the initially treated echo with time and incorporate other cells into the evaluation when they become physically interactive with the parent seeded echo. The Rosenfeld tracking software does just this. TITAN procedures in their present form do not.

TITAN determines which cells will ultimately be a part of the same complex. The echo pieces of the eventual echo mass are added to the whole at their time of origin on the radarscope and not when they are physically interactive by virtue of merger. Thus, in the evaluation of seeded echo 100/205, TITAN will make its best match for this single initial echo. As time proceeds, however, the rainfall from echo complex 100, which began with echo100/205, will be augmented by the rainfall from other clouds having the same complex designation (i.e., 100) but different simple track numbers, even though they may be miles separate from the initial echo. This does not make physical sense. The rainfall from the parent echo should not be increased by rainfall from family echoes until they interact physically with the parent. Further, the current procedure introduces noise and potential bias into the analysis. If such an analysis were possible, it should proceed by matching the initial echo and by adding other echoes to it when they interact through merger.

It would seem, therefore, that one should take the developers of the TITAN software at their word. Their analysis package should be applied only to type "A" type (single cell) storms. Even then, there are potential problems as discussed earlier. Our only recourse for the analysis of area rainfall was, therefore, to develop an analysis method of our own after we decided which radar or radars would provide the input data for the assessment of seeding effects.

3.2 Project C-Band Radar Data

The initial intention was to base the development of a new method to evaluate the operational cloud seeding programs on the C-band project radars. They were to be used for the estimation of seeded and non-seeded rainfall by converting the measured radar reflectivities to rainfall rate. A unique feature of the planned assessment is the pooling of the data from all projects in order to select controls objectively and for partitioning based on the satellite-estimated cloud microphysical structure. Effects of seeding were then to be sought within each partition. This approach would give the best chances of detecting seeding effects. Pooling the project data cannot be done, however, without normalizing all project radars to a single standard. One option is the normalization of the project radars to the orbiting TRMM radar. Although technologically feasible, this has never been done before. Even so, it was part of the original plan. A second option for data normalization that would potentially make the first unnecessary is the use of merged and normalized Texas NEXRAD data, which are produced for the entire United States through a partnership between the National Weather Service and private industry. After generating the normalized radar data, the Z-R relationships appropriate to the area could be derived and tested. These could then be used for the analyses of seeding effects.

In looking into which option would prove to be the most feasible, it was determined that none of the projects operate their radars round-the-clock, meaning that some rainfalls are not measured, thereby making it impossible to evaluate the projects thoroughly. Further, the project radars also were found to suffer from other problems, including attenuation of the energy beam in heavy rain and ground clutter, which was sometimes interspersed with rain events, especially during their later stages. Attenuation in rain is inherent to C-band radars and can be avoided only by using radar with a longer wavelength. Ground clutter due to anomalous propagation, resulting in "false rainfall," could not be removed, making it a major source of potential error in estimating the rainfall to be compared with the rain gauges.

3.3 The NEXRAD Option

At this point it was obvious that the evaluation method would have to involve the use of NEXRAD radar systems that are distributed about the state. These are S-band radars, which do not attenuate appreciably in heavy rain, and they are operated continuously unless they are down for maintenance. In addition, the NEXRAD radars have a clutter-removal algorithm that ostensibly eliminates most of the false rainfall produced during periods of anomalous propagation. Further, the project radar data are normalized to a standard during the merging process.

Investigation of the availability of NEXRAD data revealed a source at NASA's Global Hydrology Resource Center (GHRC), which receives merged 15-min, base-scan, reflectivity data from WSI, Inc. for all of the NEXRAD sites in the United States. (WSI, Inc. obtains the data from the National Weather Service.) The production of the merged or "mosaic" data were produced as described in the following quoted passage provided by WSI to WWC:

> "For over 12 years WSI has been generating the highest quality radar mosaics in the industry. Known commercially as NOWrad, this mosaic employs extensive false echo suppression techniques and quality assurance procedures to provide the most accurate depiction of severe weather from a combination of radar and other weather data.
>
> WSI has developed a three step quality control process to remove radar signal artifacts manifested from ground clutter, anomalous propagation and malfunctioning radars while maintaining the echoes, and their intensity, caused by real weather.
>
> • First, automated algorithms using the latest signal processing techniques are applied to the raw WSR-88d data from all 154 National Weather Service sites as the data is received at WSI.
>
> • This information is then automatically mosaicked into CONUS, Alaskan and Hawaiian sectors using proprietary decision-based algorithms which determine the validity of the single site information. This set of two-level quality controlled images is then immediately available and updated every five minutes.
>
> • Finally, every fifteen minutes, degreed meteorologists using advanced tools perform the third step in the quality control process. These operational meteorologists have been thoroughly trained in recognizing various meteorological and operational conditions which impact the validity of the radar data. They can remove and replace one site's radar echoes or many sites. They can dynamically change the rules that are applied during the second step in the quality control process and update these rules every fifteen minutes. Most importantly, they apply human intervention to the automated process on a constant basis every 15 minutes throughout the 24 hours of the day. This human intervention is unique to WSI and makes a difference in the quality of the products produced from radar data.
>
> This routine daily process is augmented by seasonal and technical updates to the algorithms employed. Over the years, the mosaic has improved in timeliness and quality due to the diligence and creativity invested in maintaining its leading status in the industry. WSI is committed to maintaining this product and its unique status for a very long time."

At this point it should be noted that until recently WSI, Inc. also prepared and distributed its own national radar-estimated rain map from the national network of NEXRAD radars. Upon our examination of this product for the period of interest, however, it was found to be seriously in error. Enormous rainfalls, exceeding 30 inches per month, were noted consistently in many areas even though no such rainfalls were measured by rain gauges. The errors appeared to be factors of 4 to 5 too high relative to gauge measurements and are likely due to a systematic error in the rainfall calculations. Apparently no one had brought these errors to their attention, so they could take corrective action. Dr. Woodley called the GHRC, which distributes the WSI, Inc.

rainfall product and told them of the problem and they expressed gratitude for having been provided this information. It is now of mainly academic interest, however, since WSI, Inc. no longer produces the integrated rainfalls.

With this as background, it was obvious that WWC would have to generate the radar rainfalls for all of Texas and for various sub-areas within the state. The mosaic data were secured for the period of interest and the rainfalls needed for this study were derived under the WWC contract from the 15-min reflectivity data. The relationship $Z = 300R^{1.4}$ to convert radar reflectivity (Z) to rainfall rate (R) synthesized by Woodley et al. (1975) and is used now as standard practice by the National Weather Service. Although a major undertaking no serious problems were encountered along the way. The initial work involved a test run of the data. This was followed by gauge vs. radar comparisons in the gauged portion of the High Plains target. Daily rainfalls were summed to provide monthly and seasonal (April through September) rainfall estimates (see Figures 9-11). The next step was an attempt to determine the probable accuracy of the radar rainfall estimates relative to rain gauge measurements. The results of this study, which are highly encouraging, were published in the Journal of Weather Modification (Woodley et al., 2001), which appears here as Appendix C. The seasonal radar rain estimates were within 10% of the gauges, and the two-month estimates were within 20% of the gauges. Daily comparisons could not be made because the gauges were not read on a daily basis. Daily gauge vs. radar rainfall comparisons finally were possible in the EAA program for the 2001 season.

3.4 The New Approach

The assessment of area seeding effects makes use of "merged" NEXRAD radar data (discussed earlier) rather than TITAN radar data, since the former provides greater area coverage by "merging" the observations from several radars in Texas and New Mexico. In addition, NEXRAD radars are superior to the project radars for the reasons discussed earlier. Having selected the radar system and secured the needed data, new software was written to define and track seeded echo areas (covering 1,964 km^2) and match them objectively with comparable non-seeded echo areas. This was done in several steps:

a) Define floating target areas (FTA) over the entire area of interest irrespective of the actual seeding using the NEXRAD radar composite for Texas.
b) Each FTA is defined when an echo first reaches 40 dBZ. The center of the FTA is at the center of the 40 dBZ maximum and its radius is 25 km with area coverage of 1,964 km^2. The FTA is terminated when an hour first elapses without echo in the unit.
c) A new FTA is defined just outside (i.e., > 25 km) a preexisting FTA when an echo reaches 40 dBZ. Thus, FTAs are allowed to overlap in order to make sure that no echoes escape analysis.
d) All FTAs are tracked backward and forward with time and the histories of maximum reflectivity (Zmax), rain volume rate (RVR) and Rmean for rain rates > 1 mm/hr are established. The motion vector of each FTA is determined using cross correlation maximization within a radius of 50 km.
e) A master treatment file is produced using the aircraft track and seed information provided by the individual projects and the treatment file is used to determine which of the defined FTAs were seeded. Any FTA receiving any silver iodide (AgI) is considered seeded regardless of how the AgI was delivered to the unit.

f) The pre-seeding histories of the S FTAs are defined for the 75 min prior to treatment in terms of rain-volume rate (RVR), rain volume (RVOL) and maximum unit reflectivity (Z_{max}).
g) A potential "control" FTA is defined as one that never received any AgI and never got to within 25 km of the perimeter of a S FTA.
h) Control (NS) FTAs should be selected from a region that is meteorologically representative of the S FTAs. As an example, the satellite-determined microphysical structure should be similar in the two areas. Thus, the S and NS FTAs should come from the same region and on the same day if possible.
i) Potential control FTAs must not be contaminated by seeding. Consequently, it will be necessary to consult with the surrounding projects to determine when and where seeding was conducted in their project areas. If the times and locations are not known exactly, a range of uncertainty will have to be defined in order to avoid contaminated NS FTAs.
j) A prospective NS FTA matches a S FTA when the following three conditions are met: 1) its RVR is within 25% (i.e., $\log|(RVR_s/RVR_{NS})| < 0.1$) of the seed RVR at "seed" time, 2) the maximum unit reflectivities at "seed" time do not differ by more than 5 dBZ, and 3) the correlation between the S and NS RVRs for the period of common rainfall in the 75 min before seeding must be > +0.60 (as many as 6 point pairs enter into the calculation).
k) Multiple NS FTA's are matched with each S FTA as long as they satisfy the match criteria.
l) The effect of seeding is evaluated on the whole population in various time frames (e.g., $\pm$ 12 hours of the initial seeding, or seasonal). The evaluation can also be done within various partitions such as the cloud microphysical structure and the age of the S unit when it was first seeded. It should also be possible to evaluate based on how the seeding was conducted (i.e., base vs. top seeding and/or flares vs. AgI acetone burners) and on the amount of nucleant expended.

The analysis is obviously highly complex. Such complexity is necessary, however, if the effect of seeding on an area basis is to be determined. Note that the method takes potential contamination from seeding elsewhere into account. Further, the NEXRAD radar composite makes it possible to define NS FTAs virtually anywhere in Texas as long as the control area has conditions that are similar to those in the area of seeding. In practice, however, attention is limited to an area around each subject seeding target.

This proposed assessment of seeding effects is based on relative comparisons of the radar-derived properties of the seeded and non-seeded cells. This is an acceptable approach provided the radar does not see S and NS clouds differently because of seeding-induced changes in the droplet spectrum at cloud base. This was investigated by Cunning (1976) in the FACE program under the direction of Dr. Woodley, and no evidence could be found that glaciogenic seeding produced such changes. This explains why radar is now used so extensively to evaluate cloud seeding experiments. That having been said, most people still would prefer rain gauges for the evaluation of cloud seeding experiments, because intuitively they come closest to the "bottom-line" measurement, rain on the ground. Unless they are in dense arrays, however, rain gauges are no better than radar for the measurement of rainfall and for the evaluation of seeding experiments.

A second concern is the existence of potential biases in the "merged" NEXRAD radar data. In looking at the rainfall maps generated during the course of the research effort, the individual radar scans in the rainfall data and sometimes be seen. This suggests that the interfacing and merging of the data from the various radars has problems in some cases. This problem has to be addressed such that the analysis does not run the risk of generating "seeding effects" that are a function of the radar processing and not the actual seeding. If bias does occur, it should be noted that neither WWC nor any project personnel is responsible. There is no reason to suspect, therefore, that any hypothetical biases systematically favored the seeded clouds.

4.0 PROCESSING THE DATA

4.1 Unit Tracking

The new software was used to track analysis units as defined above throughout the State of Texas. An example of the unit tracking for a rectangular area (32°N to 36°N; -101°W to -104.5°W) encompassing the High Plains seeding target on August 23, 2001, when the first author was on one of the seeding aircraft, is provided in Figures 12a to 12e. Figure 12a shows a number of analysis units at 1830 GMT before they reached 40 dBZ and "official" unit status. Five of the ten units shown reached definition status at 1845 GMT (Figure 12b), as indicated by their solid black depiction. Another reaches that status at 1900 GMT and yet another at 1930 GMT.

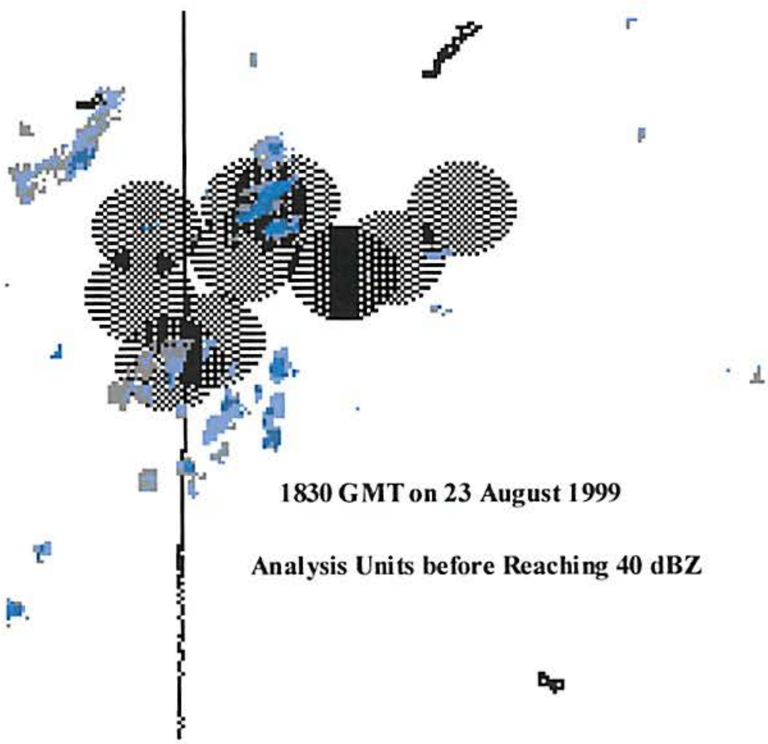


Figure 12a

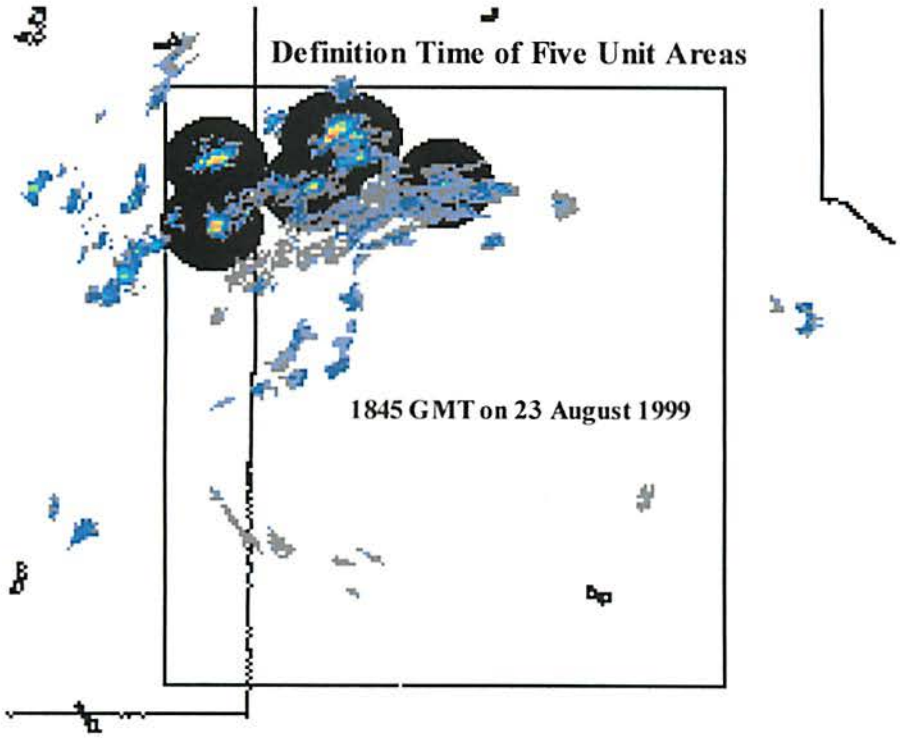


Figure 12b

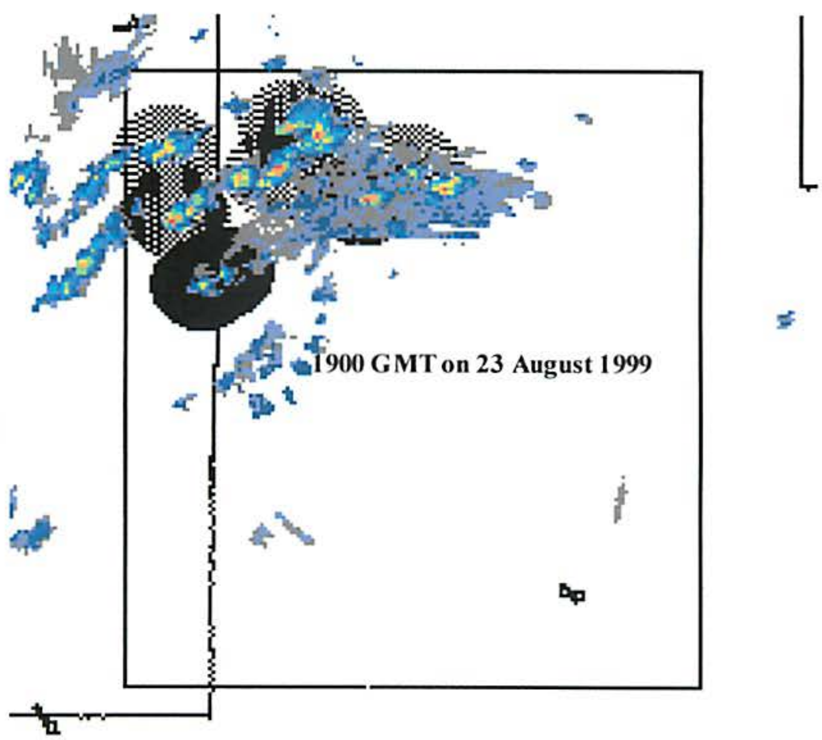


Figure 12c

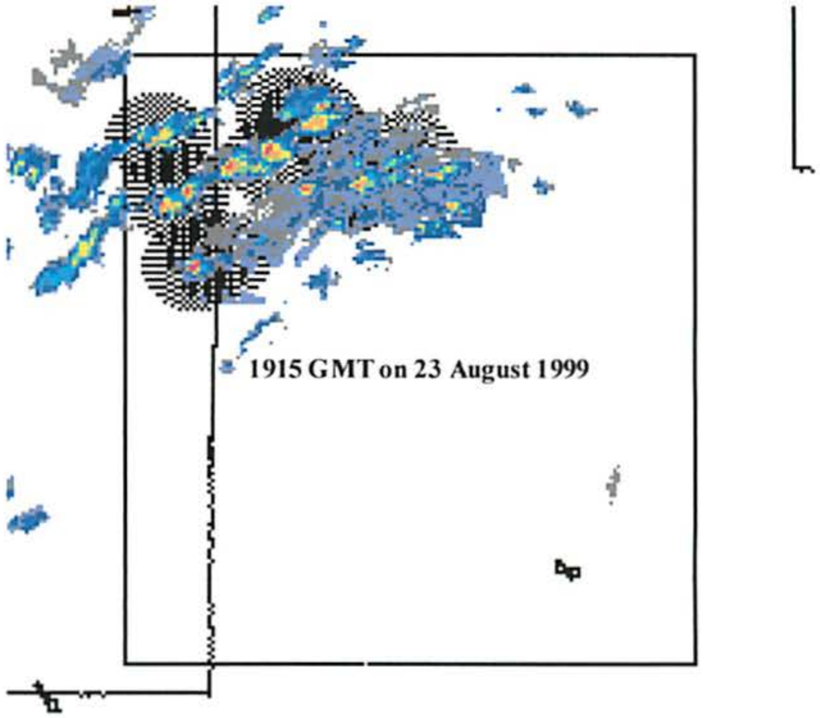


Figure 12d

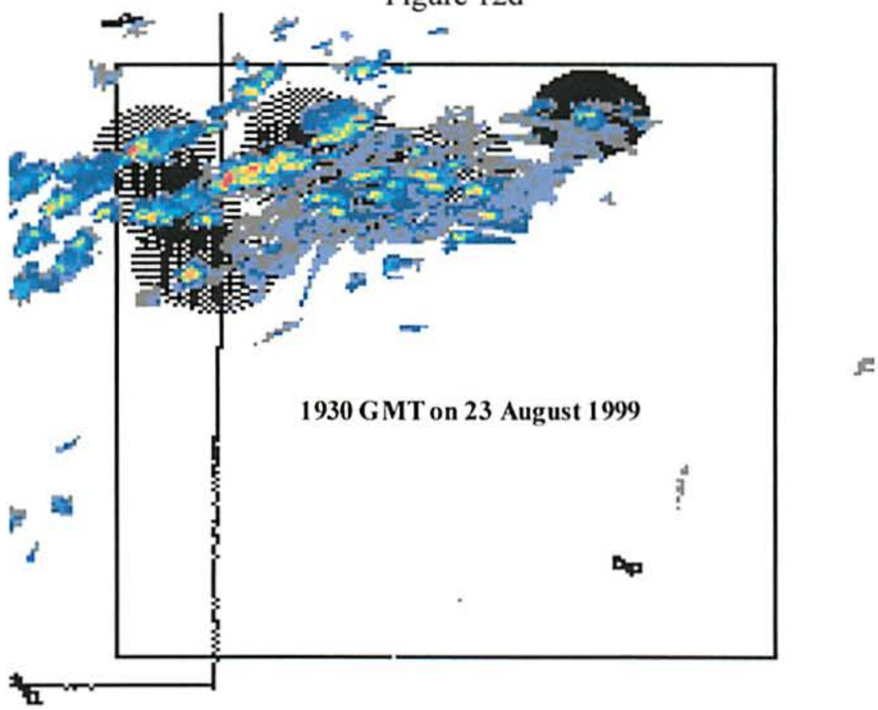


Figure 12e

Figure 12a-e. Echo and unit depiction from 1830 GMT through 1930 GMT on August 23, 1999. The circular units, which appear as ovals in this projection, have a radius of 25-km. Those appearing as solid are those that reached unit status (i.e., 40 dBZ) at the time shown.

4.2 Unit Matching

After the unit tracking had been completed, the aircraft seeding and tracking information were superimposed on the unit track maps to determine which of the units in the High Plains and Edwards Aquifer seeding programs during the 1999, 2000 and 2001 seasons had been seeded. Once that had been completed, the seeded units were matched with control units for the match areas shown in Figure 13, using the procedures discussed in the previous section. It should be noted that both match areas overlap other seeding targets. The High Plains match area includes portions of the CRMWD and Panhandle targets and the Edwards Aquifer match area includes portions of the South Texas, Southwest Texas and Texas Border targets. It was crucial, therefore, to know when and where seeding was done in these targets in order to avoid the selection of contaminated units to serve as controls.

The unit and match information for the High Plains and Edwards projects for the 1999, 2000, and 2001 seasons combined is provided in Table 2. Two match periods were used. The first permitted matches with S units with NS units that were defined within 12 hours of the initial seeding of each S unit. Thus, the number of candidate matches is small for this match period. The second match period allowed the computer to select matches from the NS units that existed in the entire archive but only on days when seeding was done in the subject target. The rationale for this restriction was that if the project meteorologist rejected a day for seeding, his/her decision should be respected and NS matches should not be selected from days when the aircraft were not seeding.

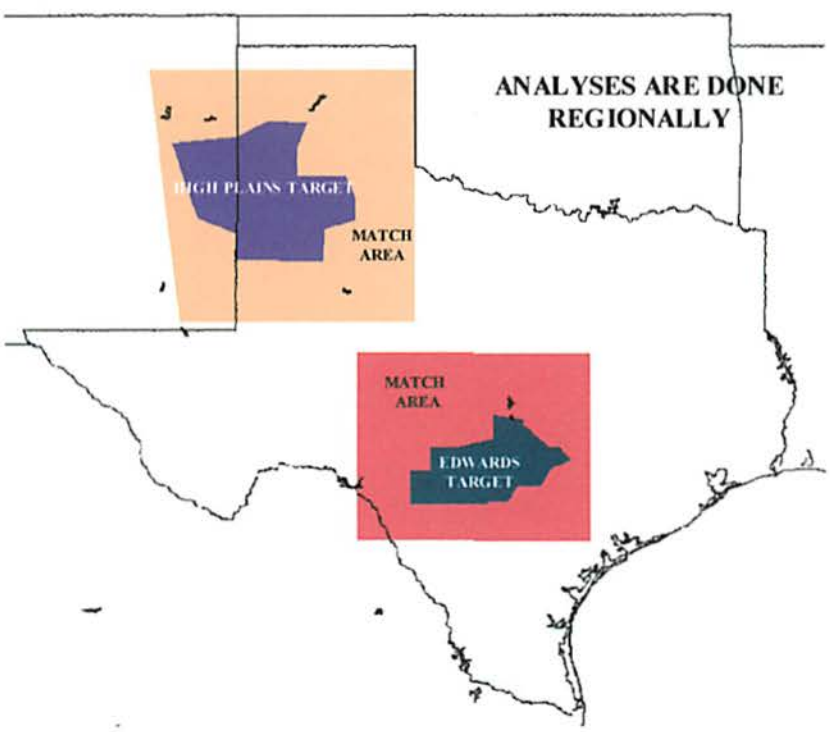


Figure 13. Depiction of the match areas and targets for the Edwards Aquifer and High Plains seeding programs.

Table 2
Unit Samples for the Program Assessments

Target	Within 12 hours of Initial Seeding # S Units	# C Units	Tot. Mtchs	Avg #/unit	1999, 2000 and 2001 (EA only) Seasons # S Units	# C Units	Tot. Mtchs	Avg #/unit
HP	381	381	1,128	3	639	639	63,097	98.7
EAA	192	192	460	2.4	305	305	29,205	95.8

Analysis Period

Focusing first on the Edwards Aquifer program and the seasonal matches, it can be seen that all 305 units were matched 29,205 times for an average of 95.8 matches per unit. When the match is limited to within 12 hours of initial seeding, however, only 192 of the 305 units (63%) could be matched for an average of 2.4 matches per unit. For comparison, 639 units were defined overall during the two seasons in the High Plains program, but only 381 of the 639 (60%) could be matched when the match period was limited to within 12 hours of the initial seeding. Thus, 258 units could not be matched in the restricted match period. Even so, there were 1,128 matches for an average of 3 matches per unit. As in the Edwards program, all 639 units were matched during the two-season match period. In fact, there were 63,097 total matches for an average of 98.7 matches per unit.

It is important to note, however, that the actual number of matches per unit is highly variable as can be seen in the bar plots in Figures 14 for the 1999, 2000 and 2001 seasons in the Edwards target. Note that a seeded unit was matched nearly 1,200 while many others were matched only 5 to 10 times. Those units that matched only a few times obviously had an unusual feature such as exceptionally heavy rainfall and/or very high reflectivities.

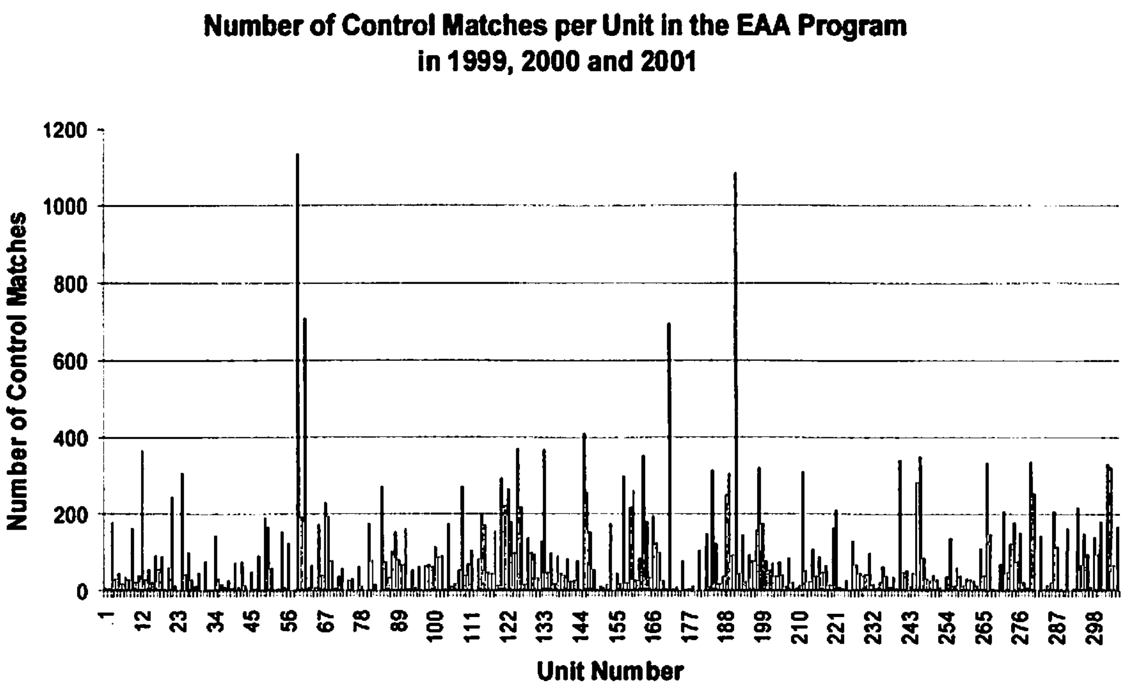


Figure 14. Number of matches per seeded unit in the High Plains target during the 2000 season.

A matter for concern was the quality of the seed vs. control unit matches. The procedures were designed to minimize pretreatment biases and it appears that was accomplished in the Edwards project, judging by the presentation in Figure 15. Shown at the time of real or simulated seeding is the rain-volume rate (RVR) for each seed unit vs. the corresponding average RVR for the matches of each unit. Very little bias, favoring either sample, is evident in this plot. The correlation between the RVRs0 and the average RVRc0 for all the units is 0.997. Thus, the matching process succeeded admirably in eliminating RVR bias at the time of initial seeding.

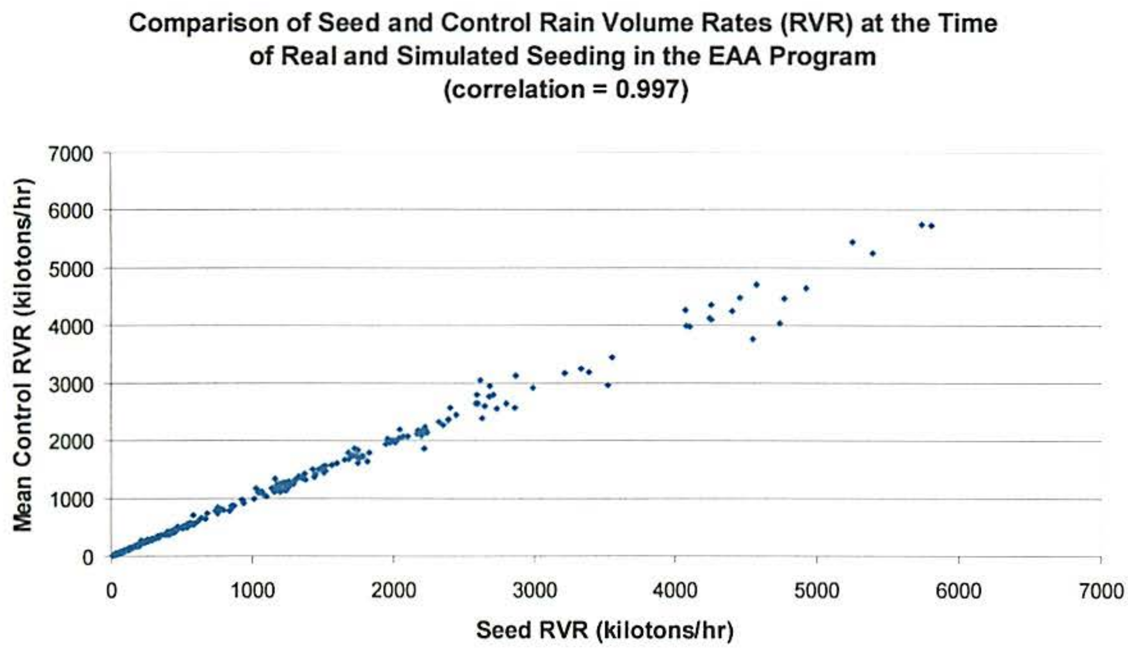


Figure 15. Comparison of seed and control unit rain-volume rates (RVR) at the time of initial seeding for the Edwards Aquifer program in 1999, 2000, and 2001 seasons.

5.0 POSSIBLE SELECTION BIAS

To the extent that the match criteria quantified the rain potential of the matching C units relative to the S units the results to be presented are representative of the effects of operational seeding. Based on our experience, however, it is likely that selection bias has confounded these assessments, where selection bias is defined as real-time pilot-seeder and radar meteorologist recognition of the best cloud and weather conditions for seeding (e.g., especially hard towers, strong cloud organization, obvious outflow boundaries, absence of upper cloud, etc.) that may not be quantified adequately by the current match criteria. Assuming that this is the case, the results in the next section should be viewed primarily as illustrative of what is possible with the method. They should not be viewed as proof of the efficacy of operational seeding, regardless of the statistical P values, since such testing is vitiated when biases are present. Even so, there are certain aspects of the results that probably were not affected significantly by systematic selection biases, as shown later.

6.0 RESULTS OF ANALYSES FOR SEEDING EFFECTS IN THE EDWARDS AQUIFER PROGRAM

6.1 Overall Results

The results of analyses for seeding effects in the Edwards Aquifer target for 10 hrs after initial seeding are tabulated in Table 3. The strengths of all findings, which are valid only in the absence of selection biases, were determined by calculating P values using a t test, assuming unequal variance, for the difference between mean S and mean C rain volumes (in kilotons). A one-tailed test, identified by underlined P values, is used in those instances when there was an *a priori* reason to expect S > C. Otherwise, all P values were obtained from a two-tailed t test. Entries recorded as 0.000 indicate that the P values were < 0.001, indicating strong results in the absence of selection biases. In addition, it should be recalled that some of the units overlap and are, therefore, not independent. Overlap was estimated at about 30% in the EA program.

Beginning with the first row of each table for the restricted match period it is noted that the S and C units are well-matched at the time of initial seeding (i.e., RVRs)/RVRc0 = 0.98). It should be noted, however, that only 192 of the 305 units could be matched when the period of matching was restricted to ± 12 hrs of the unit seeding. The ratio of S to C rainfall by 10 hours after seeding of this limited sample is 1.55. Normally, this would suggest a substantial seeding effect, but this may not be the case. Many units could not be matched in the restricted match period. Further, selection bias as discussed above may have confounded these results.

Table 3
Evaluation of the Edwards Aquifer Cloud Seeding Project in 1999, 2000 & 2001
(P-values obtained from t test; underlined P-values are one-tailed)

Analysis	Ns	RVRs0 (kt h^{-1})	Nc	RVRc0 (kt h^{-1})	S/C	RVOLs (0-10) (kilotons)	RVOLc (0-10) (kilotons)	S-C	P-value	S/C
Within 12 hrs of 1st S	192	1027	192	1044	0.98	4614	2981	1633	0.001	1.55
All	305	1047	305	1041	1.01	4179	3746	433	0.126	1.12
ICA < -2.5	30	757	30	743	1.02	1590	4405	-2815	0.001	0.36
-2.5 ≤ ICA < 0	87	846	87	857	0.99	4987	3250	1737	0.011	1.53
0 ≤ ICA < 5	119	951	119	958	0.99	3951	2702	1249	0.059	1.46
5 ≤ ICA < 10	45	1872	45	1835	1.02	5486	5565	-79	0.943	0.99
ICA ≥ 10	9	159	9	159	1.00	2180	2164	16	0.990	1.01
Weighted ICA	290	1018	190	1017	1.00	4201	3470	731	0.066	1.21
Age > 2 hrs	200	1079	200	1096	0.98	3837	3751	86	0.421	1.02
Age 1:15 to 2 hrs	68	1682	68	1651	1.02	4753	3788	947	0.091	1.25
Age ≤ 1 hr	37	88	37	88	1.00	3988	2642	1346	0.090	1.51
RVRO: 0-500	153		153			2904	2247	657	0.096	1.29
RVRO: 501-1000	30		30			3312	3717	-404	0.649	0.89
RVRO:1001-3000	100		100			5714	5113	61	0.936	1.01
RVRO: > 3000	22		22			9705	8004	1701	0.274	1.21

The second row in Table 3 gives the results for unit matches that were drawn from the entire two-season archive. An apparent seeding effect of 12% (i.e., S/C = 1.12) is indicated for the Edwards target. Here again biases may play a role, but in this case the "deck may be stacked" against an effect of seeding. This may be so, because most of the control units in the archive come from days with widespread echo activity with strong convective forcing. Thus, even though all matches satisfy the match criteria, the S units might not compare favorably to the matched controls, because they may have enjoyed stronger forcing. At this point, this is only conjecture.

6.2 Results after Partitioning

The most credible assessment of seeding effect likely comes from analyses within ICA partitions where the ICA = 8.6 – CCL + 1.72(PB) and CCL is the convective condensation level and PB is the potential buoyancy at 500 mb. Negative values of the ICA on a given day are normally associated with clouds in which coalescence processes are active while strongly positive values of the ICA are associated with clouds without much coalescence. For additional discussion of the ICA see Czys and Scott, 1993; Czys et al., 1996; and Strautins et al., 1999.

The initial plan was to partition the data based on the cloud microphysical classifications, which were determined for all targets in 1999 and 2000 from analyses of AVHRR satellite images as shown in Table 4. (This was not possible for the 2001 season because only NOAA-16 satellite imagery was available in 2001 and its passes typically came too late for quantitative calculations.) With this scheme, clouds with warm glaciation temperatures that reach an effective radius of 15 microns at warm temperature receive a classification of 5.0. These are clouds with intense coalescence activity. Conversely, clouds that remain supercooled to very cold temperatures and also do not reach an effective radius of 15 microns until cold temperatures receive a classification of 1.0. Such clouds have no coalescence activity and are highly "continental" in character. Intermediate conditions receive intermediate classifications. Additional information regarding the inference of cloud structure using satellite imagery is provided in Appendix D.

Table 4
Cloud Classification Matrix Used to Determine Cloud Properties

Temperature at Which the Effective Radius Reaches 15 microns

Glaciation Temperature (°C)	$T \geq 15$	$15 \geq T > 5$	$5 \geq T > -5$	$-5 \geq T > -15$	$T \leq -15$
$T > -10$	5.0	4.5	4.0	3.5	3.0
$-10 \geq T > -15$	4.5	4.0	3.5	3.0	2.5
$-15 \geq T > -20$	4.0	3.5	3.0	2.5	2.0
$-20 \geq T > -25$	3.5	3.0	2.5	2.0	1.5
$T \leq -25$	3.0	2.5	2.0	1.5	1.0

Although this plan appeared to have considerable merit, it could not be implemented because it was not possible to do the satellite analyses on many days due to problems with the imagery. The alternative plan was to relate the satellite cloud classifications to the ICA for days when both measurements existed, and if the relationship was strong enough, to use the ICA as the partitioning variable. Accomplishing this required the processing of the atmospheric soundings from Amarillo and Del Rio to obtain the ICA. The Amarillo sounding was viewed as representative of the High Plains Project, which is probably a good assumption. The Del Rio sounding was viewed as representative of the Edwards target, although the Corpus Christi sounding was considered for a time and then rejected, because its close proximity to the Gulf Coast was viewed as not representative of the Edwards target. Even so, the Del Rio sounding was not a perfect fit for the Edwards target and its use likely contributed to the variability.

A scatter plot that was constructed by comparing the satellite cloud classifications with the corresponding ICA values for the High Plains and Edwards targets as shown in Figure 16. Although there is considerable scatter, there is an obvious relationship between the two; the higher the satellite cloud classification the more negative the ICA, indicating strong coalescence. The linear correlation coefficient is -0.61. These results are as expected, although the variability is greater than desirable. Some of this variability likely is due to variability in the ingested aerosols observed in the satellite imagery. For example, clouds growing on days with highly negative ICA values might still have limited coalescence if they ingest large quantities of smoke from forest fires or pollution from heavy industry that acts to inhibit coalescence in the clouds.

Although the scatter is substantial, the relationship between the ICA and the satellite cloud classification appears strong enough to justify the use of the ICA for partitioning the unit data. Because of the relatively sample in the for the Edwards target, the unit data were partitioned into only four classes: a) ICA < -2.5, b) $-2.5 \leq$ ICA < 0, c) $0 \leq$ ICA 5, d) $5 \leq$ ICA $<$ 10 and e) ICA $\geq$ 10. After the partitioning had been completed, evidence for seeding effects was sought within each partition.

The ICA analysis is attractive for two reasons. First, it makes it possible to examine the effects of seeding as a function of in-cloud coalescence activity. This is important because the conceptual model on which the seeding is based calls for the largest effects of seeding to be produced in clouds with weak to moderate coalescence and least in clouds with intense coalescence, because such clouds already have high precipitation efficiency (Rosenfeld and Woodley, 1993; Woodley et al., 2002a). Second, the ICA analysis permits a closer look at the question of selection biases, since differential effects of seeding within the various ICA partitions should not be affected appreciably by selection biases.

The apparent effect of seeding in the EA is negative with strong P-value support for clouds with intense coalescence and non-existent for clouds with little coalescence. In between, for clouds with weak to moderate coalescence, the apparent seeding effects are positive with strong P-value support. Such consistency is encouraging, because it should be immune to selections biases. These results are shown in bar-graph format in Figure 17. The apparent negative effect in clouds with strong coalescence suggests that glaciogenic should not be done in these situations.

To obtain a realistic overall assessment of the apparent seeding effects, the partitioned ICA results were combined after weighting by their sample size. This sample weighting was done directly on the mean S and NS rain volume values in each partition. These results appear also in Table 3 (in the "weighted ICA" row), indicating that the best current estimate of seeding effect for the floating target units in the Edwards target is +21% (i.e., S/C = 1.21).

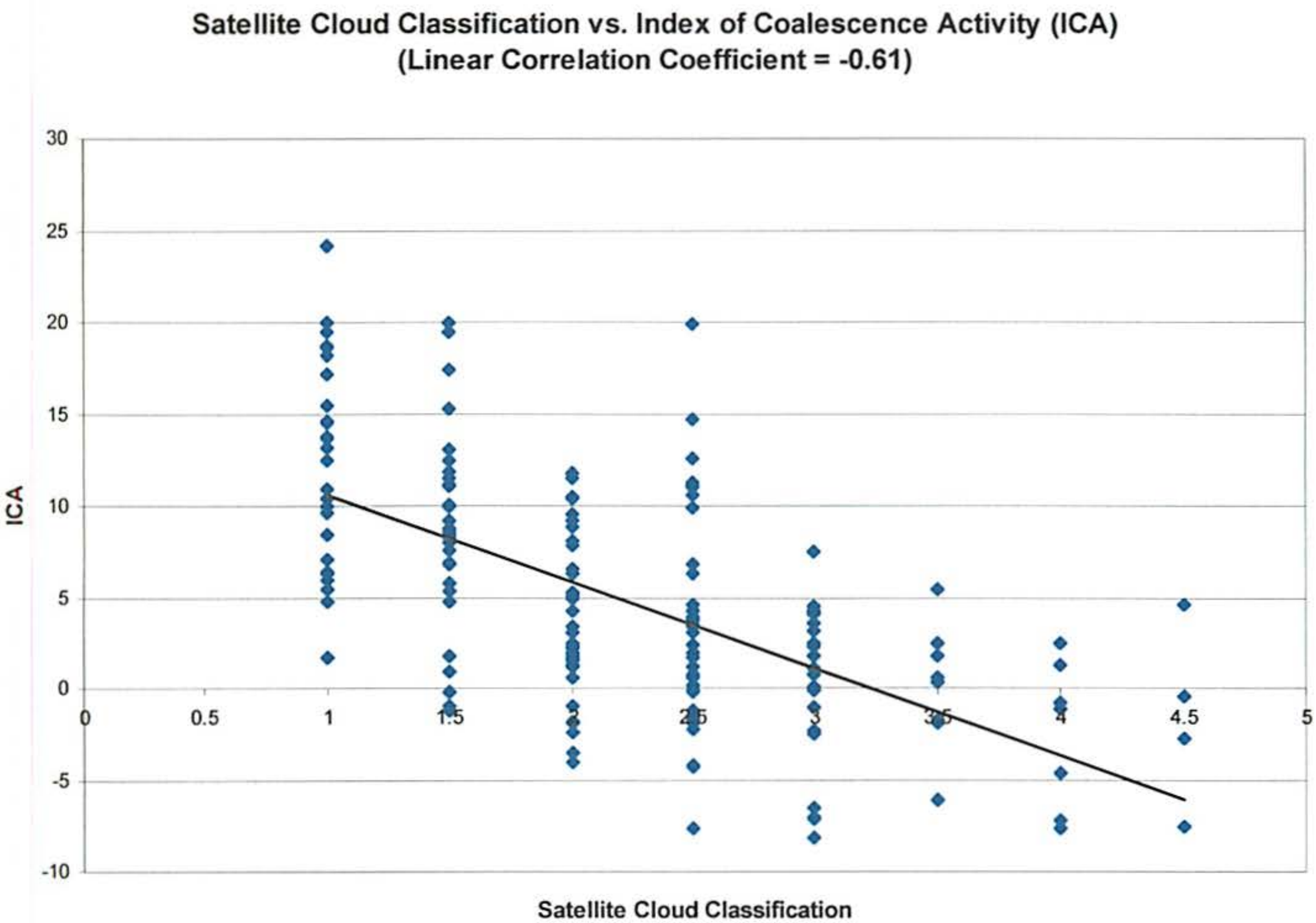


Figure 16. Satellite cloud classification vs. the Index of Coalescence Activity (ICA). The linear correlation coefficient is – 0.61.

6.3 Understanding the Effects of Seeding

The data were then analyzed to determine the S/C ratios as a function of the age of the units when they were first seeded. The results for the EA program are presented in Table 3. The S/C ratios are smallest (i.e., S/C = 1.02) for old cloud systems and largest (i.e., S/C = 1.51) for young ones, and they have no P-value support. It should be noted that 66% of the units seeded in the EA were old and this may explain why the overall effect of seeding in the EA is rather small.

Another way of looking at the apparent effect of seeding as a function of age is provided in Figure 18 in which the percent (%) of a unit's lifetime after 1st seeding is plotted vs. the seeding factor (i.e., S/C) for each unit. Note that those units that had $<$ 40% of their overall lifetimes after 1st seeding also had seeding factors generally $<$ 1.0. On the other hand, those units with most of their lifetimes after 1st seeding showed the largest seeding factors. Even then, there were instances when the seeding factors were $<$ 1.0. This quantifies the dilemma of the project meteorologist and seeding pilots. The rain enhancement potential is greatest if they seed cloud clusters early in their lifetimes. In doing so, however, they run the risk that some of the clusters may not prove responsive. Many seeding flares may be expended with nothing to show for their efforts and expenditures. Meteorologists and pilots, who can distinguish among those young cloud clusters that will be responsive and those that will not, become valuable project assets.

Looking at the apparent effects as a function of initial unit raininess in the EA (Table 3), it can be seen that the largest apparent effect of seeding was produced in clouds with light rainfall within the unit at the time of initial seeding. Although the P-value support is weak, this result is consistent with the conceptual model.

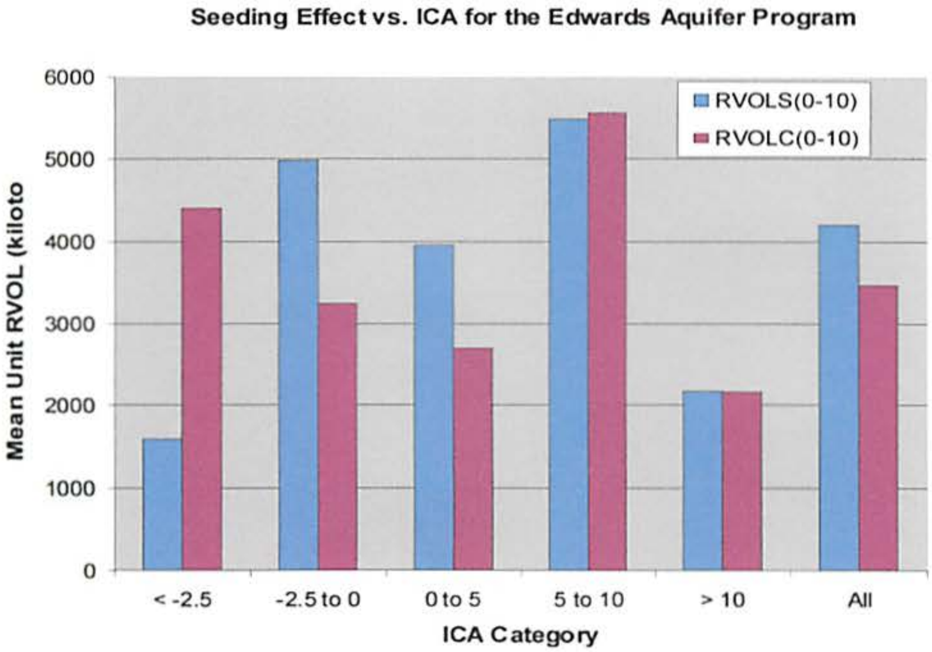


Figure 17. Bar plot of mean S and C unit rain volumes in the 10 hours after initial seeding within the indicated ICA partitions.

It is difficult to understand how the results as a function of unit age and raininess could have been produced by selection biases. Further, they are consistent with the conceptual seeding model, which indicates that for maximum effectiveness seeding should be performed on young vigorous clouds before they mature into large rain systems.

