Evaluation of the Effectiveness of Cloud Seeding in Texas from 2002 through 2006

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ABSTRACT

A method for the objective evaluation of short-term, non-randomized, operational, convective cloud-seeding projects on a floating-target area basis has been developed and tested in the context of the operational cloud seeding projects of Texas. The computer-based method makes use of NEXRAD, 15-min, mosaic, radar data to define fields of circular (25-km radius) floating-target analysis units with lifetimes from first echo to the disappearance of all echoes, and then superimposes the track and seeding actions of the project seeder aircraft onto the unit fields to define seeded (S) and non-seeded (NS) analysis units. Objective criteria are used to identify "control" (C) matches for each of the seed units from the archive of NS units. To minimize potential contamination by seeding no matching is allowed for any control unit if its perimeter came within 25 km of the perimeter of a seed unit during its lifetime.

The methodology was used to evaluate seeding effects in the Texas seeding projects existing in the period April through September in 2002 through 2006. Objective unit matches were selected from within and outside each operational target within 12, 6, and 3h of the time on a given day that seeding of a particular unit took place. These were done to determine whether selection biases and the diurnal convective cycle confounded the results. Matches were also drawn from within and outside each target using the entire archive of days on which seeding was done. Although the results of all analyses are subjected to statistical testing, the resulting P-values are used solely to determine the relative strength of the various findings. In the absence of treatment randomization P-values cannot be used as proof of seeding efficacy.

The results are presented for all seasons (2002-2006) combined instead of for individual seasons because of the limited sample size. Even so, during the analysis of the 2002 through the 2006 seasons 3,834 seed units were identified, tracked and matched during the 12 h match period when the control matches were drawn from within and outside the seeding targets. Fewer matches were made when the matching controls were selected from smaller areas over shorter match periods. Of the initial total sample, 2471 units or 63% existed 75 min prior to their seeding. The unit total had dropped to about 50% of the initial total by 195 min after their initial seeding. The unit total had decreased to 10% of the initial total by 555 min.

The evidence for seeding-induced rain increases is strongest for the Panhandle (PH), SOAR (SR), CRMWD (CR), West Texas (WT), and South Texas (ST) projects. The Southwest (SW) and High Plains (HP) projects are also quite positive, although their P-value support is a little weaker than the first five projects. Typically, the sizes of the effects range between 20 and

25%, although the apparent effects for the CR and HP projects are greater. The volumetric rain increment per seeded unit ranges between 1,600 and 2,400 acre-feet. Again, the increments for the CR and HP projects are larger. The results for the Abilene (AB) and Pecos (PC) projects appear negative although they are based on a small sample and have very weak P-value support.

A major component of the analysis involved an examination of the project seeding effects as a function of the age of the unit when it was first seeded. In doing the analysis it was required that the prospective control match be of the same age at the time in its history when it was matched with the seed unit. A young unit was defined as one that had existed no longer than 60 minutes at its time of first seeding while a middle-age unit had an age of 75 to 120 minutes at its first seeding. An old unit was one that had existed on radar 135 minutes or longer. In all ten projects the percentage seeding effect was greatest for the young seeded units and smallest, even negative for the AB project, for the old seeded units. This consistency suggests that seeding was operative even in the two weak projects (AB and PC) even though the overall seeding effects appeared negative with weak P-value support in both projects. The percentage seeding effects in young units exceeded 100% in 6 of the 10 projects studied even exceeding 200% in 2 (HP and SW) of these 6 projects.

The rain increments (mean S - mean C in acre feet) for the units as a function of age are also of intense interest. As one would expect, the volumetric rain increments are greatest for the young seeded units, reaching a huge 20,000 acre feet per young unit for the old HP program. In 4 of the other 9 projects the seeding increment exceeded 8,000 acre-feet. Even when seeding older units, however, there was still a positive payoff except for the AB and PC programs that had small negative increments. The obvious lesson here is that a project is better off seeding convective units early in their lifetimes.

The unit rainfall results were partitioned further by unit rain-volume rate (RVR) at the time of initial seeding (RVR0) into three RVR0 categories (light; 0 to 284 acre-feet/h, medium; 284 to 810 acre-feet/h and heavy; > 810 acre-feet/h at the time of first seeding (RVR0). This partitioning variable is related to unit age because a young unit will usually have correspondingly light RVR0 values whereas an old unit is more likely to have a heavy unit RVR0 at the time of seeding. In most cases the percentage seeding effect is greatest in units having light precipitation at the time of initial seeding, somewhat less for units with medium RVR0 values and least for heavy RVR0 values. The obvious exceptions are the AB and PC projects that show little to negative effects of seeding.