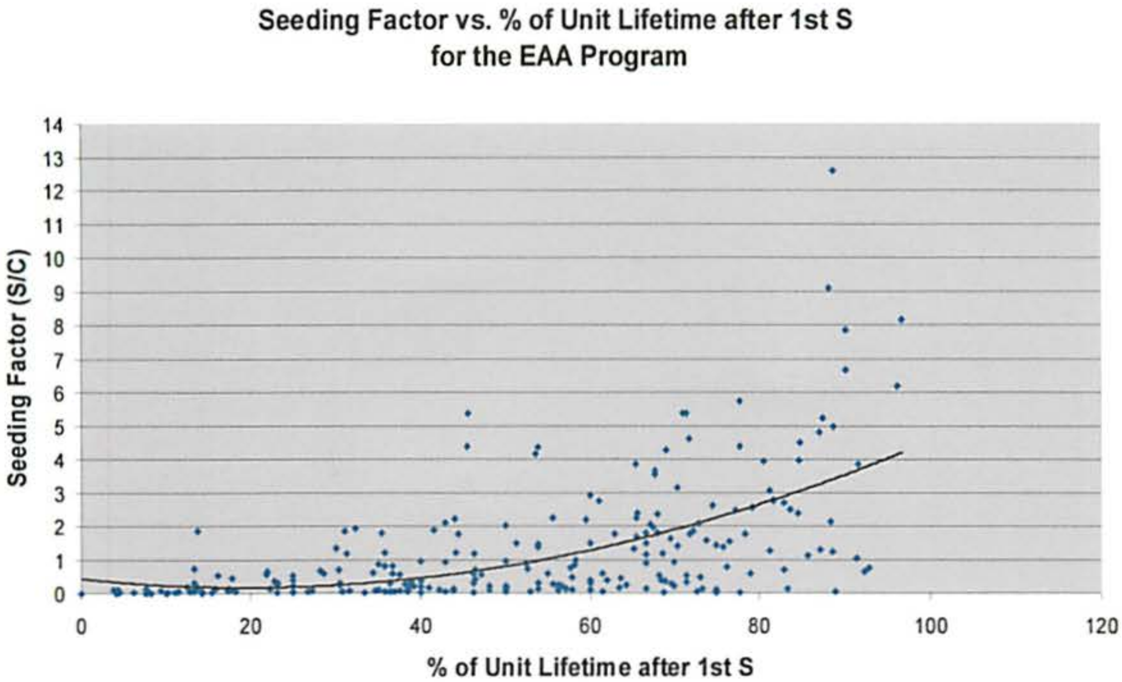
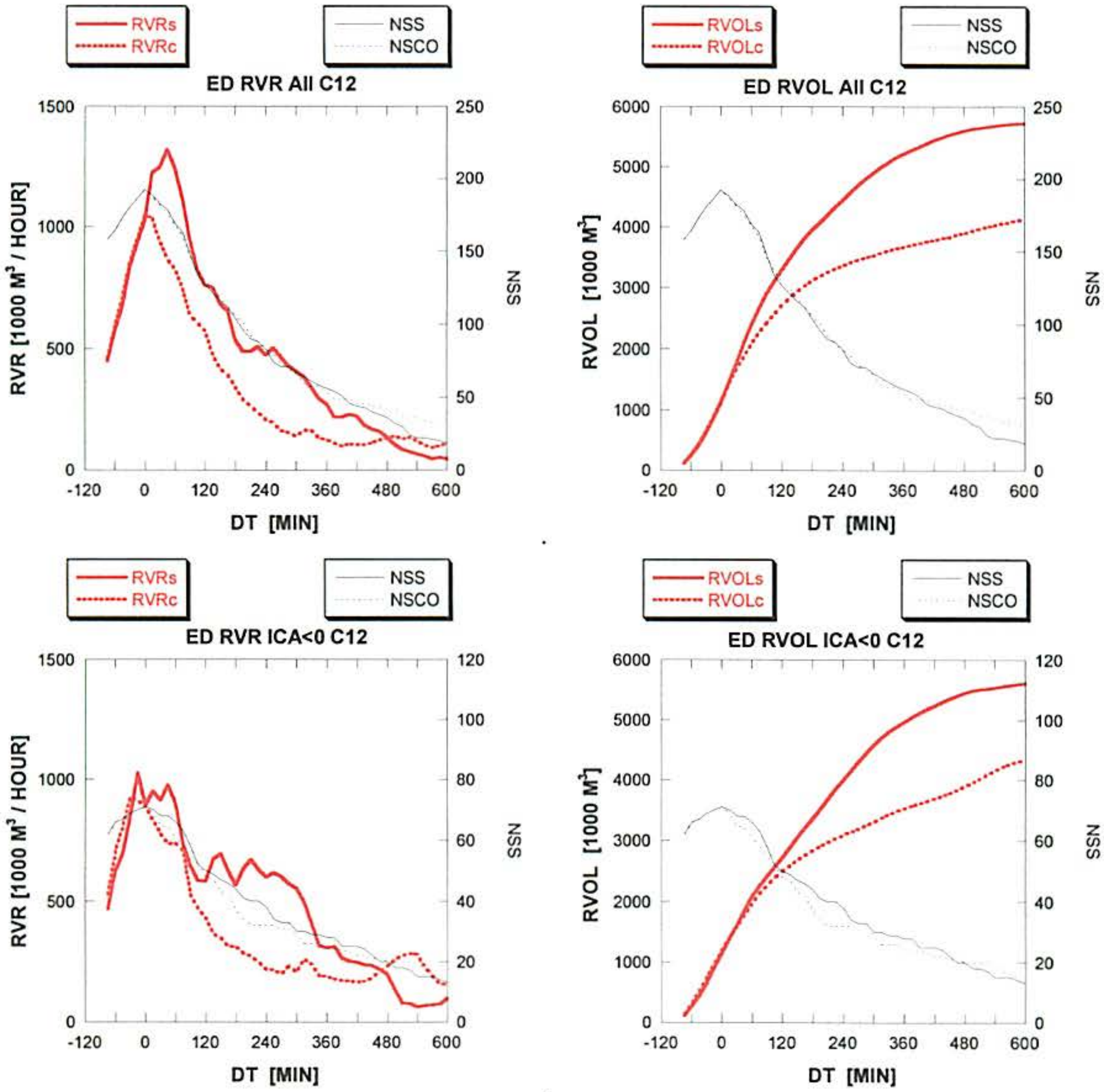


Figure 18. The seeding factor vs. the percentage (%) of unit lifetime after 1st seeding.

The temporal response to seeding was investigated next. Plots of seeded and control unit RVR (left) and RVOL (right) rainfalls referenced to the time of initial seeding are given in Figure 19 for the High Plains seeding program in 1999 and 2000. The plots are for matches that were drawn within $\pm$ 12 hours of the initial seeding. Plots of sample size also are provided. Note that the seed unit sample falls off more quickly because only one unit is involved with each point in the sample whereas many qualifying control units contributed to the unit average. Regardless, 0's for RVR for those units that had died were included in the time averages. The RVOL units are 10^3 m^3 or kilotons. Note that the cumulative differences are very small through one hour after real or simulated seeding and that the differences increase with time until decreasing to zero (0) by 8 hours (480 minutes) after real or simulated seeding. Recall that the cumulative effect for this partition is +55% (see entry in Table 3). The temporal results by ICA show fairly large positive seeding effects on either side of ICA = 0 and smaller effects thereafter.

EDWARDS 1999-2001: Control cases within 12 hours of the seeded case



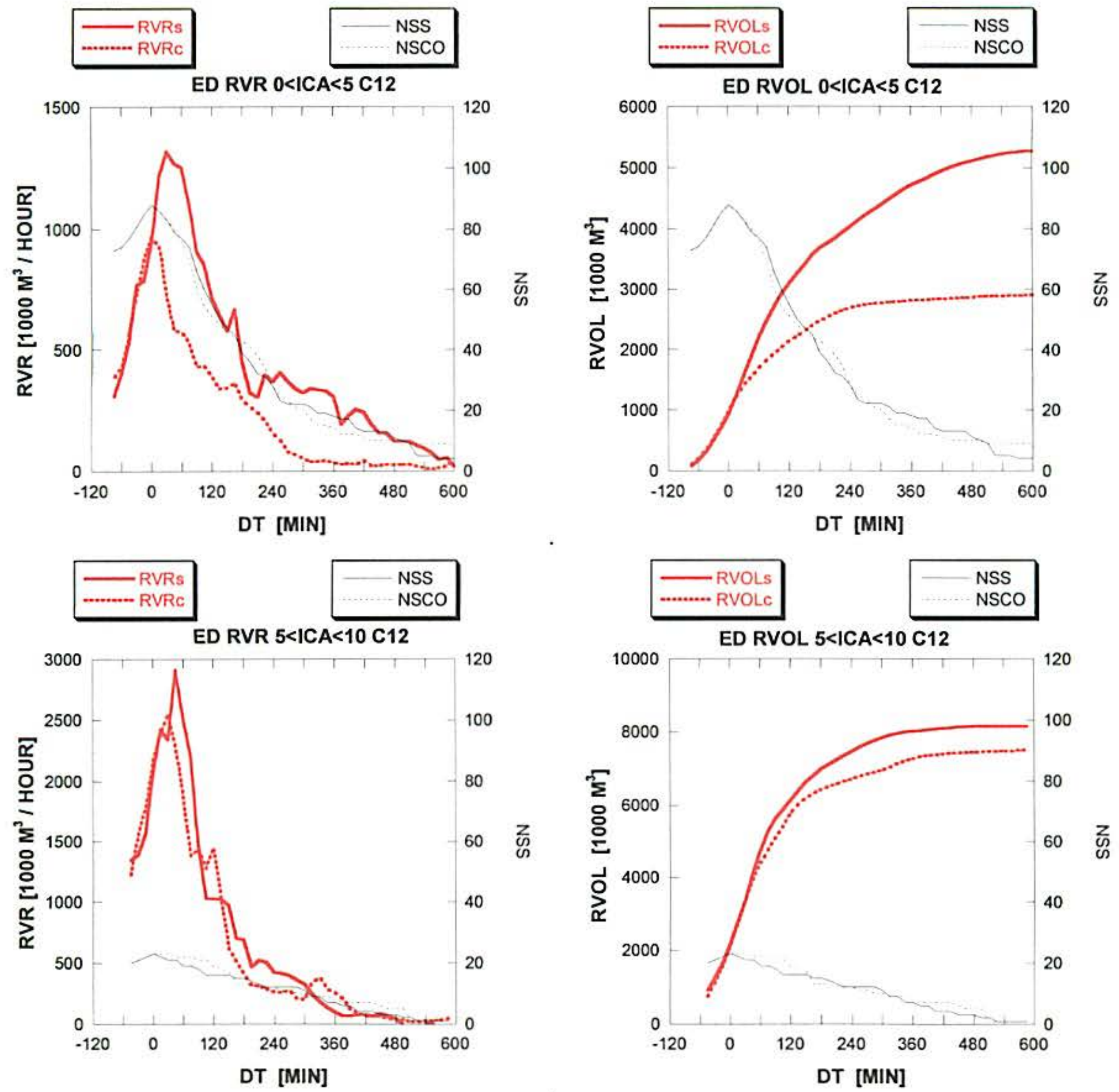
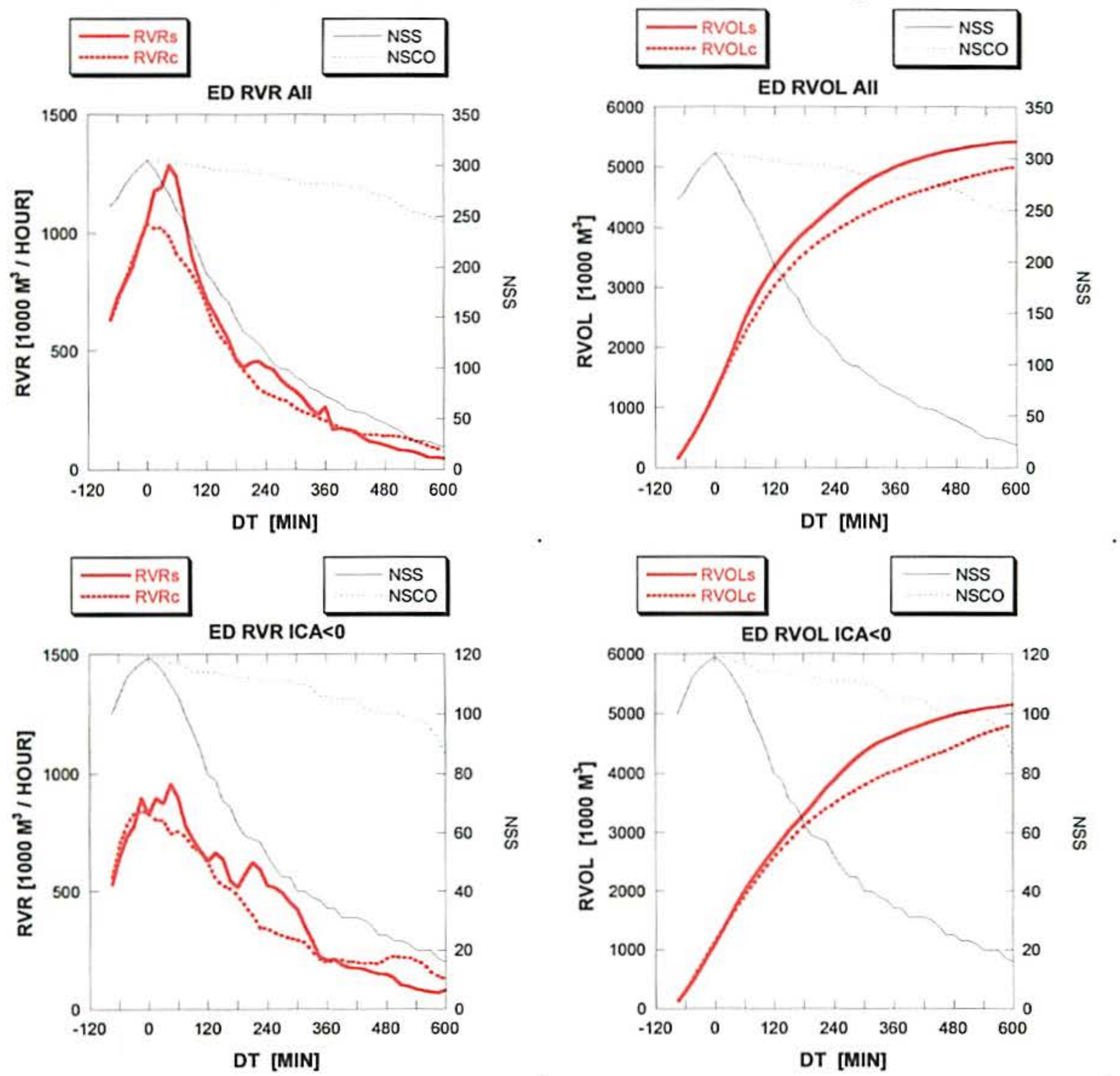


Figure 19. Plots of rain-volume rate (RVR) (left) and cumulative rain volume (RVOL) (right) vs. the time relative to the time of initial seeding for the seed and matching control units obtained in the Edwards Aquifer cloud seeding program in 1999, 2000 and 2001. The matching was done overall and within the ICA partitions shown. The match period is $\pm$ 12 hours of the initial seeding. Plots of sample size also are shown.

The second presentation shown in Figure 20 is similar to Figure 19, except that the matches are from the entire two-season archive. Not much of a seeding effect is evident in these plots in agreement with the results tabulated in Table 3. The RVR plot (left) suggests a small potential seeding response within two hours of the initial seeding and then nothing thereafter. The cumulative effect (right) amounts to only 12% with virtually all of that increment coming within two hours of seeding. A small effect is evident also in the ICA < 0 partition (i.e., S/C = 1.17), which is coming exclusively from the sub-partition -2.5 $\leq$ ICA < 0 (i.e., S/C = 1.53), because the apparent seeding effect is strongly negative for ICA < -2.5 (i.e., S/C = 0.36). Clouds in this partition likely had substantial coalescence. The next partition (i.e., $0 \leq ICA < 5$) suggests a fairly large apparent effect of seeding (i.e., S/C = 1.46). The clouds in this partition likely had some coalescence. The apparent effect of seeding disappears in the partition $5 \leq ICA < 10$ where S/C = 0.99. No effect of seeding is evident also in the last partition ($ICA \geq 10$) but the sample (i.e., 8 units) is so small it would be difficult to take any result seriously.

EDWARDS 1999-2001: Control cases from all days



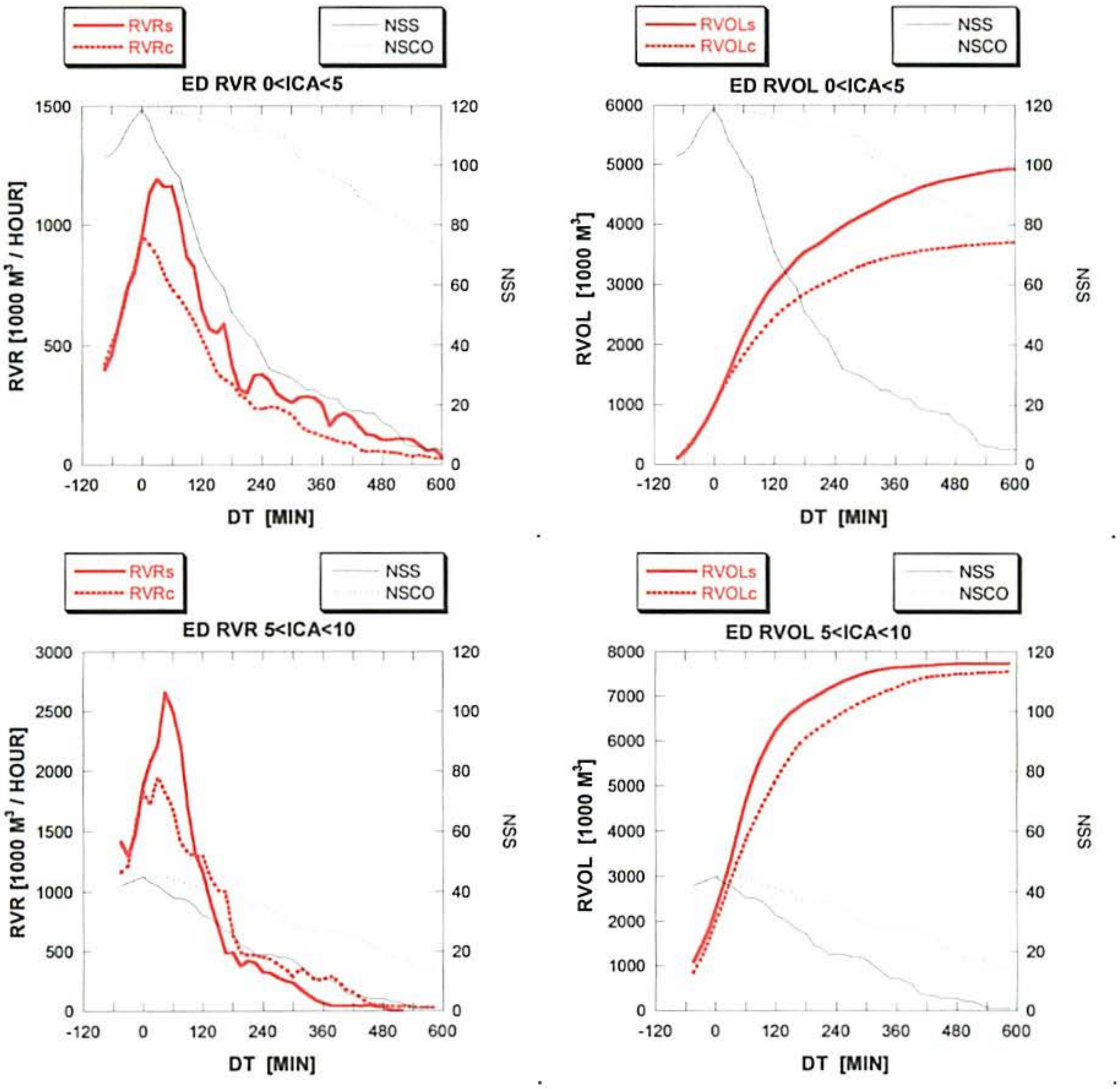


Figure 20. Plots of rain-volume rate (RVR) (left) and cumulative rain volume (RVOL) (right) vs. the time relative to the time of initial seeding for the seed and matching control units obtained in the Edwards Aquifer cloud seeding program in 1999, 2000, and 2001. The matching was done overall and within the ICA partitions shown. The match period is the entire two-year archive. Plots of sample size also are shown.

7.0 GAUGE VS. RADAR RAINFALL COMPARISONS FOR THE EAA NETWORK

As mentioned earlier in this Final Report, prior to the 2001 season it was possible only to make seasonal comparisons between gauge and radar-estimated rainfalls, using a network of non-recording rain gauges installed over the entire High Plains target. Agreement over that time frame was excellent. By the 2001 season, however, the EAA gauge network, containing 96 recording rain gauges distributed over 11,796 km^2 (Figure 21), had been activated. This made it possible to compare the daily radar rainfalls estimates with those provided by the rain gauge network. The period for the daily comparisons was May 4 through September 20, 2002. The correlation between the G and R daily estimates was 0.922 and the ratio of G to R for the period was 1.56, indicating radar underestimation of the gauge rainfall. The individual daily comparisons are listed in Table 5. The scatter plot of G vs. R values with the linear regression is given in Figure 22. These results suggest that the Z-R equation (i.e., $Z = 300R^{1.4}$), which performed well on a seasonal basis for the High Plains target in 1999 and 2002, underestimated the unit radar-estimated rain volumes by a factor of 1.56 in at least the 2001 season. Whether this was true also for the 1999 and 2000 seasons in the Edwards target is unknown, because G vs. R comparisons were not possible until the 2001 season.

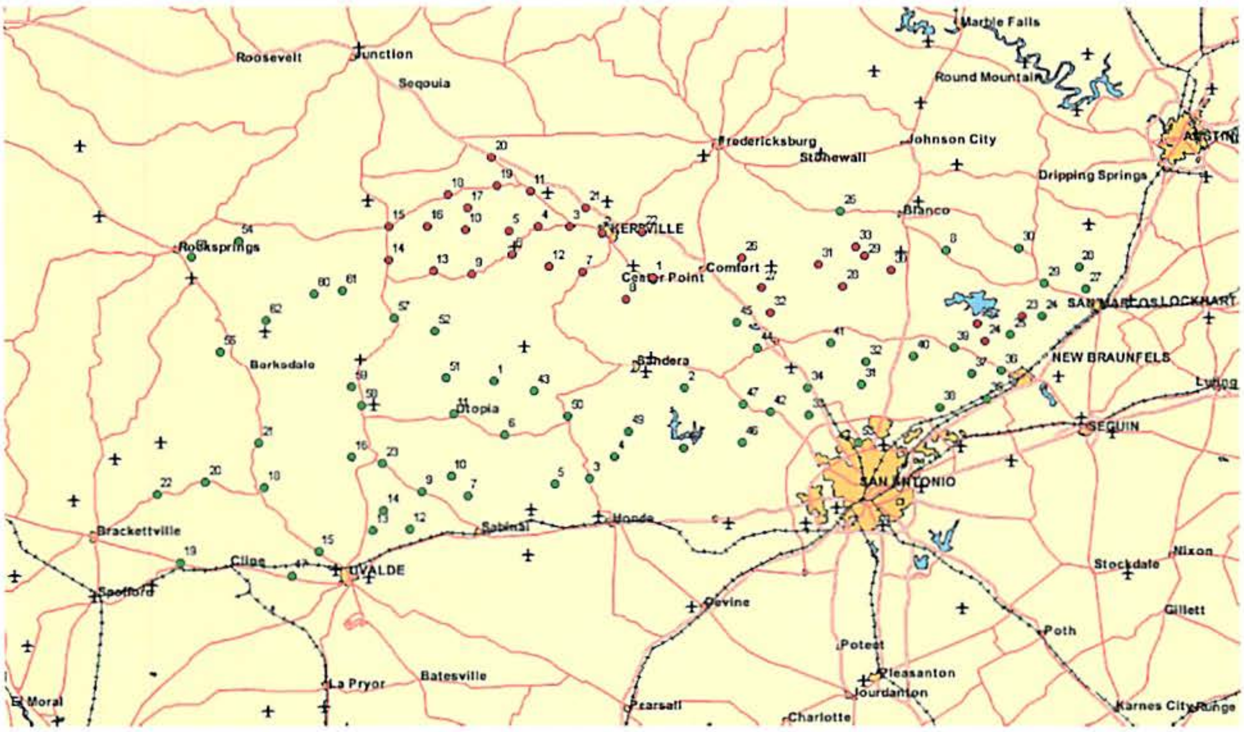


Figure 21. Map showing the positions of the 96 recording rain gauges in the EAA gauge network. Those shown in green (63 sites) were installed and are maintained by the EAA. Those shown in red (33 sites) were installed and maintained by other jurisdictions.

Table 5 Gauge vs. Radar Comparisons for the 2001 season

Date	# G	G Sum	Avg. G	Avg. Rdr	Date	# G	G Sum	Avg. G	Avg. Rdr	Date	# G	G Sum	Avg. G	Avg. Rdr
5/4	91	101.12	1.11	0.78	6/23	93	14.32	0.15	0.16	8/12	95	0.70	0.01	0.00
5/5	91	24.62	0.27	0.21	6/24	93	22.31	0.24	0.08	8/13	95	0.00	0.00	0.00
5/6	91	6.62	0.07	0.11	6/25	93	0.10	0.00	0.00	8/14	95	3.93	0.04	0.03
5/7	91	1.28	0.01	0.00	6/26	93	0.00	0.00	0.00	8/15	95	0.10	0.00	0.00
5/8	91	17.59	0.19	0.24	6/27	93	0.01	0.00	0.00	8/16	95	17.96	0.19	0.20
5/9	91	0.27	0.00	0.00	6/28	94	0.20	0.00	0.00	8/17	95	0.12	0.00	0.00
5/10	91	0.12	0.00	0.00	6/29	94	0.10	0.00	0.00	8/18	95	0.00	0.00	0.00
5/11	91	0.10	0.00	0.00	6/30	94	0.10	0.00	0.00	8/19	95	20.21	0.21	0.17
5/12	91	15.26	0.17	0.08	7/1	93	6.69	0.07	0.04	8/20	95	0.81	0.01	0.00
5/13	91	0.78	0.01	0.01	7/2	93	46.17	0.50	0.18	8/21	95	1.36	0.01	0.01
5/14	91	0.91	0.01	0.00	7/3	93	2.45	0.03	0.01	8/22	95	0.00	0.00	0.00
5/15	91	0.00	0.00	0.00	7/4	94	0.04	0.00	0.00	8/23	95	0.00	0.00	0.00
5/16	92	0.00	0.00	0.00	7/5	94	0.04	0.00	0.00	8/24	95	0.00	0.00	0.00
5/17	92	0.00	0.00	0.00	7/6	94	0.02	0.00	0.00	8/25	95	0.00	0.00	0.00
5/18	92	0.40	0.00	0.00	7/7	94	0.00	0.00	0.00	8/26	95	55.95	0.59	0.54
5/19	92	0.00	0.00	0.01	7/8	94	0.00	0.00	0.00	8/27	95	102.52	1.08	0.58
5/20	93	6.06	0.07	0.14	7/9	94	0.00	0.00	0.00	8/28	95	17.99	0.19	0.05
5/21	93	17.43	0.19	0.15	7/10	94	0.00	0.00	0.00	8/29	93	45.84	0.49	0.08
5/22	93	0.01	0.00	0.00	7/11	94	0.00	0.00	0.00	8/30	93	26.21	0.28	0.27
5/23	93	0.00	0.00	0.00	7/12	94	0.00	0.00	0.00	8/31	93	64.70	0.70	0.29
5/24	93	15.28	0.16	0.15	7/13	94	0.00	0.00	0.00	9/1	95	7.19	0.08	0.02
5/25	93	3.54	0.04	0.15	7/14	94	0.00	0.00	0.00	9/2	95	4.28	0.05	0.02
5/26	93	3.32	0.04	0.04	7/15	94	0.00	0.00	0.00	9/3	95	33.99	0.36	0.26
5/27	93	11.73	0.13	0.07	7/16	94	0.00	0.00	0.00	9/4	95	13.40	0.14	0.08
5/28	93	0.20	0.00	0.00	7/17	94	0.00	0.00	0.00	9/5	95	96.77	1.02	0.46
5/29	93	0.00	0.00	0.00	7/18	94	0.00	0.00	0.00	9/6	95	25.19	0.27	0.17
5/30	93	0.00	0.00	0.01	7/19	94	0.00	0.00	0.00	9/7	95	0.45	0.00	0.00
5/31	93	18.68	0.20	0.02	7/20	95	0.30	0.00	0.00	9/8	95	0.12	0.00	0.00
6/1	93	3.64	0.04	0.02	7/21	95	0.00	0.00	0.00	9/9	95	8.15	0.09	0.07
6/2	93	0.08	0.00	0.00	7/22	95	0.00	0.00	0.00	9/10	95	0.10	0.00	0.00
6/3	93	0.12	0.00	0.00	7/23	95	0.00	0.00	0.00	9/11	95	0.32	0.00	0.00
6/4	93	0.01	0.00	0.00	7/24	95	0.70	0.01	0.00	9/12	95	0.20	0.00	0.00
6/5	93	0.00	0.00	0.00	7/25	95	0.00	0.00	0.00	9/13	95	0.20	0.00	0.00
6/6	93	0.00	0.00	0.00	7/26	95	0.01	0.00	0.00	9/14	95	2.21	0.02	0.01
6/7	93	0.02	0.00	0.00	7/27	95	0.00	0.00	0.00	9/15	95	0.21	0.00	0.00
6/8	93	6.68	0.07	0.02	7/28	95	0.70	0.01	0.00	9/16	95	0.50	0.01	0.00
6/9	93	0.10	0.00	0.00	7/29	95	0.40	0.00	0.00	9/17	95	0.30	0.00	0.00
6/10	93	0.10	0.00	0.00	7/30	95	0.58	0.01	0.00	9/18	95	0.40	0.00	0.00
6/11	93	0.10	0.00	0.00	7/31	95	0.00	0.00	0.00	9/19	95	0.30	0.00	0.00
6/12	93	0.00	0.00	0.00	8/1	95	0.00	0.00	0.00	9/20	95	0.50	0.01	0.00
6/13	93	0.00	0.00	0.00	8/2	95	0.00	0.00	0.00					
6/14	93	5.94	0.06	0.17	8/3	95	0.00	0.00	0.00					
6/15	93	13.69	0.15	0.05	8/4	95	0.00	0.00	0.00					
6/16	93	0.00	0.00	0.00	8/5	95	0.00	0.00	0.00					

6/17	93	0.00	0.00	0.00	**8/6**	95	0.00	0.00	0.00
6/18	93	0.00	0.00	0.00	**8/7**	95	4.24	0.04	0.04
6/19	93	0.03	0.00	0.00	**8/8**	95	0.57	0.01	0.00
6/20	93	0.00	0.00	0.00	**8/9**	95	0.27	0.00	0.00
6/21	93	0.00	0.00	0.00	**8/10**	95	0.10	0.00	0.00

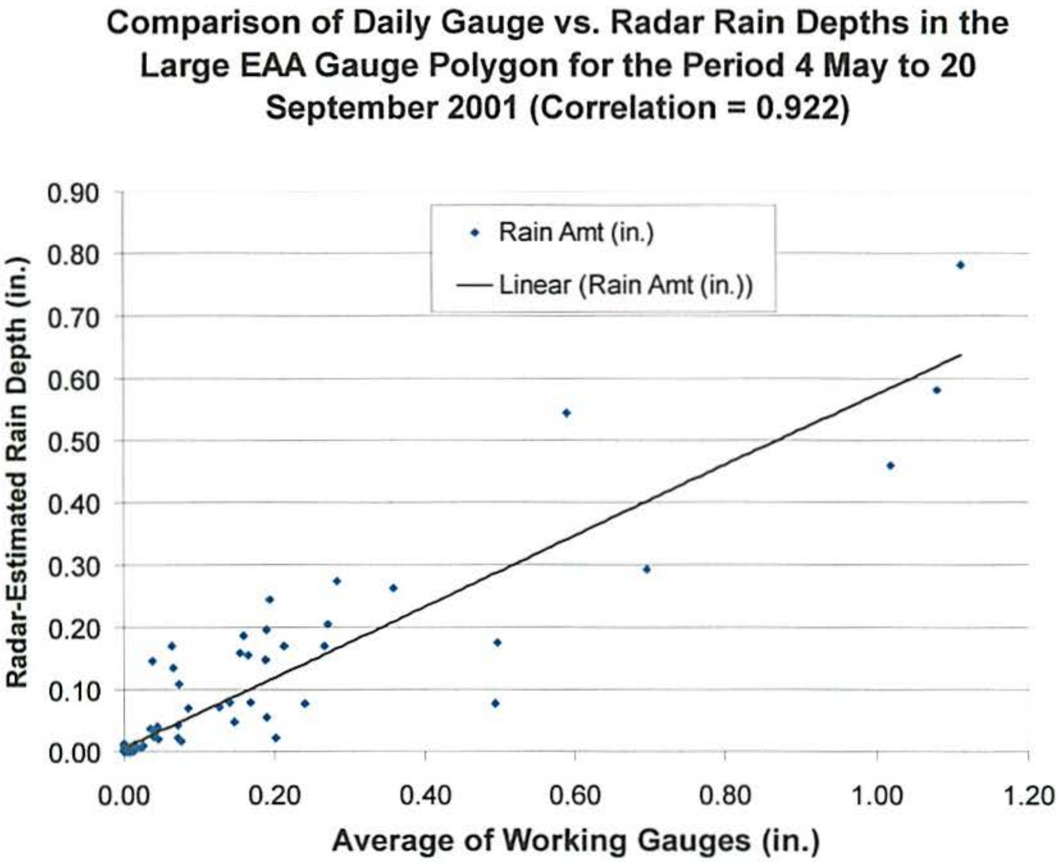


Figure 22. Comparison of daily gauge vs. radar rain depths in the large EAA gauge polygon for the period 4 May to 20 September 2001. The linear correlation is 0.922.

The 2001 results did not come as a big surprise, because the NWS Z-R relationship, which performs well for deep convection, is known to underestimate rainfall from clouds with a maritime structure by as much as a factor of two. Considering the flow of tropical air from the Gulf of Mexico into the EA target on some days, one would have expected the radar to underestimate the rainfall from clouds growing in that air mass. Under strongly tropical conditions the NWS recommends that the tropical Z-R equation derived by Rosenfeld et al. (1993) and adopted by the NWS (i.e., $Z = 250R^{1.2}$) for tropical clouds be used for radar rain estimation. This "tropical" Z-R gives about double the value of R for the same Z compared to the standard Z-R of $Z = 300R^{1.4}$. This could potentially more than compensates for the actual radar underestimate by a factor of 1.56. Only the single Z-R relationship ($Z = 300R^{1.4}$) was used in our study, however, although we reserved the option of later adjustment of the radar-rainfall estimates based on the gauge vs. radar comparisons. In any case, radar biases should not affect the estimates of seeding effect, because such biases should apply equally to both the S and C units, based on the measurements of Cunning (1976).

Based on the limited overall information at hand, it appears that the radar represented the rainfall accurately in West Texas and underestimated it East nearer to the Gulf of Mexico. The question becomes what to do with this information. First, it should be noted that this is welcome information since we had been collectively scratching our heads wondering why units in the Panhandle of Texas, which is drier climatologically that East Texas, should be more rain productive on average that the units of East Texas. This is illustrated in Figure 23 in which the mean control rainfalls for the HP and EAA projects are shown in bar format. Note that the mean EAA unit control values in all three partitions (i.e., $\pm$ 12 hours, entire archive and weighted ICA) are less than those for matching units in the HP program. If one then assumes, however, that the EAA radar-estimated unit control values should be adjusted upward by a factor of 1.56 in all seasons, based on comparisons made in 2001, note that the EAA unit control values exceed those in the HP. This is in better agreement with expectations.

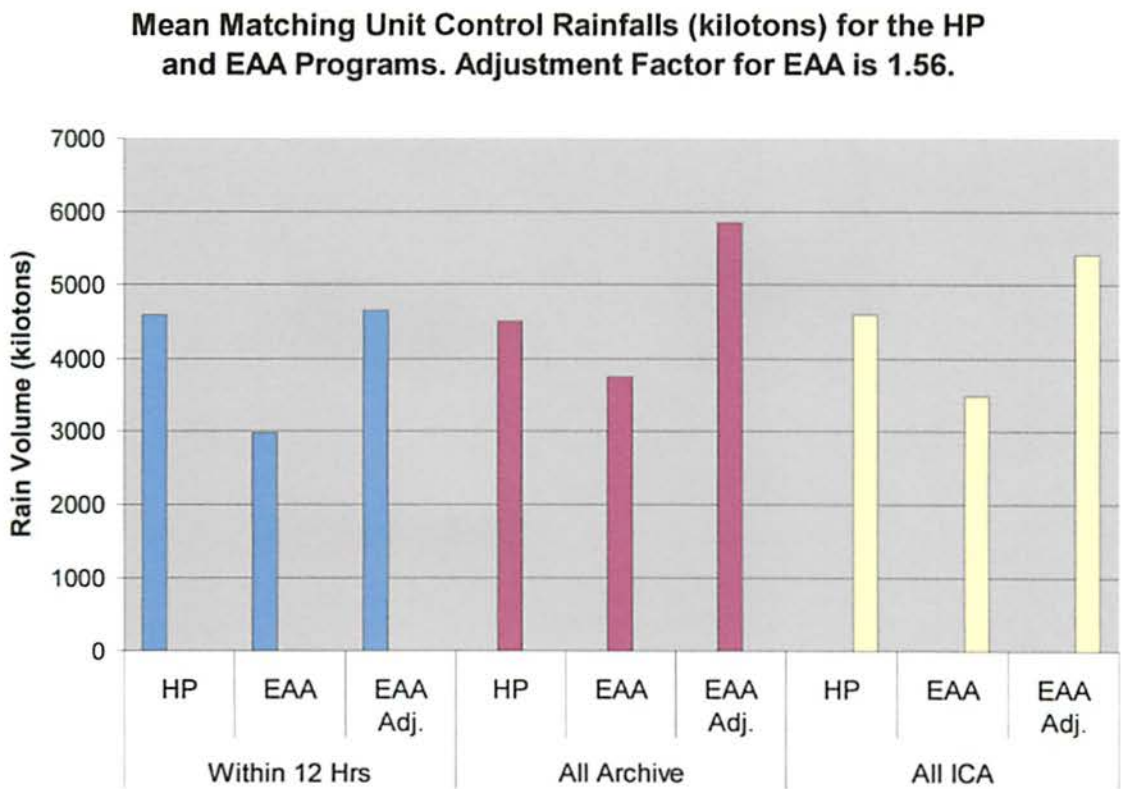


Figure 23. Mean matching unit control rainfalls for the HP and EAA Programs. The adjustment factor for the EAA is 1.56.

8.0 ESTIMATION OF THE BENEFIT TO COST RATIO FOR THE EDWARDS AQUIFER PROGRAM

A crude benefit/cost calculation for the Edwards program is made in Figures 24 and 25. Most of the information is self-explanatory except for the calculation of "independent units" in Figure 25. To understand this one must recall that when defining the analysis units some overlap was allowed, if not encouraged. Therefore, any units that overlap are not independent of one another. To do the benefit to cost calculation, however, the number of independent seeded units must be known. Although this is not known with certainty, it was approximated by multiplying the number of analyzed units by the ratio of known amount of AgI expended for the 1999 and 2000 seasons by the summed amount of AgI for all of the analyzed units. If this ratio were quite large, indicating that some of the seeding events were counted more than once, it would indicate that many of the units overlapped. This ratio is 1.30 for the EAA program, indicating that 30% of the units overlap and that 15% of them should be eliminated for the purposes of the benefit to cost calculation. Thus, 85% of them are retained in the calculation.

MOST REALISTIC ASSESSMENT OF SEEDING EFFECT IS SAMPLE-WEIGHTED ANALYSIS AFTER PARTITIONING BY ICA AND ADJUSTMENT BY G/R = 1.56

EDWARDS AQUIFER

WEIGHTED VALUES AT 10 HRS

RVOLS10 = 5308 ACRE-FEET

RVOLC10 = 4385 ACRE-FEET

S/C = 1.21

S-C = 923 ACRE-FEET

AN INCREASE OF +21 %, AMOUNTING TO 923 ACRE-FEET PER UNIT IS INDICATED

Figure 24. Best estimate of the effect of seeding as a percentage and as a volumetric rain increment.

BENEFIT VS. COST ESTIMATES FOR
THE EDWARDS AQUIFER CLOUD SEEDING PROGRAM

BENEFITS

• CALCULATION OF INDEPENDENT UNITS
305(0.85) = 259 units

• CONSERVATIVE CALCULATION OF BENEFITS

ASSUME THAT THE VALUE OF WATER IS $100 PER ACRE-FT AND THAT 75% OF THE ENHANCED RAINFALL REACHES THE GROUND

THEN, 259(923 acre-feet)(0.75)$100 per acre foot = $17,929,275

COSTS

• PROGRAM COSTS FOR THREE YEARS WAS $1,517,100

BENEFIT TO COST RATIO

• $17,929,275/$1,517,100 = 11.8:1

Figure 25. The benefit to cost calculation.

Although the calculations are conservative, one should not take them too seriously at this time. In the EAA calculation it was assumed that 75% of the radar-estimated enhanced rain volume (731 kilotons = 592 acre-feet x 1.56 for radar underestimation = 923 acre-feet) for each unit reached the ground and that an acre-foot of water is worth $100. Of course, the value of the enhanced seeded rainfall depends on how much of it can be utilized and for what purpose. This kind of detail is beyond the purview of our study. Upon dividing the calculated benefits by the known project costs the ratio is 11.8 to 1. This is a fairly substantial ratio and would appear to be large enough to justify continuation of operational seeding over the Edwards Aquifer.

9.0 DISCUSSION

Analysis of the Edwards Aquifer operational cloud seeding program after ICA partitioning indicates that the seeding increased the rainfall on an area basis in 1999, 2000 and 2001 by about 21%. A comparable analysis for the High Plains program gave apparent seeding effects over twice (i.e., +54%) those in the Edwards program. This raises two questions. First, was seeding causal of all of the apparent rainfall increases? Second, why was the apparent effect of seeding much larger in the High Plains than in the Edwards Aquifer cloud seeding program?

Addressing the first question, it should be noted that if the match criteria managed to quantify the actual rain potential of the S and C units, the estimates of seeding effect are probably valid as they are. If this is not the case, then a portion of the seeding effect could be due to selection bias on the part of the seeding pilots. Under this scenario it is assumed that the pilots and/or project meteorologist have special expertise in selecting the best clouds for seeding, based perhaps on their visual appearance, such that the present match criteria do not account adequately for these clouds.

There are several ways this potential problem might be addressed. One approach might be to identify additional criteria by which control units would be better matched to their seeded counterparts. At this writing, however, it is not clear what those additional criteria might be. A huge plus for the methodology used in this study is its versatility. If new criteria for unit matching can be identified and quantified, it would be a simple matter to rerun the matching programs.

There are other possibilities. Suppose it were known with some certainty that the amount of AgI that must be expended in a seeding unit to affect the rainfall is a minimum of 100 g. It would then be possible to look at the units receiving less than 100 g for a seeding effect, knowing full well that a seeding effect was not possible. Then, if the analysis gave a S to C ratio of 1.25, it would represent a selection bias and not an effect of seeding. Then the estimates in the other partitions in which a seeding effect were possible could be adjusted downward by this factor.

All one can say at this point is that, while a selection bias is a logical possibility in view of the high apparent effect of seeding, there is no evidence yet that this is the case in either the EA and HP program. Further, after partitioning the data it was found that the indicated seeding effects in both the HP and EA programs were largest in clouds having weak coalescence in units seeded early in their lifetime before significant natural precipitation had time to develop. No effects were indicated in clouds with intense coalescence. It is unlikely that such differential seeding effects, which are consistent with the expectations of the seeding conceptual model, could have been produced by similar differential selection biases. One is led to the conclusion, therefore, that the indicated differential seeding effects might be real. However, the selection bias needs to be quantified in absolute terms, and additional data should be analyzed before we can accept these positive results as statistically conclusive. How such biases might be quantified and eliminated, involving the incorporation of limited randomization within the context of the operational seeding effort is addressed.

The question why the apparent seeding effect is larger in the HP than in the EA program is an intriguing one. There are several possible explanations other than it being due purely to chance. It is possible that personnel and their decision making may have played a role in the project differences. As addressed earlier, the effect of seeding appears to be a function of the age of the cloud system when it is first seeded, and 21% more old (i.e., > 2 hours) units were seeded in the Edwards program than in the High Plains. This might be explained by a higher percentage of old units moving into the Edwards target as compared to the High Plains target. Although possible, this does not seem very likely. These differences might also be explained by the actions (or non-actions) of the project meteorologist and/or the seeding pilots. For example, if a project meteorologist in one project was slower to scramble his aircraft for seeding than a project meteorologist in another project, the seeding of older cloud systems would be the natural result.

10.0 ACCOUNTING FOR SELECTION BIAS BY OPERATIONAL RANDOMIZATION

The assessments of seeding efficacy with our method of evaluation will not be universally credible until some means is found to quantify and adjust for biases. The best approach would involve randomization of the treatment decision in instances when it is agreed in real time by the project meteorologist and seeder pilot(s) that there are too many suitable seeding targets to be reached by the available seeder aircraft. This is especially the case in projects that have only one seeder aircraft to cover a large target. When faced with this situation, the project meteorologist and seeding pilot(s) would identify two areas with comparable suitable clouds and declare that only one of the two could be reached by the seeder aircraft. Based on both radar and visual cues, the likely positions of initial seeding in each cloud cluster would be determined and recorded. Which is to be seeded would be determined from the draw of a randomized seeding instruction, and the pilot would then be directed to the cluster (A or B) that is to receive treatment. The second cluster would not be seeded throughout its lifetime, but nothing is lost because project personnel had already agreed in advance that only one of the clusters could be reached by the seeder aircraft. To make this work all would have to agree to live with their decision regardless of the outcome following the draw of the treatment decision.

During the analysis phase, the floating target analysis units (FTUs) corresponding to the positions of simulated and actual seeding in the randomly determined no seed (NS) and seed (S) units, respectively, would be defined. Analysis would then proceed to quantify the selection bias and to obtain an independent estimate of seeding effect, provided the randomly-determined S unit was actually seeded. If not, neither the S nor NS could be used to quantify the selection bias and for the estimation of seeding effect in the manner described below.

To determine the selection bias all randomly-determined NS units would be matched with control (C) units using the methodology described herein and the "seeding effect" would be determined by forming the ratio of mean NS lifetime unit rainfalls to the average mean C lifetime unit rainfalls (i.e., NS/C_{NS}). If a "seeding effect" were determined, it would be a measure of the selection bias since no seeding was actually done in the NS units. This calculated bias then could be deducted from the results obtained by matching non-random controls with the seeded units using the new methodology. If implemented properly, this approach would provide a credible estimate of the effect of seeding that could be compared to the estimates of seeding effect obtained by the analyses of seeding effect performed without the benefit of randomization. As we see it, there is much to be gained and virtually nothing to be lost with this approach for the quantification of possible selection biases and for the provision of an independent estimate of seeding effect.

Although none of the Texas operational seeding projects has yet made a firm commitment to employ randomization, it is receiving serious consideration. Some projects have agreed to an interim step whereby they identify control units when suitable cloud clusters cannot be reached and/or are off limits to the seeder aircraft. Although this is a step in the right direction, the selection of cloud masses that are known to be controls by individuals, who are perceived to have a vested interest in the outcome of the evaluation, is going to be suspect in some quarters. If it can be demonstrated that it will not compromise project objectives, randomization is still the better alternative to deliberate selection of control units.

11.0 CONCLUSIONS

The new computer-based method to evaluate operational cloud seeding projects that has been developed by the scientific team of Drs. Woodley and Rosenfeld works as intended. First results for the Edwards cloud seeding project are encouraging, although one cannot be certain that selection bias, as discussed herein, has not influenced the results. The work has led to the following conclusions:

- The method of matching seeded units with control units works as it was designed, allowing for the analysis of thousands of echoes, for the objective matching of seed units with hundreds of control units, and for the elimination of pre-treatment biases. Virtually any kind of seeded cloud system, ranging from isolated clouds to massive thunderstorm complexes and lines, can be matched by corresponding controls as long as the data archive is large enough.

- A major plus for the new method is the compilation of an echo archive that will grow to enormous size with time such that multiple matching of seeded units will be possible within virtually any meteorological partition.

- When matching seed with control units within 12 hours of the time of initial seeding, many seed units could not be matched because suitable controls could not be found in the match area. Making the match criteria more stringent will only exacerbate this problem.

- When matching seed and control units with the entire archive, all of the units could be matched, but the match of cloud microphysical structure is uncertain, casting some doubt on the inferences of seeding effect.

- The best method of assessment, involving the analysis of the results within ICA partitioning and then sample-weighting the results to provide an overall assessment of seeding effectiveness suggests that the effect of seeding for the 1999 and 2000 seasons was +21% in the Edwards target. The corresponding volumetric rain increase was 923 acre-feet after adjusting for the radar underestimation of the rainfall.

- Although the overall results suggest positive effects of seeding in the EA program, it is likely that "selection bias" confounded these assessments, where selection bias is defined as real-time pilot-seeder recognition of cloud and environmental characteristics favorable to future cloud growth (e.g., especially hard towers, strong cloud organization, obvious outflow boundaries, absence of upper cloud, etc.) that are not quantified adequately by the current radar-based match criteria.

- After partitioning the data, however, it was found that the apparent seeding effects in both the EA and HP programs were largest in clouds having weak coalescence in units seeded early in their lifetime before significant natural precipitation had time to develop. No effects were noted in clouds with intense coalescence.

- It is unlikely that such differential seeding effects, which are consistent with the expectations of the dynamic-mode conceptual seeding model, could have been produced by similar differential selection biases. One is led to the conclusion, therefore, that indicated differential seeding effects might be real. However, the selection bias needs to be quantified in absolute terms, and additional data should be analyzed before we can accept these positive results as physically and statistically conclusive.

- The effect of seeding appears to persist for as many as 8 hours after the initial seeding, implying that the effect of seeding extends outside the target area downwind in some instances.

- The Edwards program is estimated to have a benefit to cost ratio of about 12 to 1, which would appear to warrant its continuation.

- It is doubtful that enough seeding was done in the Edwards program to affect the overall target rainfall, giving considerable room for improvement both in the amount of seeding and its timing.

- The results presented here are for small targets (i.e., 1,964 km^2) or units that float with the wind. Only if many such units were treated on each day of operational seeding will these results translate into effects on rainfall over the entire seeding target and downwind.

12.0 RECOMMENDATIONS

As a consequence of the work under the contract, the operational recommendations below are offered for consideration. Because the EAA is no longer running its own program, most of the recommendations apply to those organizations that have accepted operational responsibility for seeding in portions of the EA target on behalf of the EAA.

- In view of the results obtained to date, the Edwards operational cloud seeding program should continue as long as provision is made for its evaluation.

- Improve the seeding coverage within the target either by increasing the number of seeding aircraft or by decreasing the size of the target. In the latter instance, the seeding should be focused on the portions of the target that will lead to recharge of the aquifer.

- Be more aggressive in the conduct of the seeding by: a) working young vigorous cloud systems that are not yet producing much rainfall, b) increasing the number of seeding passes into, under or over suitable clouds, and c) conducting multiple aircraft operations on organized cloud systems as warranted.

- Night seeding should be considered, if it can be done safely and efficiently. Up to half the natural rainfall occurs at night during some months and it should not be ignored.

- Co-locate project operations, if possible.

- Conduct flight debriefings, especially on days of large apparent seeding response and on days when significant problems were encountered.

- Install a video camera on at least one of the seeder aircraft and use the video for flight documentation in debriefings and in training sessions.

- Continue pilot training in seeding procedures and conduct periodic flight checks.

- Strive for personnel continuity, especially for the project meteorologist and the seeding pilots. Personnel turnover is highly destructive to seeding projects.

- Make a commitment to evaluate and document everything of consequence to the project to ensure efficient seeding operations and high data quality.

Besides these operational recommendations, two additional recommendations are made for the EAA. The first involves continued operation of the EAA rain gauge network and the processing of the data for comparisons of gauge and radar rainfalls. This is important to all of Texas, particularly for those projects (i.e., South Texas and Southwest Texas) in a meteorological environment comparable to that of the EA project. The rain gauge data should be processed by EAA personnel under the oversight of Mr. Jesse Mireles, who did a nice job processing the gauge data for the current study. Other groups or individuals should use these gauge data for comparison with the radar estimates of rainfall.

The second recommendation is that the EAA should conduct studies, either in house or through outside contracts, to relate rainfall to recharge of the Edwards Aquifer. This recommendation is based on the observation that the EAA is now in a position to obtain highly accurate gauge-adjusted, radar-estimated rainfalls over virtually any area on a hourly, daily, weekly, monthly and seasonal basis. In fact, Woodley Weather Consultants has already processed such data for the 1999, 2000 and 2001 seasons. In addition, the EAA already has a long-record of water levels in the Edwards Aquifer.

It is possible, therefore, to develop regression relationships between volumetric rainfalls in any sub-area within the aquifer and the aquifer recharge. This can be done with any time lag between the rainfall and the recharge. This will make it possible to determine where the major recharge areas are located as a function of rain amount, intensity and duration. This is will make it possible to prioritize the areas for cloud seeding. Knowing the total rain output from a storm system and the recharge, it should also be possible to assess how much rainfall runoff takes place, again as a function of rain intensity and duration.

Such data and relationships should be highly useful to individuals developing and verifying hydrologic models of the aquifer. Judging by the author's experience in the meteorological realm, good observational data is probably at a premium in the development of hydrologic models. Knowing what is needed for model development likely require collaboration among the meteorologists and hydrologists who are parties to the research effort.

13.0 ACKNOWLEDGEMENTS

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APPENDIX A

THE TEXAS OPERATIONAL CLOUD SEEDING PROGRAMS
(Excerpted from Bomar et al., 1999)

1.0 Introduction

Texas suffers from periodic droughts. This will always be the case in view of the semi-arid nature of the climate of much of the state. The most recent period of severe rain deficiency began in 1995 and continued through 1999 into 2000. Coping with such dry periods in the future will become increasingly difficult in Texas because of its growing population, which is predicted to nearly double, to 35 million, by the year 2030 AD.

This growing need for adequate fresh-water supplies in arid and drought-stricken parts of Texas has focused renewed attention on alternative ways of conserving existing water resources and of procuring additional water by tapping into the abundant supply of moisture available in the Earth's atmosphere. Passage of the Texas Weather Modification Act by the Texas Legislature in 1967 was a tacit acknowledgment that the use of cloud-seeding technology had earned a measure of acceptance within the water-management community in Texas. At the same time, the law recognized many uncertainties remained with respect to the effectiveness of various forms of cloud seeding. Hence, the need to regulate the level of human intervention in cloud processes to protect the interests of the public, and to promote the development of a viable and demonstrable technology of cloud seeding, was addressed by that legislative act.

To attain the objective mandated by the Texas Legislature to develop and refine cloud-seeding technologies, the State of Texas took a first step by linking up with the U. S. Bureau of Reclamation in 1973 to devise and demonstrate a viable cloud-seeding technology. Since then, an on-going, though often intermittent, research effort has ensued to corroborate and quantify the effects of timely seeding of convective clouds. Despite limited funding over the years, substantial progress has been made in pursuit of this goal.

Texas also has a long history of operational weather modification. From the time prior to World War I, when C. W. Post attempted to 'shake' rainwater out of towering cumuli along and just below the Caprock region of West Texas (1911-1914), various weather-modification methodologies have been used in the Lone Star State to prompt warm-season cumulus clouds to live longer and shed much-needed rainfall. Rain-enhancement projects sprung up intermittently in parts of semi-arid West Texas in the decades between the two world wars and during the epic drought of the 1950s, usually as a measure of last resort to ameliorate the impact of a prolonged dry spell. Even after legislation was adopted in 1967 to regulate the use of cloud-seeding technology within the state, rain-enhancement programs adopted by various water interests were for the most part locally controlled and funded, with minimal interface from the State.

The lack of state involvement in the more than a dozen independently financed and managed weather modification projects prior to 1970 meant that the bulk of these efforts received a minimum of rigorous analysis. In fact, most of the projects were poorly documented, if at all. The impact of cloud seeding was seldom quantified, and perceptions of the efficacy of the efforts were for the most part a function of who happened to be asked. By today's standards, methods of cloud seeding were rather primitive. For instance, many of the projects conducted between World War II and the passage of the Texas Weather Modification Act (in 1967) involved WWII-vintage aircraft and dry ice.

2.0 Role of Water Districts

What would eventually serve as a foundation for funding, designing, and implementing cloud-seeding operations on a large-scale basis in Texas began to evolve during the historic 1950s drought. Independent *water districts* began sprouting in rain-short areas of West and Southwest Texas after a precedent was established in the mid-1950s by the High Plains Underground Water Conservation District. This district, encompassing all or parts of 15 counties in northwestern Texas and covering some 6.9 million acres above the Caprock, materialized in order to monitor, and eventually govern, the use of fresh water from the vast Ogalalla Aquifer that underlies vast portions of the U. S. Great Plains from Nebraska to near the Permian Basis in far West Texas. Given *ad valorem* taxing authority, the District was furnished the financial wherewithal to set up a staff to quantify its ground-water resources and regulate the use of that ground water to ensure that water supplies from the aquifer would be adequate to meet the fresh-water needs of a growing populace.

Subsequent state legislation encouraged the formation of other, similarly-constructed water districts in semi-arid parts of Texas, though the 42 districts formed after 1985 (and encompassing all, or parts, of 80 Texas counties) were considerably less expansive than the original High Plains district based in Lubbock. In every instance, however, the fundamental motivation for establishing these districts (many of which are single-county districts) was to have a legal mechanism in place to control the draw-down from, and abet the recharge to, the aquifers that underlay the districts. Perhaps serendipitously, the arrangement of these districts afforded the locals a fiscal mechanism by which programs like cloud seeding for rainwater-augmentation could be equitably paid for within their respective areas of jurisdiction.

The first water district to use some of its funds to apply an innovative water-development strategy, such as precipitation enhancement through cloud seeding, was the Colorado River Municipal Water District, based in Big Spring. The formation of two reservoirs on the upper Colorado River of Texas, owned and maintained by the CRMWD, and subsequent sale of water from those lakes, created the need for additional runoff. One of Texas' preeminent pioneers in developing new and innovative water-management strategies, Owen H. Ivie, as general manager of the CRMWD, launched a cloud-seeding program in 1971.

For several years, the CRMWD seeded clouds over an area of 3500 square miles (2.24 million acres) of West Texas using a weather-modification contractor. Eventually, the CRMWD committed to a long-term rain-enhancement program by securing its own aircraft, weather radar, and qualified staff to run its cloud-seeding operation during the growing season. By renewing its Texas weather-modification license and permit from the State water agency, the CRMWD maintained its cloud-seeding program for two decades, until it suspended operations for one season (1989) due to extremely wet conditions within its 14-county operational area. It resumed its program in 1990 and has continued ever since, becoming one of the longest-running rain-enhancement projects in the world.

The CRMWD systematically documented its cloud-seeding operations, including an annual assessment of the impact of the seeding operations on runoff over the watersheds of its two reservoirs, although the analysis would not meet the standards articulated. It set up and maintained its own dense network of fence-post rain gages. Data from these gages were analyzed at the end of each year's 7-month-long program; moreover, the staff collected and analyzed crop-yield data (primarily cotton production) each year within its 14-county operational area and smaller "target" area (Jones, 1988). Repeated studies of these data revealed apparent sizable rainfall increases within, and downwind, of the target area. For all years during which seeding was conducted, rainfall was observed to have increased between 20 and 35 percent within the target area during the growing season, with lesser increases noted in areas adjacent to the watersheds of the two reservoirs.

The apparent success of the CRMWD weather-modification program encouraged other water interests to emulate the approach taken by the Big Spring organization. The City of San Angelo sponsored a 5-year cloud-seeding project during 1985-1989 to generate more runoff over the watershed of its reservoir system west and south of the city. For the first time in Texas, however, glaciogenic seeding material was disseminated using pressurized aircraft operating at or above cloud top. Silver iodide flares were ejected from the bottom of the aircraft fuselage during seeding missions. An historical target-control regression analysis of rainfall within and beyond the project's target area indicated seasonal rainfall during the 5-year period exceeded the long-term average by as much as 27 to 42 percent (Woodley and Solak, 1990). It must be emphasized, however, that the cloud seeding in the San Angelo target was not randomized, making it susceptible to bias in its conduct and evaluation. Further, the validity of historical target-control regressions has been called into question by Gabriel (1999).

3.0 Origins of a Statewide Program

Despite the apparent successes of the two multi-year projects based in Big Spring and San Angelo, it was not until 1995 that interest in using cloud-seeding technology grew enough to foster serious consideration of implementing a far-reaching, region wide cloud-seeding effort. The impetus for a statewide weather-modification program was born in the region west of San Angelo, where cloud seeding had been conducted extensively in the latter half of the 1980s. During that 5-year program, numerous ranchers living west of the city in several counties whose rivers and streams supplied water to the City's reservoir system had observed what they considered to be a positive response in many of the towering cumuli seeded by the City's contractor. These counties already had in place single-county water districts, which afforded a convenient mechanism for raising funds to support the reinstatement of a region wide cloud-seeding program.

Water-district officials from these counties began holding public meetings in and near their respective county seats and invited staff from the State's water agency to attend and give formal presentations on the state of weather-modification technology for rainfall-augmentation. Landowners and water-district officials in Irion and Crockett Counties of West Texas learned more about the potential of cloud seeding for augmenting rainfall in the summer of 1995, at which time the State's water agency was conducting a series of cloud-seeding experiments in the Big Spring, Texas area. The experiments, known as the Texas Exercise in Augmenting Rainfall through Cloud-seeding (TEXARC) Project, were designed to document the microphysical processes in growing convective clouds that were being seeded with either glaciogenic or hygroscopic materials.

As a severe drought ravaged much of West Texas in 1995, other nearby counties joined with Irion and Crockett Counties to form the West Texas Weather Modification Association (WTWMA). Its purpose was to raise funds and implement cloud seeding operations. This Association was formed under the authority given the water districts to quantify and protect ground-water reserves in the aquifers beneath them. Cloud seeding was viewed by these officials as a cost-effective means of recharging the aquifers and lessening the rate of withdrawal from the aquifers. The establishment of this alliance of eight counties to promote the use of cloud-seeding technology would serve as a prototype for other rain-enhancement projects that would form elsewhere in West, and in South, Texas in the years to follow. With a "target" area of 7.2 million acres, a contractor was identified and both cloud-base and cloud-top seeding activities got underway in May 1996.

4.0 Local Supervision of Seeding Operations

An executive Board consisting of representation from the eight participating counties was established to facilitate decision-making as the project ensued. Despite the fact that some counties making up the WTWMA target area were considerably larger than others, each county was assigned one vote. Moreover, each voting delegate had to be an elected official (e.g. water district Board member, county commissioner, city official). Such a policy ensured that control of the program resided, and was maintained, at the "grass-roots" level. Furthermore, the program was paid out of revenue raised, through *ad valorem* taxes, by each county. A county share's was determined by the total amount of acreage in that county. In one or two instances, where counties without water districts were participants, the share of funding from that county was provided by a county commissioners' court or through revenue supplied by a landowners' association.

The first year of cloud seeding was paid solely by monies raised by the water districts constituting the WTWMA. The way these member counties linked themselves together to plan and pay for the rain-enhancement project garnered the attention of both regional and national news media. The fact that the region was in the throes of a worsening and spreading drought undoubtedly contributed to the fascination shown by both media groups and by political interests statewide. In the early weeks (June 1996) of the newly formed cloud-seeding operation based in San Angelo, reporters from several major television news organizations (ABC, CBS, CNN, and NBC) visited the project site to interview project organizers and personnel. Several major newspapers (including the Dallas Morning News) did feature articles on the project as well.

Perhaps the most appealing aspect of the way the West Texas group organized themselves consisted of the control afforded the program at the local level. The executive Board made all decisions relative to the conduct of the program. Representation from each participating county meant the diverse needs of each major enterprise could be accommodated. For instance, a county with a heavy investment in cotton production would prefer to have a minimum of rainfall during the time of harvest in the autumn; input from that county through its representative on the Board would ensure that the county (or some large sector of that county) would be excluded from any advertent weather-modification activity during the period specified.

The West Texas group had as its preeminent objective to help as many as possible residing within their target area and not to hurt anyone. In fact, the State water agency regulating the use of cloud seeding for rain enhancement is required to ascertain, to the extent technologically possible, that the proposed weather-modification program will not "dissipate the clouds nor prevent their natural course of developing rainfall in the area to the material detriment of people or property" within that area; such a finding must be made before the Texas Natural Resource Conservation Commission (TNRCC) can, and will, issue a permit for the project.

Moreover, the WTWMA maintained a rain-gage network to assess soil-moisture conditions during the course of the cloud-seeding operation. These rainfall data were used to prioritize those areas within the target region most, and least, in need of rainfall. In many instances, it was possible to specify an area as small as a fraction of a county where rainwater was, or was not, needed. This policy afforded the participating counties, and ranchers within them, an added sense of control of the program.

5.0 The Proliferation of Rain-Enhancement Projects

Using the WTWMA organizational model, a second rain-enhancement program was formed in South Central Texas, south of San Antonio and some 250 miles removed from the WTWMA site. A water district (known as the Evergreen Underground Water Conservation District) based in Jourdanton, Texas served as the nucleus for this 7-county, 4.4 million-acre project. The alliance of counties, called the South Texas Weather Modification Association (STWMA), established a governing Board, developed specifications for a warm-season rain-augmentation program, went out for bid, then secured a contracting firm to perform the actual seeding operations.

A third rain-enhancement project, covering some 6.87 million acres in the Texas High Plains, materialized in 1997. This project, based in Lubbock, was unlike its two predecessors in that it was sponsored by a lone and very large underground water-conservation district covering all or parts of 15 counties in the High Plains of Texas. That district, the HPUWCD, already had in place a governing board as well as a network of county committeemen. Those two mechanisms were used to provide the kinds of locally based input needed to structure, then supervise, the cloud-seeding program to the needs of constituents.

Still more projects, encompassing an additional 12 million acres in southwest and south Texas, were drawn up for implementation in 1998. One of them got underway just weeks before the residue from a tropical storm (Charlie) dumped flash floods in Val Verde County, the heart of the Texas Border Weather Modification Association (TBWMA) target area. (Cloud-seeding operations had been suspended a full 20 hours before the onset of those torrential, floodproducing rains inundated much of the city of Del Rio in August 1998.) The project, governed similarly by a multi-county Board, resumed cloud seeding soon after the floodwaters receded.

Two additional projects were in operation by the 2000 season, bringing the total to nine projects. The new projects were in the northern Texas Panhandle. One was centered in Dumas and the other in Pampa. The tenth seeding project, centered in Abilene, Texas, began during the 2001 season.

6.0 State Support of Weather Modification

A pivotal development in the statewide weather-modification program can be traced to action by the 75th Texas Legislature, which in 1997, appropriated for the first time ever a substantial amount of funds to help the various cloud-seeding projects pay for their operations. The State support was given to those water districts sponsoring cloud seeding on a 50-50 cost share, or match, basis. The amount of State funding to each project was determined strictly on a per acreage basis. This arrangement meant that, for every $0.0425 per acre raised at the local level, an equivalent amount was contributed by the State water agency (TNRCC). Funds totaling $4.197 million were also made available for operations during the warm seasons of 1998 and 1999.

To unify the various rain-enhancement projects within Texas, an 'umbrella' organization was formed in 1997 known as the Texas Weather Modification Association. A voting representative from each of the state's five operational cloud-seeding programs served on the Association's executive Board. The TWMA worked to resolve problems encountered with the use of various types of flares at the five project sites. Moreover, the association advises the TNRCC staff in the allotment of state revenue to help pay for the weather-modification programs. The group also sponsored training sessions for project personnel, including specialized training from a scientific consultant for those meteorologists running the programs.

The end result of the collaborative efforts of state and local officials to orchestrate a well-designed, coordinated weather-modification effort for the state of Texas has fostered a virtually ideal environment for continued research into, and development of, an appropriate cloud-seeding technology for the region. This was evidenced by the successful completion of the 1998 TEXARC Project in the vicinity of San Angelo, Texas. It is also apparent in continued monetary support from the State water agency, with the bright prospect that State funding can, and will, be maintained through at least the summer of 2001 for both operational cloud seeding activities and relevant research and assessment work in support of those activities.

Appendix B

Documentation of the Seeding Flights in the Edwards Aquifer Seeding Project

TOTALS	flights=	65		174:56	1826	6:08	
Date	Aircraft	Take-off	Landing	Duration	eject	acetone	Type
24-Apr-99	340FR	21:50	23:05	1:15	0	0:00	patrol
25-Apr-99	340FR	3:10	5:05	1:55	0	0:00	patrol
25-Apr-99	3904G	13:45	18:59	5:14	47	0:00	seed
25-Apr-99	340FR	18:45	21:07	2:22	12	0:00	seed
26-Apr-99	3904G	12:28	15:55	3:27	38	0:00	seed
30-Apr-99	3904G	20:25	22:47	2:22	8	0:36	seed
30-Apr-99	340FR	20:25	21:44	1:19	0	0:00	patrol
1-May-99	340FR	2:05	6:11	4:06	27	0:00	seed
2-May-99	3904G	15:18	20:18	5:00	61	0:00	seed
2-May-99	340FR	19:55	22:15	2:20	7	0:00	seed
10-May-99	3904G	5:29	7:07	1:38	3	0:00	seed
17-May-99	3904G	2:57	5:33	2:36	0	1:01	seed
17-May-99	340AX	20:45	0:08	3:23	14	0:00	seed
18-May-99	340AX	0:38	1:00	0:22	0	0:00	reposition
18-May-99	3904G	6:53	7:47	0:54	0	0:00	reposition
18-May-99	3904G	13:35	14:37	1:02	0	0:00	reposition
23-May-99	340AX	19:43	21:15	1:32	2	0:00	seed
26-May-99	3904G	21:28	23:01	1:33	0	0:00	patrol
26-May-99	340AX	23:55	3:41	3:46	47	0:00	seed
28-May-99	3904G	9:57	12:20	2:23	32	0:00	seed
28-May-99	340AX	16:30	19:45	3:15	32	0:00	seed
29-May-99	3904G	11:50	14:50	3:00	24	0:00	seed
29-May-99	3904G	21:30	0:10	2:40	27	0:00	seed
4-Jun-99	3904G	14:35	15:20	0:45	0	0:00	NWS visit

4-Jun-99	3904G	17:50	18:29	0:39	0	0:00	NWS visit
13-Jun-99	340AX	0:15	3:45	3:30	37	0:00	seed
13-Jun-99	3904G	4:01	5:18	1:17	9	0:00	seed
13-Jun-99	340AX	18:20	20:40	2:20	26	0:00	seed
13-Jun-99	3904G	22:33	2:28	3:55	65	0:00	seed
14-Jun-99	340AX	2:40	2:52	0:12	0	0:00	patrol
14-Jun-99	340AX	18:05	21:47	3:42	46	0:00	seed
14-Jun-99	3904G	21:41	1:22	3:41	75	0:00	seed
15-Jun-99	340AX	14:45	18:12	3:27	38	0:00	seed
15-Jun-99	3904G	20:45	23:31	2:46	64	0:00	seed
16-Jun-99	340AX	0:29	3:11	2:42	63	0:00	seed
16-Jun-99	3904G	20:56	0:42	3:46	45	0:00	seed
19-Jun-99	340AX	19:30	23:27	3:57	80	0:00	seed
20-Jun-99	3904G	13:00	14:21	1:21	0	0:00	patrol
3-Jul-99	3904G	18:33	22:06	3:33	64	0:00	seed
3-Jul-99	340AX	22:22	0:50	2:28	39	0:00	seed
4-Jul-99	3904G	17:13	21:47	4:34	81	0:00	seed
6-Jul-99	340AX	22:30	2:00	3:30	0	2:02	seed
7-Jul-99	340AX	22:06	1:24	3:18	46	0:00	seed
10-Jul-99	3904G	19:49	0:20	4:31	47	0:00	seed
11-Jul-99	340AX	0:25	2:20	1:55	21	0:00	seed
11-Jul-99	3904G	18:06	20:48	2:42	0	0:00	patrol
11-Jul-99	340AX	22:10	0:45	2:35	30	0:00	seed
17-Jul-99	3904G	14:45	19:15	4:30	83	0:00	seed
18-Jul-99	340AX	21:09	23:03	1:54	15	0:00	seed
21-Jul-99	3904G	19:52	22:55	3:03	50	0:00	seed
4-Aug-99	340AX	19:45	23:25	3:40	31	0:00	seed
17-Aug-99	3904G	23:28	1:18	1:50	3	0:00	seed
20-Aug-99	340AX	22:25	23:55	1:30	0	0:00	patrol
23-Aug-99	3904G	17:50	20:15	2:25	3	0:00	seed
24-Aug-99	340AX	19:32	20:20	0:48	0	0:00	patrol
24-Aug-99	3904G	20:20	22:45	2:25	12	0:00	seed
29-Aug-99	340AX	18:52	22:15	3:23	71	0:00	seed
5-Sep-99	3904G	20:40	1:00	4:20	63	0:00	seed

5-Sep-99	340AX	22:29	1:59	3:30	26	0:00	seed
6-Sep-99	340AX	19:45	23:14	3:29	62	0:00	seed
6-Sep-99	3904G	20:45	23:45	3:00	33	0:00	seed
8-Sep-99	340AX	17:32	20:00	2:28	51	0:00	seed
8-Sep-99	3904G	21:35	0:30	2:55	56	0:00	seed
9-Sep-99	3904G	19:50	23:06	3:16	0	2:29	seed
13-Sep-99	3904G	19:45	21:45	2:00	10	0:00	seed

Edwards Aquifer Precipitation Enhancement Program 2000
Operations Flights

TOTALS	flights=	71		194:25	965	2491		
Date	Aircraft	Take-off	Landing	Duration	eject	acetone	Type	
March 6, 2000	340FR	23:43	1:29	1:46		31	rain	1.77
March 9, 2000	340FR	23:42	0:52	1:10	11	17	rain	1.17
March 10, 2000	340FR	17:45	19:37	1:52			recon	1.87
March 14, 2000	340AX	13:40	15:45	2:05	3	37	rain	2.08
March 14, 2000	340AX	19:05	19:50	0:45			repos	0.75
March 16, 2000	340AX	19:55	22:29	2:34		30	rain	2.57
March 16, 2000	340AX	22:59	0:55	1:56	12		rain	1.93
March 18, 2000	340AX	0:52	2:59	2:07	1		rain	2.12
March 23, 2000	340AX	14:00	15:30	1:30			recon	1.50
March 26, 2000	340AX	22:42	0:44	2:02			recon	2.03
March 28, 2000	340FR	23:53	1:16	1:23	1		rain	1.38
April 2, 2000	340FR	13:40	16:45	3:05	1		rain	3.08
April 11, 2000	340FR	19:30	23:45	4:15	24	22	rain	4.25
April 12, 2000	340FR	21:03	22:39	1:36			recon	1.60
April 12, 2000	340AX	13:30	15:16	1:46			recon	1.77
April 20, 2000	340AX	4:00	6:30	2:30			recon	2.50
April 22, 2000	340FR	23:34	2:16	2:42	4		rain	2.70
April 23, 2000	340FR	2:53	3:37	0:44		2	repos	0.73
May 1, 2000	340FR	16:37	18:37	2:00		79	rain	2.00
May 1, 2000	340AX	14:00	17:03	3:03	1	12	rain	3.05

May 2, 2000	340FR	22:37	0:53	2:16	21	2	rain	2.27
May 2, 2000	340AX	12:50	16:35	3:45	11	2	rain	3.75
May 19, 2000	340FR	20:46	0:25	3:39	63	2	rain	3.65
May 19, 2000	340AX	20:15	23:40	3:25	24	2	rain	3.42
May 26, 2000	340FR	21:20	23:57	2:37	17	2	rain	2.62
June 2, 2000	340FR	18:43	22:20	3:37	19		rain	3.62
June 2, 2000	340FR	22:45	1:45	3:00	9		rain	3.00
June 3, 2000	340FR	17:27	21:10	3:43	49	2	rain	3.72
June 4, 2000	340FR	17:40	21:40	4:00	54		rain	4.00
June 8, 2000	340FR	19:15	23:02	3:47	27	2	rain	3.78
June 9, 2000	340FR	13:10	16:20	3:10	16		rain	3.17
June 9, 2000	340FR	19:55	22:54	2:59		137	rain	2.98
June 10, 2000	340AX	18:12	21:00	2:48	37		rain	2.80
June 12, 2000	340FR	17:33	21:25	3:52	17	2	rain	3.87
June 17, 2000	340FR	0:23	2:14	1:51	2	2	rain	1.85
June 17, 2000	340AX	20:50	0:30	3:40	62		rain	3.67
June 18, 2000	340FR	14:23	18:12	3:49	11	2	rain	3.82
June 18, 2000	340AX	21:40	1:05	3:25	42		rain	3.42
July 14, 2000	340FR	22:59	1:15	2:16	17		rain	2.27
July 23, 2000	340FR	20:47	0:40	3:53		184	rain	3.88
July 23, 2000	340AX	19:31	23:00	3:29		148	rain	3.48
July 25, 2000	340AX	23:31	1:42	2:11	11	15	rain	2.18
July 29, 2000	340FR	19:15	19:45	0:30			recon	0.50
July 30, 2000	340FR	17:51	21:44	3:53	69	2	rain	3.88
July 30, 2000	340FR	22:46	0:18	1:32		12	rain	1.53
July 30, 2000	340AX	18:22	20:50	2:28		89	rain	2.47
July 30, 2000	340AX	21:47	23:55	2:08		48	rain	2.13
July 31, 2000	340FR	17:40	22:00	4:20		223	rain	4.33
July 31, 2000	340AX	18:15	22:10	3:55	24		rain	3.92
July 31, 2000	340AX	23:32	0:30	0:58			repos	0.97
August 1, 2000	340FR	18:12	22:13	4:01	23	70	rain	4.02
August 1, 2000	340FR	22:58	0:44	1:46		55	rain	1.77
August 1, 2000	340AX	19:07	23:05	3:58	16	84	rain	3.97
August 8, 2000	340FR	22:01	0:17	2:16	15	16	rain	2.27

August 8, 2000	340AX	21:15	0:45	3:30		167	rain	3.50
August 21, 2000	340FR	22:52	1:45	2:53	39	2	rain	2.88
August 21, 2000	340AX	18:15	20:35	2:20	24	2	rain	2.33
August 22, 2000	340FR	20:16	23:50	3:34	52		rain	3.57
August 22, 2000	340AX	18:50	23:15	4:25		168	rain	4.42
August 25, 2000	340FR	19:23	0:03	4:40		242	rain	4.67
September 5, 2000	340FR	22:08	0:58	2:50		129	rain	2.83
September 5, 2000	340AX	21:32	0:53	3:21	29		rain	3.35
September 9, 2000	340AX	23:00	1:40	2:40		89	rain	2.67
September 12, 2000	340FR	22:14	1:42	3:28	63		rain	3.47
September 12, 2000	340AX	23:55	2:40	2:45		114	rain	2.75
September 14, 2000	340FR	19:37	0:12	4:35		189	rain	4.58
September 24, 2000	340FR	22:00	23:44	1:44		52	rain	1.73
September 24, 2000	340AX	21:05	0:05	3:00	43	2	rain	3.00
October 6, 2000	340FR	12:50	14:30	1:40	1		rain	1.67
October 6, 2000	340FR	22:13	23:45	1:32		2	recon	1.53
October 6, 2000	340AX	8:35	10:15	1:40			recon	1.67

Edwards Aquifer Precipitation Enhancement Program 2001
Operations Flights

TOTALS	flights=	58		152:58	834	24:46	9:44	34:30		
Date	Aircraft	Take-off	Landing	Duration	eject	L Burner	R Burner	Tot Burner	Type	
April 15, 2001	3904G	23:56	3:15	3:19	27			0:00	rain	3.32
April 23, 2001	340AX	6:12	8:20	2:08				0:00	recon	2.13
May 4, 2001	340AX	23:33	3:33	4:00		0:50	2:30	3:20	rain	4.00
May 4, 2001	3904G	22:40	1:30	2:50	41	0:15		0:15	rain	2.83
May 5, 2001	340AX	6:21	7:18	0:57				0:00	repos	0.95
May 5, 2001	3904G	19:30	22:35	3:05	17			0:00	rain	3.08
May 6, 2001	340AX	23:53	1:18	1:25	4			0:00	rain	1.42
May 7, 2001	3904G	19:55	21:00	1:05				0:00	recon	1.08
May 8, 2001	3904G	17:55	21:25	3:30		2:25	0:14	2:39	rain	3.50
May 8, 2001	3904G	22:10	23:55	1:45	13			0:00	rain	1.75
May 8, 2001	340AX	12:47	14:21	1:34	5			0:00	rain	1.57

May 8, 2001	340AX	18:43	21:50	3:07		0:51	1:17	2:08	rain	3.12
May 12, 2001	340AX	19:31	21:43	2:12	17			0:00	rain	2.20
May 21, 2001	3904G	4:50	8:20	3:30	57	0:24		0:24	rain	3.50
May 25, 2001	340AX	0:50	2:14	1:24				0:00	recon	1.40
May 26, 2001	3904G	3:55	5:35	1:40	2			0:00	rain	1.67
May 30, 2001	340AX	17:08	18:20	1:12				0:00	recon	1.20
June 1, 2001	340AX	22:06	0:54	2:48	9			0:00	rain	2.80
June 8, 2001	3904G	19:35	23:00	3:25		1:36	1:04	2:40	rain	3.42
June 15, 2001	340AX	3:46	6:11	2:25	7			0:00	rain	2.42
June 22, 2001	3904G	18:50	22:50	4:00	64			0:00	rain	4.00
June 22, 2001	340AX	20:30	22:48	2:18		1:26		1:26	rain	2.30
June 24, 2001	3904G	0:35	2:05	1:30				0:00	recon	1.50
July 2, 2001	340AX	17:34	19:46	2:12		1:26		1:26	rain	2.20
July 3, 2001	3904G	19:42	23:07	3:25	15			0:00	rain	3.42
August 5, 2001	340AX	21:50	0:40	2:50	13	0:01	0:05	0:06	rain	2.83
August 7, 2001	3904G	19:05	21:50	2:45		1:32	0:07	1:39	rain	2.75
August 7, 2001	340AX	20:02	21:58	1:56	1			0:00	rain	1.93
August 13, 2001	340AX	23:00	1:40	2:40				0:00	recon	2.67
August 16, 2001	340FR	19:20	22:20	3:00	27			0:00	rain	3.00
August 16, 2001	340FR	23:55	2:25	2:30		1:16	0:43	1:59	rain	2.50
August 16, 2001	340AX	20:30	0:24	3:54	2		0:59	0:59	rain	3.90
August 17, 2001	340FR	2:57	3:30	0:33				0:00	repos	0.55
August 19, 2001	340FR	16:27	18:47	2:20	24	0:05	0:05	0:10	rain	2.33
August 19, 2001	340AX	14:00	17:25	3:25		2:37		2:37	rain	3.42
August 26, 2001	340FR	23:05	2:10	3:05		2:32		2:32	rain	3.08
August 26, 2001	340AX	22:40	1:54	3:14	9			0:00	rain	3.23
August 27, 2001	340FR	19:55	23:45	3:50	68		1:15	1:15	rain	3.83
August 27, 2001	340AX	19:10	22:24	3:14	23			0:00	rain	3.23
August 28, 2001	340AX	15:35	18:00	2:25	15			0:00	rain	2.42
August 30, 2001	340FR	13:25	15:10	1:45				0:00	recon	1.75
August 30, 2001	340FR	19:25	23:45	4:20		2:00	0:58	2:58	rain	4.33
August 30, 2001	340AX	18:07	21:38	3:31	25			0:00	rain	3.52
August 30, 2001	340AX	0:16	1:17	1:01				0:00	recon	1.02
August 31, 2001	340FR	0:35	2:30	1:55				0:00	recon	1.92

August 31, 2001	340FR	23:05	1:40	2:35	58			0:00	rain	2.58
August 31, 2001	340AX	20:45	0:15	3:30	52			0:00	rain	3.50
August 31, 2001	340AX	2:20	3:06	0:46			0:27	0:27	rain	0.77
September 1, 2001	340FR	19:15	21:55	2:40	47			0:00	rain	2.67
September 2, 2001	340FR	20:15	23:25	3:10		2:26		2:26	rain	3.17
September 2, 2001	340AX	18:25	21:40	3:15	28			0:00	rain	3.25
September 3, 2001	340AX	23:00	2:18	3:18	48			0:00	rain	3.30
September 4, 2001	340FR	22:25	1:30	3:05	40			0:00	rain	3.08
September 4, 2001	340AX	1:40	2:40	1:00				0:00	recon	1.00
September 5, 2001	340FR	12:40	14:55	2:15	18			0:00	rain	2.25
September 5, 2001	340FR	19:55	0:45	4:50		3:04		3:04	rain	4.83
September 5, 2001	340AX	18:20	22:05	3:45	24			0:00	rain	3.75
September 9, 2001	340AX	11:50	15:40	3:50	34			0:00	rain	3.83

APPENDIX C

Results of Monthly and Seasonal Gauge vs. Radar Rainfall Comparisons in the Texas Panhandle

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado

Roni Drori and Daniel Rosenfeld
Hebrew University of Jerusalem
Jerusalem, Israel

Scott Orr
High Plains Underground Water Conservation District
Lubbock, Texas

George Bomar
Texas Natural Resource Conservation Commission
Austin, Texas

Abstract. Gauge and radar estimates of monthly and seasonal (April-September in 1999 and 2000) convective rainfall were compared for a large network in the Texas Panhandle. In 2000, the network, covering approximately 3.6 x 10^4 km^2 (1.4 x 10^4 mi^2), contained 505 fence-post rain gauges with individual, subterranean, collector reservoirs at a density of one gage per 72 km^2 (29 mi^2). These were read monthly to produce area-averaged rain totals, obtained by dividing the gauge sums by the number of gauges in the network. The gauges were not read in September 2000 because of negligible rainfall. Comparable radar-estimated rainfalls for the same time periods were generated using merged, base-scan, 15-min, NEXRAD radar reflectivity data supplied by the National Weather Service through WSI, Inc. and the Global Hydrology Resource Center.

The gauges vs. radar comparisons were made on the basis of rain patterning and area averages. The Z-R relationship used to relate radar reflectivity (Z) to rainfall rate (R) was $Z = 300R^{1.4}$, which is the equation used in standard NEXRAD practice. Because all of the rain gauges could not be read on a single day, the gauges do not provide an absolute basis of reference for comparison with the radar estimates, which were made in time periods that matched the average date of the gauge readings. The gauge and radar monthly rain patterns agreed in most instances, although the agreement in August 2000 was poor. The monthly correlations of gauge and radar rain amounts were 0.86 in 1999, 0.96 in 2000 and 0.93 for the two years combined. The radar tended to underestimate heavy rain months and overestimate those with light rain. The radar overestimate for months with light rain may be due to evaporative losses beneath the level of the radar scan as the drops fell through dry air to the ground.

The period of comparison affected the results. The area-average gauge vs. radar comparisons made on a monthly basis agreed to within 20% on 5 of the 11 months compared. Upon comparison of the gauge and radar rainfalls on a two-month basis to diminish the impact of variations in the date of the gauge readings, it was found that all but one of the five comparisons was within 5%. The exception (April/May 1999) differed by 16%. The seasonal gauge and radar estimates in 1999 and 2000 agreed to within 4% and 8%, respectively, which is extraordinary considering the uncertainties involved. Thus, the longer the period of comparison the better the agreement appeared to be. It is concluded that the use of radar in Texas can provide an accurate representation of rain reaching the ground on a monthly and seasonal basis.

1. DEDICATION

This paper is dedicated to the memory of Mr. A. Wayne Wyatt (Figure 1), past Manager of the High Plains Underground Water Conservation District (HPUWCD), who died suddenly on December 5, 2000. Mr. Wyatt assumed his duties as general manager of the High Plains Water District on February 1, 1978 and remained in this position until his death. Besides overseeing the Water District's many programs and activities, including the installation of the gauge network used in this study, he was serving as chairman of the Llano Estacado Regional Water Planning Group at the time of his death. The regional water-planning group is charged with developing a 50-year water plan for a 21-county area in the southern high plains of Texas. Wayne was a prime mover for the investigation of the potential of cloud seeding for enhancing the water resources for the area, and oversaw the operational cloud seeding effort under the sponsorship of the HPUWCD since its inception in 1997. In addition, he also kept a close watch on state and federal legislative issues that could affect ground water use within the region. During his 43-year career in ground water management, many peer groups and professional organizations honored him.

Figure 1. Photograph of A. Wayne Wyatt, manager of the High Plains Underground Water Conservation District No.1 since 1978 until his death. During the latter portion of his tenure, Wayne promoted the investigation of cloud seeding for enhancing the water resources of the Texas Panhandle. He is also responsible for the implementation of the rain gauge network used in this study.

2. INTRODUCTION

The measurement of precipitation is of concern to many interests and disciplines. Although simple conceptually, accurate measurement of precipitation is a difficult undertaking, especially if the precipitation takes the form of convective showers having high rain intensities, strong gradients and small scale. Rain gauges are the accepted standard for point rainfall measurement, although individual gauge readings are subject to errors in high winds and in turbulent flow around nearby obstacles. Rain gauges do not, however, provide accurate measurements of convective rainfall over large areas unless they are distributed in sufficient density to resolve the salient convective features. In some circumstances this might require hundreds, if not thousands, of rain gauges (Woodley et al.., 1975).

Radar is an attractive alternative for the estimation of convective rainfall, because it provides the equivalent of a very dense gauge network. Radar estimation of rainfall is, however, a complex undertaking involving determination of the radar parameters, calibration of the system, anomalous propagation of the radar beam, ground clutter and "false rainfall", concerns about beam filling and attenuation, and the development of equations relating radar reflectivity (Z) to rainfall rate (R), where radar reflectivity is proportional to the sixth power of the droplet diameters in the radar beam. A good source for discussion of these matters is Radar in Meteorology (Atlas, 1990)

Some scientists have spent virtually their entire careers perfecting radar rainfall estimates, but even then the results are not always to their liking. Variability due to calibration uncertainties and changes of rain regimes must be accounted for by comparisons with rain gauges, especially for rainfall measurements that are based on reflectivity-only radar data.

Woodley et al.. (1975) provide an extensive discussion of the trade-offs in the gauge and radar estimation of convective rainfall and discuss the combined use of both to increase the accuracy of the rain measurements. Radar provides a first estimate of the rainfall and rain gauges, distributed in small but dense arrays, are used to adjust the radar-rainfall estimates.

Accurate representation of the rainfall is crucial to the evaluation of cloud seeding programs for the enhancement of convective rainfall. Some have used rain gauges over fixed targets; others have used radar for the estimation of rainfall from floating targets (e.g., Dennis et al.., 1975; Rosenfeld and Woodley, 1993; Woodley et al.., 1999), while still others have made use of radar and gauges in combination (e.g., Woodley et al.., 1982, 1983). The operational cloud seeding programs of Texas (Bomar et al., 1999), which numbered nine as of the summer 2000 season (Figure 2), make extensive use of TITAN-equipped C-band radars to conduct project operations and for subsequent evaluation.. For those using radar there is the nagging uncertainty about the accuracy of their radar-rainfall estimates. This is addressed in this paper.

The initial intention was to use the C-band project radars to generate rain estimates for comparison with rain gauges that provide readings on a daily basis, but this proved to be unfeasible. None of the projects operate their radars round-the-clock, meaning that some rainfalls are not measured, thereby making it impossible to make daily comparisons. Further, the project radars may suffer from other problems, including attenuation of the beam in heavy rain and ground clutter, which is sometimes interspersed with rain events, especially during their later stages. Because this "false rainfall" cannot not be removed objectively without a removal algorithm, it is a potential source of error in estimating the rainfall to be compared with the rain gauges. In addition, non-standard calibration procedure between the different radars can result in systematic differences in the Z-R relations that needed to be applied for unbiased rainfall measurements.

At this point it was obvious that a change in plan had to be made. If rainfall were to be estimated around-the-clock in Texas and spot-checked by comparison with rain gauges, it would have to be done with a different radar system. An obvious possibility was the NEXRAD radar systems that are distributed about the state. These are S-band radars, which do not attenuate appreciably in heavy rain, and they are operated continuously in a volume-scan mode unless they are down for maintenance. In addition, the NEXRAD radars have a clutter-removal algorithm that eliminates most of the false rainfall produced during periods of anomalous propagation.

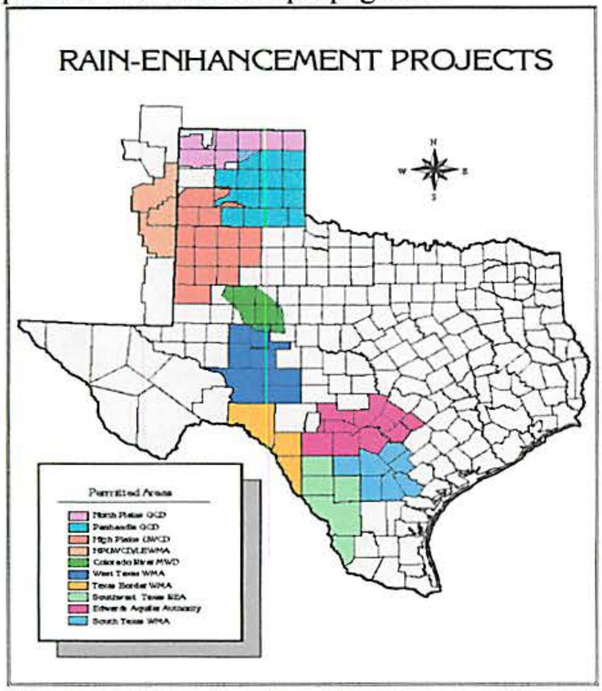


Figure 2. Map showing the nine operational cloud-seeding targets in existence in Texas as of the summer of 2000.

The availability of gauge data for this effort also posed a serious challenge. Upon looking for rain-gauge data from dense arrays big enough to resolve large convective systems on a daily basis, nothing suitable was found. It was obvious immediately, however, that it would be possible to make gauge vs. radar rainfall comparisons on a monthly and seasonal basis, using a unique network installed in the High Plains target (brown area in the Texas Panhandle shown in Figure 2). It would at least be possible, therefore, to assess the accuracy of long-term radar-rainfall estimates. These results could then be used for the benefit of the seeding projects and for others interested in the accuracy of the NEXRAD rainfall estimates.

3. GAUGE NETWORK AND DATA

Over the course of several years the High Plains Underground Water Conservation District (HPUWCD) has been instrumenting its District with fence-post rain gauges having tubing to individual, sealed, subterranean, collector reservoirs as shown in Figure 3. Evaporation is negligible under such circumstances. The network had 458 gauges in 1999 and 505 gauges in 2000 as shown in Figure 4. The gauge density in 2000 was one gauge every 72 km^2 (i.e., 1 per 29 mi^2), which would have been sufficient to resolve most individual convective systems if the gauges had had recording capability.

District personnel read and emptied the gauge reservoirs once per month, but they could not be read on one day. Typically, it took two to three days to read all of the gauges. This injected some uncertainty and noise into the gauge measurements of monthly rainfall, since the rain falling into gauges after they had been read would be ascribed to the following month whereas same rain falling into gauges that had not yet been read would be ascribed to the current month. Thus, the gauge measurements cannot be considered an absolute basis of reference for comparison with the radar rainfall inferences.

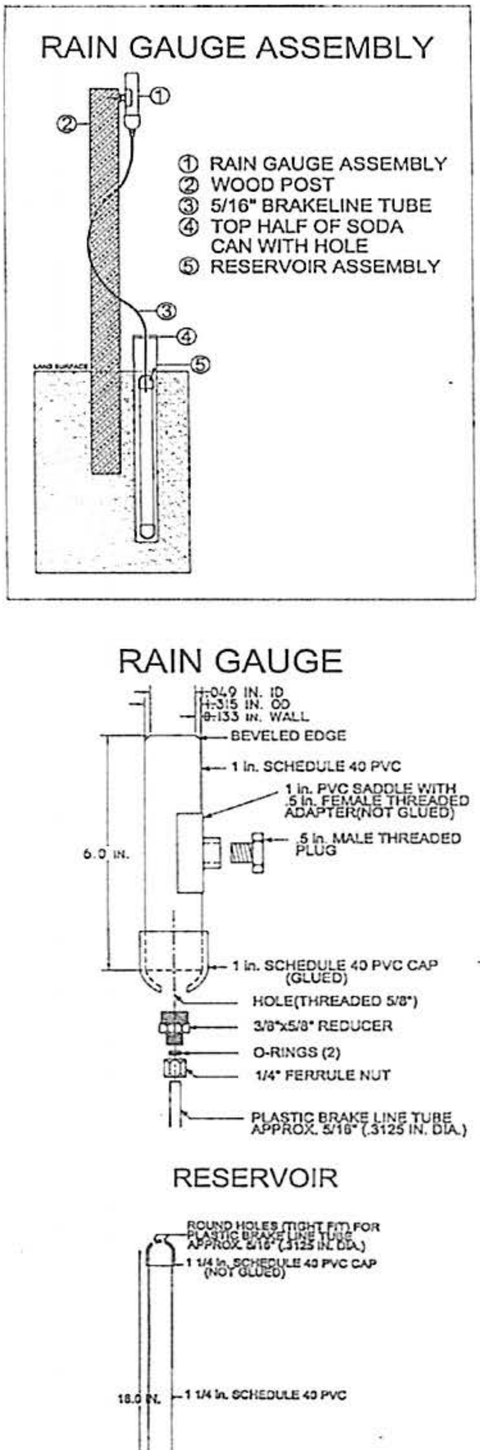


Figure 3. Design of the rain gauge system developed at the HPUWCD. a) the rain gauge assembly, b) the rain gauge, and c) the reservoir.

The monthly gauge readings were made in the period April through September 1999 and April through August 2000. The gauges were not read in September 2000 because of miniscule rainfall --- 1.52 mm (0.06 in) area-average as measured by the radar --- and this month is not included in the gauge vs. radar comparisons. The gauge area means were computed by two methods. In the first method all gauge values were summed and divided by the total number of gauges in the network. The second method involved performing an isohyetal analysis, plannimetering the areas between the rain contours, the calculation of summed rain volumes, and the calculation of the area average by dividing the rain volume by the network area. Although the results for both methods are presented, the first method is preferred because of its objectivity. The gauge products and results are presented in Section 5.0, dealing with the gauge vs. radar comparisons.

4. THE NEXRAD RADAR, DATA AND PRODUCTS

Investigation of the availability of NEXRAD data revealed a source at WSI, Inc., which was made available through NASA's Global Hydrology Resource Center (GHRC). WSI Inc., receives instantaneous reflectivity data from the operational National Weather Service (NWS) radar sites located in the United States. These sites include S-band (10 cm) WSR-88D radars. The national and regional radar images are created from a mosaic of radar data from more than 130 radar sites around the United States, including new NEXRAD Doppler radar sites as they become available. A merged data set for the continental United States (CONUS) is produced by WSI, Inc., every 15 minutes, which is subsequently broadcast to the GHRC. The broadcast is

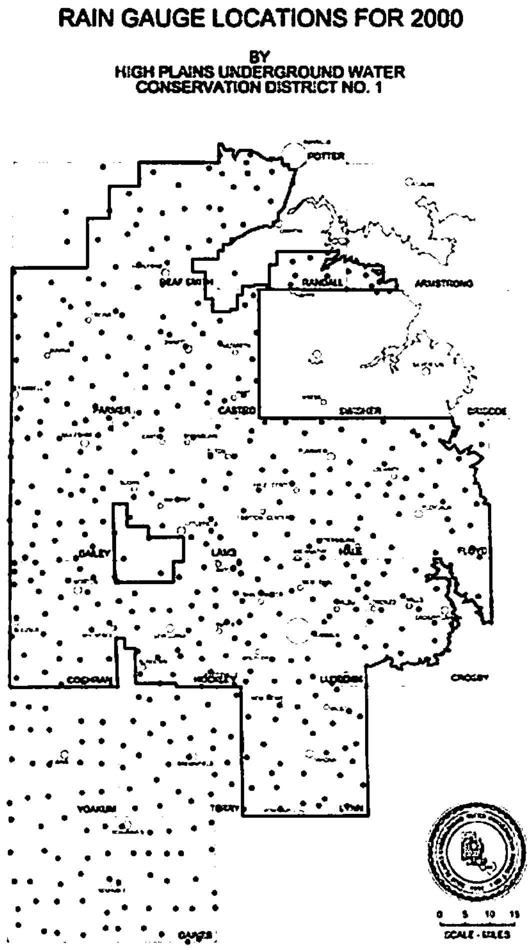


Figure 4. Map of the HPUWCD rain gauge network showing the location of its 505 gauges for the 2000 season

ingested at the GHRC and stored therein at 16 reflectivity levels from 0 to 75 dBZ, every round 5 dBZ. This product has the designation of NOWrad (TM), a registered trademark of the WSI Corporation.