The time plots of the mean rain-volume rates for the S and matching C units are strongly supportive of a positive effect of seeding. Typically, the plots are nearly coincident up to and immediately after the time of initial seeding. Subsequently the mean S and mean C plots diverge with the S units peaking later and producing more rainfall than the C units. This pattern is enhanced greatly in young units that were seeded before they reached an age of 1 hour. Such units are apparently more responsive to seeding intervention.

Although the results of these and other analyses make a strong case for enhanced rainfall by the Texas operational seeding programs, such programs must not be viewed as substitutes for randomized seeding efforts that are conducted in conjunction with realistic cloud modeling that are followed by replication, preferably by independent groups for maximum credibility.

1.0 INTRODUCTION

Woodley Weather Consultants (WWC) has developed an objective and comprehensive method of evaluating the operational cloud seeding programs in Texas. The new procedures were applied by WWC to the High Plains and Edwards Aquifer projects for the 1999 and 2000 seasons under contracts with the High Plains Underground Water Conservation District and the Edwards Aquifer Authority. The results were published in the Journal of Applied Meteorology (JAM) in February 2004 (Woodley and Rosenfeld, 2004). In addition, WWC applied its methodology to all ten Texas seeding projects existent in 2002 with the sponsorship of the Texas Department of Agriculture (TDA) and later the Texas Department of Licensing and Regulation (TDLR).

The evaluation of seeding efficacy involved the use of NEXRAD (Next Generation Radar) base-scan, mosaic, radar data a new assessment method developed by the research team of Drs. William L. Woodley, President of Woodley Weather Consultants, and Professor Daniel Rosenfeld of the Hebrew University of Jerusalem in Jerusalem, Israel. The method builds on their research studies and publications dealing with the effect of seeding in randomized seeding programs in Florida, Texas and Thailand.

The interest, therefore, was in large, rain-productive cloud systems on a scale of roughly 2,000 km^2, because this is the scale of convection that contributes significantly to the water budget of a region. Seeding must ultimately be shown to be effective on this and larger scales, if it is to have practical significance for Texas. Coincidently, Woodley and Rosenfeld had determined that 2,000 km^2 is the scale of convection that can be worked efficiently by a single seeder aircraft. Further, this is the scale over which evaluations of randomized seeding programs have been conducted by Woodley and Rosenfeld (e.g., Rosenfeld and Woodley, 1989, 1993 for Texas and Woodley et al., (2003a,b) for Thailand. These analyses made it possible to document the effect of seeding on the directly-seeded clouds and then their effect on nearby non-seeded clouds through downdraft interactions and through secondary seeding as discussed by Woodley et al. (2003a,b)

The special Rosenfeld/Woodley (R/W) analysis methodology was used to analyze the effect of seeding in the Texas cloud seeding programs for the periods of seeding in 2002 through 2006. The template for the proposed analyses is provided in the peer-reviewed JAM paper (Woodley and Rosenfeld, 2004). Virtually all that was done to analyze the old High Plains and Edwards cloud seeding programs was repeated as data permitted for all of the Texas programs in existence in the years 2002 through 2006 using the methodology that is unique to WWC. This is crucial, because the methodology has been subjected to intense scientific scrutiny. This will give the results of the Texas assessment strong scientific credibility. This JAM template already had been used to assess the 2002 season with support from the Texas Department of Agriculture (TDA) and the Texas Department of Licensing and Regulation (TDLR).

1.1 The Analysis Method Developed by Drs. Woodley and Rosenfeld

(Additional details are provided in the JAM paper in Appendix A)

The R/W method for the evaluation of seeding effectiveness in Texas satisfies the following requirements:

- Minimizes the possibility of human bias affecting the analyses.
- Radar-based for rainfall estimation with checks on radar accuracies using rain gauge vs. radar comparisons whenever possible.
- Focuses on the effect of seeding on an area basis rather than on individual clouds, because this must be of most interest to operational cloud seeding programs. Although the effect of seeding on individual clouds is of intense academic interest, it is of little practical import unless it can be shown to affect larger scales to produce area increases in rainfall.
- Compensates for the absence of randomization by providing for the objective matching of moving uncontaminated "control" units from selected areas.
- Provides for the concurrent examination of all of the seeding programs both within and downwind of their targets.
- Accounts for the confounding effects of "selection biases" and the diurnal convective cycle by varying the time and space scales for the control matches.
- Provides for the partitioning of project data for assessments of seeding effectiveness within various meaningful meteorological partitions (e.g., age of the unit when first seeded, unit rain-volume rate (RVR) at the time of initial seeding, seeding effect as a function of coalescence activity, etc.)