These base-scan 5-dBZ thresholds reflectivity data were secured for this study for the 1999 and 2000 April-September convective seasons and daily rainfall (0700 CDT on the day in question to 0659 CDT the next day) was obtained by converting the reflectivity data into rainfall rates using the Z-R relation ($Z = 300R^{1.4}$) proposed by Woodley et al.. (1975) and now used as standard NEXRAD practice. Rain rates greater than 120 mm/hr were truncated to that value. The application of the Z-R relation to the threshold reflectivity values every 5 dBZ is not expected to compromise appreciably the accuracy over large space-time domains, given the fact that even a single threshold was shown to provide a remarkable agreement with the exact integration of the full dynamic range of intensities (Doneaud et al.., 1984; Atlas et al., 1990; Rosenfeld et al.., 1990). The rain totals were obtained for all of Texas and for various subareas, including the gauged High Plains network.

The GHRC also generates its own rainfall product for the United States For reasons unknown at this writing the GHRC rainfalls were found to be too high relative to the High Plains rain gauges by factors of 4 to 5, and with poor spatial matching, prompting us to do the integration of the 15-minute reflectivity maps, which is the basis for the analyses in this study.

5. RESULTS

The gauges vs. radar comparisons were made on the basis of rain patterning and area averages. Because of a day or two variations when the gauges were read (discussed earlier), the gauges do not provide an absolute basis of reference for comparison with the radar estimates. The gauge and radar maps for the seasonal rainfalls in 1999 and 2000 are presented in Figures 5-8. Comparable products were produced for each month, but they are not shown here because of space and cost considerations. The gauge maps are isohyetal analyses of the plotted gauge data (not shown), which were provided by the HPUWCD. The units are in inches.

RAINFALL FOR APRIL - SEPTEMBER 1999
(CONTOURED IN INCHES)
BY
HIGH PLAINS UNDERGROUND WATER
CONSERVATION DISTRICT NO. 1

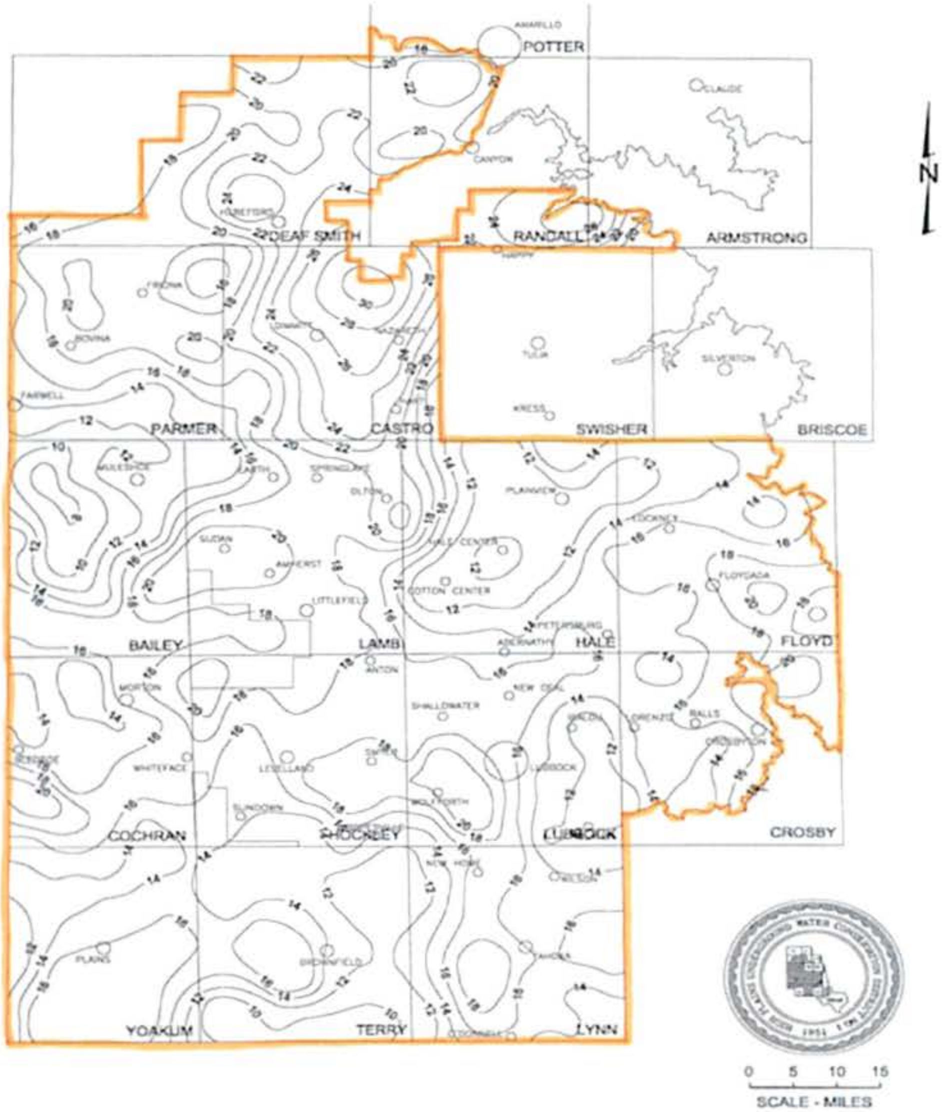


Figure 5. Isohyetal analysis (inches) in the seasonal (April through September) rainfall in 1999. The gauge maps were produced six months to a year prior to this study by personnel at the High Plains Underground Water Conservation District.

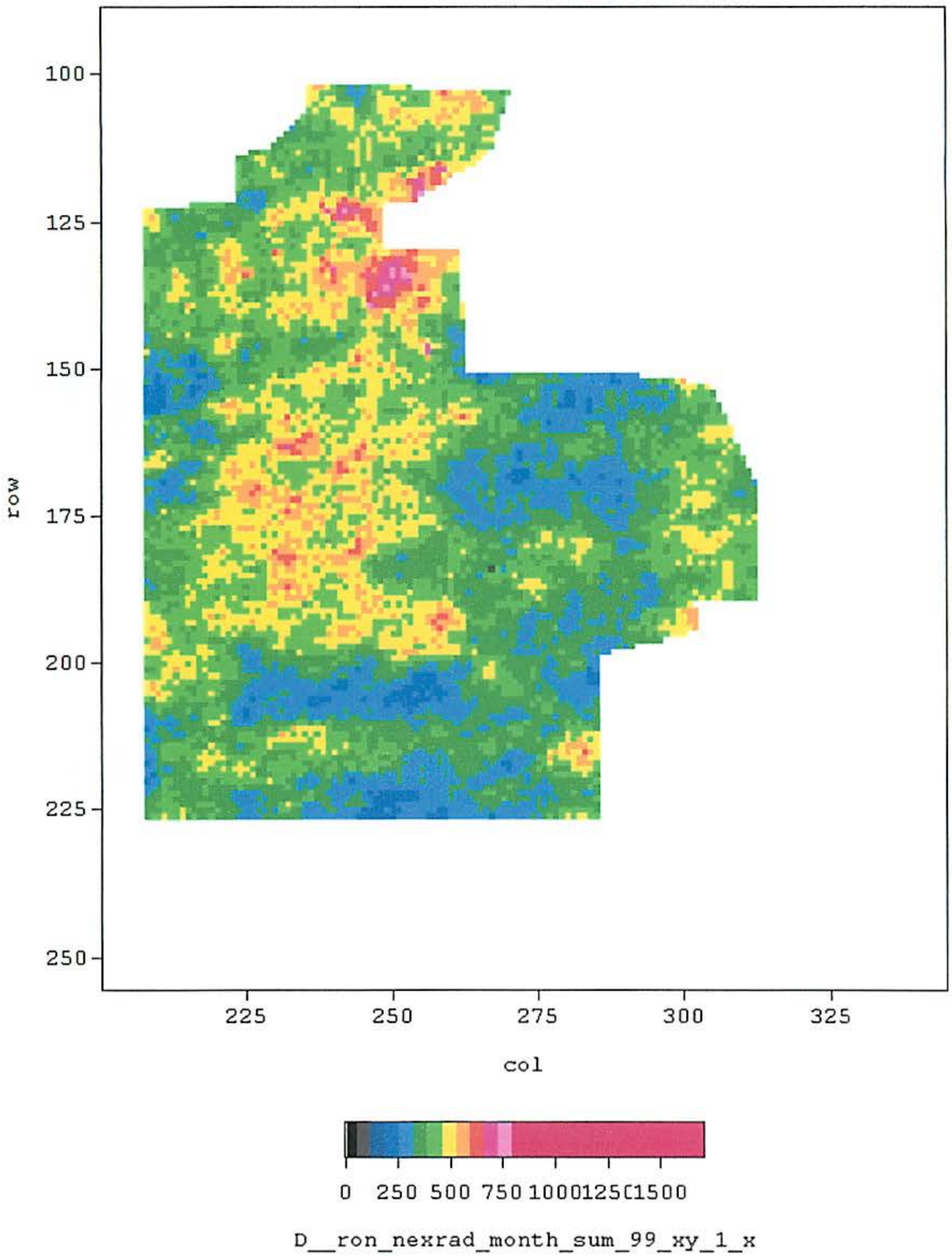
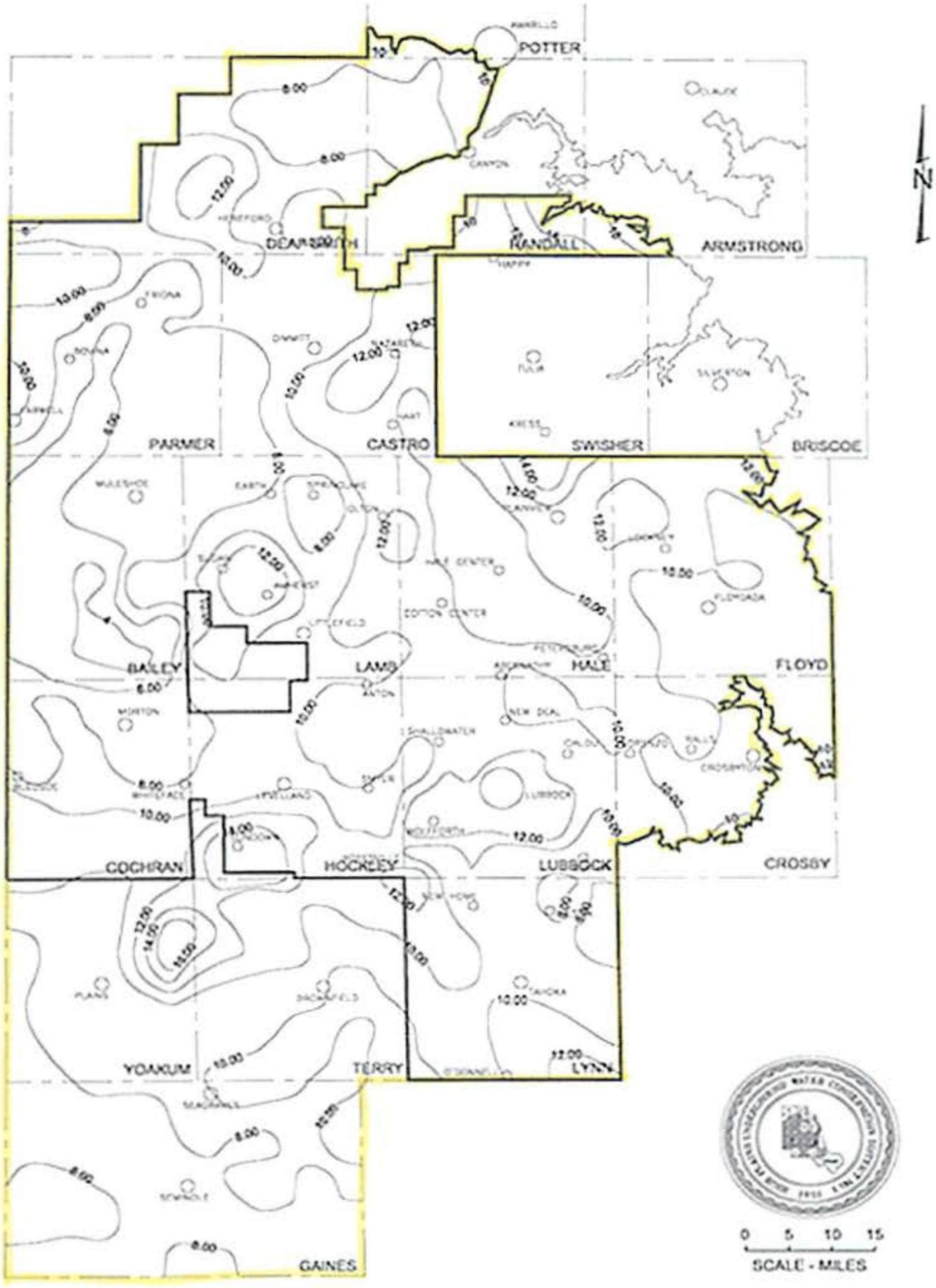


Figure 6. Map of the radar-estimated rainfalls (mm) for the 1999 season (April through September). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.

RAINFALL FOR APRIL - AUGUST 2000
(CONTOURED IN INCHES)
BY
HIGH PLAINS UNDERGROUND WATER
CONSERVATION DISTRICT NO. 1



Figures 7. Isohyetal analysis (inches) in the seasonal (April through August) rainfall in 2000. Because of negligible rainfall, the rain gauges were not read in September 2000.

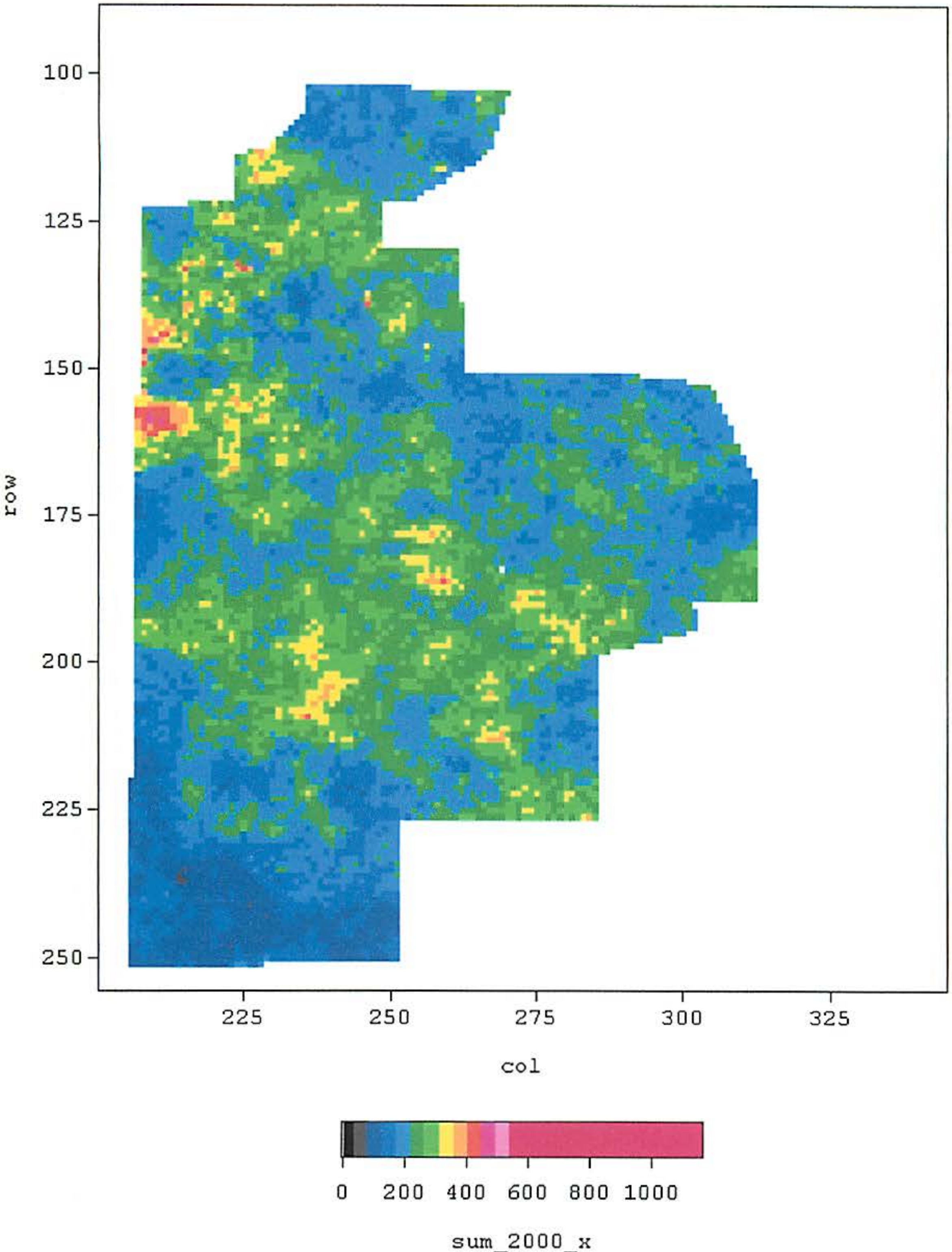


Figure 8. Map of the radar-estimated rainfalls (mm) for the 2000 season (April through August). The rainfall was negligible in September 2000). The colorized pixels in the radar maps can be converted to rainfall in mm by using the legend at the bottom of the figure.

The radar maps are colorized pixels, which can be related to rain depths in mm using the scale at the bottom of the figure. The first three authors generated these radar products. The independent production of the gauge and radar maps accounts for the differing rainfall units, where 1 inch is 25.4 mm.

The first step in the assessment was comparison of the rain patterning and maxima. This was a subjective process by which the agreement in each month was rated on a scale from 0 to10, where 0 means that there was no agreement and 10 indicates perfect agreement. The results are presented in Table 1. Although the results are good to excellent in most months, there were a few serious mismatches of maxima, especially in June 2000 (not shown) along the central portion of the Texas-New Mexico border. At first it was thought that this might be the result of heavy rain during the period the gauges were read, resulting in the errors discussed earlier. Only after all of the analyses had been completed was it determined that a gauge reading of 6 inches in the area of radar maximum had been thrown out as unreasonable prior to the isohyetal analysis, because it was much higher than the surrounding gauge readings. Upon adding this 6-inch maximum to the pattern, the gauge vs. radar disparity is reduced, but not eliminated entirely.

Quantification of the gauge vs. radar comparisons is presented in Table 2. Before making the comparisons the rainfall that appears in the eastern finger (covering 585 km^2) of the network on the gauge maps was subtracted from the overall gauge totals. This was necessary because the radar did not estimate rainfall for this small area.

The gauge sums divided by the number of network gauges served as the standard for the gauge vs. radar comparisons. The correlation of the monthly gauge and radar rain estimates was 0.86 in 1999, 0.96 in 2000 and 0.93 for the two years combined. The radar tended to underestimate heavy rain months and overestimate those with light rain with the crossover point at 50mm. The radar overestimate for months with light rain may be due to evaporative losses beneath the level of the radar scan as the drops fell through dry air to the ground.

The area-average gauge vs. radar comparisons agreed to within 20% on 5 of the 11 months compared (Table 2). The gauges were not read in September 2000 because of negligible rainfall. Agreement was appreciably better in months with heavy rain. The longer the period of comparison the better is the agreement. The seasonal gauge and radar estimates in 1999 and 2000 agreed to within 4% (i.e., G/R = 1.04) and 8% (i.e., G/R = 0.92), respectively.

Note that the G/R values oscillate around 1.0 from one month to the next and that the "all months" G/R values are nearly 1.0. This suggests that a portion of the monthly differences can be explained by the gauges measuring some rains not observed by the radar and vice versa. As discussed earlier, this can occur when it rains heavily during the two to three days that it takes to read all of the rain gauges. If this is true, the oscillating errors should diminish when the comparisons are done for periods of two months or longer.

This hypothesis is tested in Table 3 and the results are dramatic. Using method 1 as the standard, note that four of the five two-month comparisons agree to within 5%, and that in the lone exception the gauges and radar differ by only 16%.

Table 1

Subjective Comparison of the Gauge and Radar Rainfall Patterning
(Scale of 0 to 10 where 0 = no agreement and 10 = perfect agreement)

Month(s)	Pattern	Maxs/Mins	Comments
April 1999	8	6	Good correspondence
May 1999	7	6	Good overall agreement, few maxima do not match
June 1999	8	8	Very good agreement everywhere in a heavy rain month
July 1999	9	9	Excellent overall agreement
August 1999	8	7	Very good overall agreement except for radar maximum not on gauge map
September 1999	9	9	Excellent overall agreement
April-Sept 1999	9	9	Excellent overall agreement
April 2000	8	8	Very good agreement except for a few mismatches
May 2000	9	6	Excellent pattern match but radar maxima greater than gauge maxima
June 2000	6	5	General agreement but poor match of rain maximum, especially along New Mexico border
July 2000	6	5	General pattern match, but some serious mismatches
August 2000	5	4	Poor match of pattern and maxima
April-Sept 2000	8	8	Very good overall agreement except for poor match of maximum along central Texas-New Mexico border

Table 2
Comparison of Gauge and Radar-Estimated Rainfalls (in mm) for the
High Plains Rain Gauge Network

Month	Gauge Mean (1)	Gauge Mean (2)	Radar Mean	(G/R)[1]	(G/R)[2]
		1999	Season		
April	97.14	97.06	68.26	1.42	1.42
May	69.58	70.41	75.60	0.92	0.93
June	114.63	117.78	101.92	1.12	1.16
July	44.79	34.02	59.81	0.75	0.57
August	34.44	35.82	46.95	0.73	0.76
September	60.17	56.38	50.42	1.19	1.12
April-Sept	420.75	411.47	402.96	1.04	1.02
		2000	Season		
April	25.85	24.14	14.59	1.77	1.65
May	9.62	7.16	21.92	0.44	0.33
June	103.52	95.30	92.57	1.12	1.03
July	56.13	49.37	64.31	0.87	0.77
August	2.01	1.42	18.57	0.11	0.08
September	NA	NA	1.53	---	---
April-Aug	197.13	177.39	213.49	0.92	0.83
1999 & 2000	617.88	588.86	616.45	1.002	0.96

Table 3
Two-Month Comparisons of Gauge and Radar-Estimated Rainfalls (in mm) for the
High Plains Rain Gauge Network in 1999 and 2000

Months	Gauge Mean (1)	Gauge Mean (2)	Radar Mean	(G/R)[1]	(G/R)[2]
April/May 99	166.72	167.47	143.86	1.16	1.16
June/July 99	159.42	151.80	161.73	0.99	0.94
Aug/Sept 99	94.61	92.20	97.37	0.97	0.95
April/May 2000	35.47	31.30	36.51	0.97	0.86
June/July 2000	159.65	144.67	156.88	1.02	0.92

6. CONCLUSIONS

The results of this study suggest that NEXRAD data can be used to provide accurate measurements of monthly and seasonal convective rainfall in Texas. Contrary to our expectations, no changes in the Z-R equation appear warranted. The accuracy of the radar-rainfall inferences is certain to decrease as the period of comparison is decreased to individual days or even shorter time frames. This can be readily documented using the NEXRAD data, provided suitable rain gauges in dense arrays can be found to serve as a basis for reference.

As mentioned before, the project radars are poorly equipped for area rainfall measurements. Their best use would appear to be in the conduct of seeding operations, particularly in the real-time assessment of the properties of the convective cells and in the tracking of the aircraft, and in the post-evaluation of the properties of individual storms. Such analyses are possible now thanks to the TITAN systems that are installed on the radars. These are not readily feasible using the NEXRAD radars in their present configuration.

The radar-based evaluation of seeded storms, regardless of the radar system, is still a problem in the minds of some, because it is presumed that seeding somehow alters the cloud-base (i.e., base-scan) drop-size distribution and, therefore the radar-measured reflectivity and inferred rainfall. This would indeed be a problem compromising the use of radar for the evaluation of seeding experiments, if it were true, but the available evidence suggests that it is not for glaciogenic seeding, such as done in Texas. Cunning (1976) made measurements of raindrops from the bases of AgI-seeded and non-seeded storms in Florida and found that the intra-day and inter-day natural drop-size variability was as large as that measured in rainfall from seeded storms.

It is recommended that these studies be continued in order to evaluate the accuracy of daily radar-rainfall estimates using the NEXRAD radar products. This is possible now, provided a suitable recording rain gauge standard can be found.

7. ACKNOWLEDGMENTS

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Appendix D

THE INFERENCE OF CLOUD MICROSTRUCTURE USING MULTI-SPECTRAL AVHRR SATELLITE IMAGERY

1.0 INTRODUCTION

The method of Rosenfeld and Lensky (1998) to infer cloud microstructure using multi-spectral AVHRR satellite imagery has been used in Texas since 1999 for many purposes. First, the method was used to determine whether pollution within the state or outside affects cloud structure and precipitation-forming processes in Texas clouds. Second, the method was used to determine whether operational cloud seeding produces changes in cloud microstructure as required by the conceptual models guiding cold-cloud seeding. Third, the technique was used to demonstrate its potential for assessing in real time when and where seeding should be conducted and what type of seeding should be employed. Fourth, the method was used to classify the cloud microstructure prevalent on each day of the summer within each of the seven operational targets. This information is available for partitioning during the analysis phase of the operational cloud seeding experiments.

This research has been supported by the Texas Natural Resource Conservation Commission (TNRCC) through two contracts with Woodley Weather Consultants. The second contract was completed under the auspices of the Texas Department of Agriculture. The High Plains Underground Water Conservation District and the Edwards Aquifer Authority also have supported the development of this satellite technique. The current contract with the EAA calls for assessment of the microphysical structure of the clouds in Texas with a focus on the area in and around the EAA target. Although the needed imagery were obtained and processed, the sensors aboard the satellite and its orbit with respect to Texas did not permit the quantitative assessments that were possible for the 1999 and 2000 seasons. Even so, selected images of interest are provided at the end of this appendix following the appropriate documentary sections.

2.0 RATIONALE FOR THE RESEARCH

Peoples of the world are increasingly concerned about the collective effect of human habitation on the planet. Arguments abound on many environmental matters, among them the reality of global climate change, the likely consequences of biomass burning, the destruction of the rain forests, the impact of holes in the protective ozone layer in the upper atmosphere and the effect of increased industrial and urban pollution. Interactive with these issues is the overriding concern whether the world of the 21st Century will have enough fresh water to support its population and whether current and projected human activity will lead to increases or decreases in the natural rainfall.

The reality of specific instances of inadvertent modification of the weather is no longer a matter for dispute. A long series of meteorological and climatological studies of the atmospheric effects resulting from large irrigated areas, condensation trails from jet aircraft ("contrails"), power plants, paper mills, and urban areas have determined that definable changes in clouds, precipitation and storm activity do occur (Weather Modification Advisory Board, 1978). The altered climates have been documented, and the climates altered well beyond the source defined (Changnon, 1992). Human influence on the atmosphere occurs either as a result of land-use changes that alter the fluxes of sensible and latent heat, evaporation and transpiration, and momentum, or through the emission of particulates and gases that alter cloud formation processes and the radiation balances (Wigley, 1989; Braham, 1981). Cloud condensation nuclei (CCN), moisture and heating from industry have been found to affect the regional frequency of clouds (Hindman et al, 1977a; Hindman et al. 1977b) as well as the regional amount of precipitation (Hindman et al., 1977b).

Studies of climate records at several North American cities revealed the presence of urban anomalies (increases) in precipitation and storm conditions for cities with populations greater than one million (Huff and Changnon, 1973). In general, the area extent and magnitude of the precipitation anomaly are related to the size of the urban area. Warm-season, highly-organized, rain-productive convective clouds were the most affected (Changnon, et al., 1991); Changnon et al., 1981; Changnon and Semonin, 1979).

The above studies took years of painstaking research to complete and for the most part were focused on the United States. Inadvertent modification of the environment, especially the natural rainfall, is a global phenomenon. Not until recently, however, did a means exist to document inadvertent changes in cloud microstructure and precipitation-forming processes on a global basis. Within the past 10 years new capabilities of remote sensing from space have been developed, allowing the detection of "tracks" of enhanced cloud reflectivity over the open ocean. These became widely recognized as the impact of ship-stack effluent on the cloud drop size distribution and water content (Coakley et al., 1987, Radke et al., 1989). These ship tracks provided a vivid demonstration of the profound effect of anthropogenic aerosols on the radiative properties and microphysical structure of maritime stratocumulus clouds.

In addition to inadvertent alteration of the weather, deliberate attempts to increase rainfall through cloud seeding in semi-arid regions have been underway worldwide for many years. Texas is currently the most active state in the United States for attempts to increase the warm season rainfall through operational cloud seeding. Buttressing the Texas operational seeding programs is a long-term program of weather modification research that is being conducted now under the acronym TEXARC (Texas Exercise in Augmenting Rainfall through Cloud Seeding). This partnership between research and operations is developing a highly productive weather modification program in Texas.

The challenge to those interested in inadvertent and/or deliberate alteration of the weather is quantification of the effects. Modern technology is progressing at a dizzying pace. Even scientists have difficulty keeping up with recent developments in their own disciplines. The situation is more difficult for the decision-makers, who might best be served by new scientific developments. This is certainly the case for the rain enhancement programs of Texas, whose managers can hardly be expected to be experts in cloud physics, nucleation theory and radar meteorology. This is also the case for managers of programs to monitor the effects of human activity on the environment. It is important, therefore, for these managers to seek out the best expertise possible for the betterment of their programs.

The rain enhancement programs of Texas already incorporate modern technology in the form of radar systems, including the new TITAN system, the latest in nucleation technology, aircraft telemetry systems and access to more information via the Internet than can be assimilated. Despite these advances, more help is needed by the Texas rain enhancement programs in deciding when and where to seed and in assessing after-the-fact whether seeding had the desired effect on the clouds. Environmental programs would benefit also if there were a way to monitor the effects of various sources of pollution (e.g., major cities, heavy industry, power plants, etc.) on clouds and precipitation.

This help is now available through the use of multi-spectral satellite imagery as described in the paper by Rosenfeld and Lensky (1998), which was published in the Bulletin of the American Meteorological Society in November 1998. The method makes use of AVHRR multi-spectral data from polar orbiting satellites to infer the evolution of convective cloud particles and precipitation at various heights within the clouds. This capability should be enormously beneficial to both the research and operational cloud seeding programs of Texas. Use of the Rosenfeld technique will make it possible to determine which clouds contain supercooled water and are suitable for seeding according to the AgI seeding conceptual models and which clouds are already frozen and unsuitable for seeding.

Just as important, the use of this imagery in Texas should make it possible to determine which clouds have coalescence and rain drops and which do not. In making this distinction, it should be possible to identify which clouds might be responsive to hygroscopic seeding according to the various hygroscopic seeding conceptual models.

Multi-spectral satellite imagery also has great potential for the evaluation of either AgI and/or hygroscopic seeding. The former should produce cloud glaciation and the latter should induce the formation of raindrops where none were present previously. The changes produced by AgI seeding should be observable from space over wide areas in the multi-spectral satellite imagery. Those produced by hygroscopic flare seeding may not be detectable if the seeding-induced concentration of raindrops is too small for detection at cloud top.

Of equal importance the application of the multi-spectral satellite imagery will make it possible to determine which Texas cities are having the greatest impact on the internal structure of the clouds and on their ability to develop rainfall. The very high resolution (i.e., 1 km) of the AVHRR imagery provided by the polar-orbiting NOAA-14 satellite will even make it possible to bring the focus down to specific sources of pollution such as power plants, oil refineries and other major industrial complexes in both Texas and Mexico. That this can be done is demonstrated by Rosenfeld and Lensky (1998) and Rosenfeld (1999) for forest fires in Indonesia and by Rosenfeld (2000) for pollution in southeastern Australia.

3.0 SCIENTIFIC BACKGROUND

In laying the foundation for the research results, it is important to understand the physical processes leading to precipitation. Cloud droplets nucleate on cloud condensation nuclei (CCN) and grow, at least initially, by condensation. This condensational growth alone is incapable of producing raindrops in clouds. Raindrops can be formed by coalescence of cloud droplets that grow beyond a radius of about 15 microns (Gerber, 1996). The depth of cloud in which the droplets reach this size depends mainly on the initial drop size distribution (DSD) at its base. It can be seen, therefore, that the efficiency of the conversion of cloud water into precipitation depends strongly on the cloud DSD and its evolution with height.

The vertical growth of clouds often extends through the 0C level, where cloud water can remain in a supercooled state at temperatures colder than -30C (Sukarnjanaset et al., 1998; Rosenfeld and Woodley, 2000). Ice particles of precipitation size grow in the supercooled cloud by collecting the cloud water, forming a mixed-phase zone. Finally, all the cloud water freezes, forming a glaciated cloud.

With the above as background, it is obvious that clouds having large concentrations of small droplets precipitate much less efficiently than clouds containing the same amount of water in fewer but larger drops. The most important factor determining the cloud DSD are the CCN aerosols on which cloud droplets are formed, typically at cloud base. Too many small CCN can be highly detrimental to the ability of the cloud to form precipitation. A major source of such CCN is air pollution, especially smoke from the burning of vegetation (i.e., biomass burning). Therefore, clouds forming in a smoke-laden atmosphere are composed of numerous small droplets, which are too small to fall from the clouds, thereby causing a reduction in the natural precipitation.

4.0 METHODOLOGY

The method to deduce the microphysical structure of clouds from space makes use of data from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA operational weather satellites, which provide sub-satellite 1.1 km data in 5 channels centered at 0.65, 0.9, 3.7. 10.8, and 12.0 microns. The visible wave band (0.65 microns) is used to select points with visibly bright clouds for the analyses. The thermal infrared (0.9 microns) is used to obtain cloud-top temperatures. Cloud- top particle size is inferred from the solar radiation component of the 3.7-micron wave band.

In making the inferences of cloud microphysical structure, the effective radius (r_{eff}) of fully cloudy pixels is retrieved in the manner described by Rosenfeld and Gutman (1994) and Lensky and Rosenfeld (1997). This is done by inverting a radiative transfer model developed by Nakajima and King (1990), using the solar reflectance component of the 3.7 micron channel and the viewing geometry as inputs. Retrieval of particle size at cloud top is based on the fact that water absorbs part of the solar radiation at the 3.7micron wave band. While the back-scattered solar radiation is determined mainly by the surface area of the particles, the amount of absorption is determined by the volume of the particles. Therefore, larger particles absorb more and reflect less, so clouds that are made of larger droplets are seen darker in the reflected 3.7micron radiation.

Knowing the energy radiated from the sun and the portion of that energy reflected back to the satellite sensor, the fraction of the solar energy absorbed can be retrieved. This provides the basis for calculating the ratio between the integral volume and integral surface area of cloud particles in the satellite measurement volume. Conventionally, this ratio has been defined as the particle effective radius, r_{eff}.

The initial research suggests that a r_{eff} of 14 microns is a threshold value above which clouds contain precipitation-size particles that can be detected by weather radar (Rosenfeld and Gutman, 1994). The maximum value of r_{eff} that can be retrieved by this method is 30 microns.

The evolution of r_{eff} as a function of cloud-top height or temperature (T) of growing convective elements can reveal the microphysical evolution of the clouds as they grow vertically and undergo the various microphysical process that lead to the formation of precipitation. However, the satellites carrying high-resolution AVHRR sensors typically provide only a twice-daily snapshot image of a specific portion of the earth. Thus, a single cloud cannot be viewed continuously in the imagery. This difficulty is overcome by observing an area containing a convective cloud cluster composed of cloud elements at various stages of vertical growth. This allows the compositing of the r_{eff} calculations for many clouds as if they represented a singe cloud at different times in its lifetime.

The actual composite is done in the following steps:

a) Define a window, typically of several thousand pixels, encompassing convective cloud clusters with growing elements at various stages of development.

b) Calculate the median and other percentiles of the r_{eff} for pixels within each 1°C interval of cloud top temperature (T).

c) Display graphically the T vs. r_{eff} curves of the 10, 25, 50, 75, and 90 percentiles.

d) Analyze the shape of the median (50^{th} percentile) to find the microphysical zones as discussed below.

The shape of the T vs. r_{eff} diagrams contains much information on the microphysical processes in the clouds. It is known that droplets grow by diffusion a small distance above the base of convective clouds while higher up in the clouds the hydrometeor growth rate is often accelerated by coalescence and ice processes. Because nearly all cloud droplets are nucleated at cloud base and cloud water mass increases less than linearly with depth, it is found that the r_{eff} in clouds with mostly diffusional growth increases by a power law of less than $D^{1/3}$, where D is depth above cloud base. D can be approximated using T_b-T, where T and T_b are cloud top and base temperatures, respectively. It can then be seen that r_{eff} is proportional to $(T_b\text{-}T)^{1/3}$ and a plot of r_{eff} versus temperature will look like an upward convexed curve. Therefore, a deviation from such a curve (i.e., an upward concave curve) indicates the existence of amplification mechanisms for the cloud-particle growth rate, such as coalescence and ice formation processes, which lead ultimately to precipitation.

Based on about a hundred analyzed cases well distributed over the globe, the evolution of convective cloud-top particles as a function of depth above cloud base and cloud-top temperature can be characterized into five distinct vertical zones, not all necessarily appearing in a given cloud system:

1) *Diffusional droplet growth zone:* Very slow growth of cloud droplets with depth above cloud base, indicated by shallow slope of dr_{eff}/dT.

2) *Droplet coalescence growth zone:* Large increase of the droplet growth rate dr_{eff}/dT at $T > 0^oC$, indicating rapid growth of the cloud droplets with depth above cloud base. This can only occur by drop coalescence.

3) *Rainout zone:* A zone where r_{eff} remains stable at about 20 microns, probably determined by the maximum drop size that can be sustained by rising air near the cloud top, where the larger drops are precipitated to lower elevations and may eventually fall as rain from the cloud base. This zone is so named, because the clouds seem to be raining out much of their water while growing. The radius of the drops that actually rain out from cloud tops is much larger than the indicated r_{eff} of 20 microns, being at the upper end of the drop size distribution.

4) *Mixed phase zone:* The large growth rate that may occur at $T < 0^oC$ can be attributed to coalescence as well as to mixed phase precipitation formation processes. Therefore, the mixed phase and coalescence zones are ambiguous at temperatures below freezing. Because the first ice phase in growing continental clouds appears typically at $T < -10^oC$, the zones are separated arbitrarily at -10^oC.

5) *Glaciated zone:* A nearly stable r_{eff} zone at below freezing temperatures at a value greater than that of the rainout zone. The value is probably determined by the maximum ice particle size that can be sustained near cloud top, where the larger particles are precipitated to lower elevations while aggregating and forming snowflakes. Several examples of the above cloud-microphysical zones as inferred from the AVHRR imagery are provided in the following case studies. Plotted are the 25%, 50%, 75% and 90% percentiles of the r_{eff} for each 1^oC interval. The median is indicated by the thick line. The numbers in the plots refer to the growth zones as numbered above.

The first two examples are from continental situations in Israel, where it can be seen that there was a deep diffusional growth zone capped by a zone of mixed-phase growth (Figures 1a and 1b). In the second example a glaciated zone lay above the mixed phase zone (Figure 1b).

In contrast with the first two examples are plots of r_{eff} versus temperature for two AVHRR windows in an image covering the Bay of Bengal (Figure 2a) and Thailand (Figure 2b). In these plots the diffusional growth zone is virtually non-existent in clouds over the Bay of Bengal, where the droplet coalescence growth zone is already well developed a small distance above the bases of the maritime clouds. Even in the interior of Thailand (Figure 2b) the diffusional growth zone is shallower than in the examples shown for Israel above which there is a zone of droplet growth by coalescence.

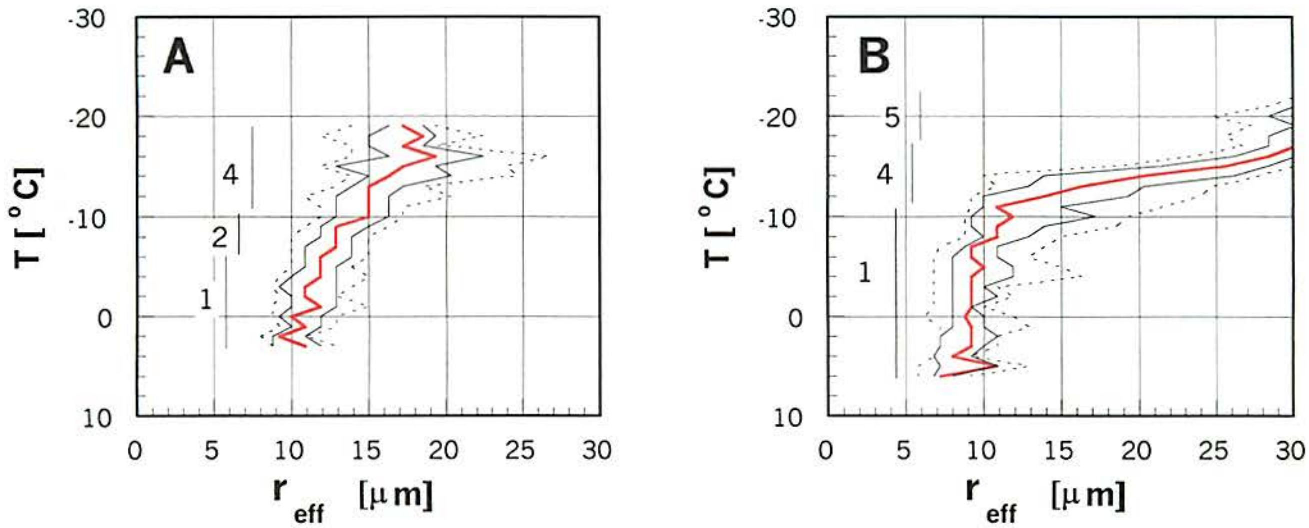

Figure 1: The effective radius as a function of cloud-top temperature for two AVHRR windows over Israel on 25 March (A) and 3 April 1995 (B). Plotted are the 10%, 25%, 50%, 75% and 90% percentiles of the r_{eff} for each 1°C interval. The thick line indicates the median. The vertical bars denote the different microphysical zones as numbered in the text.

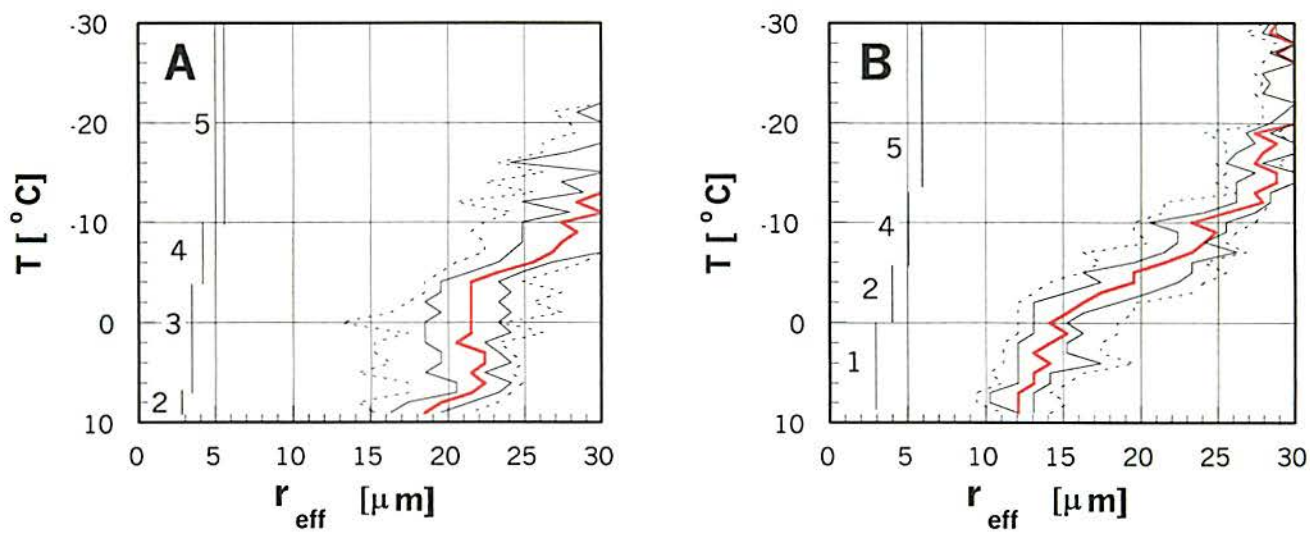

Figure 2: The same as Figure 1 but for two AVHRR windows containing clouds growing in monsoon flow on 12 November 1992. Window A covers a portion of the Bay of Bengal to the Burmese coastal areas and window B is in the interior of Thailand.

The rainout zone can exist only in clouds with well-developed coalescence that has progressed to the extent that further increase of drop size is compensated by the large drop fallout from the cloud tops. Therefore, the rainout zone exists just above the droplet coalescence growth zone. As can be seen (Figure 2a), the rainout zone is well-developed in maritime clouds, but its extent is reduced in less maritime clouds (Figure 2b) and completely vanishes in continental clouds (Figure 1a and 1b).

The mixed-phase zone exists above the glaciated zone. Often the coalescence and mixed phase zones overlap to one continuous region of rapid growth of r_{eff} through the 0°C isotherm. In such cases the separation between the zones is set arbitrarily to –6°C (Figure 2b). The transition from the rainout zone to the glaciated zone (Figure 2a) is also defined as a mixed-phase zone.

A glaciated cloud is one in which practically all of its water has turned into ice particles. Cloud-top glaciation occurs at temperatures of about –5°C to –10°C for clouds with well-developed coalescence, typical of maritime clouds (Figure 2a), in agreement with the laboratory experiments of Hallett and Mossop (1974). Glaciation occurs typically at about –15°C for continental clouds with some coalescence (Figure 2b) or –20°C for more continental clouds. In the extreme, glaciation can occur at temperatures as cold as –38°C for highly continental clouds (Rosenfeld and Woodley, 2000).

With the above as background, it becomes obvious that the new method should be enormously beneficial to both the research and operational cloud seeding programs of Texas. Use of the Rosenfeld technique will make it possible to determine which clouds contain supercooled water and are suitable for seeding according to the AgI seeding conceptual models and which clouds are already frozen and unsuitable for seeding.

Just as important, the use of this imagery in Texas should make it possible to determine which clouds have coalescence and rain drops and which do not. In making this distinction, it should be possible also to identify which clouds might be responsive to hygroscopic seeding according to the various hygroscopic seeding conceptual models and which might not.

This can be visualized and quantified in the color-coded satellite images. The color-coding is a means of visualizing the information in the three spectral channels. In the visible channel very bright clouds are reds while clouds dim to the eye have little red. The 3.7-micron channel is used to infer drop size, where clouds with very small drops are green and those with large drops have no green. The 10.8-micron channel is used to infer cloud top temperature. Warm surfaces are blue while very cold surfaces have no blue.

Upon combining the information in the three channels, the three basic colors (red, blue and green) are combined to produce a colorized image along with the plots of effective radius vs. temperature. Thus, supercooled clouds will appear yellow in the images, which is the resultant of some green (small drops) and some red (bright clouds) but little blue (cold tops). Conversely, clouds with coalescence will appear magenta, which is the combination of some red (bright clouds) and some blue (relatively warm cloud tops) but little green, because the drops are large.

This is illustrated in processed images from the 1999 Texas season. The first at 2212 GMT on May 30, 1999 shows a field of clouds in west Texas between Midland and Del Rio that include cumulonimbus clouds having a yellow-orange tint (Figure 3). This coloration suggests the clouds are bright but contain small particles. The plots of effective radius (r_{eff}) vs. temperature on the left side of the figure show this is true. Note the clouds in both areas 1 and 2 have a deep zone of diffusion growth (vertical yellow line) with only a slow increase of r_{eff} with a decrease in temperature. The effective radius does not reach the 15-micron threshold for precipitation formation until the clouds are well supercooled. Such clouds are highly inefficient. Hygroscopic rather than AgI seeding would probably be the better seeding approach for these clouds.

In contrast to the continental clouds of Figure 3 are those in Figure 4 at 2146 GMT on August 3, 1999. The clouds of interest are near and to the NE of Del Rio, but this time they have a much different coloration. Instead of being yellow-orange, they are mostly red and magenta. Indeed, the plots of r_{eff} vs. temperature are very different. These clouds have no discernible zone of diffusional growth and a deep zone of coalescence growth (the vertical green line). The clouds reach the 15-micron threshold for precipitation development at a temperature of +5°C. The mixed phase zone (the magenta vertical line in the plot) begins at about –8°C and glaciation is not complete until about –25°C (the vertical red line). Such clouds are ideally suited to AgI seeding.

Finally, consider the clouds pictured in area 3 near San Angelo in Figure 5 at 2125 GMT on June 21, 1999. Most of the clouds are distinctly purple and magenta and the r_{eff} plot vs. temperature shows a shallow zone of coalescence growth (vertical green line) overlain by a zone of precipitation fallout (vertical blue line), a shallow mixed-phase zone beginning near 0°C (vertical magenta line) and finally a deep zone of glaciation (vertical red line). Such clouds are probably not suitable for any kind of seeding intervention.

If the meteorologist had this information pictured in the three figures in real time, he could make a decision whether any seeding is warranted and, if so, what type of seeding would work best for the clouds. In addition, this kind of information could be used to classify all days of cloud seeding operations to be used for partitioning during the analysis phase.

5.0 SATELLITE CLASSIFICATION OF CLOUD MICROSTRUCTURE

The target classifications of cloud microstructure for 1999 and 2000 are provided in Appendix A. The targets were identified in the body of this report (the NP and PH targets were not operative in 1999). The classifications were made using the matrix in Table 1 by determining the temperature ranges of inferred glaciation (table "ordinate") and when r_{eff} first reaches 15 microns (table "abscissa"). The imagery from which the classifications were made is available on CD-ROM.

Table 1
Cloud Classification Matrix of Rankings

Glaciation Temperature (°C)	Temperature (°C) when r_{eff} first equals 15 microns: T > 15	15 ≥ T > 5	5 ≥ T > -5	-5 ≥ T > -15	T ≤ -15
T > -10	5.0	4.5	4.0	3.5	3.0
-10 ≥ T > -15	4.5	4.0	3.5	3.0	2.5
-15 ≥ T > -20	4.0	3.5	3.0	2.5	2.0
-20 ≥ T > -25	3.5	3.0	2.5	2.0	1.5
T ≤ -25	3.0	2.5	2.0	1.5	1.0

A comparison of the monthly and seasonal satellite cloud classifications for the seeding targets in 1999 and 2000 is provided in Table 2. The Panhandle and North Plains targets were not defined at the time of analysis of the 1999 data and no information is available for these targets in 1999. The data are very limited in some months, due either to a lack of clouds and/or data. In looking at the "overall" column (the second column from the right) both years show an increase in cloud classification from northwest to southeast through Texas. This means that the clouds in Texas become more maritime in character, having increasing coalescence and warm glaciation temperatures as distance from the Gulf Coast decreases. This is an expected result.

Table 2
Mean Convective Rankings for the Texas Operational Seeding Targets
By Month and Overall for April through September in 1999 and 2000
(The 1st number is sample size in days and the 2nd number is the cloud classification.)

Target	April	May	June	July	August	Sept.	Overall Cld Cls
NP00	7, 1.3	6, 1.3	16, 1.9	5, 2.2	2, 2.0	4, 1.4	40, 1.8
PG00	8, 1.4	6, 1.3	16, 2.2	5, 2.1	2, 2.0	4, 1.4	41, 1.8
HP99	5, 1.4	9, 1.9	16, 1.6	7, 2.3	16, 1.9	12, 2.1	65, 1.9
HP00	8, 1.4	10, 1.5	19, 2.2	7, 2.8	2, 2.8	4, 1.4	50, 2.0
CR99	6, 1.2	12, 1.8	15, 1.8	11, 2.9	12, 1.8	12, 2.4	68, 2.0
CR00	5, 1.2	5, 1.5	14, 2.6	9, 2.3	2, 2.3	4, 1.6	39, 2.1
WT99	4, 1.6	10, 2.1	15, 2.2	9, 2.4	14, 1.9	13, 2.5	61, 2.3
WT00	7, 1.1	7, 1.3	13, 2.6	9, 2.4	1, 2.0	5, 1.7	42, 2.0
TB99	4, 1.3	7, 1.9	10, 2.8	5, 2.8	7, 2.0	9, 3.0	42, 2.4
TB00	7, 1.4	5, 1.4	9, 3.6	4, 2.1	2, 2.5	4, 1.4	31, 2.2
EA99	1, 2.5	4, 2.5	8, 2.7	10, 2.8	7, 2.1	12, 2.8	42, 2.6
EA00	3, 2.3	2, 2.5	10, 3.3	5, 2.4	4, 3.0	4, 2.4	28, 2.8
SWT99	2, 2.5	4, 2.8	8, 3.2	12, 3.6	6, 2.6	9, 3.4	41, 3.2
SWT00	1, 1.0	1, 1.5	9, 3.4	2, 2.8	4, 3.0	3, 2.5	20, 2.9
ST99	1, 2.5	5, 2.9	8, 3.2	13, 3.3	5, 2.4	10, 3.4	42, 3.1
ST00	1, 1.0	3, 2.3	10, 3.3	4, 3.1	3, 3.0	3, 3.0	24, 3.0

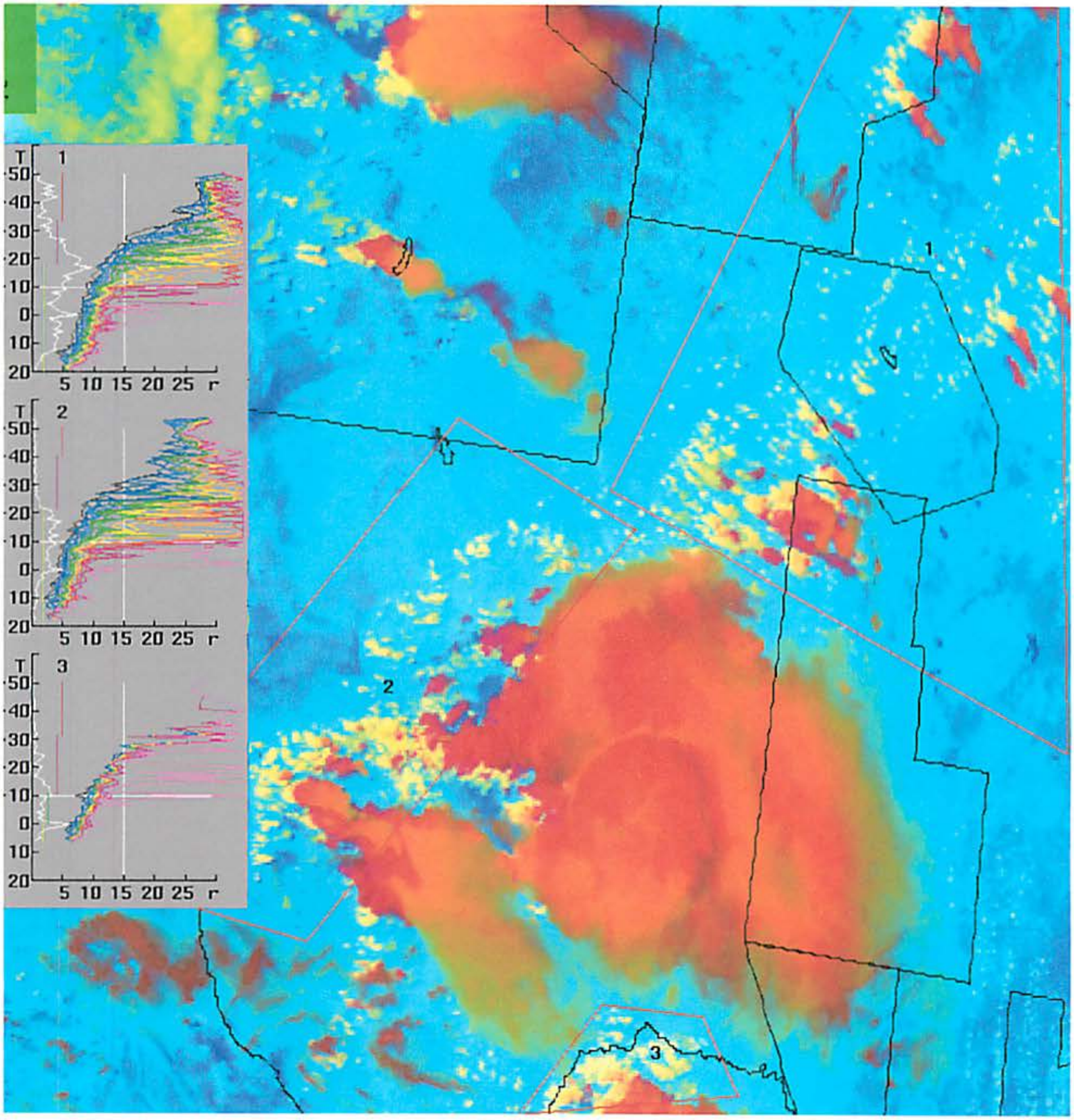

Figure 3. Processed NOAA-14 satellite image at 2212 GMT (1646 CDT) on 30 May 1999. See text for details.

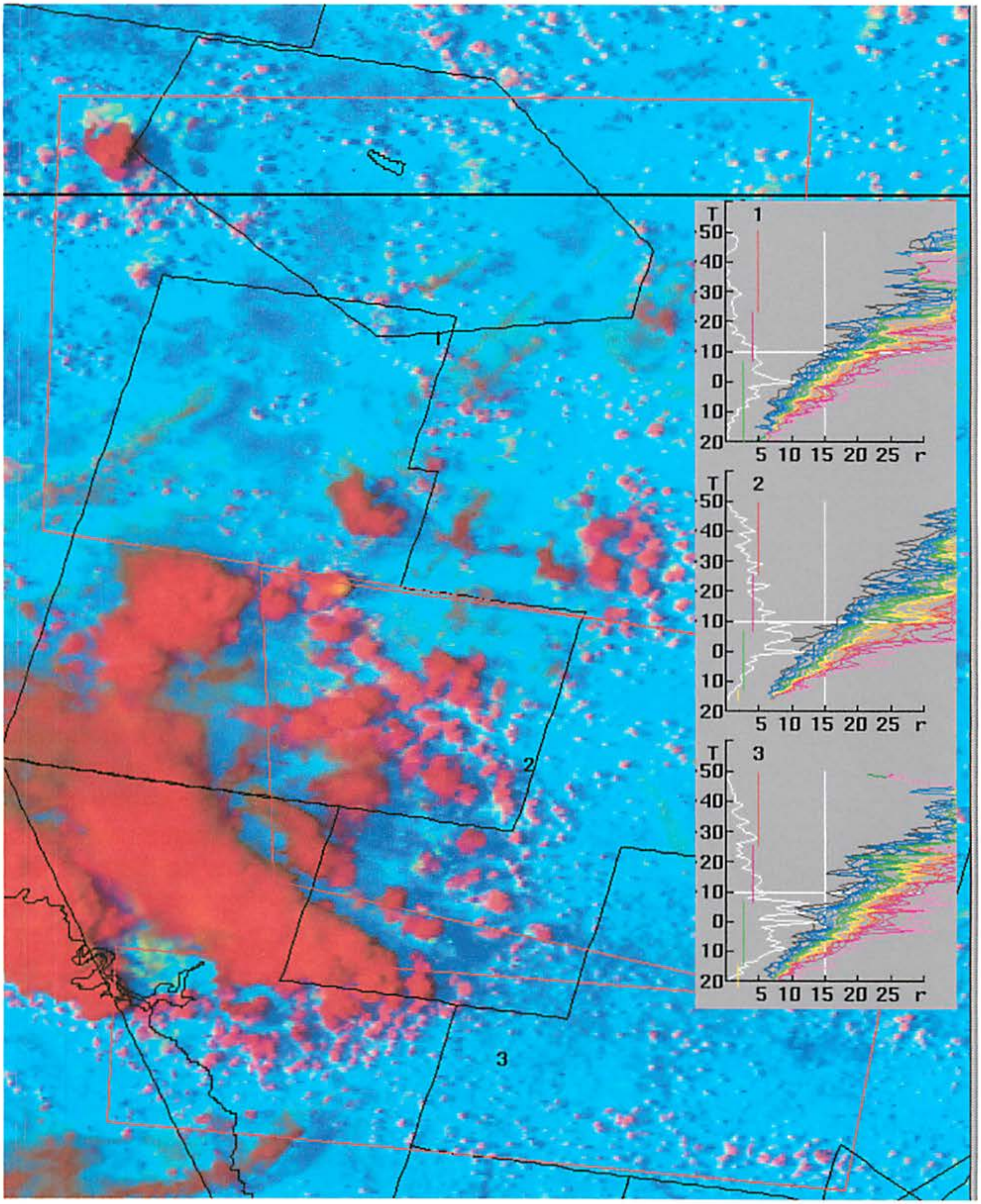

Figure 4. Processed NOAA-14 satellite image at 2146 GMT (1646 CDT) on 3 August 1999. The image is centered on Del Rio, Texas. See text for details.

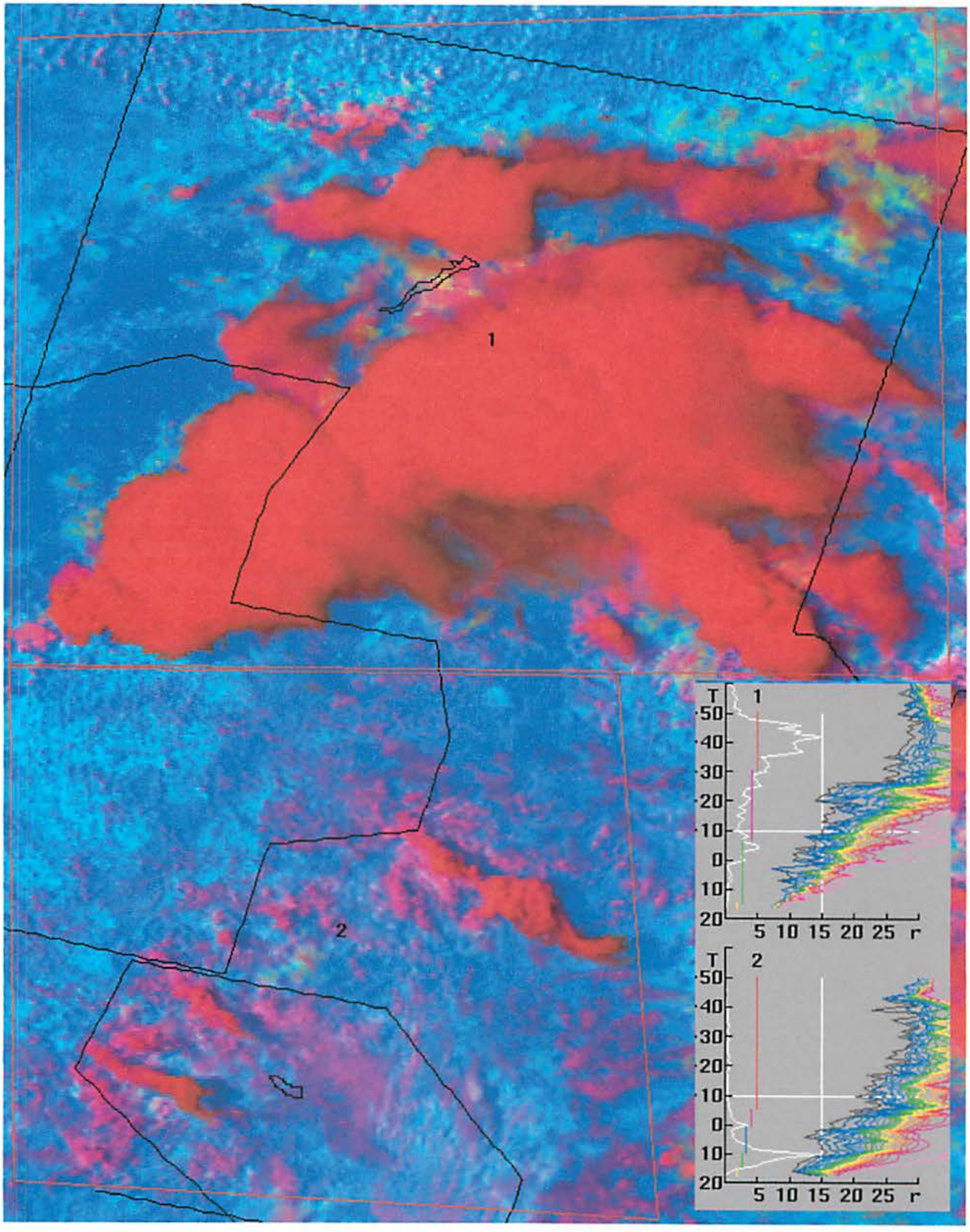

Figure 5. Processed NOAA-14 satellite image at 2125 GMT (1625 CDT) on 21 June 1999. See text for details.

6.0 IMAGES FOR THE 2001 SEASON

A few images of interest from the NOAA-16 orbiting satellite were excerpted from the entire record on CD-ROM that accompanies this Final Report. These are provided here.

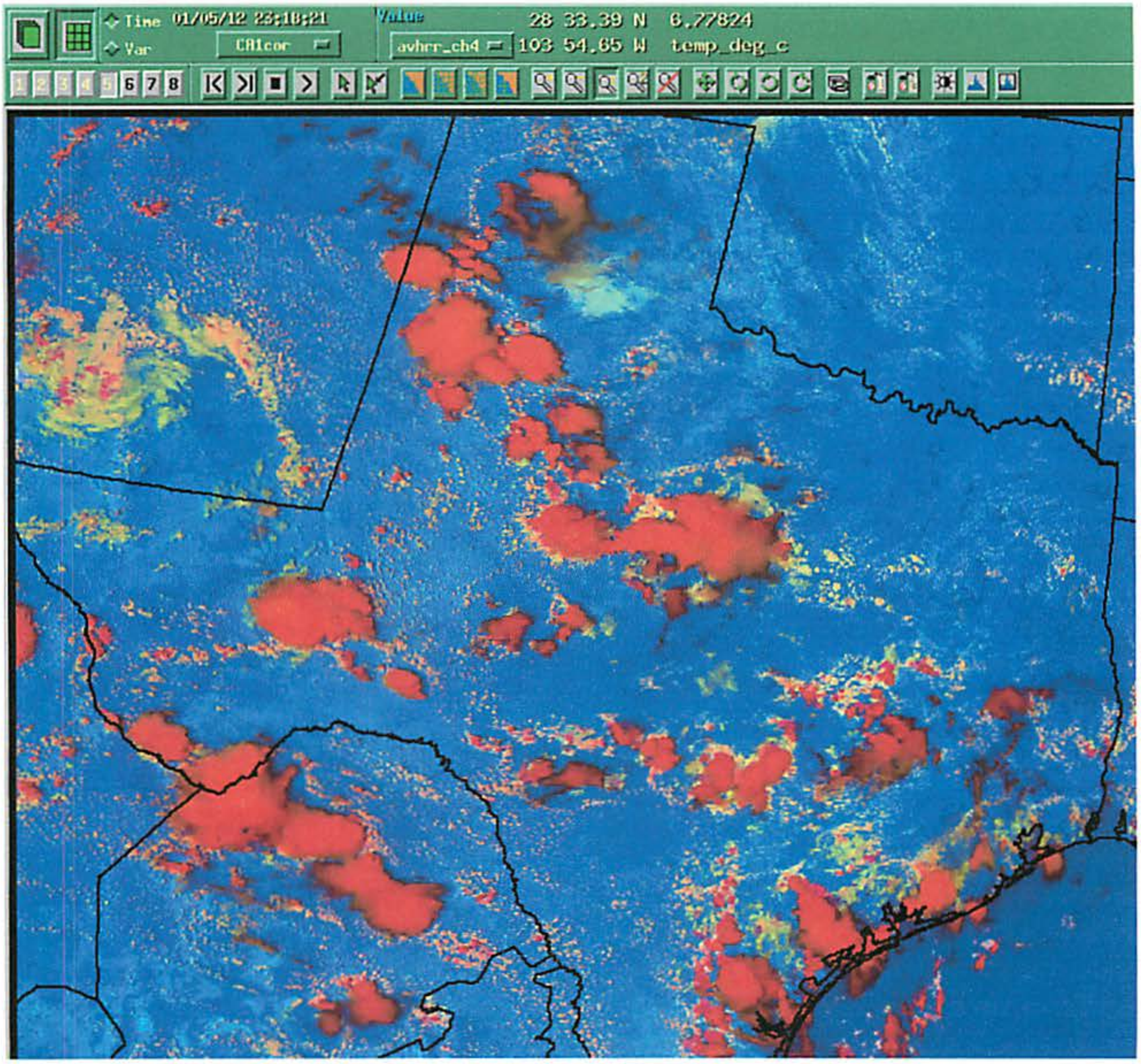

Figure 6. Portion of processed, color-coded, NOAA-16 image at 23:18:21 GMT on May 1, 2001, that shows portions of Texas. Widely scattered cumulonimbus clouds can be seen over much of Texas. No seeding flights were conducted in the EAA target on this day.

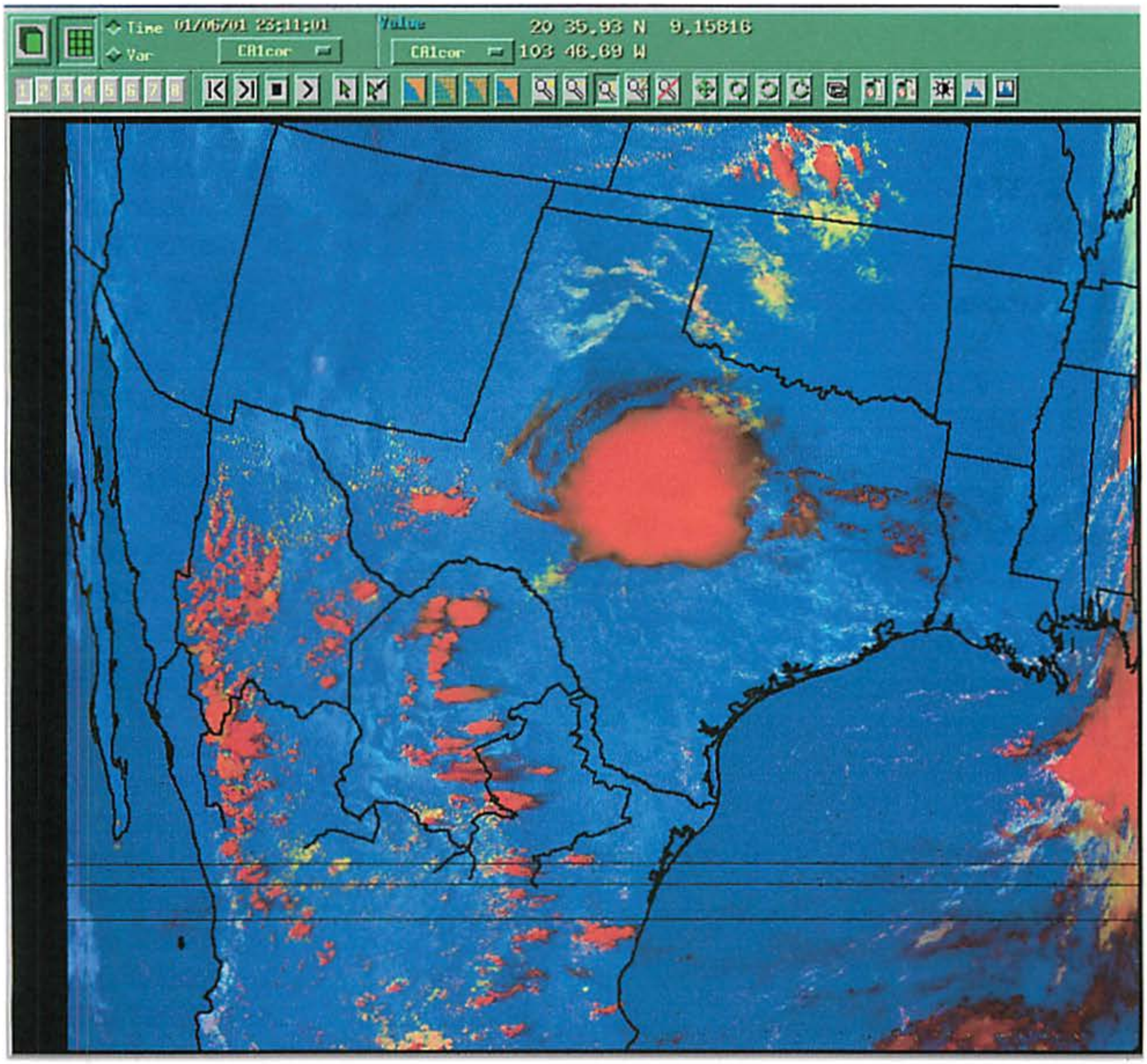

Figure 7. Portion of processed, color-coded, NOAA-16 image at 23:11:01 GMT on June 1, 2001, that shows portions of Texas. One seeding flight was conducted in the EAA target on this day, but only 9 flares were ejected near cloud top. The average rainfall in the EAA gauge network on this day was 0.04 in.

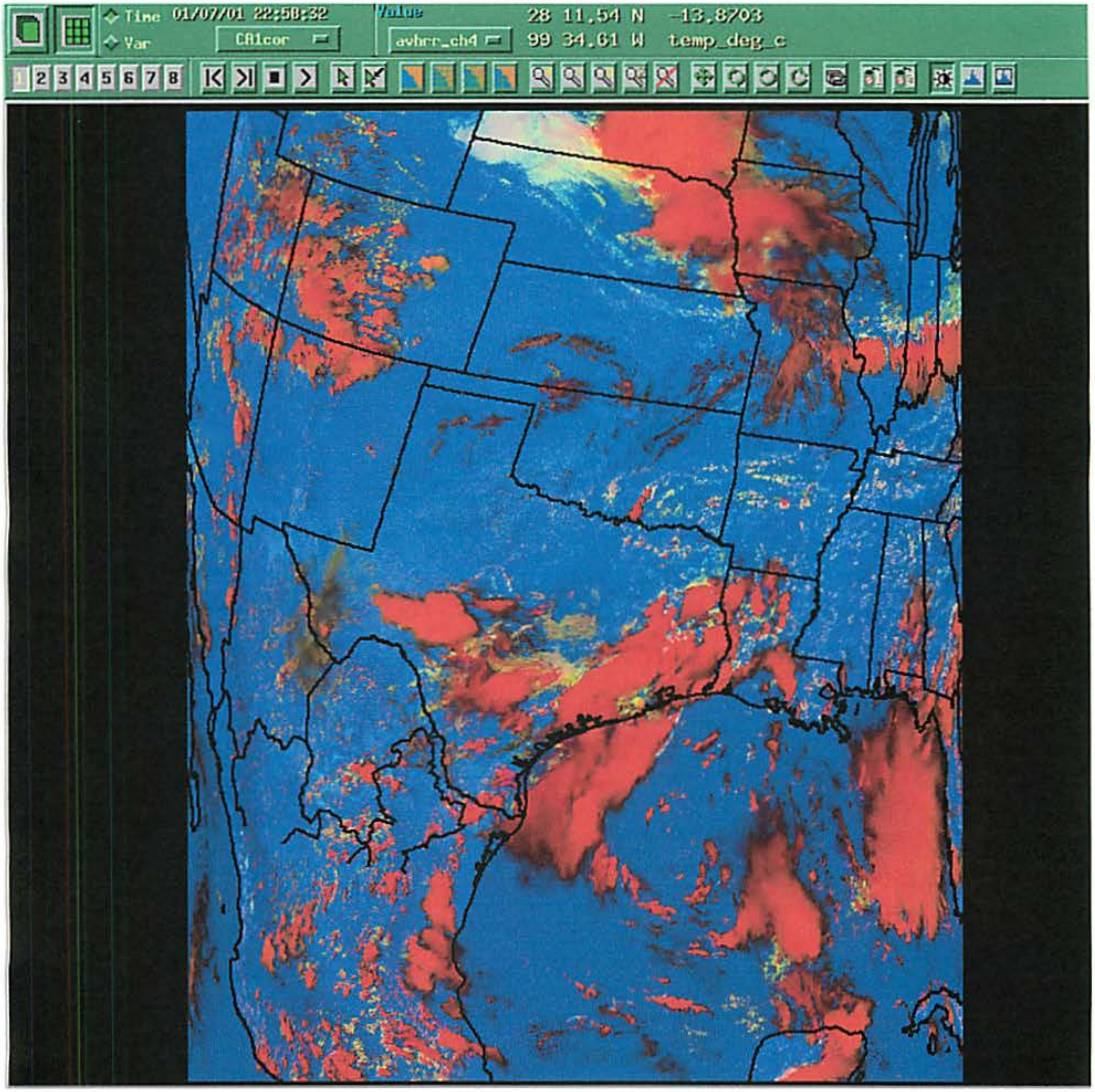

Figure 8. Portion of processed, color-coded, NOAA-16 image at 22:58:32 GMT on July 1, 2001, that shows portions of Texas. Although the EAA gauge network had an average of 0.07 in. on this day, no seeding flights were conducted.

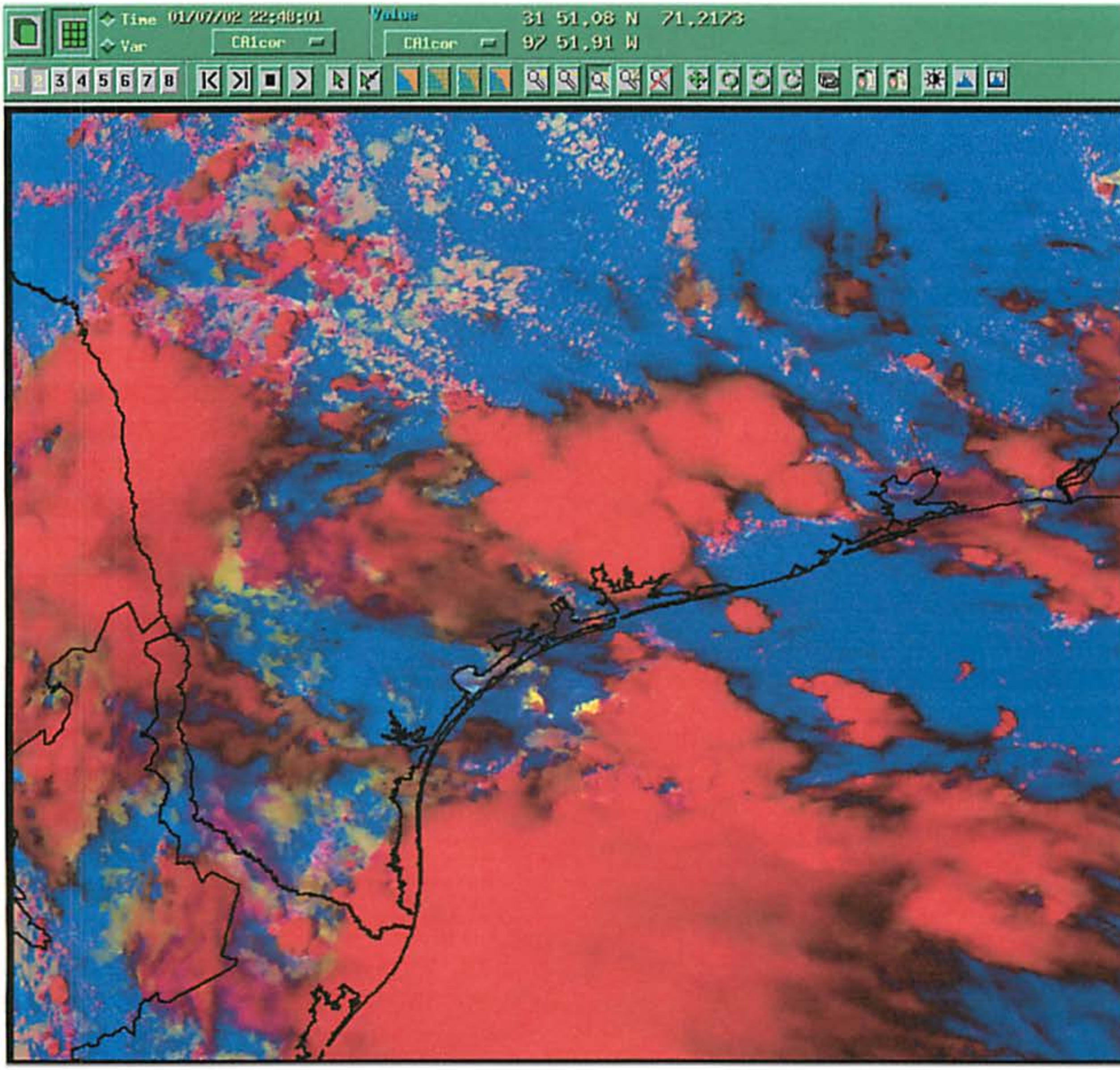

Figure 9. Portion of processed, color-coded, NOAA-16 image at 22:48:01 GMT on July 2, 2001, that shows portions of Texas. The EAA gauge network had 0.50 in. on this day and one seeding flight was conducted.

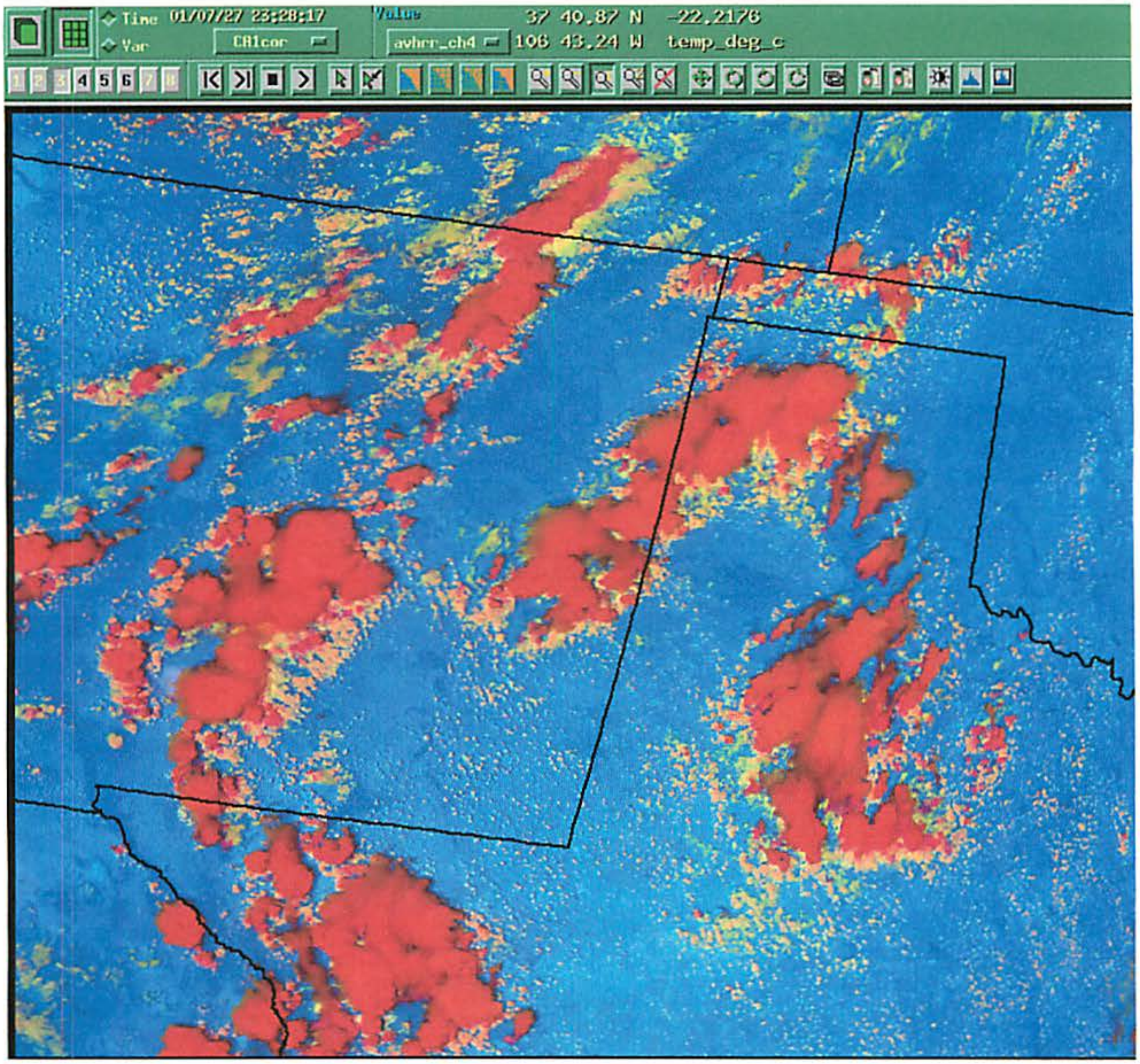

Figure 10. Portion of processed, color-coded, NOAA-16 image at 23:28:17 GMT on July 27, 2001, that shows portions of Texas. No rain occurred in the EAA gauge network on this day and no seeding flights were conducted.

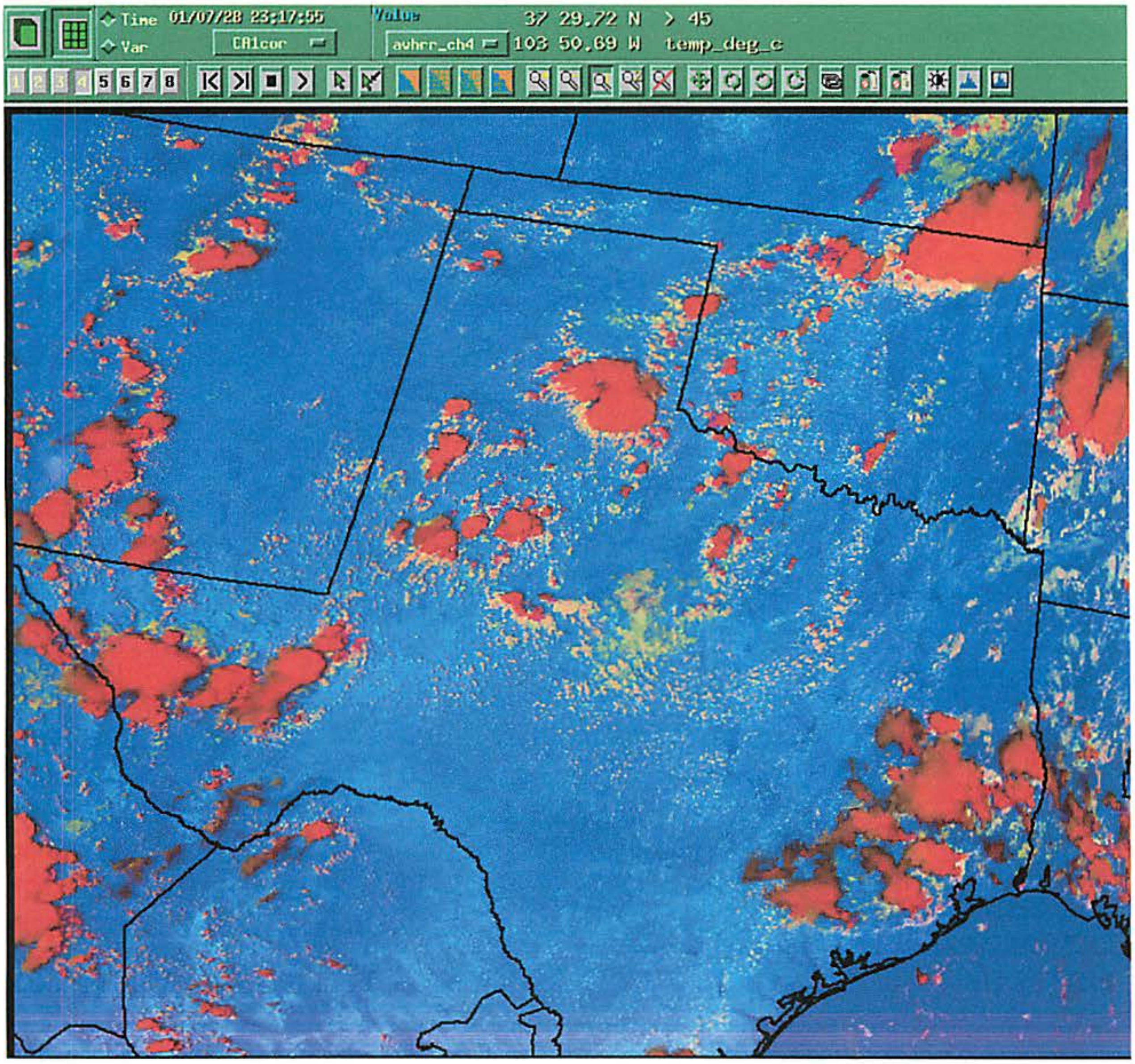

Figure 11. Portion of processed, color-coded, NOAA-16 image at 23:17:55 GMT on July 28, 2001, that shows portions of Texas. The area-averaged rainfall in the EAA gauge network on this day was 0.01 in., but no seeding flights were conducted.

Figure 12. Portion of processed, color-coded, NOAA-16 image at 23:13:57 GMT on August 1, 2001, that shows portions of Texas. No rainfall fell in the EAA gauge network and no seeding flights were conducted on this day.

Figure 13. Portion of processed, color-coded, NOAA-16 image at 22:52:22 GMT on August 9, 2001, that shows portions of Texas. Note that all of the significant convection is confined to West Texas. There was no rainfall in the EAA gauge network and no seeding flights.

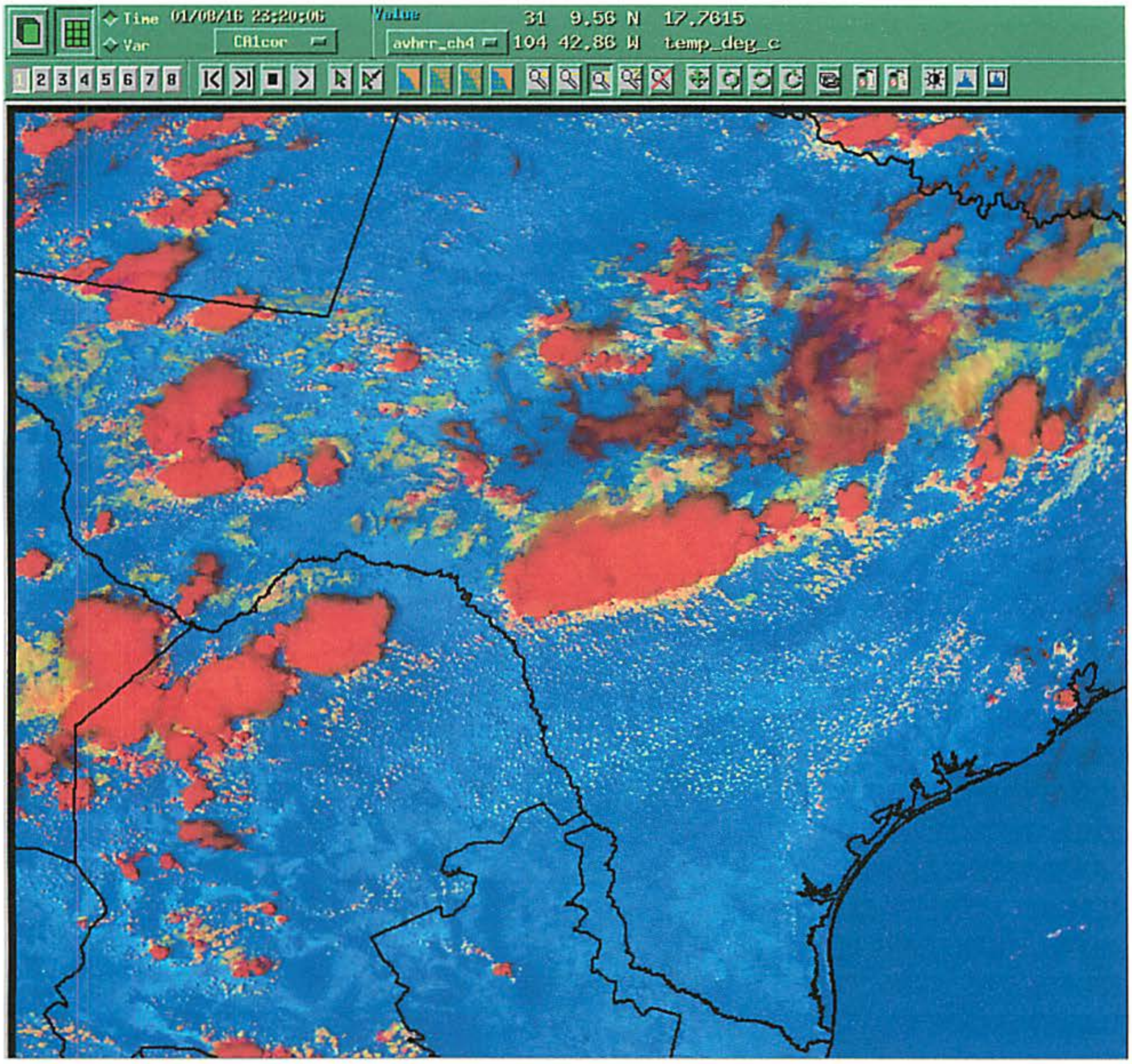

Figure 14. Portion of processed, color-coded, NOAA-16 image at 23:20:06 GMT on August 16, 2001, that shows portions of Texas. The picture shows a strong line of convection in the northwestern portion of the EA target with smaller new clouds growing on the south side of the line. An average of 0.19 in. of rain was measured in the EAA rain gauge network and there were three seeding flights on this day.

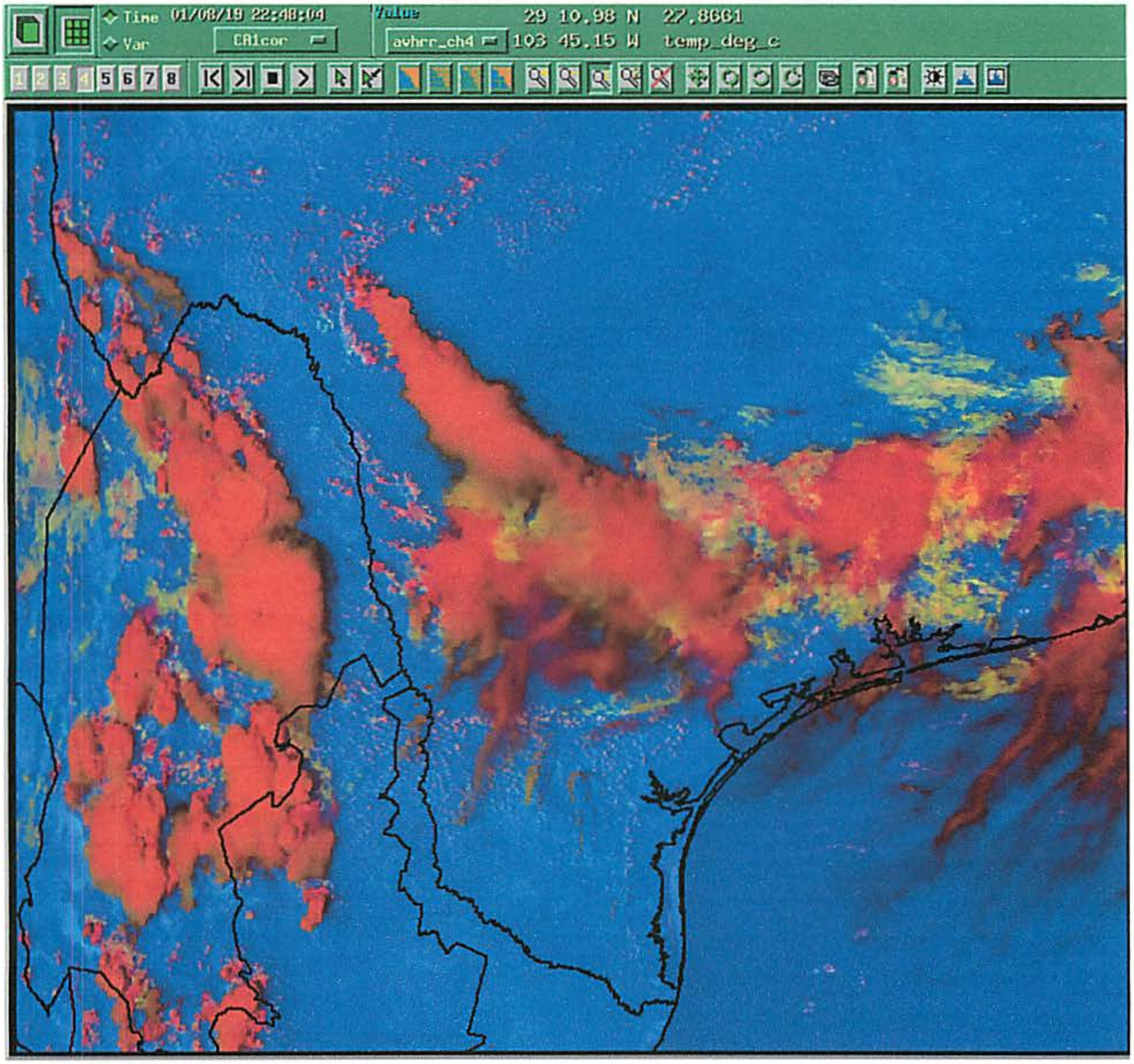

Figure 15. Portion of processed, color-coded, NOAA-16 image at 22:48:04 GMT on August 19, 2001, that shows portions of Texas. A portion of the EA target is covered by cloud debris from convection earlier in the day. A total of 0.21 in. was measured in the EA gauge network and there were two seeding flights on this day.

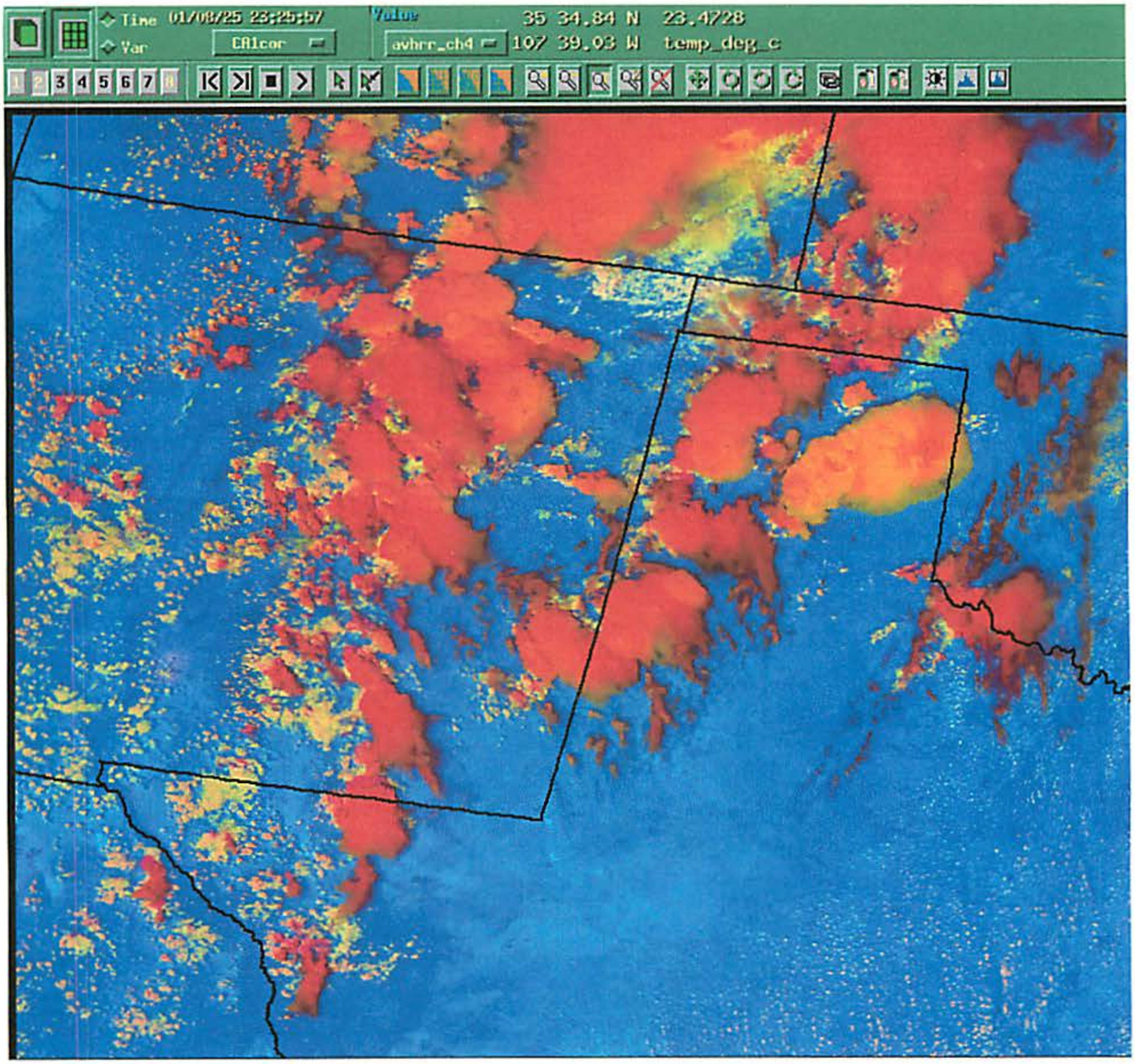

Figure 16. Portion of processed, color-coded, NOAA-16 image at 23:25:57 GMT on August 25, 2001, that shows portions of Texas. All of the significant convection on this day was confined to extreme West Texas and the Texas Panhandle. There was no rainfall in the EA gauge network and there were no seeding flights.