Because the method is based on radar rainfall (R) estimation, an effort was made during the early stages of the work to check the radar-rainfall estimates against networks of rain gauges (G). The first involved comparisons of R and G seasonal rain measurements for the High Plains (HP) target in 1999 and 2000. The agreement was within 10% in both years (Woodley et al., 2001). Subsequently, seasonal G and R comparisons for the 2001 and 2002 seasons for the new gauge network of the Edwards Aquifer Authority, averaging 90 rain gauges, revealed that the radar underestimated the total rainfall relative to the gauges by 56% in 2001 and 31% in 2002. Because such discrepancies have been shown to apply equally well to both seeded and non-seeded clouds (Cunning, 1976), they do not affect the inferences of seeding effect that are based on relative S vs. NS comparisons. Based on these findings, the radar estimates of rain volumes in the West Texas projects are likely close to reality. On the other hand, the radar estimates of rain volumes in the eastern and southern projects are probably low by 30% to 50% relative to gauge-based reality. The point to be made is that the inference of seeding effectiveness does not depend on radar accuracy as long as the radar inaccuracies apply equally well to the seed and control sample.

As with the 2002 season, the application of the R/W method to the 2003 through the 2006 seasons made use of NEXRAD 15-minute mosaic reflectivity data, obtained from an archive at the National Center for Atmospheric Research 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 (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 center of 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 the time of 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 automated algorithm. Thus, the analysis focused on the effect of seeding on a moving area basis rather than on individual clouds, because this must be of most interest to operational cloud seeding programs. The reader is referred strongly to Woodley and Rosenfeld (2004) for important details about the development of the method and its application.

After the units on each day had been defined, the positions and seeding actions of all project aircraft flying in and around their targets as a function of time were 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 AgI acetone 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. The "official" times and locations of each seeding event was provided by each seeding project. This was a problem for some projects that did not take good care of their documentary seed data.

In order to be considered a match, the control unit at the time of match with a seeded unit had to satisfy the following conditions: 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 $\geq$ 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 several time periods (e.g., 3, 6 and 12 hrs before or after initial seeding) within 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 may not be matched due to a lack of suitable controls. There is to be no matching of the "best" control units within a chosen time frame if those best units do not satisfy the match criteria. 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.

Although this match process is objective and comprehensive, even perfect matches do not guarantee that inadvertent selection bias 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. A reverse bias is also a possibility.

It is possible to quantify this bias by comparing the inferred seeding effects when doing the matching within the seeding targets as compared to limiting the matching to control units outside all seeding targets and off-limits to the seeding aircraft. If the seeding effect is systematically larger when matching with controls within the targets as opposed to matching with control units outside the targets, the disparity of effect provides a crude estimate of the effect of bias on the evaluation. Thus, a program that exhibits a “seeding effect” only when matching with control units within the seeding target and none when matching with control units outside the target will have less scientific credibility even though the weather is better matched when using within-target matches..

The main advantage of the R/W method is its versatility and objectivity. 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. It is also objective and comprehensive, accounting for biases during the conduct of the cloud seeding and potential human bias during the analysis phase. Further, the size of the analysis unit (presently 1,964 km^2) and the match criteria can be changed and the analysis can be redone with the new parameters. This makes the analysis of all projects possible and facilitates comparisons of effects among projects. It also makes it possible to infer seeding effects as a function of cloud structure, unit age and rain activity at the time of initial seeding, the amount of nucleant, and the method whereby it was delivered to the clouds

1.2 Doing the Analyses

Many tasks had to be addressed during the analyses. These included the following:

Task 1: Retrieval of the NEXRAD mosaic radar data in the required format

The computer code for the R/W methodology was written for 15-min NEXRAD mosaic radar data that were obtained previously at no cost from NASA’s Global Hydrology Research Project in Huntsville, Alabama. In consulting with NASA personnel Dr. Woodley learned that production of the data needed for the proposed effort had been terminated and that the previously-existing archive no longer existed. There was a time when it appeared that the analysis would not be possible because of a lack of suitable data, unless the data archived by the TWMA for the Texas projects in TITAN format could be secured and converted to the needed format. After several days on the telephone and on the Internet pursuing leads to secure the desired data, Woodley discovered that an individual (Dr. David Ahyevych; 303-497-8922) now at the National Center for Atmospheric Research (NCAR) had learned of NASA’s intentions and had obtained the old NASA archive and taken the actions needed to continue the production of the specialized radar products. These can be obtained to the present time from a NCAR website. Thus, the radar data needed for the proposed WWC Texas analyses were available through NCAR. Dr. Rosenfeld retrieved the needed radar data from the NCAR website.

Task 2: Development of the master treatment file for all projects

The key need for the proposed assessment effort was a master file of all seeding activity during the 2002 to 2006 seasons. Compiling this master file was the responsibility of Dr. Woodley, who asked the project meteorologists to provide him documentation of all seeding times and locations and amounts plus lat/long documentation of target boundaries for each year of new analysis (i.e., 2003-2006 seasons). Woodley already has this information for the 2002 season. Although all project personnel were cooperative in attempting to provide the needed data, it was not readily available in the appropriate format from a few of the projects. In a few instances one to two entire seasons or portions of seasons were not available for a couple of the projects. After this analysis was done, projects were reminded to take an aggressive approach to quality control of their TITAN data.

Task 3: Tracking the analysis units

As soon as the Texas mosaic radar data had been downloaded from the NCAR archive, analysis units were identified and tracked in accordance with the R/W methodology. Their rainfall histories were calculated through the conversion of the radar reflectivities (Z) to rainfall rate (R) using the relationship: $Z = 300R^{1.4}$. This was done, typically for March through October for each season over a domain that encompassed all of the seeding programs. The identification and tracking began on the first day of the season unless there was an interruption of the radar data. In such instances the identification and tracking began anew after the interruption.

Task 4: Identification of the seeded units

After the tracking of all analysis units, the master project treatment file was superimposed on the tracked units to identify the seeded units. Any unit receiving as little as 1 AgI flare was identified for all time as a seeded unit until its disappearance from the radar. This was a very complicated process because the seeded units had to be identified and tracked with time for the entire domain, so that it was known when a seeded unit from one project target had moved into the target of another seeding project. If the unit was seeded again, it continued to be tracked for the original target of seeding. It was also tracked as a seeded unit for the second target and put into a special category for units that were seeded by more than one seeding jurisdiction. These are special cases and they were treated as such.

Task 5: Matching of the seeded units with control units

All seeded units were matched with qualifying control units that were drawn temporally within 3, 6, and 12 h of the initial seeding and from the entire control archive. The control units were drawn spatially: 1) from the subject target, 2) from the subject target and any nearby target and 3) only from outside all the seeding targets in which there is active seeding on a given day. Although our past experience suggests that matches closest in space and time to the actual seeding is to be preferred, limiting the matches to within 3 h of the seeding meant that many seed unit units could not be matched. Further, limiting the matches to the target in which the seeding took place produced a higher risk of a biased match when all of the strong storms had been seeded, making them off limits for a control match.

Task 6: Calculation of parameters to be used for partitioning

A major component of the assessment was the calculation of parameters such as the Index of Coalescence Activity (ICA) that was used to partition the results where the $ICA = 8.6 – T_{CCL} + 1.72(PB)$ and T_{CCL} is the temperature at the convective condensation level and PB is the potential buoyancy for a saturated parcel raised from the CCL to 500 mb. This and other such parameters were calculated from the relevant atmospheric sounding that is best matched spatially and temporally to the seeding events.

Task 7: Assessment of project seeding effects with and without partitioning

During the matching of the seed and control units under Task 5, rainfall histories were calculated for all units and S vs. C differences and ratios were calculated. This was done for each project as a function of match interval and location without any meteorological partitioning and within a number of partitions such as the ICA and unit RVR and age at initial seeding.