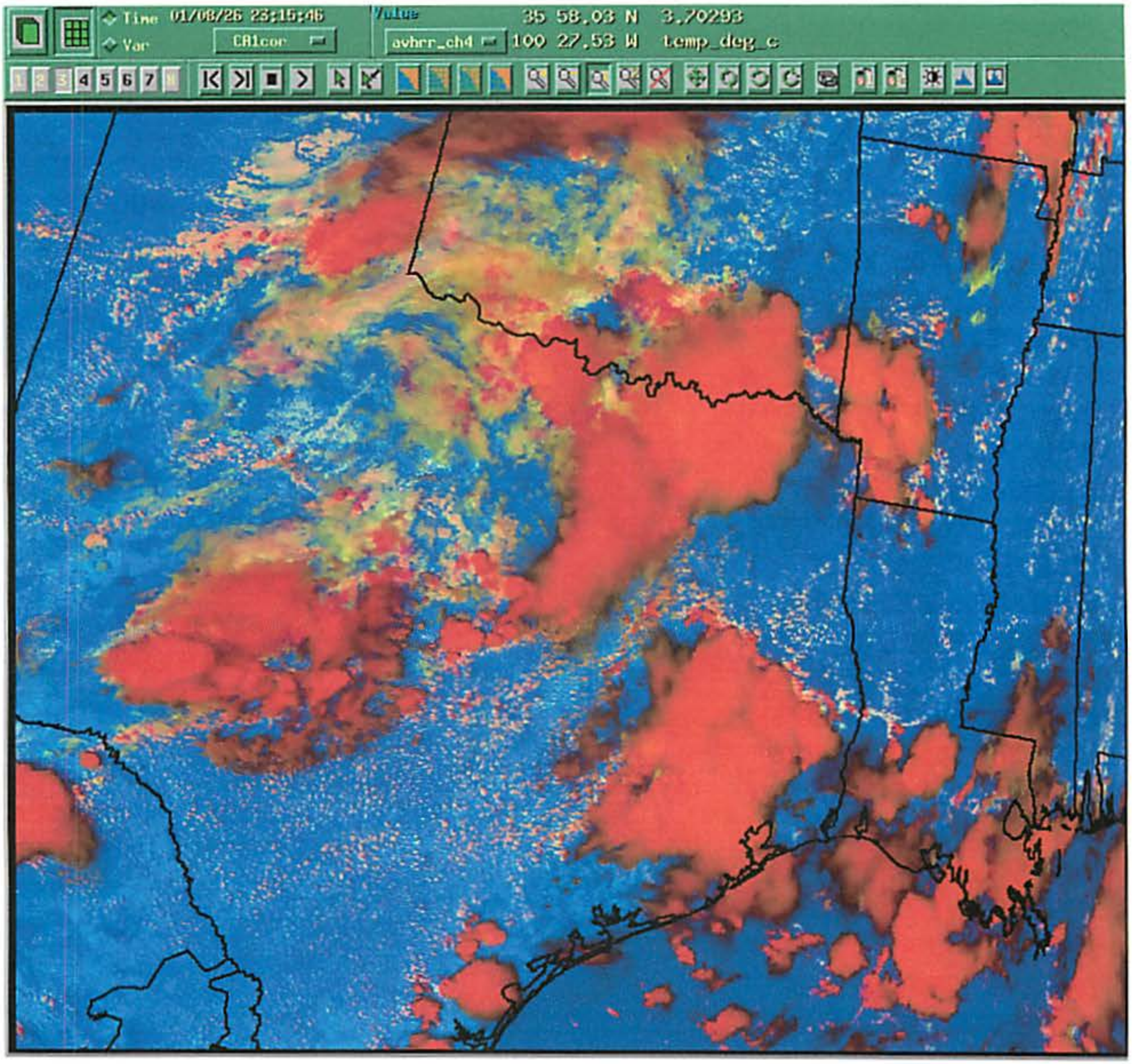

Figure 17. Portion of processed, color-coded, NOAA-16 image at 23:15:46 GMT on August 26, 2001, that shows portions of Texas. A portion of the EA target was covered by active convection and cloud debris from earlier convection when the NOAA-16 satellite passed overhead. The EA gauge network measured an average of 0.59 in. and there were two seeding flights on this day.

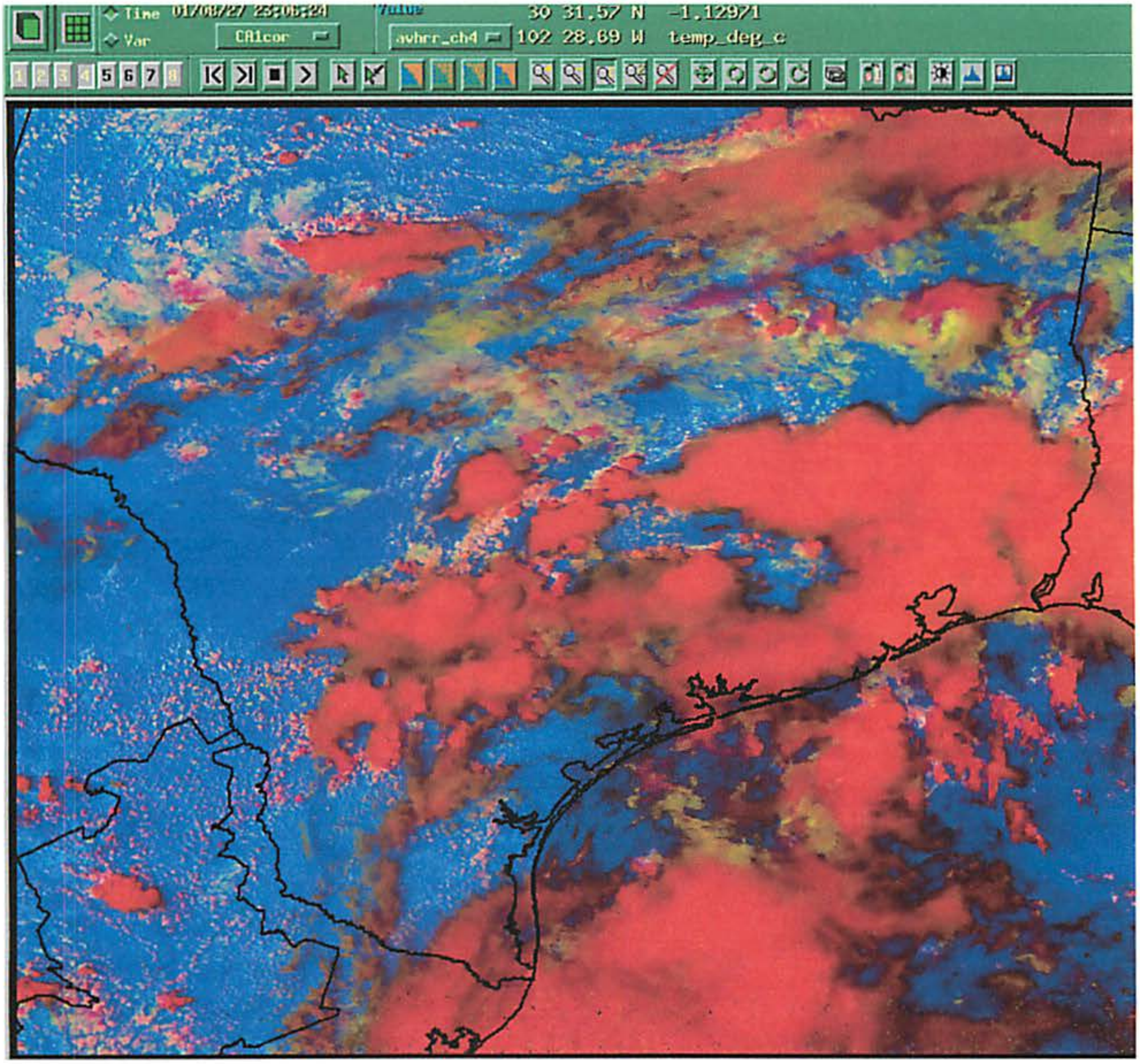

Figure 18. Portion of processed, color-coded, NOAA-16 image at 23:06:24 GMT on August 27, 2001, that shows portions of Texas. Mainly cloud debris exists in the EA target at this time. An average of 1.08 in. of rain was measured in the EA gauge network on this day, which was the largest total measured during the 2001 summer season. There were two seeding flights on this day.

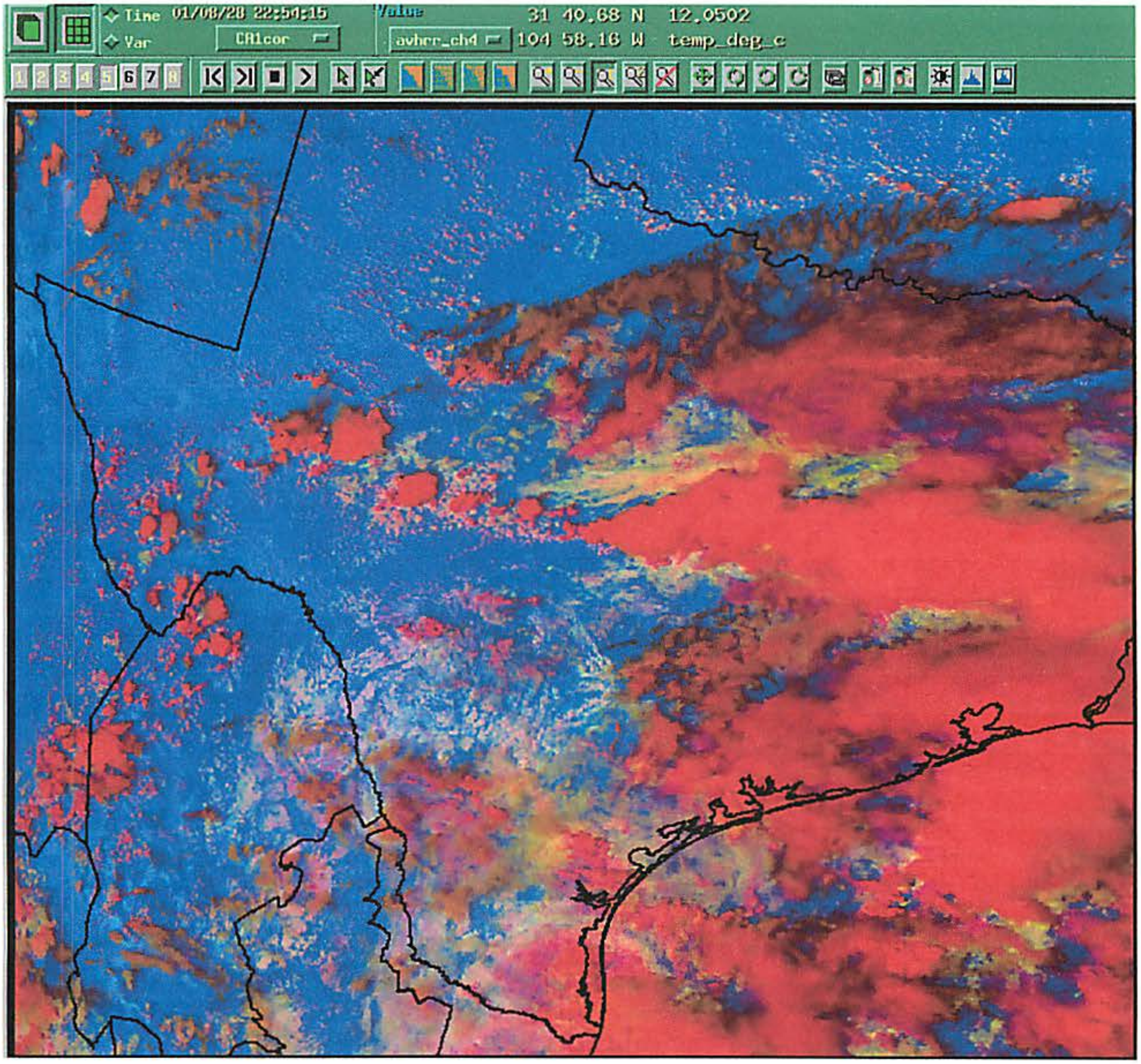

Figure 19. Portion of processed, color-coded, NOAA-16 image at 22:54:15 GMT on August 28, 2001 that shows portions of Texas. Most of the EA target was covered by cloud debris from convection earlier in the day. The EA gauge network measured an average of 0.19 in. and there was one seeding flight on this day.

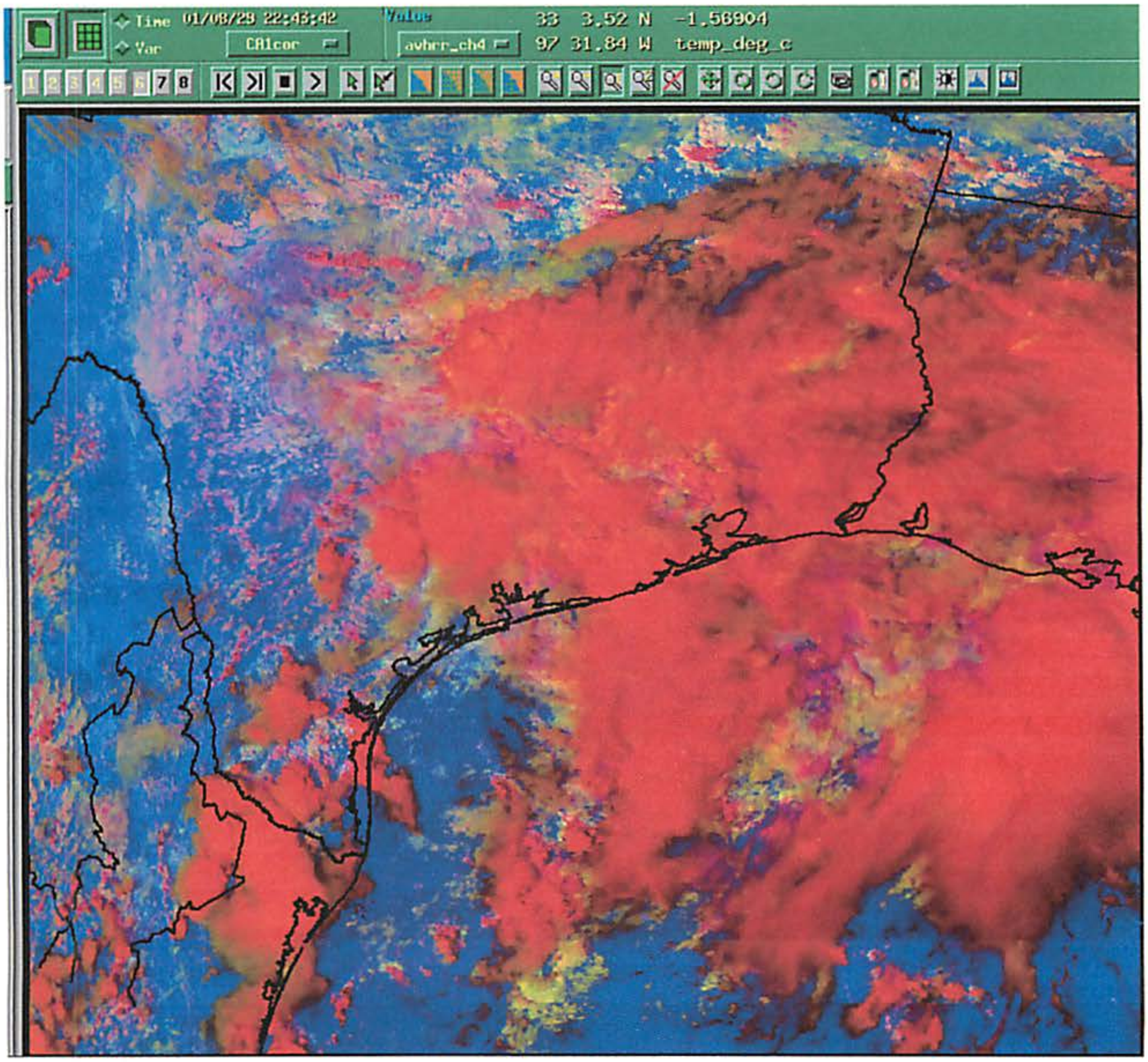

Figure 20. Portion of processed, color-coded, NOAA-16 image at 22:43:22 GMT on August 29, 2001, that shows portions of Texas. Although there is some active convection in the EA target at this time, most of the target was covered by cloud debris from convection earlier in the day. An average of 0.49 in. was measured in the EA target but there was no seeding in the target on this day.

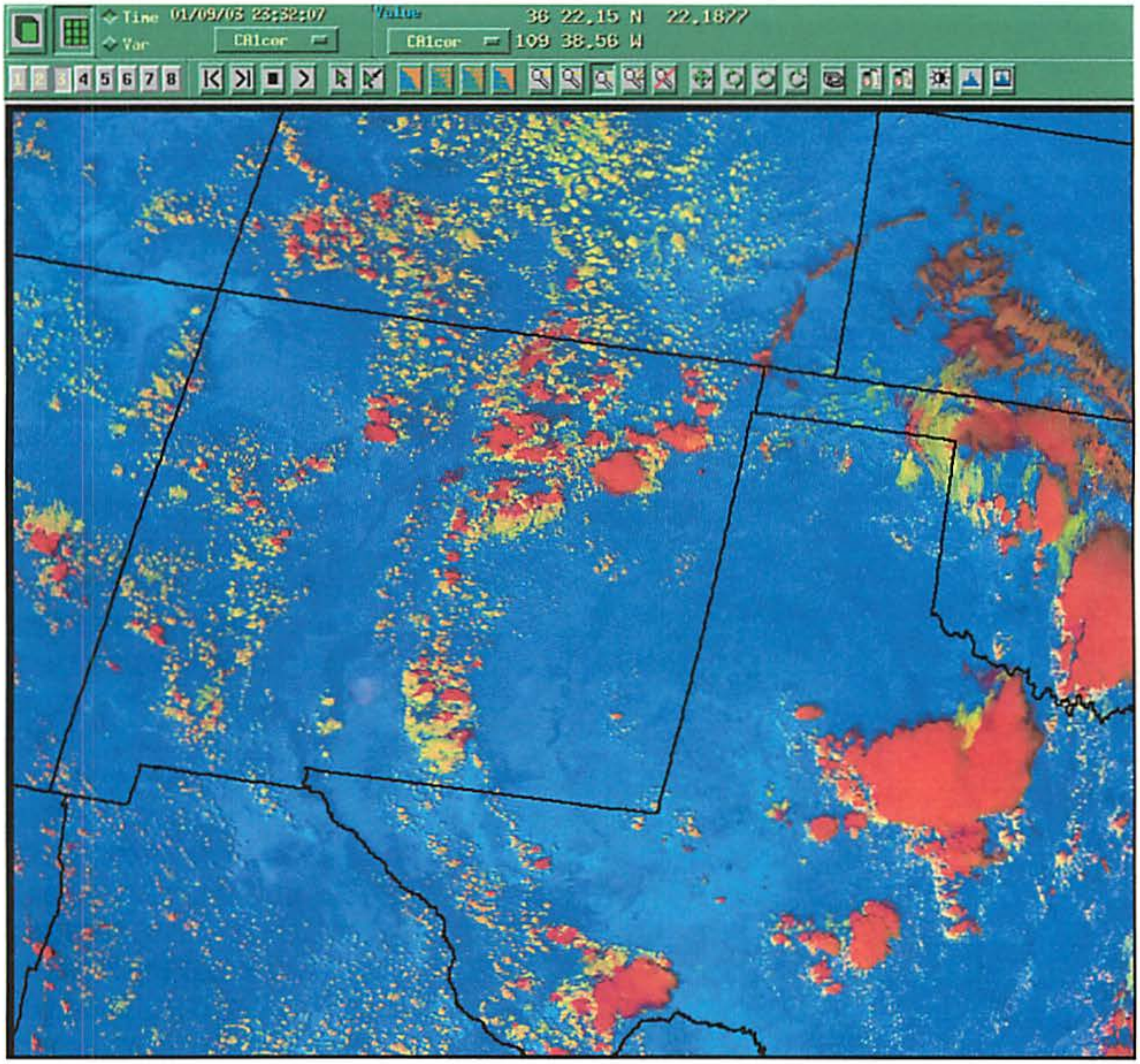

Figure 21. Portion of processed, color-coded, NOAA-16 image at 23:32:07 GMT on September 3, 2001, that shows portions of Texas. Although there was convection and rainfall in the EA target on this day, it could not be seen in this satellite image. Only the widely scattered convection in Central and West Texas can be seen in the image. An average of 0.36 in. fell in the EA target and there was one seeding flight on this day.

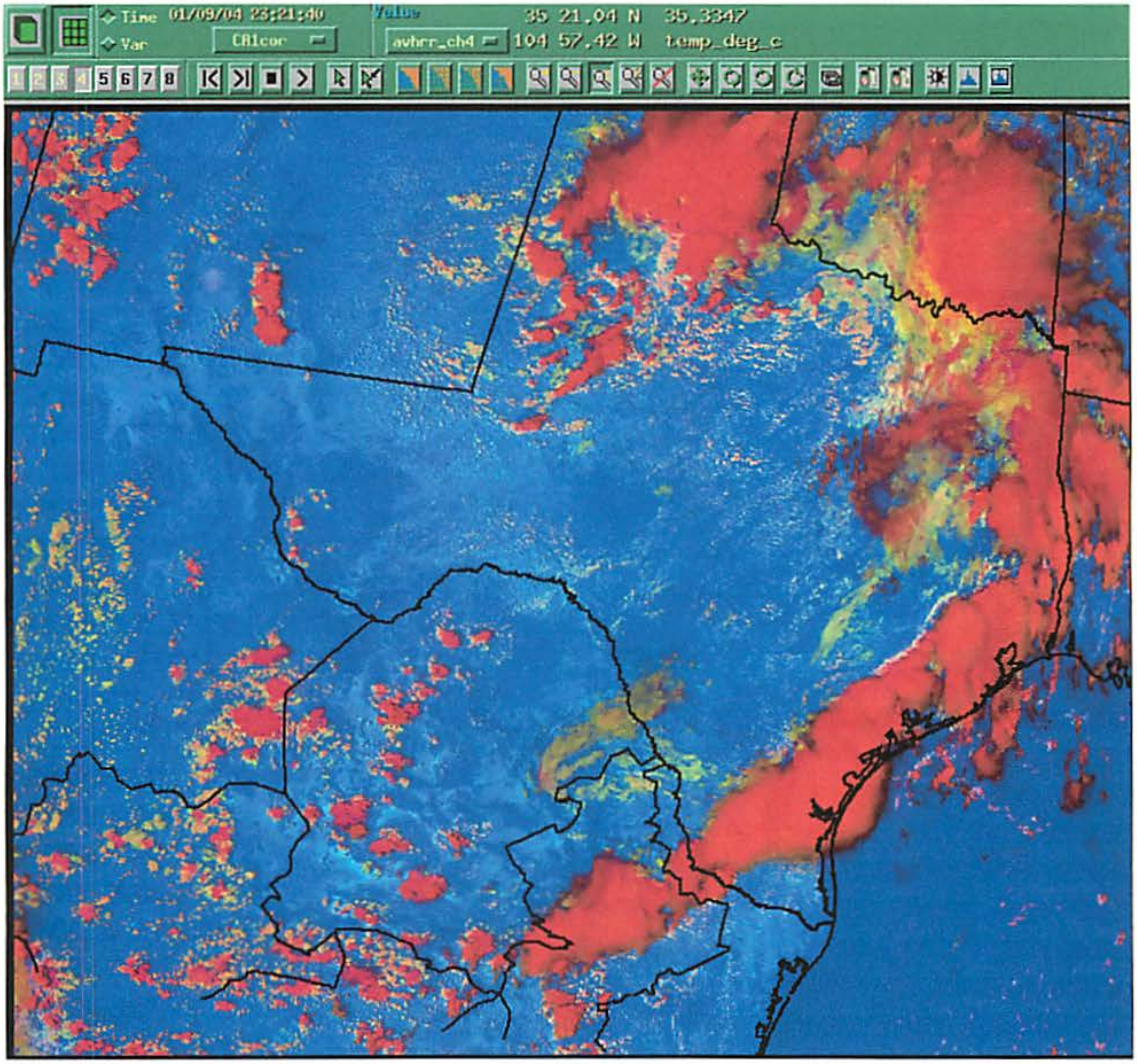

Figure 22. Portion of processed, color-coded, NOAA-16 image at 23:21:40 GMT on September 4, 2001, that shows portions of Texas. The strong line of convection in extreme East Texas along the Gulf Coast had moved through the EA target earlier in the day with an average of 0.14 in. measured in the gauge network. There were two seeding flights in the EA target on this day.

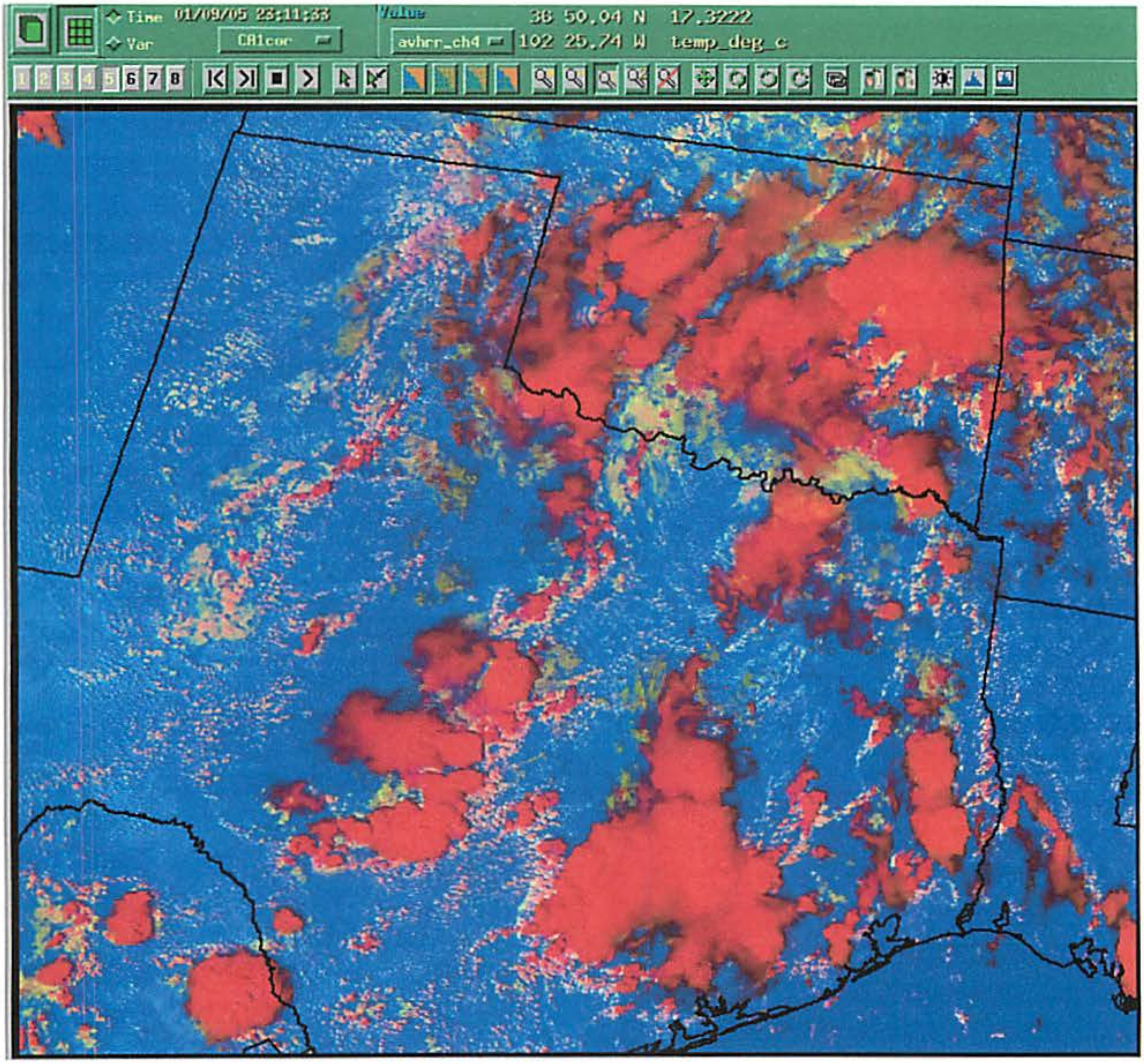

Figure 23. Portion of processed, color-coded, NOAA-16 image at 23:11:33 GMT on September 5, 2001, that shows portions of Texas. Strong active convection can be seen in and around the EA target at this time. An average of 1.02 in. was measured in the EA gauge network on this day. This was the second largest total (after August 27th) during the 2001 summer season. Three seeding flights were conducted in the EA target on this day.

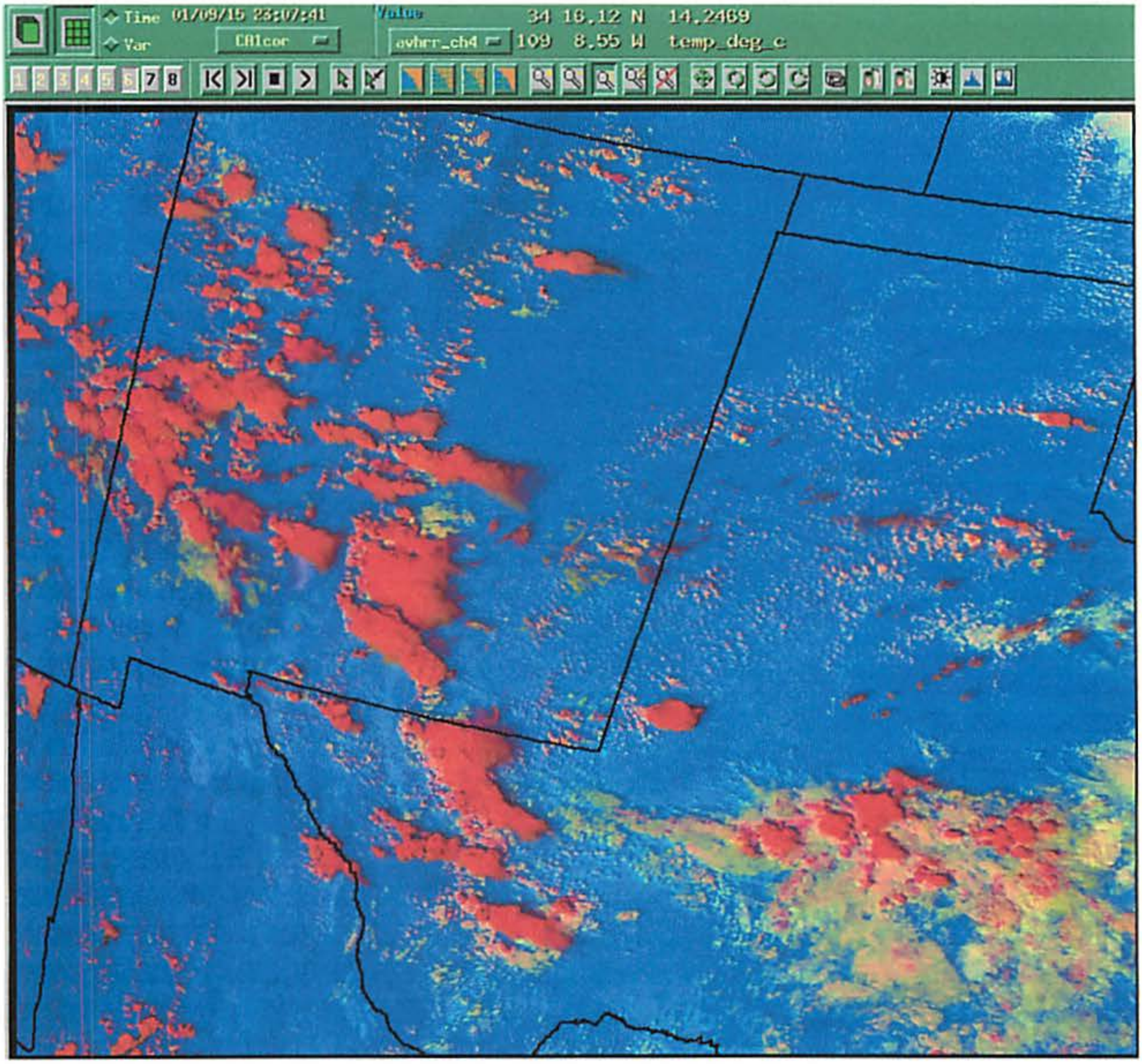

Figure 24. Portion of processed, color-coded, NOAA-16 image at 23:07:41 GMT on September 15, 2001, that shows portions of Texas. Mostly cloud debris can be seen in the EA target in this image. There was no rain in the EA gauge network and no seeding flights in the EA target on this day.

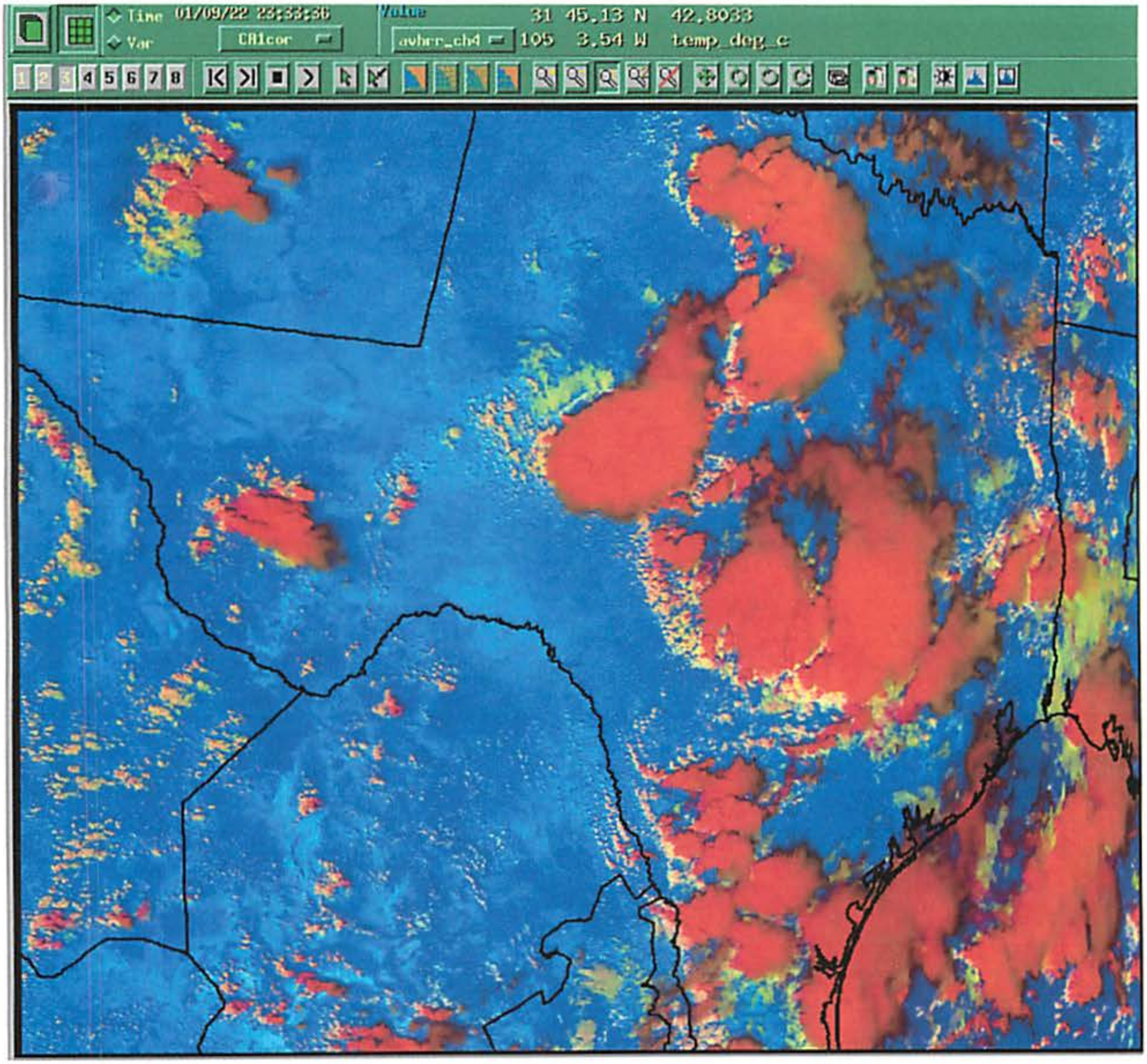

Figure 25. Portion of processed, color-coded, NOAA-16 image at 23:33:36 GMT on September 22, 2001, that shows portions of Texas. Strong convection existed in the EA target at this time. This likely would have been a good day for cloud seeding, but the project had ended as of September 15, 2002. An average of 0.25 in. was measured in the EA gauge network on this day.

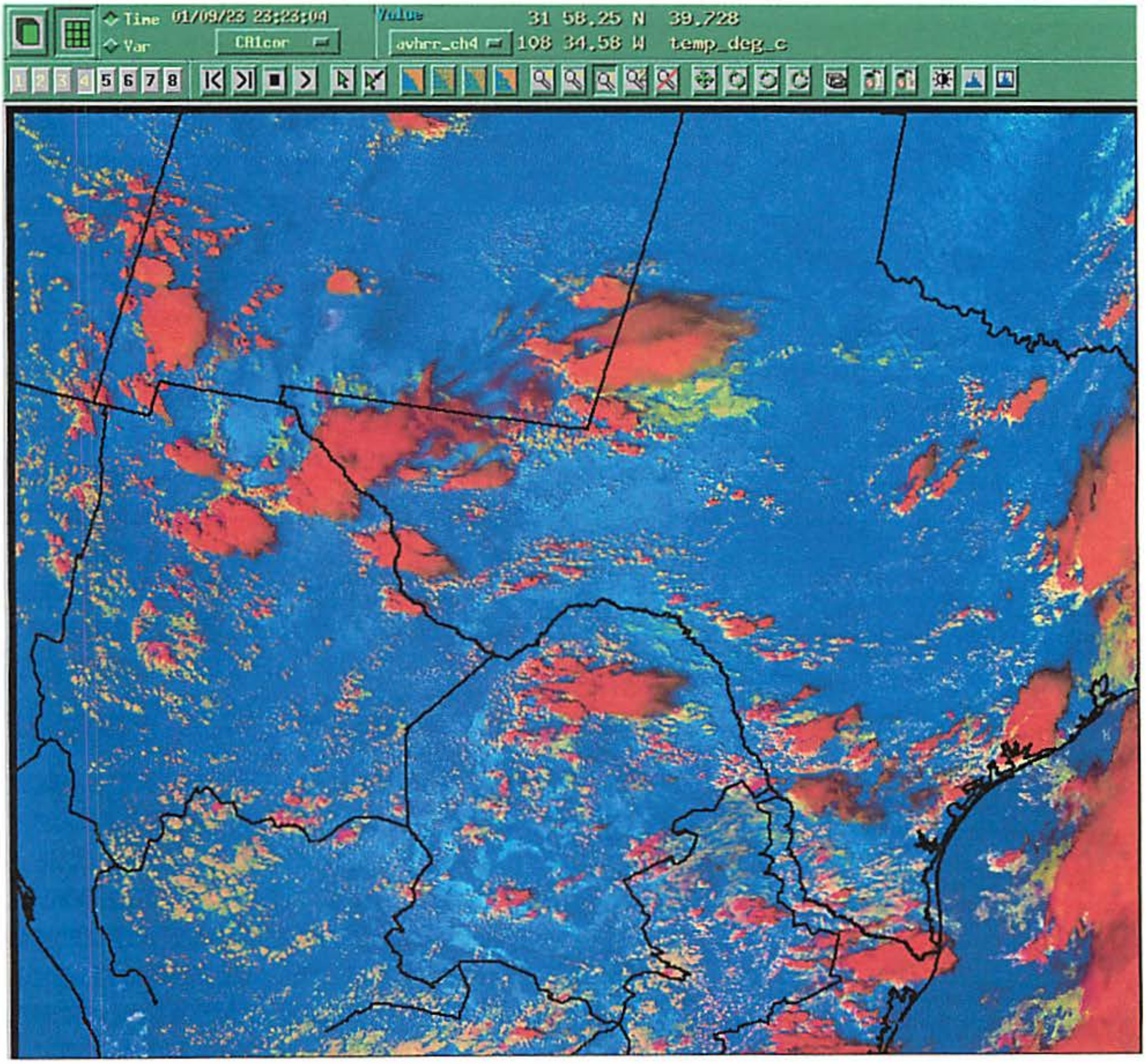

Figure 26. Portion of processed, color-coded, NOAA-16 image at 23:23:04 GMT on September 23, 2001, that shows portions of Texas. Most of the convection was to the south of the EA target on this day. The EAA seeding project had ended, so there were no seeding flights on this day. No rainfall was measured in the EA gauge network.

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Appendix E

THE BASIS AND HISTORY OF CLOUD SEEDING FOR RAIN ENHANCEMENT
(This Appendix is Included for the Benefit of Those Individuals Not Well-Versed in All Aspects of Cloud Seeding for Precipitation Enhancement)

1.0 INTRODUCTION

Since first appearing on earth, human beings have struggled to improve their environment for their welfare and comfort. Most of these have involved small-scale improvements, including the building, lighting, heating and cooling of homes and workplaces. In recent years such efforts have been extended to enormous sports facilities, allowing for the comfortable and protected viewing of sporting events. These efforts will continue as long as there is pleasure and profit to be gained by such changes.

Concurrent with attempts to improve the immediate living environment have been dreams and actions directed at beneficial alterations of the weather. Most have focused on the enhancement of precipitation or the suppression of hail, but they have been directed also at the suppression of lightning and the reduction of hurricane winds. Early attempts to bring about increased precipitation involved explosions and/or the production of smoke to simulate a battle scene, since a body of anecdotal "evidence" had accumulated over the years that heavy rains often followed large battles. There is no objective evidence, however, that such attempts increased the precipitation.

The modern era of weather modification began with the discovery of the ice nucleating properties of dry ice (Schaefer, 1946) and silver iodide (Vonnegut, 1947). The latter was effective as a seeding agent because of the similarity of its crystallographic structure to that of ice. The use of these agents in supercooled stratocumulus clouds produced seeding tracks in the clouds and light precipitation, which was viewed as proof that seeding had affected the clouds. Following these discoveries there was a proliferation of attempts to increase precipitation through cloud seeding, ranging from randomized research experiments to operational cloud seeding programs. These are summarized in Section 3.0 to provide the historical context for the evaluation of the potential of cloud seeding for Texas. It is important first, however, to understand the physics of clouds and precipitation and the physical principles behind attempts at their modification. Some of the information to be presented has been obtained from Grant et al.. (1995), Bruintjes et al.. (2000) and other cited sources.

2.0 AN OVERVIEW OF THE PHYSICS OF CLOUDS AND PRECIPITATION

2.1 Cloud Formation

Clouds form when moist air rises and cools to the point where it can no longer hold the water in vapor form, since the ability of air to hold water decreases as the temperature decreases. At this point the air is saturated, where the temperature and dew point are equal and the relative humidity is 100%. Tiny cloud droplets a few microns in diameter (1 micron is one millionth of a meter) form and grow by condensation on dust and salt particles called cloud condensation nuclei (CCN). The end result is a visible cloud, which will grow further, if the mechanism forcing its growth continues. Under the right conditions the cloud droplets will grow more through collision and coalescence. If the air is cooled to temperatures well below 0°C, the excess moisture in the cloud can be deposited by a sublimation process directly on tiny particles called ice nuclei (IN). The temperature at which these IN nucleate ice is variable, depending on their size and chemical makeup. The nucleated ice particles can then grow by a number of processes, including vapor deposition, riming and aggregation. All processes figure prominently in weather modification theory.

Many mechanisms can cause moist air to rise. It might be a mountain range that stands in the way of a moist current, forcing the air to rise to cross the barrier. Such orographic uplift results in the formation of clouds that shroud the mountaintops and ridges and in the enhancement of the precipitation relative to nearby valley areas. Fronts provide another means of lift, as the moist air glides up and over the more dense cooler air. This is why clouds and precipitation are associated with fronts. Even in the absence of fronts, convergence of air near the earth's surface will cause rising motion, because the converging air cannot penetrate downward into the earth's surface and, therefore, has no alternative but to rise. Dry lines, which are common to the Texas southern high plains in the spring and early summer, are hybrid systems that also produce convergence and rising motion, resulting in clouds and precipitation. Such lines have density contrasts but they are not fronts in the classic sense in that they represent a discontinuity in moisture content and not temperature. Simple heating of the earth's surface also produces rising motions, clouds and precipitation, especially during the summer months when the heating is intense and prolonged.

The stability of the air determines in large part the types of clouds and precipitation that will be produced by the forced rising motions. The atmosphere is said to be stable if a parcel of air returns to its previous equilibrium state after its forced displacement. Stable air moving across a mountain barrier in winter is a good example. Clouds and precipitation are produced by the orographic uplift despite the atmospheric stability. In contrast, air is said to be unstable when displacement of an air parcel results in even more displacement, sometimes through much of the troposphere. Large masses of cumulonimbus clouds and thunderstorms are a manifestation of an unstable atmosphere. Clouds under unstable or conditionally stable conditions produce much of the precipitation in Texas.

2.2 The Development of Cloud Condensates

The total amount of condensate produced in a rising air parcel is a function of the amount of water vapor in it initially, which in turn is a function of its initial temperature. How much of the water vapor is "squeezed out" depends on the depth of the lifting process and its final temperature --- the greater the depth the greater the produced condensate.

The growth of the droplets produced during cloud ascent determines whether the cloud will produce precipitation. If growth continues, the droplets may reach precipitation size before the cloud dies, and precipitation will be produced. If the cloud dies before its condensates can reach precipitation size, the cloud will not precipitate and the condensates will be lost ultimately to evaporation. The percentage of condensed water in a cloud that reaches the ground as precipitation is defined as the cloud's precipitation efficiency (PE) by Grant et al.. (1995). Clouds that produce no precipitation have a PE of 0%. The challenge of cloud seeding is to increase a cloud's PE. If that is not feasible, it may be possible to increase precipitation by increasing the total amount of water vapor processed by the cloud, even though the PE is unchanged. Before getting into cloud seeding concepts and practice, however, it is crucial to understand natural processes.

Clouds of the same size often differ in the amount of rain they produce. This observation is not unique to meteorologists. The observant traveler knows by experience there are regional differences in the rainfall from clouds. Shallow innocuous clouds in the deep tropics often produce brief but torrential rain showers, while more ominous-looking clouds of comparable or greater depth in continental regions may not produce any rain showers. These regional differences in the rainfall from clouds have been quantified using volume-scan radar data to relate cloud echo heights to their volumetric rain production in Florida (Gagin et al.. 1985; 1986) in Israel and South Africa (Rosenfeld and Gagin, 1989), and in Texas (Rosenfeld and Woodley, 1993).

The reasons for the regional differences in the rainfall from clouds are many and varied. A major factor is cloud microstructure, which leads to early precipitation formation in some clouds and no precipitation in others. As discussed earlier, cloud droplets nucleate on cloud condensation nuclei (CCN) and grow by condensation. However, this condensational growth alone is incapable of producing raindrops in clouds. The concentrations of cloud droplets are typically hundreds per cubic centimeter and the competition for the water vapor excess among the droplets is strong. This slows droplet growth, making it impossible for most clouds to develop drops of precipitation size during their lifetimes. Such clouds are colloidally stable and their PE is 0%.

One means for a cloud to overcome its colloidal stability involves direct collision and coalescence among the drops so that successively larger water drops form. This requires the coexistence of a few larger drops with many smaller ones such that their collision and coalescence is favored. The height above cloud base at which droplets finally reach precipitation size depends mainly on the initial drop size distribution (DSD) at cloud base, which in turn is a function of the CCN that are ingested and the cloud-base temperature. Therefore, the efficiency of the conversion of cloud water into precipitation depends strongly on the ingested CCN and on the resultant DSD and its evolution with height in the cloud. This is backed by model simulations, which show a strong link between CCN concentrations and the rainfall from clouds.

Some clouds do not produce precipitation by coalescence of liquid drops. If they extend through the 0°C level, where cloud water can remain in a supercooled state to nearly –38°C (Rosenfeld and Woodley, 2000), precipitation-size particles can be grown through ice processes. After initiation by ice nuclei (IN), tiny ice particles can grow to precipitation size as ice crystals by diffusion of water vapor to the surface of the ice particle or as graupel by collecting the supercooled cloud liquid water.

In many clouds both coalescence and ice processes are operative simultaneously in the production of precipitation. Such clouds are the most precipitation efficient. Raindrops are formed early and low in the cloud and, when they are carried above the freezing level, they freeze earlier than smaller drops and continue their growth as large graupel particles by collecting supercooled cloud droplets as they fall. Further, it also has been shown that, when some larger droplets (24 microns diameter) are present in the cloud in the temperature range from about –3°C to –8°C, ice crystals are multiplied by several orders of magnitude by a splintering process when the drops freeze. This process, which is typical in maritime clouds, can contribute to the formation of precipitation in clouds. Finally, aggregation of ice crystals is another mechanism for the growth of cloud hydrometeors to precipitation size. This process is most typical at cloud temperatures less than –10°C, especially in the thick "anvil" cloud that forms and persists after intense convection.

The net effect of all of these processes is the growth of ice particles to precipitation size, usually as irregular graupel. This graupel melts when it falls below the freezing level and reaches the ground as rain. Which processes predominate on a given day will determine how readily the clouds precipitate.

With the above as background, it is obvious that clouds having large concentrations of small droplets and narrow droplet distributions will precipitate much less efficiently than clouds containing the same amount of water in fewer but larger drops in broad droplet distributions. In such clouds the drops cannot get large enough to grow by coalescence. The most important factors determining the cloud DSD are the updraft velocity at cloud base and on the CCN aerosols on which cloud droplets are formed. A major source of excessive concentrations of small CCN is air pollution, especially smoke from the burning of vegetation (i.e., biomass burning) or from heavy industrial areas. Therefore, clouds forming in a smoke-laden atmosphere usually are composed of numerous small droplets that may cause a reduction in the natural precipitation as shown by Rosenfeld and Lensky (1998). The irony here is that human beings are already altering the precipitation, but the alterations have been inadvertent and in the reverse sense than is .

2.3 Dynamic Factors

Dynamic cloud factors also enter into the precipitation equation. Without favorable dynamics that govern cloud circulations all attempts at rain enhancement will fail. On the other hand, if a cloud lives long enough, it can overcome almost all microphysical inefficiencies and produce precipitation. Doing this requires convective forcing. Clouds growing under mesoscale and/or synoptic forcing will have their lives prolonged and more readily precipitate after seeding than clouds growing in isolation without forcing.

3.0 PRECIPITATION AUGMENTATION CONCEPTS

It should be possible to increase precipitation through cloud seeding, if it is possible to shorten the time necessary for clouds to grow particles of precipitation size or if it is possible to prolong the lifetime of the cloud or both. The unique properties of water in its various forms and its behavior in clouds make both a possibility. These properties and behaviors include the following:

Water, existing in clouds as tiny droplets, does not freeze at the temperature people normally associate with the freezing of water (i.e., 0°C). This is due to a deficiency of natural ice nuclei. More are activated at progressively colder temperatures. In the extreme the cloud droplets may not freeze until they reach –38°C or colder (Rosenfeld and Woodley, 2000) with the freezing taking place homogeneously, that is, without the benefit of ice nuclei. An aircraft flying through such a cloud picks up a coating of ice when it impacts the supercooled drops, which then freeze. Clouds that are already glaciated (i.e., frozen) will not ice up a penetrating aircraft.

The vapor pressure over an ice surface is lower than the vapor pressure over a water surface. Thus, in clouds with a mixture of ice crystals and water drops, the water vapor will move to the ice particles at the expense of the water drops. The ice particles grow as the water drops evaporate.

When water changes phase, heat is either released or taken away from the air parcel containing the water substance. When moist air condenses to form a cloud of water drops, the latent heat of condensation (597.3 calories per gram at 0°C) is given off to the cloudy air. When these drops are carried to colder temperature and then freeze to form ice particles, the latent heat of fusion (79.7 calories per gram at 0°C) is released to the cloudy air. Both transformations warm the cloud and increase its buoyancy, which may promote further cloud development. When the processes are reversed (i.e., melting to water and then evaporation to vapor), the cloudy air is cooled.

Clouds that develop larger drops earlier in their lifetimes precipitate more readily and produce more total rainfall than clouds that are not able to grow such drops. Further, clouds with active coalescence processes that result in early raindrop formation glaciate (i.e., freeze) earlier than clouds without raindrops.

With these facts as background, it is possible to develop precipitation augmentation concepts, which can be tested by randomized physical/statistical experimentation. This process has been underway for many years with varying degrees of success.

3.1 Cloud Seeding to Improve Precipitation Efficiency (PE)

When one understands the physics of natural rainfall involving ice processes as articulated first by Bergeron (1935) and Findeisen (1938), the challenge of augmenting that rainfall becomes conceptually simple. If the formation of ice particles in unseeded supercooled clouds promotes the development of precipitation, why not replicate this natural process by the seeding with an ice nucleant (e.g., silver iodide) in clouds that are unable to develop ice naturally? These seeding-induced ice particles would then grow at the expense of the water drops until large enough to fall from the cloud as precipitation. This is the "classic" seeding concept behind the earliest of seeding experiments and it is the basis of seeding programs around the world even today. This seeding approach was called "static seeding" in early years, because its intent is to improve precipitation efficiency without affecting the dynamics of the cloud system. If a cloud can be viewed as a sponge containing water, the purpose of "static" seeding is to squeeze more water from the sponge.

Calling this seeding approach "static seeding" is a misnomer, because it is not possible to produce the hypothesized microphysical changes in the clouds without changing their dynamics. If "static" seeding initiates and augments rainfall from clouds, their downdrafts are going to be affected. This is a dynamic effect, so "static" seeding affects cloud dynamics. Conversely, "dynamic seeding," which is focused primarily on enhancing rainfall by altering the circulations that sustain the clouds, can only attain its purpose by first producing changes in the cloud microphysical structure.

Seeding to improve the PE of cold clouds can be accomplished from the ground using silver iodide generators and in the air using either generators at cloud base or flares ejected into the cloud tops near –10°C. It is estimated that between 10 and 100 ice crystals per liter are needed to best utilize the cloud condensate for the production of precipitation. Because there is a one-to-one relationship between the number of ice crystals and the number of cloud nuclei in the absence of ice multiplication processes, this is accomplished with modern seeding generators and flares.

Depending on the cloud structure and temperature, the seeding will produce ice crystals and/or graupel in the cloud, which might grow by a number of processes (diffusion of water or accretion of supercooled liquid water or aggregation of ice crystals) to precipitation size. These will then reach the ground in solid or liquid form. Silverman (1986) addresses these seeding concepts in more detail.

In recent years there has been renewed interest in improving the efficiency of warm-cloud collision-coalescence processes through hygroscopic salt seeding. Two salt seeding methods are currently in use. One method applies hundreds of kilograms of salt particles (dry sizes are 10 microns to 30 microns in diameter) above cloud base to produce drizzle-size drops almost immediately (Silverman and Sukarnjanaset, 2000). The second method uses salt flares to disperse one micron or smaller size particles into updrafts near cloud base, a method which is currently receiving renewed interest in cloud seeding efforts (Tzivion et al.., 1994; Mather et al.., 1997; Cooper at al., 1997: Bigg, 1997). The salt material is released from kilogram size flares carried by aircraft; several flares are burned per cloud. The salt particles change the size distribution of the CCN in the updraft, creating a more maritime-type cloud. Coalescence is enhanced and raindrops form in the seeded volume, eventually spreading throughout the cloud. This accelerates the warm-rain process and makes it more efficient. In addition, if the updraft lifts the raindrops into the supercooled region, many of them will freeze and splinter, thereby enhancing the ice processes. This too makes the cloud more precipitation efficient. This method of seeding is thought to work best on continental-type clouds in which natural coalescence is weak or non-existent.

3.2 Cloud Seeding to Promote Cloud Growth

Besides increasing the PE, cloud seeding might also be used to promote the growth of clouds through the release of latent heat (80 calories per gram of water frozen) accompanying the rapid seeding-induced freezing of the supercooled cloud condensate and its subsequent growth as ice particles. This is the approach that has been developed by the senior author of this report for application in Florida, Texas and Thailand. For maximum effectiveness the seeding should be done in vigorous convective clouds having large quantities of supercooled condensate. An example of such a cloud is shown in Figure 1. Model simulations of cloud processes suggest that the seeding might increase cloud temperature by 0.5°C to 1.0°C and result in modest increases in cloud size. The warmed cloud air would then have increased buoyancy, resulting in an invigorated updraft, more cloud growth and potentially additional rainfall. This would occur primarily in an atmosphere that is marginally stable such that the seeding-induced release of heat would promote the subsequent development of the cloud.

Figure 1. Picture of hard vigorous cloud towers at 1818 CDT on June 5, 2001 taken from 17,000 feet from "Cloud 2", the Cessna 340 seeder of the High Plains operational cloud seeding project. The clouds shown were typical on this day.

These hypotheses evolved into a conceptual model that focused initially on the hypothesized dynamic invigoration of the cloud as a consequence of the released latent heats resulting from seeding-induced glaciation. It was argued that as a consequence of this invigoration, the cloud would grow taller and broader, last longer and produce more rainfall. The details of the microphysical processes were not addressed other than to require the seeding to produce more glaciation. It was even speculated that the seeding might decrease the PE in the seeded volume but that the great increase in cloud size and duration would more than compensate for the momentary microphysical inefficiencies. The seeding was viewed as a trigger that would set in motion natural processes that would account for the increased rainfall. This conceptual model became known as the dynamic seeding conceptual model, although the effects of the seeding are not limited to cloud dynamics. In fact, the effects of seeding begin with microphysical changes (i.e., freezing of the condensate, the formation of ice particles, etc.) that ultimately affect cloud dynamics.

During the development of this conceptual model, Simpson (1980) argued persuasively for downdrafts as the mechanism whereby a seeded cell might communicate to the larger scales by generating new clouds and cloud mergers in the convergent regions between storm outflows and the ambient flow.

Early in the Texas experimentation it was argued (Rosenfeld and Woodley, 1993) that the seeding-induced increases in precipitation from cells were larger than could be explained simply by the increase in cell height, as estimated from echo height vs. rain volume relationships. They argued that the seeded clouds must actually be <u>more</u> precipitation-efficient, if the cell rainfall results were to be explained. The finding that seeded clouds of a given echo height produce more rainfall than non-seeded clouds of the same echo height (Rosenfeld and Woodley, 1993) supported their contention. Further, the argument for more microphysically efficient seeded clouds was consistent with Simpson's arguments regarding downdrafts, because more efficient clouds should produce additional rainfall and stronger downdrafts. These interactions culminated in the revised cold-cloud seeding conceptual model (Rosenfeld and Woodley, 1993), which places more emphasis on cloud microphysical processes and their feedback to cloud dynamics than the earlier model (Woodley et al., 1982).

> This conceptual model involved a hypothesized series of events beginning initially on the scale of individual treated clouds or cells and cascading ultimately to the scale of clusters of clouds. This seeding is hypothesized to produce rapid glaciation of the supercooled cloud liquid water content (SLWC) in the updraft by freezing preferentially the largest drops so they can rime the rest of the cloud water into graupel. This seeding-induced graupel is postulated to grow much faster than raindrops of the same mass so that a larger fraction of the cloud water is converted into precipitation before being lost to other processes. Ice multiplication is not viewed as a significant factor until most of the cloud water has been converted into precipitation. This faster conversion of cloud water into ice precipitation enhances the release of latent heat, increases cloud buoyancy, invigorates the updraft, and acts to spur additional cloud growth and/or support the growing ice hydrometeors produced by the seeding (Rosenfeld and Woodley, 1993). These processes result in increased precipitation and stronger downdrafts from the seeded cloud and increased rainfall in the unit overall through downdraft interactions between groups of seeded and non-seeded clouds, which enhance their growth and merger (Rosenfeld and Woodley, 1993). "Secondary seeding," whereby non-seeded clouds ingest ice nuclei and ice crystals produced by earlier seedings, is thought also to play a role in the precipitation enhancements.

A summary of this conceptual model, revised further as of June 1999, is provided in Figure 2 below. Validation of this model using recent observations and modeling is discussed later in this report.

Figure 2

Idealized Cold-Cloud Conceptual Seeding Model

(Revised in June 1999)

Optimum Initial Conditions

1. Vigorous supercooled clouds with some coalescence, growing in close association with other clouds of similar characteristics.
2. Strong solar heating.
3. Little upper cloud.
4. Strong boundary layer forcing
5. Middle and upper troposphere stratified to allow for seeding-induced vertical cloud growth.
6. Weak to moderate wind shear at and above the level of seeding (about $-8^{o}C$)

Seeded Stage I: Initial Response to Seeding

1. On-top seeding with ejectable AgI flares with the number a function of the cloud cross-section (typically an average of five 20-g flares).
2. Rapid glaciation of the supercooled cloud liquid water content (SLWC) in the updraft by freezing preferentially the largest drops so they can rime the rest of the cloud water into graupel (A few large raindrops are necessary for optimum rapid freezing.)
3. The seeding induced graupel grows faster than raindrops of the same mass so that a larger fraction of the SLWC is converted into precipitation before being lost to other processes
4. Ice multiplication is not a factor until most of the SLWC has been converted to precipitation
5. Release of latent heat (fusion and sometimes deposition), increased cloud buoyancy, invigorated updraft
6. Increased cloud growth and/or support of the growing ice hydrometeors produced by the seeding

7. Dynamic entrainment of drier environmental air just below the invigorated rising tower
8. Evaporation and melting of water and ice falling from the invigorated cloud tower into the entrained dry air
9. Accelerated and strengthened downdraft processes as the precipitation mass and evaporatively cooled air moves down through the cloud
10. Increased precipitation beneath the seeded cloud tower

<u>Seeded Stage II: Communication of Seeding Effects within the Seeded Cloud</u>

11. Increased convergence at the interface between the augmented downdraft and the ambient flow, instigating tower ascent fed by the warm most inflow
12. Growth and joining of new cloud towers and expansion of the cloud system, leading to wider protected updrafts, augmented condensation and water content
13. More efficient processing of the ingested water
14. Secondary seeding of new cloud towers with precipitation embryos from originally seeded cloud towers
15. Augmented rainfall from the cloud system

<u>Seeded Stage III: Communication of Seeding Effects to Neighboring Clouds</u>

16. Intensification and expansion of downdrafts from seeded neighboring clouds
17. Growth of new clouds in convergent regions produced by interacting downdrafts, forming a cloud bridge between the parent clouds
18. Merger of the parent clouds resulting (on average) in an order of magnitude more rainfall than would have been produced by the components of the merger had they remained separate
19. Formation of a large cumulonimbus system

<u>Seeded Stage IV: Communication of Seeding Effects to the Entire Unit</u>

20. Propagation and interaction of downdrafts from the seeded cloud systems with non-seeded clouds
21. Increased convergence on the mesoscale, further deepening of the moist layer, continued growth of new clouds which were never seeded
22. Second order mergers (i.e., merger of mergers) producing an additional order of magnitude increase in rainfall

23. Secondary seeding (i.e., ingestion of ice nuclei and/or ice particles from seeded clouds) of non-seeded clouds
24. Formation of a thermally direct mesoscale circulation with rising motion within the cloud system and sinking on its periphery
25. Additional mass and moisture convergence which fuels new cloud development and prolongs the lives of the older cloud systems
26. Enhanced stratiform ("anvil") rainfall
27. Increased unit rainfall

This is a complicated conceptual seeding model, which serves to emphasize the complexity of atmospheric processes and their potential alteration by seeding. Attempts to validate some of the links in the conceptual chain are addressed later in the report.

4.0 LAY PERSON'S GUIDE TO IMPORTANT ISSUES OF RELEVANCE TO CLOUD SEEDING FOR RAIN ENHANCEMENT

4.1 Need for Pre-Experiment Measurements

Seeding experiments begin with a conceptual model of the sequence of meteorological events to be expected after seeding, leading ultimately to increased precipitation. This is followed by a systematic program of measurement using aircraft, radar and satellites to determine whether the clouds in the projected target area have the characteristics assumed by the conceptual model. If the model requires vigorous supercooled convective clouds before seeding, but the results of the pre-experiment measurement program indicate that such clouds are usually glaciated, there would be no point in proceeding with the cloud seeding experiment. In most regions it is usually not an either-or situation. The clouds might be suitable on some days but unsuitable on others. The challenge, therefore, is to identify which situation prevails before seeding begins. Failing that, it is important to determine after-the-fact the conditions prevailing on each day of seeding. Much more will be said about this later in this report.

4.2 Selection of a Design

The pre-experiment measurements are followed by the selection of a design (e.g., crossover, target-control and single target) by which the efficacy of the seeding in increasing precipitation is to be tested. The crossover design involves two targets with a buffer zone between them. On each day of suitable conditions a treatment decision, which specifies which target is to be seeded and which is to be left untreated, is drawn from a randomized sequence. The experiment then proceeds according to the randomized instructions. The evaluation of the crossover experiment is made by forming the double ratio: R1S/R2NS//R1NS/R2S where R1S and R1NS refers to the rainfall (R) in Target 1 when it was seeded (S) and not seeded (NS), respectively, and R2S and R2NS refers to the rainfall (R) in Target 2 when it was seeded (S) and not-seeded (NS), respectively.

The crossover design is the most efficient in that it that it normally allows the experimenters to reach a decision as to the efficacy of seeding in the shortest possible time. It only works, however, if the rainfalls in the two targets are highly correlated (i.e., correlation > 0.70). Two such areas are not possible in Texas since the seeding tests are usually conducted on days with scattered to widely scattered convection. Under such conditions, the correlations of area rainfall amounts are too small for the crossover design.

A second alternative is the target-control experiment. With this design the treatment decision is randomized for the target (i.e., S or NS) and the upwind control is never seeded. The evaluation of the target-control experiment is done by forming the double ratio: RS/CS//RNS/CNS where RS and RNS refer to the target rainfall on S and NS days, respectively, and CS and CNS refer to the rainfall in the control area on S and NS days, respectively. The control area is never seeded. Thus, the control area serves to detect biases on the S and NS days and this mean bias in the form of the ratio CS/CNS is used to correct for what is assumed to be a corresponding bias in the target. Again, the utility of this approach depends on a strong correlation between the rainfall in the target and the rainfall in the upwind control area. Such correlations normally do not exist in convective regimes such as those in Texas. Only when the precipitation is widespread does this approach have any potential.

The third alternative is the single target design for which the treatment decision is randomized (i.e., either S or NS). The single target can be fixed to the earth or it can drift with the wind. The Florida experiments to be discussed later employed a large (1.3×10^4 km^2) fixed target while the Texas and Thai experiments made use of a much smaller floating target (1.964×10^3 km^2). This design is the least efficient, because only one target rainfall measurement is made on each day of experimentation, whereas two are made with the other designs on each day (one for each target with the crossover design and one for the target and one for the control area with the target-control design). Despite its limitations, the single target design is the only one that is possible for convective cloud seeding experiments in Texas.

4.3 Randomization

After the selection of a design the next step is treatment randomization. This is done to avoid the possibility of human bias in the selection of the treatment decision. Further, randomization, if employed for many cases, is useful in minimizing the possibility of natural rainfall bias confounding the interpretation of the experiment. A 50-50 randomization for the S and NS treatment decisions is typical, but it is not a requirement. The randomization can be weighted in favor of a particular treatment decision (e.g., 70-30 in favor of the S decision) if more seeding events are needed. Randomization can also be done within blocks. In the Thai experiment to be discussed later, the randomization was done within two cloud-temperature blocks. The first block was employed on days when the cloud-base temperature was $\leq 16^{o}$C and the second block was used when the cloud-base temperature was $> 16^{o}$C.

Operational cloud seeding efforts are rarely randomized, because the organizations paying for the seeding activity typically do not want to leave any suitable cloud unseeded, so it can be used as a control. This is unfortunate because the evaluation of a seeding effort is extremely difficult without the benefit of randomized controls.

When randomization is employed it is desirable, but not absolutely necessary, to keep the treatment decision from those conducting and evaluating the experiment. This is called the "double-blind" approach that is often used in medical trials. The double-blind approach was used in the Florida experiments, because those sponsoring and supporting the experiments were willing to purchase placebo flares for use on days without actual seeding. The seeder aircraft carried both silver iodide (AgI) and placebo flares in racks affixed to the aircraft, and the randomization determined which rack was to be used. Because the placebo flares sounded just like the actual seeding flares when they left the aircraft, the individual directing the seeding (Woodley) did not know whether he was actually seeding. Further, he did not have the treatment decisions until after he had done the analysis.

In the Texas and Thai experiments, however, no provision was made for the use of placebo flares. Thus, although the selection of an experimental unit was not biased by a fore knowledge of the upcoming treatment decision, one could argue that the conduct of the experiment and its subsequent evaluation could have been biased once the treatment decision was known.

4.4 Types of Experiments

There are several types of experiments. The most powerful and persuasive is one in which the design, conduct and evaluation of the experiment is specified beforehand (i.e., *a priori*, which is Latin for before the fact). Then everything is done according to the *a priori* design and the results of the experiment are evaluated, where a P value of 5% normally is deemed necessary to achieve statistical significance. "P-values" refer to the results of statistical tests where a P-value is the probability that a particular result could have occurred by chance. The lower the P-value the higher the significance of the result and the lower the probability it could have occurred by chance.

If the intent of a particular experiment is to confirm the results obtained by seeding obtained elsewhere in the world, it should attempt to duplicate all that was done in that experiment. Further, it should state what is to be done beforehand. When this is done, the experiment becomes an *a priori* confirmatory experiment. If completed successfully with P values < 0.05, it would be a powerful result.

Experiments whose designs and execution change during the course of the experiment are considered exploratory. Likewise, experiments that achieve P values < 0.05 for analyses of seeding effects not specified in advance of the experimentation are also considered exploratory. Most experiments fall into this category. An exploratory experiment deemed successful on the basis of its P values is still not as powerful and persuasive as the *a priori* experiment. The only way to solidify the results from an exploratory experiment is to confirm them with an *a priori* experiment, either in the same area or in another part of the world.

4.5 Conduct of the Experiment

The biggest problem in the conduct of an experiment is delivering the nucleant to the clouds at the times and places it is needed. If individual clouds are to be seeded and evaluated, the nucleant must be introduced when the cloud is in its active growth phase as shown in Figure 1. If seeding takes place late in the life of the cloud, the hypothesized changes are not likely to take place, not necessarily because the conceptual model is faulty but because the execution of the experiment is flawed. Likewise, if groups of clouds are to be seeded over either a fixed or floating target area, many clouds actually must be seeded in a timely fashion in order to enhance the rainfall over that area. Despite the best of intentions, this is often not achieved, and it is a major obstacle to the success of a seeding experiment. Rainfall cannot be enhanced unless the clouds are seeded at the time and in the manner assumed by the conceptual model that is guiding the experimentation.

A good example of this problem comes from past seeding experiments in mountainous regions using seeding generators placed on the upwind side of the mountains. In some programs some of these generators were placed in the upwind valleys and much of the nucleant was trapped beneath low-level temperature inversions and never found its way to the target clouds. Obviously, no seeding effect is possible under such circumstances.

Even if the nucleant is delivered to the clouds properly, it is always possible that the seeding devices will fail in the clouds. This was the case during a portion of the Thai experiment when it was determined that during the middle portion of the experiment about 45% of the seeding flares failed to ignite after release from the seeder aircraft. This was likely detrimental to the experiment, but quantification of this problem has not been possible. Such problems, which may have occurred also in FACE-2, add to the uncertainty surrounding cloud seeding.

4.6 Estimation of Target Rainfalls

A major challenge in all rain enhancement experiments is the estimation of target rainfalls. The word "estimation" is used rather than "measurement," because there is no way to measure rainfall with absolute accuracy, especially convective rainfall that by its very nature has strong cores and gradients.

Radar is the preferred tool for the estimation of rainfall in cloud seeding experiments. Radars measure a quantity called "reflectivity" (Z) and these reflectivity measurements are converted to rainfall rates using Z-R equations, which depend on the drop sizes in the clouds. If the scanned clouds contain drop sizes that are different from those that went into the derivation of the equation, the radar is going to make errors in estimating the precipitation. Further, if the clouds of interest do not fill the radar beam, their rainfall also will be underestimated.

Such problems are not likely to engender much confidence in the radar estimation of rainfall. Fortunately, the interest in cloud seeding experiments is in the ratio of S to NS rainfalls. Thus, if the radar errors apply equally well to the S and NS clouds, the estimate of seeding effect should be unaffected by the errors. If on the other hand, the radar under or overestimates the rainfall from the S clouds relative to the NS clouds, the apparent seeding effect may be spurious, due not to the seeding but to radar errors.

The possibility that the radar "sees" S and NS clouds differently was investigated during the Florida experiments by measuring the droplet sizes in rainfall from S and NS clouds. No differences in drop sizes were detected (Cunning, 1976). Thus, the radar estimate of seeding effect should still be valid.

The absolute amount of rainfall to be realized from seeding is still in question, however, because of evaporative losses in the drier air beneath the clouds. The only way this can be estimated is through comparison of the radar rainfall estimates with the measurement of rainfall by rain gauges in clusters or small arrays. Such comparisons will allow for adjustment of the radar rainfall estimates everywhere within scan of the radar. With such a system the estimates should be better than those provided by radar or rain gauges alone. This issue is revisited later in this report.

4.7 Evaluation of the Experiment

The evaluation phase of an experiment focuses on the results of the seeding. Even if the conceptual model is valid and even if the seeding was conducted properly, there is still no guarantee of success. Only if the natural rainfall variability can be overcome will it be possible to detect a seeding effect. Even the non-meteorologist understands that natural rainfall is highly variable in space and time and that it can mask an effect of seeding.

In theory, randomization of the treatment decision should take care of the natural rainfall variability. If the experiment goes on long enough, it is theorized that an equal percentage of the naturally wet and dry days will be apportioned randomly to seeding and controls (i.e., not seeded). If so, the mean rainfall differences between the seeded and non-seeded storms should be a measure of the effect of seeding. If this is not so, the mean rainfall differences might be due to the disproportionate random allocation of wet or dry days to either the seeded or not seeded categories.

There are two ways to beat this unwanted outcome. The first is to conduct the experiments for long periods to insure that the allocation of rain events is not biased. The second is to come up with a way to make accurate forecasts of rainfall in the target in the absence of seeding. If this were possible, the evaluation of a seeding experiment would be trivial. One would predict the target rainfall in the absence of seeding and then measure what actually occurred, secure in the knowledge that the difference between measured and predicted rainfall is due to the seeding. Unfortunately, this is not yet possible in the evaluation of seeding experiments, and it explains the continuing uncertainty over the results of cloud seeding.

An ideal experiment is one in which the treatment decision is not known to the individuals conducting and evaluating the experiment. This ideal is rarely achieved, however, because of the complexity and cost involved. Thus, human bias also is a potential problem in the evaluation of cloud seeding experiments, and care must be exercised to avoid it. Independent evaluation of experiments by highly competent but disinterested scientists is another way to minimize the effect of human bias on experiments. Suffice it to say that it is far easier to address this potential problem than it is to address the bias that results from the natural rainfall variability.

5.0 ASSESSMENT OF PRECIPITATION ENHANCEMENT EXPERIMENTS

5.1 Worldwide Overview

The number of worldwide seeding projects for precipitation enhancement and hail suppression since 1950 is in the hundreds. The interest here is in precipitation enhancement projects. Most of these programs have involved operational cloud seeding. Typically, they were evaluated using historical target vs. control relationships. Unfortunately, Gabriel and Petrondas (1983) have shown that reliable conclusions cannot be drawn from comparisons of operational data with historical records, and have demonstrated the biases encountered in trying to do so. Thus, the results of these operational projects were not weighted very heavily in assessing the status of cloud seeding for precipitation enhancement. The focus here is on projects that have employed randomization of the treatment decision. A sampling of such projects around the world is provided in Table 1. Listed from left to right are the project location and its focus. The next three columns give the results and the P-value support for the result for *a priori* projects, for *a priori* confirmatory projects, and for projects deemed exploratory either because they were not designed as *a priori* efforts or because changes in the conduct of the experiments or their evaluation were changed after project commencement. Most projects fit into this last category.

In some cases the evidence is confusing and contradictory. Some projects apparently produced statistically significant precipitation increases; others did not. Some even appeared to have decreased the rainfall despite intentions to the contrary. The clear message here is that cloud seeding for precipitation enhancement is a complex business. In order to avoid unintended consequences, it is crucial that cloud seeding efforts be based on sound physics and that they have good designs and evaluations.

It is beyond the purview of this research effort to provide a worldwide assessment of precipitation enhancement projects other than to draw attention to the more important programs. Such evaluations have been done by distinguished scientific panels in various organizations over the years. Excerpts from the "official" views of the status of weather modification by the American Society of Civil Engineers, the Weather Modification Association, the American Meteorological Society, and the World Meteorological Organization are provided in Appendix A. Although the details differ from assessment to assessment, there is a general consensus that cloud seeding to enhance precipitation works under some conditions and produces no effect or even a negative effect under other conditions. The evidence is strongest for the seeding of individual clouds and weakest for area precipitation. For example, it should be noted that no *a priori* project, involving the seeding of warm season convective clouds over a fixed or floating target area has achieved statistical significance.

The next two subsections take a closer look at the status of the seeding of orographic and convective clouds, respectively. Some of the cited seeding efforts are listed in Table 1. Others are listed for Australia (Smith, 1963), Missouri (Braham, 1996), Arizona (Battan, 1966), Mexico (Betancourt, 1966) and Montana (Super, 1983) without comment. Because the seeding of convective clouds using a dynamic approach is to be employed for rain enhancement in Texas, the results of past experiments making use of this approach receive closer scrutiny than the rest. This is done in Table 2. The venerable Israeli series of cloud seeding experiments are examined in considerable detail in the section dealing with the uncertainty surrounding cloud seeding programs.

5.2 Overview for Orographic Clouds

After the initial experiments in the 1940's by Schaefer and Vonnegut at the General Electric Laboratories under the direction of Nobel Laureate Irving Langmuir there were several weather modification projects that suggested seeding had enhanced the winter snow pack in the mountains of the West (Elliott, 1986). These and subsequent orographic seeding experiments typically involved the release from ground generators or from aircraft of silver iodide nuclei upwind of a mountain barrier into the region of the orographic cloud containing supercooled water. If accomplished successfully, it was expected this would result in the nucleation, growth and fallout of ice crystals before the cloud moved across the barrier and evaporated.

Table 1 Summary of Important Randomized Cloud Seeding Experiments

Project Location	Project Focus	Type of Experiment		
		A priori	*a priori*, confirm	Exploratory
		Result, P value	Result, P value	Result, P value
New South Wales, Australia	Precipitation in Snowy Mountains	None	None	+19%, 0.03
Israel I (crossover)	Rainfall in both targets	+15%, 0.009	None	
Israel II (target-control)	Rainfall in north target	None	None	+13%, 0.028
Israel II (crossover)	Rainfall in both targets	None	-2%, 0.64	
Israel II (target-control N and S)	Rainfall in the N and S targets	None	None	+15%N, 0.17 - 17%S, 0.15
Israel III	Rainfall in both targets	None	-4.5%, 0.64	
Climax I	Rainfall in target	None	None	+52%, 0.03
Climax II	Rainfall in target	None	+9%, 0.02	
Bridger Mountains, Montana	Snow in target	None	None	+15%, 0.02
Veracruz, Mexico	Rain over three targets	None	None	+14%, 0.03
Santa Catalina Mts. Arizona	Rain over target	None	None	-30%, 0.16
Missouri	Rain over target for deep clouds	None	None	-69%, 0.03
Missouri	Rain over target for shallow clouds	None	None	+100%, 0.02

A series of Australian randomized crossover experiments in the 1950's and early 1960's gave promising, but not statistically significant, results after two years. However, after an extension of the effort for four to five years, a steadily decreasing ratio of seeded to unseeded rainfall was indicated (Dennis, 1980). Bowen (1966) hypothesized that this strange result was due to a carry-over effect such that the distinction between seed and no-seed days became obscured after one or two years. To counteract this hypothesized effect a Tasmanian Project, which used control areas that were never seeded, was operated on even numbered years from 1964 to 1970 (Smith et al.., 1971; Smith, 1974). The results were comparatively uniform on each of the seeded years. The evidence of rainfall increases of 15 to 20% during the autumn and winter seasons agreed with the early Australian results, and no detectable increases during the summer season was also in accord with previous Australian results (Dennis, 1980).

The well known randomized snowfall enhancement seeding projects, Climax I (1960-1965) and Climax II (1965-1970), were carried out in the Colorado Rockies near the town of Climax. Areas near the Continental Divide were seeded by silver iodide generators, which were operated high on the western slopes of the Rocky Mountains. One of the most important results of Climax I was the finding that snowfall was increased when the ambient 500 mb temperature was warmer than –25°C and decreased at colder temperatures (Mielke et al.., 1970). For the similar follow up project called Climax II, Mielke et al.. (1971) presented results that essentially confirmed the findings for Climax I. However, reanalyses of the Climax data reported by Rangno and Hobbs (1987; 1993) cast doubt on the original findings regarding the effectiveness of the cloud seeding.

The Colorado River Basin Pilot Project (CRBPP) was another randomized follow up project to the Climax experiments (Cooper and Saunders, 1980: Cooper and Marwitz, 1980). The results of the CRBPP indicated that the best candidate for seeding is the unstable stage of a wintertime storm because this portion of the storm has the highest liquid water content along with portions that have low ice concentrations. Seeding these regions should result in snow increases.

The Sierra Cooperative Pilot Project (SCPP) took a physical approach to cloud seeding experiments by emphasizing physical understanding and the documentation of the chain of events in both natural and artificially-stimulated precipitation processes (Marwitz, 1986). One of the most important results of the project was that shallow widespread wintertime orographic cloud systems, containing long-lasting supercooled cloud liquid water, provided the best potential for precipitation augmentation through cloud seeding operations. These findings were then applied in a seeding project in the upper elevations of the American River Basin with the aim of increasing precipitation and the subsequent runoff.

Research to determine the potential for increased winter season precipitation through cloud seeding has continued in the following projects: 1) the Bridger Range of Montana (Super and Heimbach, 1988), 2) the Arizona Snowpack Augmentation Program (Super et al.., 1989; Bruintjes et al.., 1994), 3) the Australian Winter Storms Experiment (Long and Huggins, 1992) and 4) the Utah-NOAA cooperative weather modification field campaigns (Sassen and Zhao, 1993). All of these projects are consistent in showing that supercooled liquid water exists in at least a portion of their storms and that the supercooled liquid water is concentrated in the low layers of the storms in shallow clouds with warm tops. It has also been determined that a large amount of supercooled liquid water typically passes over the mountain barriers on a seasonal basis. This implies considerable seeding potential, provided a portion of the excess supercooled water could be brought to the surface through cloud seeding.

5.3 Overview for Convective Clouds

A number of experiments focused on warm-season convective clouds followed the initial seeding experiments of the late 1940's. Some focused on rain augmentation by improving the efficiency of the precipitation processes. Others focused on manipulating cloud dynamics by producing rapid glaciation. Still others attempted to document the changes in the clouds produced by the seeding.

In the first category, the Rapid Project in western South Dakota from 1966 to 1969 made use of ground-based and aircraft releases of silver iodide and dry ice in a crossover design to affect cloud microphysical processes, improve precipitation efficiency, and increase the precipitation. This was the first randomized project in the United States to give indications of rainfall increases over a fixed target area by seeding convective clouds on a prespecified class of days. Further similar work in North Dakota did not provide statistically significant results (Dennis et al.., 1975). Previous work in Arizona (Battan and Kassander, 1960) and Missouri (Braham, 1979) failed to produce evidence of rainfall increases, and may have produced net rainfall decreases. The distinctive feature of the Missouri program called "Whitetop" was the release of silver iodide in the boundary layer in the morning before convective clouds had formed. This was apparently not a good seeding strategy.

Experimentation in wintertime convective clouds in Israel since the mid 1960's has indicated net increases in precipitation (Gagin and Neuman, 1974; 1981). Israel 1 was a target-control experiment conducted in the north of Israel, while Israel 2 was designed as both a target-control and a crossover. Israel 1 was statistically significant as was the target-control portion of Israel 2, but the crossover was not. Indications of rainfall increases were noted in the north but no effect or even decreases were indicated in the south target. Israel 3 confirmed the decreases in the south target and all operational seeding was subsequently terminated in this area. Rosenfeld and Farbstein (1992) have postulated that incursions of desert dust during seeding in the south are responsible for the apparent rainfall decreases. Because the desert dust can act as ice nuclei, it is thought that the rainfall decreases from seeding during dust episodes were due to an excess of ice nuclei (i.e., overseeding). Recent criticism of the Israeli experiments by Rangno and Hobbs (1995, 1997) has raised some doubts concerning the analysis and operations.

Experiments on warm-season convective clouds to affect cloud dynamics began with the well-known seeding with 136 kg of powdered dry ice of an individual supercooled convective cloud in Australia (Kraus and Squires (1947). The seeded cloud developed into a large cumulonimbus cloud, producing over 12 mm of rain over a 130-km^2 area. This was followed by a series of experiments on individual convective clouds, beginning over the Caribbean in the 1960's and continuing in Florida, Texas, South Africa, Cuba and Thailand. Most of these experiments were focused on altering cloud dynamics. Many have indicated increases in cloud height and/or increases in rainfall over the Caribbean (Simpson et al.., 1967, Florida (Simpson and Woodley, 1971; Gagin et al.., 1986), Texas (Rosenfeld and Woodley, 1993; Woodley and Rosenfeld, 1996), Cuba (Koloskov et al.., 1996) and Thailand (Woodley et al., 1999).

In addition, renewed interest in hygroscopic seeding of individual convective clouds, aimed at improving their precipitation efficiency by enhancing the coalescence process, has resulted in experiments that have produced positive results. Randomized experiments in South Africa (Mather et al.., 1997) using hygroscopic flares and in Thailand (Silverman and Sukarnjanaset, 1999) using bulk salts have produced statistically significant increases in radar-estimated rainfall from the seeded clouds, ranging from 30% to 60%. Numerical simulation of the growth of the salt particles to precipitation size particles support the field results (Cooper et al.., 1997). Most impressive has been the replication of the South African results in Mexico (Bruintjes et al.., 1998). The method, involving the production of hygroscopic salts from burning flares affixed to the seeder aircraft circling in updrafts at cloud base, has not yet been tested over a large area.

If the seeding of warm-season convective clouds is to prove economically feasible, it must be demonstrated over a large area. This is not a new revelation and experiments over the years have been directed at documenting area effects of seeding. These are addressed in the next section addressing the results of experimentation of most relevance to Texas.

5.4 Results of Relevance to Texas

The current Texas operational cloud seeding program has a long ancestry of experiments. These are discussed in more detail than in the previous section in order to lay the groundwork for the assessment of the potential of cloud seeding as a water management tool for Texas. The current operational seeding programs are employing techniques and concepts that were learned from these research experiments and, therefore, are most relevant to Texas.

The results to be discussed are presented in summary form in Table 2, including all known randomized Texas seeding experimentation. Project location and the parameter of interest in the experiment are noted first. These are followed by columns identifying the type of experiment where column 1 refers to experiments that were conducted according to an "*a priori*" design, 2 refers to *a priori* experiments that were also were attempts to confirm previous findings and 3 refers to experiments that are viewed as exploratory, because the conduct and/or analysis of the experiment differed in some way from what was specified in advance. Within these last three columns are listed the result for the parameter of interest and the corresponding P value.

The randomized cold-cloud seeding experiments, which began over the Caribbean Sea (Simpson et al.., 1967) and were moved to Florida (Simpson and Woodley, 1971) and then to Texas (Rosenfeld and Woodley, 1993), continued in Thailand until scheduled program termination at the end of the 1998 season. The early experiments focused on the response of vigorous, individual, supercooled clouds to on-top seeding with silver iodide (AgI) free-fall rockets and flares. On average the seeded clouds grew about 20% taller (Simpson et al.., 1967; Simpson and Woodley, 1971) as measured by aircraft and produced > 100% more radar-estimated rainfall than comparable non-seeded clouds (Simpson and Woodley, 1971). All results are significant at better than the 5% level.

The next step involved area-wide experimentation in Florida The first Florida Area Cumulus Experiment (FACE-1) was carried out in south Florida from 1970-1976 (Woodley et al.., 1982). It was a single-area, randomized, exploratory experiment to investigate whether seeding convective clouds according to the dynamic-mode seeding concept could enhance precipitation over a substantial area covering 1.3 x 10^4 km^2. Seeding was accomplished from three aircraft dropping pyrotechnic flares of 50-70 g each into the tops of convective towers which satisfied both visual and measurement criteria. The primary response variables were rain-gauge-adjusted, radar-estimates of rainfall in the total target (TT) and in the floating target (FT), the most intensely treated portion of the target. During the course of the experiment a number of important design changes were made, some based on economic necessity and some as a result of new information.

Table 2 Summary of the Results of Experiments of Relevance to Texas (All but the Nelspruit, South African experiment made use of AgI. Dry Ice was used in the South African experiment)

Project Location	Parameter of Interest	Type of Experiment		
		A priori	*a priori*, confirm	Exploratory
		Result, P value	Result, P value	Result, P value
Caribbean	Cloud Height	None	None	+22%, 0.01
Florida 1968	Cloud Height	None	+11,400 ft, 0.005	None
Florida 1968	Cloud Rainfall	None	None	+116%, 0.20
Florida 1970	Cloud Height	None	+6,200 ft, 0.01	None
Florida 1970	Cloud Rainfall	None	+180%, 0.05	None
Florida, 1971-1976 (All Days)	Floating Target Rainfall	+46%, 0.03	None	None
Florida, 1971-1976 (All Days)	Target Rainfall	+29%, 0.05	None	None
Florida, 1971-1976 (B days only)	Floating Target Rainfall	None	None	+49%, 0.01
Florida, 1971-1976 (B days only)	Target Rainfall	None	None	+23%. 0.08
Florida, 1971-1976 (B days only)	Floating Target (linear analysis of covariance)	None	None	+58%, 0.02 (From Woodley et al.., 1982)
Florida, 1971-1976 (B days only)	Total Target (linear analysis of covariance)	None	None	+33%, 0.02 (From Woodley et al.., 1982)
Florida, 1971-1976 (B days only)	Total Target (guided exploratory linear modeling)	None	None	+30 to 45%, ≤ 0.05 (From Flueck et al.., 1986)
Florida, 1978-1980 (All days)	Floating Target Rainfall	None	+21%, 0.30	None
Florida, 1978-1980 (All days)	Total Target Rainfall	None	+3%, 0.45	None
Florida, 1978-1980 (B days only)	Floating Target Rainfall	None	+8%, 0.42	None
Florida, 1978-1980 (B days only)	Target Rainfall	None	+4%, 0.45	None
Florida, 1978-1980	Total Target	None	None	+10 to 15%, > 0.05

(B days only)	(guided exploratory linear modeling)			(From Flueck et al.,, 1986)
Texas, 1986-1994 (intermittent)	Echo Height	None	None	+10%, 0.21
Texas, 1986-1994 (intermittent)	Cell Rainfall	None	None	+163%, 0.01
Texas, 1986-1994 (intermittent)	Target Rainfall	None	None	+45%, 0.16
Nelspruit, South Africa, 1984/1985 to 1986/1987 seasons	Rain mass with height of cloud turrets on flanks of multicellular storms	None	None	+129% and +66% for 0-10 and 10-20 periods, p < 0.05 -57% for 20-30 period, p < 0.05
Nelspruit, South Africa, 1984/1985 to 1986/1987 seasons	Storm rain flux Storm volume Storm area	None	None	+76%, < 0.05 +43%, < 0.05 +43%, < 0.05
Cuba Experiments 1985	Single Cld & Cloud Cluster Heights and Rain Volumes	None	None	Suggested Hgt and Rainfall Increases for Clouds 6-8 km Tall at Treatment
Cuba Experiments, 1986-1990	Cloud Echo Hgts (All Sample)	None	+4%, 0.77	None
Cuba Experiments, 1986-1990	Cloud Rainfall (All Sample)	None	+47%, 0.22	None
Cuba Experiments, 1986-1990	Cloud Echo Hgts (Tops 6.5 to 8 km at seeding)	None	+8%, 0.49	None
Cuba Experiments, 1986-1990	Cloud Rainfall (Tops 6.5 to 8 km at seeding)	None	122%, 0.07	None
Cuba Experiments, 1986-1990	Cloud Cluster Echo Heights	None	+4%, 0.06	None
Cuba Experiments, 1986-1990	Cloud Cluster Rainfall	None	+43%, 0.04	None
Cuba Experiments, 1986-1990	Cloud Cluster Echo Heights (Tops 6.5 to 8 km at seeding)	None	+17%, 0.01	None
Cuba Experiments, 1986-1990	Cloud Cluster Rainfall (Tops 6.5 to 8 km at seeding)	None	+65%, 0.02	None
Thailand, 1994-1998	Cell Echo Height	+5%, 0.21*	None	None
Thailand, 1994-1998	Cell Rainfall	+35%, 0.11*	None	None
Thailand, 1994-1998	Target Rainfall	+91%, 0.08*	None	None
Thailand, 1991-1998 (intermittent)	Cell Echo Height	None	None	+3%, 0.25
Thailand, 1991-1998 (intermittent)	Cell Rainfall	None	None	+37%, 0.07
Thailand, 1991-	Target Rainfall	None	None	+92%, 0.03

1998 (intermittent)				
Thailand, 1991-1998 (intermittent)	Target Rainfall (multiple regression)	None	None	+43% to +73%, 0.14 to 0.06

There were 104 days of experimentation, 53 seed and 51 no seed. Of these, 29 (14 seed and 15 no seed) are so-called A days and 75 (39 seed and 36 no seed) are so-called B days. B days are days on which the clouds received 60 flares or more and, according to Woodley et al. (1982), comprise the data set to which the FACE conceptual model best applies. A days are days on which clouds received less than 60 flares because the flight scientist decided that the target suitability criteria were no longer satisfied. A re-randomization analysis of the B days yielded S/NS ratios of 1.49 with a one-sided P-value of 0.01 and 1.23 with a one-sided P-value of 0.08 for the FT and TT, respectively. For the combined A and B days, the re-randomization analysis yielded S/NS ratios of 1.46 with a one-sided P-value of 0.03 and 1.29 with a one-sided P-value of 0.05 for the FT and TT, respectively. A linear model analysis of the data was carried out in an attempt to take into account some of the natural rainfall variability and this resulted in somewhat larger point estimates of the seeding effect with somewhat stronger P-value support than did the re-randomization analyses.

The next step was an attempt to confirm the results of FACE-1. FACE-2 was carried out during the summers of 1978, 1979 and 1980 (Woodley et al., 1983). Whereas FACE-1 was an exploratory experiment, FACE-2 was designed and conducted as a confirmatory experiment. It attempted to confirm the principal seeding effects observed in FACE-1 in accordance with clarified and sharpened confirmatory specifications provided by Woodley et al. (1982), and to replicate the main analyses of FACE-1. Three levels of confirmation, ordered from weakest to strongest, were specified. Failure to confirm at one level precluded moving on to the next strongest level of confirmation.

FACE-2 failed to confirm the findings of FACE-1 at the first and weakest level of confirmation. FACE-2 also failed to replicate the main analyses of FACE-1. The FACE-2 re-randomization analysis of the B days yielded S/NS ratios of 1.08 with a one-sided P-value of 0.42 and 1.04 with a one-sided P-value of 0.45 for the FT and TT, respectively. The re-randomization analysis of the combined A and B days yielded S/NS ratios of 1.21 with a one-sided P-value of 0.30 and 1.03 with a one-sided P-value of 0.45 for the FT and TT, respectively. The linear model analysis of the data by Flueck et al.. (1986) yielded equally disappointing results with apparent seeding effects on the total target of 10 to 15%. The reason for the different results in the two Florida experiments is unknown.

One is left with perhaps three alternatives in interpreting the FACE-2 result: 1) cloud seeding as practiced in Florida does not work or 2) the sample size at experiment termination was too small and the seeding effect was masked by the natural rainfall variability, or 3) the seeding flares failed to perform as expected. If one accepts the first interpretation, he must be able to explain the results of FACE-1 and the results in Texas, Thailand and Cuba (see Table 2) to be discussed next. If seeding does not work, it ought not to work anywhere under similar conditions. The second interpretation is always a possibility, although the linear model analysis should have accounted for some of this variability. The third interpretation is a possibility since the seeding flares produced by Nuclei Engineering, Inc. were having serious ignition problems during the program as verified by night tests of the flares. Some were seen to eject from the aircraft but failed to ignite. Others ignited after ejection but extinguished a few seconds later. Still others ejected and burned as designed. At one point a night flare test indicated that the problem had been corrected, but that may not have been the case, since the performance of the flares was known to vary from batch-to-batch. Regardless, the program proceeded with the conviction, based on the last night flare test, that the flare problem had been corrected and flare failure has never been mentioned formally as a possible explanation for the results of FACE-2. The offering of such an excuse after-the-fact would have been greeted as a "lame" attempt to explain away the "failure" of FACE-2.

By the late 1980's the randomized area experimentation had been moved to Texas where experiments on clustered clouds within a floating experimental unit covering 1,964 km^2 were conducted on an intermittent basis through 1994. The design of the Texas experiments was based on the findings of Matthews (1983) that most of the rainfall in Texas is produced by clustered rather than isolated convective clouds. One seeder aircraft worked this area, which was nearly seven times smaller than the fixed FACE target. The experiments were terminated after the 1994 season due to a lack of funds. At program termination 38 randomized cases had been obtained. The average radar-estimated seed rainfall exceeded the average radar-estimated non-seed rainfall by 45% by 2.5 h after unit qualification. This result is not statistically significant (P value = 0.16, Woodley and Rosenfeld, 1996).

Analyses of the effect of seeding on the treated convective cells were conducted within the context of both the Florida and Texas area experiments. All treated convective cells within a particular experimental unit had the same treatment decision, because the randomization was done on a unit basis. Because of this lack of independence, the cells in a particular unit had to be viewed as a single data point, obtained by averaging the cell properties, for the purposes of statistical testing. Each data point was weighted according to the number of cells contributing to its average in relation to the overall cell sample. Further, the cells in a particular unit were not independent physically of one another. Thus, a cell seeded an hour after seeding commenced in the unit probably was affected in some way by the earlier treated cells. This complicates the interpretation of the cell results.

The initial impetus for these cell analyses was the second Florida Area Cumulus Experiment (FACE-2), which failed to confirm the results of the first experiment (FACE-1; Woodley et al.., 1983). The obvious question at this point was whether an effect of treatment was evident in the cells, which received the actual AgI treatment. Gagin et al.., (1986) did this analysis, finding radar-estimated seeded height and rainfall increases of 22% and 160%, respectively, for cells treated early in their lifetimes with $\geq$ 9 50-g AgI flares with exploratory, one-tailed P-values of 2% and < 1%, respectively. There was no evidence of effects for the entire cell sample, suggesting the overall seeding effect was indeed weaker in the FACE-2 experiment.

The finding that an effect of seeding on the cell scale in FACE-2 was noted only when more than 9 flares were expended tends to support the unverifiable hypothesis discussed above concerning the flares. If the flares were indeed having ignition problems, only with the expenditure of a large number of flares could one be confident that at least some of them burned in the clouds.

Comparable cell analyses were completed in the context of the Texas area experiments with the finding for the overall sample that the radar-estimated seeded cell heights were 10% taller and produced 163% (i.e., SR = S/NS = 2.63) more rainfall than the non-seeded cells at P-values of 21% and 1%, respectively. The apparent seeding effects are larger for clouds having base temperatures > 16°C in which coalescence is active, suggesting clouds with coalescence are more responsive than the overall sample (Woodley and Rosenfeld , 1996).

These results satisfied the requirement that seeding effects must be evident first on the cell scale before one can hope to see seeding effects on an area basis. Considering it is the cells, which receive the treatment, this has seemed a reasonable requirement. How treated cells might communicate any effects to groups of cells and to the unit overall is addressed in the conceptual model.

Simultaneous with the early years of the Texas experimentation was a series of randomized glaciogenic cloud seeding (dry ice) experiments near Nelspruit, South Africa during the 1984/1985 to 1986/1987 seasons (Mather et al.., 1996). The experiments involved the on-top seeding of new cloud turrets growing on the flanks of isolated multicellular storms using dry ice delivered from a Learjet near the height of the –10°C isotherm. All 94 storms meeting the selection criteria were tracked by radar operating in computer-controlled volume-scan mode. Because cloud physics measurements indicated that the effect of seeding would be greatest in clouds having coalescence and raindrops, the main screening criterion involved the ratio of cloud-base temperature (T_{CCL}) to the potential buoyancy (PB) at 500 mb. Clouds growing on days when T_{CCL}/PB > 2.0 constituted the main data partition in which coalescence and positive seeding effects were expected.

The seeding rate in the South African experiments was 1.3 g of dry ice per meter of flight path, giving 3.9 x 10^3 g for a cloud tower having a diameter of 3 km. Since the effectiveness of dry ice has been estimated to be between 10^{12} to 10^{13} ice crystals per gram of dry ice (Cooper et al.., 1982), this hypothetical cloud would have received between of 3.9 x 10^{15} and 3.9 x 10^{16} ice crystals. Current AgI seeding flares produce about 10^{14} ice nuclei per gram of formulation at –10°C. The expenditure of five 20-g flares on a cloud pass would produce about 10^{16} ice nuclei in the cloud at –10°C. Assuming that each ice nucleus produces an ice crystal, the number of ice crystals produced during a typical AgI seeding run is comparable to that produced by dry ice seeding in the randomized South African experiments.

The results are summarized in Table 2. Within the coalescence partition, radar detected a statistically significant increase in the height of the center of the rain mass in the seeded clouds relative to the unseeded storms in the 10-min period after storm selection. This increase persisted into the 10-20-min period. In the 20-30 min period, however, the seeded storms showed a statistically significant decrease of storm mass with height. Simultaneous with this was the appearance of the first increases in rainfall at cloud base, which were apparently caused by an increase in rain rate rather than an increase in storm area. In the 30-40 min period the seeded clouds had 76% more rain flux, 43% more storm volume and 43% more storm area than the unseeded clouds. All results, which are likely the result of static and dynamic effects, have P values $\leq 5\%$.

The recent Thai results are especially relevant to the Texas effort. These randomized, cold-cloud, rain enhancement experiments were carried out during 1991-1998 in the Bhumibol catchment area in northwestern Thailand. These experiments involved exploratory experimentation in 1991 and 1993, which suggested increases in rainfall due to seeding. This was followed by a "demonstration" experiment to determine the potential of on-top AgI seeding for the enhancement of area (over 1,964 km^2) rainfall. It was conducted in accordance with a moving-target design. The treatment units were vigorous supercooled clouds forming within the experimental unit, having a radius of 25 km and centered at the location of the convective cloud that qualified the unit for initial treatment. The unit drifted with the wind as the S-band project radar collected 5-min volume-scan data to be used for the evaluation of cell and unit properties. The criteria for unit qualification and termination and the experimental procedures, involving the ejection of 20-g AgI flares near cloud top, are addressed in the design and summarized herein.

Evaluation of the demonstration experiment until its scheduled termination in 1998, consisting of 62 experimental units (31 S and 31 NS), gave a S (11,519 x 10^3 m^3) to NS (6,021 x 10^3 m^3) ratio of mean rain volumes over the unit lifetimes of 1.91 at a statistical P value of 0.075. The ratio of S (5,333 x 10^3 m^3) to NS (3,516 x 10^3 m^3) median rainfalls is 1.52. Evaluation of the units at 300 minutes after their qualification, which has historical precedent, gave a S (7,930 x 10^3 m^3) to NS (5,348 x 10^3 m^3) ratio of mean unit rainfalls of 1.48 at a P value of 0.123. Thus, the demonstration experiment fell short of statistical significance at a P value of 0.05, regardless of the period of evaluation.

Although the Thai "demonstration" experiment did not reach significance in the time allotted to it, there is much to be gained by exploratory examination of the entire data set (43 S and 42 NS). Beginning on the scale of the individual treated cells, it was found that the ratio of S to NS rain volumes is 1.37 at a P-value of 0.066. The other cell parameters have P-values < 0.05 except for the echo height. These results suggest that seeding increases the rain volume from individual cells by increasing their maximum radar reflectivities, inferred maximum rainfall rates, maximum areas, maximum rain-volume rates, duration, and their clustering and merger with other cells. These results are similar to comparable exploratory cell analyses in Texas.

The mean rain volumes for the unit durations are 10,398.78 x 10^3 m^3 for the S sample and 5,404.19 x 10^3 m^3 for the NS sample, giving a S/NS ratio of 1.92. This result is dominated by six huge S units, whose rain volumes exceed the largest value in the NS sample. Deletion of the wettest S (105,504 x 10^3 m^3) and wettest NS (17,709 x 10^3 m^3) units as a sensitivity test gave a revised S (8,134 x 10^3 m^3) to NS (5,104 x 10^3 m^3) ratio of rain volumes of 1.59 at a P value of 0.040. Normalization of the entire sample to the overall NS mean unit rainfall to account for year effects decreased the apparent effect slightly (1.88) but improved the P value slightly to 0.009.

Linear regression analyses to account for the natural rainfall variability in the experiment suggest a smaller apparent effect of seeding. The ratio of S to NS unit rainfalls after accounting for as much as 29% of the natural rainfall variability ranges between 1.43 and 1.73 at P values of 0.136 and 0.063, respectively. Although the poor correlations between the individual covariate candidates and the unit rainfalls (all < 0.45) suggest that the value of these estimates is problematic, it is still likely that the factor of 1.92 for the seeding effect in Thailand is an overestimate of the real effect, if such could be known.

A major uncertainty in the Thai experiments is whether and how the apparent effects of seeding were propagated in space and time, considering that seeding had ended typically by two hours after unit qualification. Upon tracking echoes that had treated ancestry, it was determined that 43% of the S and 53% of the NS rain production in the units came from echoes having such ancestry. The balance was produced by cells without this direct physical connection. In the case of the S sample, cells with treated ancestry could be tracked to nearly 480 minutes after unit qualification, although their rain production by that time was small relative to the unit total. It was found also that the apparent effects of seeding were propagated beyond the unit boundaries. It is hypothesized, in accordance with the predictions of Simpson (1980), that downdrafts, beginning on the cell scale and propagating through the unit, are the primary mechanism for the propagation of seeding effects in space and time. Analyses of the treated cells, indicating increased rainfall and increased cell clustering and merger, are consistent with this expectation. Secondary seeding, whereby unseeded clouds ingest ice nuclei and ice particles from previously seeded clouds, also has been hypothesized as a likely contributor to the apparent effect of seeding. The direct evidence supporting either hypothesis is presently weak and circumstantial.

The results of experimentation in Cuba, which was conducted concurrent with the Thai cold-cloud experiment, are also quite supportive. These randomized seeding experiments on tropical convective clouds were conducted in the Camaguey area of Cuba from 1985 to 1990 (Koloskov et al., 1996). The purpose of the experiment was to assess the capability of cold-cloud seeding with silver iodide pyrotechnics to augment radar-estimated rainfall from individual convective clouds and convective cell clusters over Cuba.

The Cuba experiment was carried out in two steps. An exploratory experiment was carried out in 1985 in order to determine the type of convective clouds that responded best to seeding. A total of 46 convective clouds, 29 seeded and 17 unseeded, were studied. An analysis of these data indicated that clouds thought to be most suitable for seeding were optically dense growing clouds whose tops had risen to at least the height of 6 - 8 km (cloud top temperatures between -10° and -20°C) and have cloud top diameters between 2 and 5 km. Seeded clouds meeting these criteria appeared to grow taller, live longer and produce more radar-estimated rainfall than their unseeded counterparts.

A confirmatory phase of the experiment was carried out during 1986-1990 on both individual convective clouds and convective cell clusters. A total of 46 individual convective clouds, 24 seeded and 22 unseeded, and a total of 82 convective cell clusters, 42 seeded and 40 unseeded, were obtained. The analysis focused on the effects of seeding on the radar-estimated properties of both the individual convective clouds and cloud clusters including rain volume, maximum echo height, maximum radar reflectivity, maximum echo area, total echo area and duration. A cell short-tracking methodology similar to that of Rosenfeld (1987) was developed to derive the radar-estimated cloud properties. Using the Mann-Whitney 2-sample test, the analysis of the individual convective clouds indicated that the S/NS ratio for radar-estimated rain volume was 1.47 with a P-value of 0.22 and the S/NS ratio for maximum echo height was 1.04 with a P-value of 0.77.

For the subset of the individual convective clouds with tops between 6.5-8.0 km, the S/NS ratio for radar-estimated rain volume was 2.22 with a P-value of 0.07 and the S/NS ratio for maximum echo height was 1.08 with a P-value of 0.49. The analysis of convective cell clusters indicated that the S/NS ratio for radar-estimated rain volume was 1.43 with a P-value of 0.04 and the S/NS ratio for maximum echo height was 1.04 with a P-value of 0.06. For the subset of convective cell clusters with tops between 6.5-8.0 km, the S/NS ratio for radar-estimated rain volume was 1.65 with a P-value of 0.02 and the S/NS ratio for maximum echo height was 1.17 with a P-value of 0.01.

Taken collectively, the results of relevance to Texas over the years would appear to suggest that seeding with an ice nucleant may be useful for enhancing area rainfall. Proof from a single experiment that is the case is still lacking. Despite these uncertainties, operational cloud seeding to increase precipitation has been conducted intermittently over the past 40 years at various locations around the world. The current program in Texas, which now involves ten project sites, is only the latest in a long line of such programs.

6.0 AREAS OF DISAGREEMENT AND UNCERTAINTY

There is considerable dissent concerning the efficacy of seeding with an ice nucleant (i.e., glaciogenic seeding) for the enhancement of rainfall. The underlying theme of some current criticism is that not much worthwhile has been accomplished with glaciogenic seeding in the past 40 years and that research money would be better spent in investigations of the effects of hygroscopic seeding. The results of a hygroscopic Thai experiment (Silverman and Sukarnjanaset, 2000) and the results of an experiment in South Africa (Mather et al.., 1997) and preliminary results of a follow-up experiment in Mexico (Bruintjes, 1999) for the seeding of individual clouds with hygroscopic flares are highly encouraging, but they are no better than the results obtained for the seeding of individual clouds using an ice nucleant.

Their criticism of cold-cloud seeding has been summarized as follows:

"Based on a rigorous examination of the accumulated results of the numerous experimental tests of the static-mode and dynamic-mode seeding concepts conducted over the past 4 decades, it has been found that they have not yet provided either the statistical or physical evidence required to establish their scientific validity. Exploratory, post-hoc analyses of some experiments have suggested possible positive effects of seeding under restricted meteorological conditions, at extended times after seeding and, in general, for reasons not contemplated in the guiding conceptual seeding models; however, these exploratory results have never been confirmed through subsequent experimentation.

If glaciogenic seeding of convective clouds for rain enhancement is to be pursued further, well-defined physical-statistical tests of the static-mode and dynamic-mode seeding concepts, in accordance with the proof-of-concept criteria, are needed to determine if they are, in fact, scientifically valid. People with water interests at stake who are investing in operational glaciogenic cloud seeding projects for precipitation enhancement should be aware of the inherent risks of applying an unproven cloud *seeding technology and provide a means for evaluation in order to assess the scientific integrity and effectiveness of the operational seeding projects (Silverman, 2001)."*

Some of the pessimism expressed in the statement above is due to challenges to two apparently successful "static mode" seeding experiments. The most venerable is the series of Israeli experiments. Some scientists have become disillusioned by these challenges.

6.1 Uncertainty over the Israeli Experiments

The Israel-1 cloud seeding experiment (Gagin and Neumann, 1974) was conducted during the period 1961-1967. It was designed as a randomized crossover experiment with North and Center target areas separated by a buffer zone. Each day was randomly allocated for seeding in either the North or Center target area with the non-seeded area acting as control for the seeded area. Seeding was accomplished by dispersing silver iodide smoke from an airplane at cloud-base level, parallel to the coastline upwind of the randomly selected target area. The Root-Double-Ratio (RDR) was designated as the test statistic in evaluating the experiment (Gabriel, 1999b). The evaluation yielded an RDR of 1.15, i.e., a rain enhancement of 15%, with a one-sided P-value of 0.009 for the combined targets. It was found through exploratory analysis that the rain increase peaked in the interior part of the targets located 25-50 km downwind of the seeding line, yielding a suggested rain increase of 22% for the combined targets with a one-sided P-value of 0.002. Exploratory analyses of the North and Center targets separately were also conducted (Neumann and Shimbursky, 1972; Gagin and Neumann, 1974). The single area ratio (SAR) for the North and Center target areas were 1.15 and 1.16, respectively, with associated P-values of about 0.16 for both target areas.

The Israel-2 cloud seeding experiment (Gagin and Neumann, 1981) was conducted during the period 1969-1975 as a randomized crossover experiment with North and South target areas separated by a buffer zone. The Center target in Israel-1 was extended far to the south to form the South target for Israel-2, nearly doubling its area. As in the Israel-1 experiment, each day was randomly allocated for seeding in either the North or South target area with the non-seeded area acting as control for the seeded area.

Gagin and Neumann (1981) stated that the Israel-1 experiment was based on several working hypotheses and its exploratory results formed the basis of the "confirmatory" Israel-2 experiment. They reported that the primary purpose of Israel-2 was to enhance rainfall through seeding in the Lake Kinneret catchment area that serves as the principal reservoir of the Israel National Water Carrier. Therefore, the seeding line for the North target was shifted inland in an attempt to focus the maximum seeding effect on the catchment area. This created an upwind control area for the North target al.lowing a target-control evaluation of seeding effects on the North target al.one. The seeding line for the South target was on the coastline as before. A network of ground generators was installed in the North and South target areas to supplement the aircraft seeding.

Using the double ratio (DR) statistic (Gabriel, 1999b), Gagin and Neumann (1981) indicated that the rainfall in the North target area was increased by 13% with a P-value of 0.028.

The largest seeding effect was found over the catchment area of Lake Kinneret where the suggested rainfall increase was 18% with a P-value of 0.017.

A third randomized experiment (Israel-3) was launched in 1975 that was designed to evaluate the seeding effect on the South alone. The South target area of Israel-2 became the primary target of Israel-3, excluding its southwest corner that was designated as an upwind control area to facilitate this evaluation. An intermediate analysis was done for 682 experimental days in the period November 1976 to April 1991 (Nirel and Rosenfeld, 1994). Based on a Double Ratio (DR) statistic, a 4.5% decrease in rainfall with a two-sided P-value of 0.42 was indicated; there was no statistical support for a change in rainfall in the South target area.

The Israeli experiments were what is called "black-box" experiments, that is the clouds were seeded with the silver iodide particles and the primary variable measured and analyzed was the precipitation on the ground (Cotton, 1986). The Israeli experiments were based on a general conceptual model that evolved from previous physical studies of clouds and cloud systems in the experimental area, and the experimental results were analyzed for their physical plausibility within stratifications of the experimental data. Gagin (1986) acknowledged that the Israeli approach was risky because of the complexity in making sound physical hypotheses on the basis of circumstantial scientific evidence only; however, he justified its use on the grounds that it required less human and equipment resources, and had the potential of providing quicker answers at a reduced cost under favorable conditions.

According to Gagin (1981) physical plausibility of the results of the Israeli experiments rests on statistical analyses of the rainfall data that confirm the microphysical predictions based on the general conceptual model that evolved from previous field studies. Previous field studies indicated that continental clouds over Israel exhibit high colloidal stability as indicated by the narrowness of the cloud droplet spectra and the apparent inefficiency of the collision-coalescence mechanism at the droplet sizes observed. From these observations, Gagin and Neumann (1974) concluded that ice crystals are essential for the formation of precipitation in these clouds and this, coupled with the absence of ice crystal multiplication mechanisms, formed the basis for cloud seeding with glaciogenic seeding agents in Israel.

Gagin (1981) stated that the most physically significant result of the Israeli experiments was the statistically stratified analyses of the data according to cloud top temperature. The largest seeding effect with the smallest P-value was found in the cloud-top temperature stratification of -15 to -21°C, the temperatures at which seeding should be most effective according to the general conceptual model. For both warmer and colder cloud-top temperature stratifications the magnitudes of the seeding effect decreased and their P-values increased. As additional physical evidence Gagin (1981) stated that known patterns of turbulent diffusion of the seeding material released at cloud base altitudes was sufficient to explain the finding that maximum seeding effect was consistently found 30-50 km downwind of the seeding line. He concluded that these studies, while far from being complete, provide a fair basis for understanding and accepting the statistical results and thus also indicate which criteria should be used to transfer the static-mode seeding technique to other geographical areas.

Gabriel and Rosenfeld (1990) reanalyzed Israel-2 as a randomized crossover (North vs South) experiment, asserting that the experiment was designed and conducted with this in mind.

Indeed, Gagin and Neumann (1974) analyzed the first 2 years of Israel-2 as a randomized crossover experiment. Gabriel and Rosenfeld (1990) used the RDR as the test statistic, as was done for Israel-1, and obtained a 2% decrease in rainfall with a two-sided P-value of 0.64; there was no apparent effect on the rainfall in the combined targets. Applying the crossover RDR analysis to the Lake Kinneret catchment area in the North (which was targeted for maximum effect) and the central area in the South, a 2% decrease in rain with a two-sided P-value of 0.67 was obtained. In an effort to discover if there was a suggestion of seeding effects on the individual targets, especially in light of the results of Israel-1, they conducted a series of exploratory analyses. In particular, they examined the evidence with regard to 3 possible alternative hypotheses: (1) N_0S_0, seeding had no effect on either the North or South target, (2) N_+S_0, there was a positive effect of seeding in the North and no effect in the South, and (3) N_+S_-, there was a positive effect of seeding in the North and a negative effect of seeding in the South. While there was some evidence in support of all 3 hypotheses, they concluded that the weight of the evidence, while not conclusive, tended to favor the third hypothesis, N_+S_-. The single ratio evaluation of the North and South targets separately indicated a 15% increase in rain with a two-sided P-value of 0.23 and a 17% decrease in rain with a two-sided P-value of 0.15, respectively. The single ratio evaluation of the catchment and south central areas separately yielded similar results.

Rosenfeld and Farbstein (1992) sought to explain the ineffectiveness of seeding in the South by proposing a desert-dust hypothesis. They postulated that desert dust, advected from the north African, Sinai and Negev deserts, acting as ice nuclei and/or giant CCN (sulfate-coated desert dust as shown by Levin et al., 1996), seeded the clouds in the South, thereby negating the effect of the silver iodide seeding particles. Studies by Levi and Rosenfeld (1996) and Rosenfeld and Nirel (1996) provide some support for the desert-dust hypothesis. On the other hand, Levin et al. (1997) suggested that seeding was less effective in the South because the effective concentration of silver iodide particles at activation temperatures was much lower than it was in the North. Using a 3-dimensional meso-scale model, they simulated the seeding operation in the Israel experiments and the resulting dispersal of the seeding particles. They found that high concentrations of seeding particles were removed from the atmosphere by downdrafts below the clouds in the South, resulting in seeding particle concentrations at activation temperatures that were about one-third that obtained in the North.

Rangno and Hobbs (1995) challenged both the statistical results of the Israel-1 and Israel-2 experiments, and the appropriateness of the static-mode seeding concept upon which these experiments were based. An examination of the distribution of rainfall in the target areas and buffer zones as well as the areas surrounding them led them to suggest that the results of both Israel-1 and Israel-2 were compromised by a type-I statistical error (that is false positives or "lucky draws"); however, they (Rangno and Hobbs, 1997) did admit that the chances of lucky draws occurring in both experiments were very slim. Citing the results of analyses of the precipitation climatology of Israel and measurements of the microstructure of Israeli clouds by Levin (1992), Rangno and Hobbs (1995, 1997) showed that convective clouds in Israel produce large cloud droplets, precipitation-sized drops, high concentrations of ice crystals, and precipitation at relatively warm cloud-top temperatures, all of which are not consistent with the physical criteria for applying the static-mode seeding concept. Without any concomitant cloud physics measurements taken during the Israeli experiments, it is not possible to determine what fraction of the clouds that were treated was actually conducive for rainfall enhancement by the static-mode seeding concept.

6.2 Uncertainty over the Climax Experiments

As mentioned in section 5.1, the Climax experiments were accepted widely as successful orographic cloud seeding experiments. Climax I (1960-1965) and Climax II (1965-1970), were carried out in the Colorado Rockies near the town of Climax. Areas near the Continental Divide were seeded by silver iodide generators, which were operated high on the western slopes of the Rocky Mountains. One of the most important results of Climax I was the finding that snowfall was increased when the ambient 500 mb temperature was warmer than –25°C and decreased at colder temperatures (Mielke et al.., 1970). For the similar follow up project called Climax II, Mielke et al.. (1971) presented results that essentially confirmed the findings for Climax I. However, reanalyses of the Climax data reported by Rangno and Hobbs (1987; 1993) cast doubt on the original findings regarding the effectiveness of the cloud seeding.

Rangno and Hobbs (1993) made the following points: 1) Cloud seeding had no effect on precipitation in Climax I after the control stations had been chosen halfway through the experiment. 2) Faulty execution of the randomization scheme resulted in a misleading precipitation climatology and a misleading relationship between cloud-top and 500-mb temperatures for the control days. 3) The method of assigning upper-level winds and temperatures to experimental days emphasized widespread, synoptic-scale weather systems with cloud tops far above 500 mb rather than the orographic "blanket" clouds that were sought. 4) Particle trajectory calculations show that it is unlikely that the silver iodide released from the ground could have affected precipitation at Climax in southwest flow, the category for which the greatest seeding effect was reported. These matters have not been resolved.

6.3 Uncertainty over warm-season cloud seeding experiments

Silverman (2001) is critical also of dynamic-model seeding experiments. The concluding section of his assessment states the following:

> "According to the proof-of-concept criteria, numerous investigations of the dynamic-mode seeding concept over the past 35 years have failed to provide either the statistical or physical evidence required to establish its credibility. None of the experiments resulted in a statistically significant increase in rainfall in accordance with its *a priori* design. The first version of the dynamic cold-cloud conceptual model postulated a seeding-induced increase in maximum cloud-top or echo-top height and, indeed, it appeared to occur in the Caribbean and South Florida experiments. The results of the Texas experiment prompted a significant revision to the dynamic cold-cloud seeding conceptual model whereby a seeding-induced increase in the invigoration of the updraft, but not necessarily an increase in the maximum cloud-top or echo-top height, was postulated; however, the postulated invigoration of the updraft has never been verified. Each of the dynamic-mode seeding experiments was based on a stated seeding conceptual model with explicit hypotheses, the testing of which resulted in evaluations based on the *a priori* design that failed to reach statistical significance and numerous exploratory analyses that purported

to show positive seeding effects. In the opinion of this reviewer, the reports of the results of these experiments placed greater (exaggerated) emphasis and meaning on the suggestive-but-iffy rainfall results of the exploratory analyses, which have never been confirmed or replicated in subsequent experiments, than on the disappointing-but-valid evaluations in accordance with their *a priori* designs."

Woodley and Rosenfeld (2001) commented on the Silverman (BAS) assessment, but it had not been published as of November 2001. Excerpts from the concluding section of their Commentary are provided below:

"In our view the BAS assessment of the status of glaciogenic cloud seeding experimentation is unduly pessimistic. Although we agree that dynamic-mode seeding has not yet been proven scientifically, we contend that the collective weight of the evidence gives scientific credibility to dynamic-mode seeding, based on the criteria set forth at the outset. Virtually every entry in his Table 2, providing a summary of the main statistical results of the various dynamic-mode seeding experimentation discussed in his article has a SR (ratio of Seed to Non-Seed measurement) value > 1 with varying levels of P-value support. The probability of this happening by chance is minuscule. Quantification of the apparent seeding effect, requiring the proper form of meta-analysis, is much more difficult. It should be cautioned that the results of such an analysis would pertain to dynamic cloud seeding as a whole and would not necessarily provide statistical evidence for the efficacy of cloud seeding in any particular experiment.

"Likewise, we think BAS is overly critical of the physical evidence accumulated to date in support of dynamic-mode seeding experiments. Although direct physical measurements were not made in the experimental units, a major effort has been made over the years to make measurements of relevance to the "dynamic" seeding experiments. Several of the studies involved the randomized seeding of the physical experimental units. Collectively, these measurements support the conceptual model as articulated by Rosenfeld and Woodley (1993). As such, they provide a measure of scientific credibility for the physical aspects of dynamic-mode seeding."

All versions of the conceptual models guiding on-top glaciogenic seeding experiments also have called for increased vertical growth of the seeded clouds. Statistically significant increases in cloud growth averaging about 20% have been documented for clouds over the Caribbean and Florida (Simpson et al., 1967; Simpson and Woodley, 1971). Clouds seeded in Texas (Woodley and Rosenfeld, 1996) and Thailand, however, have shown much less vertical growth with weak P-value support (see Table 2). These apparently contradictory results have been criticized also by Silverman (2001). Fortunately, there appears to be a plausible physical explanation for the contradictory results.

During the Caribbean and Florida single cloud experimentation the visible cloud tops were measured by flying a B-57 jet aircraft just above the cloud top, even if the cloud were a tall cumulonimbus. In the Texas and Thai experimentation, however, the estimates of cloud top were made using 5-cm and 10-cm radar, respectively, at a reflectivity threshold of 12 dBZ. Thus, the visible cloud tops were measured in the Caribbean and Florida and the echo tops at 12 dBZ were measured in Texas and Thailand. Because echo tops are less than the visible cloud in the absence of sidelobe errors, the actual heights of cloud tops in Texas and Thailand have been underestimated relative to clouds over the Caribbean and Florida.

This would not a problem for the estimate of the effect of seeding on cloud growth, however, as long as the radar "sees" seeded and non-seeded clouds the same way. However, this is not likely the case. Seeding changes the microphysical structure of the clouds, causing glaciation at higher temperatures (Sudikoses et al.., 1998). As such, they resemble natural more maritime clouds (Rosenfeld and Lensky, 1998), which are characterized by early glaciation and fallout of precipitation-sized particles. The reflectivity of these clouds falls off faster with height above the 0°C-isotherm level than more continental clouds (Zipser and Lutz, 1994). Thus, if seeded clouds are made to resemble glaciated natural maritime clouds, it follows the radar is going to underestimate their tops at 12 dBZ more than non-seeded clouds, which do not glaciate until colder temperatures. The seeded clouds may be taller physically than the non-seeded clouds but that cannot be known through the radar measurements. The measurement of cloud tops using aircraft and/or infrared satellite imagery is necessary to resolve this important uncertainty.

6.4 Stringent Criteria for Assessing the Success of Cloud Seeding Experiments

In order to understand the major points of the criticisms, it is necessary to take a closer look at the 1998 AMS Policy Statement on Planned and Inadvertent Weather Modification (AMS, 1998). The relevant portion of that document is quoted (in Italics) here:

"Because the expected effect of cloud seeding is within natural meteorological variability, statistical as well as physical evidence is required to establish the success of any cloud seeding activity. Statistical evidence is most efficiently obtained through a randomized, statistical experiment based on the seeding conceptual model that is conducted and evaluated in accordance with its a priori design, and results in the rejection of the null hypothesis (hypotheses) at an appropriate level of significance and power of detection. The physical plausibility that the effects of seeding suggested by the results of the statistical experiment could have been caused by the seeding intervention i.e., the physical evidence is consistent with the statistical evidence, must then be established through measurements of key links in the chain of physical events associated with the seeding conceptual model. Physical evidence is essential in confirming the validity of the seeding conceptual model, which provides the basis for transferring the cloud seeding methodology to other geographical areas."

To assess whether any glaciogenic seeding experiments have satisfied this policy statement, stringent "proof-of-concept" criteria have been developed, which emphasize the results of randomized statistical experiments conducted and evaluated in accordance with their *a priori* design as the most credible evidence of seeding effects (Gabriel, 1999a). In his application of these "proof-of-concept criteria" Silverman (2001) notes that "when the *a priori* design specifies or implies more than one hypothesis for testing, the statistical level of significance (usually 5%) will be shared equally among the number of hypotheses indicated whether the reported results do so or not." He emphasizes further that failure to reject any null hypothesis does not connote that seeding is ineffective; rather, it simply means that the evidence was insufficient to establish that seeding worked as hypothesized. Conversely, he states that a statistically insignificant result with a test statistic (e.g., S/NS, seed/no-seed ratio) greater than unity is not and should not be interpreted as a positive effect of seeding any more than a S/NS ratio less than unity is not and should not be interpreted as a negative effect of seeding.

Upon using these strict "proof-of-concept" criteria, it is found that no warm-season area seeding experiment in which the design and evaluation were specified in advance (i.e., a priori) has reached statistical significance. This applies to hygroscopic seeding experiments as well, since they have not yet been carried out on an area basis.

Although the strict "proof-of-concept" criteria as applied to "a priori" experiments do not provide proof that seeding increased the area rainfall, much can be learned about the effects of seeding through exploratory analyses of the entire data sets. Virtually all past cloud seeding experiments have engaged in exploratory data analysis (see Table 2) and it is on the results of such analyses that operational cloud seeding programs are based. Most of the results quoted herein have been obtained from exploratory analyses. The reader is cautioned that P-values associated with exploratory analyses cannot be used to reject null hypotheses as is the case for analyses specified *a priori* (Gabriel, 1999a); however, they can be used as an indication of the strength of suggested effects, effects which can only be confirmed through new, *a priori* experiments specifically designed to establish their validity. How small a P-value has to be before an exploratory result is considered strong enough to be taken seriously (as "encouraging" or "promising") is not generally defined but, in view of the problem of multiplicity of analyses, conventional wisdom dictates that it must be smaller than the P-value of 0.05 usually associated with the rejection of a null hypothesis in an *a priori* evaluation.

7.0 REASONS FOR THE UNCERTAINTY SURROUNDING CLOUD SEEDING EXPERIMENTS

Cloud seeding research is inherently an uncertain and controversial undertaking. There are many reasons for this situation. The biggest contributor to the uncertainty is the natural rainfall variability, which can confound the interpretation of the results. It can hide an effect of seeding in the natural rainfall noise or it can conspire to suggest an effect of seeding when in fact none is present. This is especially a problem for projects with small samples. The huge Thai seeded "blockbuster" day discussed in this report is a case in point. If this unit had not been seeded, our conclusions regarding the effect of seeding in Thailand might be different. On the other hand, one has to admit the possibility that seeding may have been partially responsible for the blockbuster nature of this event.

In the utopian world there are two ways to overcome natural rainfall variability. One is to obtain a huge sample such that the effect of seeding, assuming that one is present, is readily detected despite the background noise from the natural rainfall variability. The notion that "things will even out in the long run" is applicable here. The second way to overcome the natural rainfall variability is to use covariates to develop equations that predict the natural target rainfall. This was attempted with limited success in the analysis of the Thai cold-cloud experiment (see next section). If this were possible, departures from the predicted rainfall then could be attributed to the seeding intervention.

Another reason for the uncertainty surrounding cloud seeding experiments has been the lumping together of all seeding events in which the effects of seeding were mixed such that there appears to be no effect of seeding. As will be seen in the next section in a closer look at the results of the Thai experiment, the apparent effect of seeding depends on the cloud microstructure with large apparent effects in one category and no apparent effect in another. It is crucial, therefore, to know how seeding affects the clouds so that the data can be partitioned into analysis categories and seeding effects can be sought within each category. If no effect is evident in the category thought most suitable for seeding, there will be legitimate reason for concern. Under such circumstances, all seeding should stop until the matter is resolved.

Sample size is an obvious contributor to the uncertainty surrounding cloud seeding experiments. Even if the seeding is working as intended, its effect will not be detected unless the experiment runs long enough to make the detection possible. There are statistical procedures to estimate the size of the needed sample, but the estimate is only as good as the estimate of the probable effect of seeding and the quantification of the natural rainfall variability. If the variability is large and the expected effect is small, the needed sample to establish the effect of seeding could be in the hundreds. Neither the Texas nor the Thai experiments, discussed earlier in this report, ran long enough to establish an effect of seeding. The exploratory Thai analyses suggest that another 40 units might have been adequate to establish an effect of seeding on an *a priori* basis. In the case of Texas, an additional 135 cases might have been necessary, if the 45% apparent seeding effect at project termination is the real effect. In both cases, the programs were terminated, not because the seeding was not working, but because of funding considerations. It is unfair, therefore, to characterize them as scientific failures when the problem lay not necessarily with the science but with project planning and administration.

Scientists have also added to the uncertainty by applying new criteria and new insights to old experiments, thereby forcing them to measure up to the modern age. The notion that statistical P-values should be shared among the various hypotheses being tested has caused old results to be re-evaluated downward, thereby diminishing their credibility among some modern scientists. Additionally, they discount physical measurements of relevance to the seeding experiment that have been made separately from the actual seeding experiment. They would require that the measurements be made during the actual randomized experimentation. The logic in this is obvious in that the observations are relevant immediately to the seeding experiment, but practical considerations, especially the availability of funds, often do not permit the needed observations to be made concurrent with the randomized experimentation.

The last and most obvious contributor to the uncertainty surrounding cloud seeding is that there are situations in which it does not produce the intended effect. Cloud seeding is an exceptionally complicated undertaking involving complex cloud and environmental processes that are poorly understood. Upon adding to this the difficulty of conducting the seeding as required to produce the effect, it is easy to understand why many seeding experiments are viewed as failures or at best inconclusive.

8.0 A CLOSER LOOK AT THE THAI EXPERIMENT AND ITS IMPLICATIONS FOR TEXAS

8.1 Overview

The Thai cold-cloud experiment is highly relevant to Texas for several reasons. First, the design and conduct of the randomized experiments in Texas and Thailand are very similar. In fact, the design of the Thai experiment was copied from Texas. Second, the scientists who directed and evaluated both programs are Woodley and Rosenfeld. Third, after accounting for some of the natural rainfall variability in Thailand, the results for Thailand and Texas are similar. Fourth, the conduct of the seeding operations in both Texas and Thailand is similar to what is being done now in some of the operational cloud seeding programs of Texas. Although it is not a perfect match, the Thai experiment is the most relevant of any known experiment to what is being done in Texas.

Because of its relevance to Texas, it is important to take a closer look at the results of the Thai experiment, which are summarized in Table 3 for the experimental units. Moving from left to right in the table are the analysis type, the sample sizes, the mean S and NS unit rain volumes, the ratio of the former to the latter and the P-value significance of the result. The smaller the P value, the more significant is the result. It is emphasized that P-values for exploratory analyses do not have the same weight as P-values for *a priori* analyses. The former should be interpreted as providing the relative strength of the various analyses.

Beginning with the first row, the mean rain volumes for the unit lifetimes are 10,399 x 10^3 m^3 for the S sample and 5,404 x 10^3 m^3 for the NS sample, giving a S/NS ratio of 1.92. This result has a rerandomization P-value of 0.033 (Table 3). This apparent effect is larger than was expected at the outset of the experiment, suggesting that the S days may have been more favored by the natural rainfall variability than the NS days. The ratio of S (5,337 x 10^3 m^3) to NS (3,421 x 10^3 m^3) median rainfalls is 1.56. The ratio of the S (296.2 minutes) to NS (242.2 minutes) unit lifetimes (time from unit qualification to the time echo disappears from the unit) is 1.22 at a P value of 0.014, suggesting that seeding prolongs the unit lifetimes.

The S exploratory sample consists of six huge units, whose rain volumes exceed the largest value in the NS sample. Two of the six exceed the S mean rainfall by two standard deviations and dominate the outcome of the experiment. As mentioned eaerlier, deletion of the wettest S (105,504 x 10^3 m^3) and wettest NS (17,709 x 10^3 m^3) units as a sensitivity test gives a revised S (8,134 x 10^3 m^3) to NS (5,104 x 10^3 m^3) ratio of rain volumes of 1.59 at a P value of 0.040. Thus, with the deletion of the wettest unit from each sample the apparent seeding effect, although considerably smaller, still has a P value < 0.05.

The unit findings were partitioned by the supercooled rainwater (SCR) index and the results are presented also in Table 3. The SCR index was selected to see whether the apparent effect of seeding was affected by the intensity of in-cloud coalescence. Before discussing these results, some background information is in order.

Table 3. Summary of the Thai RVOL (rain volume) Results for the Unit Lifetimes
(RVOL in units of $10^3 m^3$)

Analysis	N_S, N_{NS}	RVOL(S)	RVOL(NS)	S/NS	P Value
All Units	43, 42	10,399	5,404	1.92	0.033
Median Results	43,42	5,337	3,421	1.56	
Unit Durations	43,42	296.2 min	242.2 min	1.22	0.014
All Units w/o wettest S and NS	42,41	8,134	5,104	1.59	0.040
All Units SCR Index					
0%	11, 9	4,857	2,119	2.29 (1.70)	0.052
0 to 9%	11, 10	5,206	2,239	2.32 (1.72)	0.029
10 to 49%	8, 8	24,688	6,675	3.70 (2.74)	0.116
50 to 89%	13, 15	7.806	4,925	1.59 (1.18)	0.171
90 to 100%	11, 9	8,793	7,904	1.11 (0.82)	0.383
100%	3, 5	9,054	7,708	1.17 (0.87)	0.379
All Units with Nrmztn	43, 42	10,157	5,404	1.88	0.009
All Units w/o & w/ Multiple Regression	43,42	10,399 obs 9,067 pred	5,404 obs 6,767 pred	1.92 All 1.34 Bias 1.43 Net	0.033 0.136

N_S and N_{NS} = Seed and No Seed sample sizes.

The cold-cloud conceptual seeding model indicates that the optimal cloud structure for seeding intervention is a strong updraft containing low concentrations of raindrops generated from below by coalescence interspersed within high quantities of cloud water. Supercooled clouds without raindrops are not viewed as optimal because glaciation and the growth of graupel to precipitation size proceeds more slowly in such clouds, even with seeding intervention

(Rosenfeld and Woodley, 1993). Conversely, clouds low in cloud water and laden with raindrops are not optimal either because such clouds usually glaciate at -10°C or even warmer through natural droplet freezing and ice multiplication, resulting in the early formation of precipitation.

Rosenfeld and Woodley (2001) have investigated the importance of coalescence in the production of rainfall from Thai convective rain cells. The radar estimates of the properties of non-seeded cells were partitioned using in-situ observations of detectable raindrops on the windshield of the project AeroCommander seeder aircraft as it penetrated the updrafts of growing convective towers, 200 - 600 m below their tops at about the –8°C level (about 6.5 km MSL). Cells observed to contain detectable raindrops during these aircraft penetrations were found to have smaller first-echo depths than cells without observed raindrops when growing through the aircraft penetration level. This faster formation of raindrops is attributed to a rapid onset of coalescence in the convective cells.

It was noted that convective cells exhibiting a rapid onset of coalescence produced over a factor of two more rainfall than cells in which the onset of coalescence was slower (no detectable raindrops when growing through the aircraft penetration level). These findings highlight the important role that coalescence plays in the production of rain from clouds.

These results were extended to the evaluation of the seeding experiments. On each day of unit qualification the percentage of cloud passes on which raindrops were observed to impact the aircraft windshield was calculated. A scale of coalescence intensity was developed from the measurements, ranging from 0% of the passes with detectable raindrops (weak coalescence) up to 100% of the cloud passes having detectable raindrops (strong coalescence). Six classes were defined in all (0%, 0% to 9%, 10% to 49%, 50% to 89%, 90% to 100% and 100%). Note that the second and fifth categories overlap with the first and sixth categories, respectively.

Despite the small sample and enormous variability within each partition, the partitioned unit results are very interesting. (The S/NS values in parentheses were obtained after adjusting the results for the natural rainfall biases as discussed later in this report. The largest and most significant apparent effect of seeding is seen on days when the SCR index was < 50%, that is, on days when less than 50% of the cloud passes had detectable raindrops. On days when raindrops were much more prevalent the apparent effect is much smaller without P-value support. Again, the results suggest there is not much point in seeding clouds when they are laden with raindrops.

Because the effect of seeding is strongly dependent on cloud structure, the importance of using AVHRR satellite imagery and the method of Rosenfeld and Lensky (1998) to specify the cloud structure is readily obvious. This was done for Texas during the summers of 1999 and 2000 as a precursor to the estimation of the potential effects of seeding over the State.

Because the sample is dominated by six large units, especially those qualified in 1998, some means should be used to adjust for year effects. One approach is normalization of the unit RVOL values for each year. This involves calculating the ratio of the mean yearly NS rainfall to the mean NS rainfall for all years. This ratio is then applied to all the unit rainfalls for that year. Then, the overall seeding effect is the ratio of normalized S to NS rainfalls.

This scheme accounts for year-to-year differences in rainfall, which might have natural or artificial causes (e.g., radar mis-calibration that survived the clutter re-calibration). Normalization also compensates for a disproportionate draw of a particular treatment decision in a given year that might be overly dry or wet. In so doing, it changes the unit values within each year but preserves the seed vs. no seed relationships and makes it possible for all years to compete on an equal footing. Put colloquially, normalization "levels the playing field."

The normalization analysis, using mean NS rainfalls for the unit lifetimes as the reference (i.e. mean NS unit RVOL = 5,404 x 10^3 m^3) shows 1993, 1995 and 1997 as drier than the overall NS sample mean and 1994, 1996 and 1998 as wetter than the overall NS sample. The normalization factors by year since 1993 are 2.790, 0.675, 1.378, 0.692, 1.554 and 0.774. Only one unit was obtained in 1991 and a normalization factor of 1.0 was used for that unit.

Applying these yearly normalization factors produced mean normalized rain volumes for the unit lifetimes of 10,157 x 10^3 m^3 for the S sample and 5,403 x 10^3 m^3 for the NS sample, giving a ratio of 1.88 at a P value of 0.009.

The radar-estimated rain increment for the duration of the experimental units, regardless of whether one uses normalized or non-normalized data is nearly 5,000 kilotons (i.e., 5 x 10^6 m^3) or 4,050 acre-feet of water per seeded unit. If real, this would represent a substantial impact on water supplies. As mentioned earlier and to be shown in more detail in subsection 8.3, the apparent seeding effect in Thailand probably has been aided by the natural rainfall variability.

8.2 Time Plots of Unit Rainfalls

Plots of mean unit rain volume rate (RVR) and mean cumulative rain volume (RVOL) relative to the time of unit qualification are provided in Figures 3 and 4, respectively. The plots give the S and NS values from two hours prior to unit qualification to 8 hours subsequently. The cumulative RVOL plot (Figure 4) was obtained by integrating forward and backward from the time of unit qualification such that the pretreatment accumulations are shown as negative.

Beginning with the RVR plots (Figure 3), note the S RVR exceeds the NS RVR before treatment with a maximum at –30 minutes. This disparity had diminished greatly by the time of unit qualification. After qualification the NS RVR plot exceeds the S RVR plot early in the treatment period (Figure 3). From 80 minutes after unit qualification onward, however, the S plot exceeds the NS plot out to 480 minutes, reaching a secondary peak at 400 minutes.

Integration of the RVR values with time gave the cumulative RVOL plots shown in Fig. 4. Note there is a pre-qualification bias favoring the S cases. The mean difference in cumulative S and NS rain volumes is only 194 x 10^3 m^3 by 120 minutes before unit qualification. This average difference is less than the rain volume from a typical NS cell, which averages 243 x 10^3 m^3. In the period 0 to 80 minutes the mean cumulative RVOL plots are virtually coincident. After that the lines diverge out to 480 min. By the end of the period of evaluation, the S to NS ratio had increased to a factor of 1.92.

It is obvious from these plots that natural rainfall bias played a role in the Thai experiments, as it does in virtually all experiments having rather small samples. This was the feeling when first determining that the S to NS ratio for the duration of the experimental units is 1.92, which is a very large apparent effect of seeding. The challenge is in accounting for this bias. It is definitely not as simple as forming the double ratio between the post- and pre-qualification single ratios. This would only be valid if the pre- and post-qualification rain volumes are highly correlated. This is not the case. The correlation is only 0.18 for the 30 min immediately prior to unit qualification and 0.23 for the cumulative rain volume in the 120 min before qualification.

An interesting aspect of the time plots is the suggestion that seeding effects persist for several hours after seeding has ceased. This can amount to 6 hours. In that time frame the clouds will have moved well downwind of the initial seeding. In Texas where the echo motion averages 10 to 15 kts, the initial seeded clouds have moved 60 to 90 n.mi. downwind and in many cases well outside the target area. This reality must be considered when estimating the potential impact of cloud seeding in Texas.

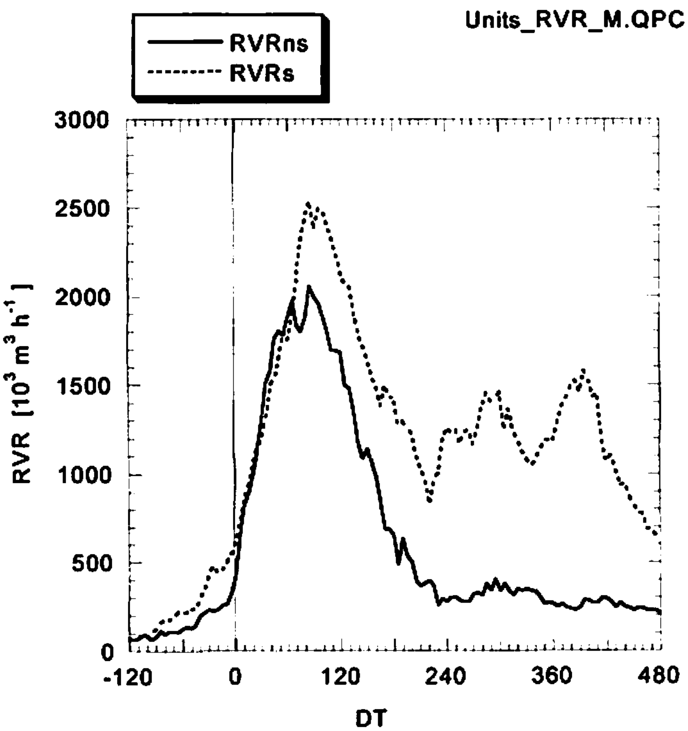

Figure. 3. Plots of S and NS mean RVR values vs. time interval after unit qualification for the cold cloud experimental units obtained in Thailand in the period 1991-1998.

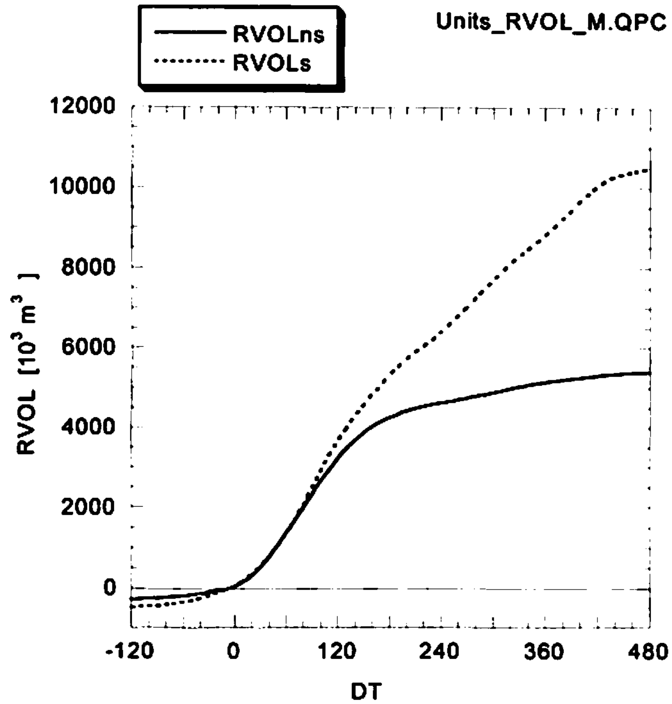

Figure 4. Plots of mean integrated S and NS RVOL values vs. time interval after unit qualification for the cold cloud experimental units obtained in Thailand in the period 1991-1998.

8.3 Attempts to account for the natural rainfall variability

The variability of the natural rainfall in any cloud seeding experiment is always considerably greater than the claimed seeding effect. Using the Thai experiment as an example, the smallest non-seed unit rainfall was 0.02 x 10^6 m^3 whereas the largest was 17.71 x 10^6 m^3. Thus, the largest and smallest unseeded units in the small Thai sample differ by a factor of 886. Such natural rainfall variability is typical of virtually all cloud seeding experiments, and it can "bury" any effect of seeding. That is why all cloud seeding experiments employ randomization for the selection of seeding units. In theory, randomization can mitigate the deleterious effect of natural rainfall variability if the sample is large enough such that very wet and very dry days are allocated equally to the Seed and No Seed samples. In the real world, however, experiments rarely go long enough to negate the effect of the natural rainfall variability, which confounds their interpretation. Statistical procedures are not a panacea for this problem. There is always a finite probability that the randomization favored one treatment category with a disproportionate assignment of naturally wet days. Under such circumstances an effect of seeding might be inferred even though seeding had no effect on the clouds. In statistical parlance this is called a "Type I" error.

If one is to engage in weather modification experiments, there must be two objectives. First, there must be a commitment to conduct the experiments long enough to obtain the needed sample, which can be estimated in advance if the natural rainfall variability is known. Second, there must be major effort to develop good predictive relationships for the natural rainfall. The better the predictive equations the smaller the sample can be. In the perfect world only a small sample might be needed if the predictive equations are perfect predictors. In this eventuality, the evaluation of cloud seeding experiments becomes a trivial exercise. One need only conduct the experiments and compare the results to the predicted rainfall. The disparity between what is observed and what was predicted is the seeding effect. Unfortunately, no experiment to date has been able to cope with the natural rainfall variability so simply.

Woodley and Rosenfeld (2001) addressed this problem through multiple linear regression using covariate variables as input. The best two proved to be the precipitable water (PW) through the depth of the atmospheric column and the mean control cell rainfall, calculated external to the units on each day. (The pre-qualification rainfall biases did not figure significantly in the regressions.) Their correlations with the lifetime unit rainfalls are only 0.363 and 0.458, respectively. Their multiple correlation with the lifetime unit rainfalls is 0.543, which means that these two covariate variables account for only 29% of the rainfall variability.

The results of the regression exercise are summarized also in Table 3. Note that the ratio of predicted S to predicted NS unit rainfalls is 1.34 suggesting that the natural rainfall variability favored the S sample by 34%. Thus, the apparent effect of seeding is the double ratio between the observed apparent seeding effect (1.92) and the natural rainfall bias (1.34). The result is an apparent seeding effect of 1.43 or +43%. This is a conservative estimate of the effect of seeding on the unit scale in Thailand. This is the value that will be used in the studies to make a conservative estimate of the potential impact of cloud seeding in Texas.

It is interesting that the best estimate of seeding effect in Texas that was obtained before termination of the randomized seeding experimentation was 1.45. Thus, the revised, conservative, estimate of seeding effect in Thailand and that in Texas are in good agreement. In addition, the apparent effect of seeding in FACE-1 (Woodley et al.., 1982) for the large floating target was +46% and in Cuba the apparent effect of seeding on the scale of cloud clusters was +43%. Although this general agreement among the estimates of seeding effect does not assure that any of them are correct, it does support the base estimate of seeding effect for areas of about 2,000 km^2 to be used in the study for the TWDB. As will be seen, however, as area size increases the hypothetical increases due to seeding will decrease.

Finally, the estimates of seeding effect as a function of the SCR presented in Table 3 were revised downward by 34% (i.e., division by 1.34), based on the overall regression analysis. These estimates are provided in parentheses by SCR category. These are the conservative values that will be used for the TWDB studies.

8.4 Summary

Careful consideration of the results presented in Task 1 has taught us the following with respect to the seeding of warm season convective clouds:

- The evidence for seeding-induced rainfall increases from individual convective clouds is fairly strong.
- Proof of seeding-induced area rainfall increases does not yet exist.

- Although the evidence for seeding-induced rainfall increases over fixed and floating target areas is weaker, it has been judged strong enough by users of the technology to warrant operational cloud seeding during drought conditions.
- The effects of seeding are variable in space and time, due in part to changes in the cloud microstructure.
- Most experiments probably have produced inconclusive results, because clouds with varying microstructure and, therefore, varying responses to seeding were seeded and grouped together during the analysis phase.
- Future experiments should consider cloud microstructure during the seeding operations and especially during the analyses.
- The assessment of seeding opportunities in Texas must take cloud conditions into account.

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