Task 8: Adjust the project unit rainfall estimates based on seasonal gauge vs. radar rainfall comparisons

The assessment of seeding efficacy is based on radar-estimated rainfalls. Although the accuracy of these radar rainfall estimates is always of concern, the relative seed vs. control rainfall differences should still be valid, since there is no evidence that the radar "sees" the rainfall from seed and control clouds differently (Cunning,1976). It is important nevertheless to adjust the regional radar estimates of rainfall to a rain gauge standard so that regional comparisons of unit rainfalls can be made. How this was done for the HP and EA studies is explained in the JAM paper. The gauge vs. radar seasonal rainfall comparisons were within 10% in both 1999 and 2000 for the HP program. In the EA program, however, the radar underestimated the seasonal rainfall by factors of 1.56 and 1.31 in 2001 and 2002, respectively. If left uncorrected, one might conclude erroneously that the units are wetter on average in the Lubbock area as compared to the units in the vicinity of San Antonio. This is not the case, however, after applying the G/R corrections.

The original proposal called for making the same type of G vs. R comparisons for the proposed study for the seasons of study as were made for portions of Texas for the 1999, 2000, 2001 and 2002 seasons as described in the JAM paper, but this did not prove possible. Thus, it will be necessary to rely on relative seed vs. control comparisons for the evaluation. If one wants to make absolute comparisons among unit rainfalls, however, the rain volumes for a unit in southeast Texas (e.g., South and Southwest Texas projects) should be increased by at least 30% relative to those in northwest Texas (e.g., North Plains, Panhandle, High Plain, SOAR) based on earlier gauge vs. radar comparisons.

Task 9: Generation of the target S and C unit rainfalls with estimates of seeding effects

Once the work on Tasks 1 through 8 had progressed to the point where the master run of the radar data could be made, the S and C unit rainfalls and the estimation of seeding effects were calculated.

Task 10: Assessment of the results of the master run

The master computer run generated an enormous output that had to be examined first for possible problems and inconsistencies. After this had been done, the output data were used to assess the seeding results for the individual projects for all five years of analysis.

Task 11: Confer privately with project management and meteorologists on the results of the assessment

Because the assessments will address the past, present and possibly the futures of the individual seeding projects, it is essential that their management and their meteorologists be shown the courtesy of a private briefing on the results of the analyses. This was done by providing them the Final Report when it was in draft form.

Task 12: Preparation of the draft contract Final Report, its review by the WWC research team and by project representatives

The draft contract Final Report was prepared during May 2007, and it was submitted for project review. This paper was excerpted from portions of that report.

Task 13: Revision of the draft contract Final Report followed by submission of the last version

Dr. Woodley actively sought comments on the draft Final Report and he made revisions based on the feedback. He will then revise the Final Report and submitted it to the TWMA and to the Sandyland Underground Water Conservation District to fulfill contract requirements. This was done during June 2007.

2.0 PREPARING FOR THE MASTER ANALYSIS RUN

The R/W methodology was used to evaluate seeding effects in the Texas operational seeding projects that existed in the period 2002 to 2006. The year 2002 was the last year of operation for the High Plains and Texas Border projects. The Abilene program was discontinued after the 2003 season. The Pecos program came on board in 2003 and continued through the 2006 season. Several projects had significant losses of their documentary seed data and this compromised their assessments to varying extents. Included in this were the North Plains, Abilene, CRMWD, Pecos and Southwest Texas programs. In a few instances the current project meteorologist manually recreated the missing documentary seeding information. This was a very difficult phase of the analysis.

Preparations for the overall evaluation of seeding efficacy in Texas had been underway for several years. In preparation for this overall task and to refine and test the method the R/W methodology was used to evaluate the effect of seeding in the old High Plains (HP) and Edwards Aquifer (EA) programs during the 1999, 2000 and 2001 (Edwards Aquifer only in 2001) as is documented in Woodley and Rosenfeld (2004). Objective unit matches were selected from within and outside each operational target within 12, 6, 3 and 2 h of the time on a given day that seeding within a particular unit took place. Matches were drawn also from within and outside each target on the day of unit seeding and from the entire archive of days on which seeding was done. Limiting the matches to within 2 to 3 hours of the actual seeding with the target of seeding is highly desirable because variations of the weather in space and time are minimized by such limitations. Further, it is possible to determine whether unintended selection biases (i.e., seeding the “best” cloud mass in a region, leaving inferior ones to serve as controls) and the diurnal convective cycle confounded the results. However, as the space and time frame for S and C matches is compressed, fewer and fewer matches can be made, because the match pool becomes progressively smaller. Thus, there is no single “best answer” in the analysis. One has to look at the totality of the results under several analysis scenarios to determine probable seeding effectiveness.

In doing the current analysis, control matches were drawn within 3, 6 and 12 hours of the first seeding in each S unit and these were drawn within 300 km of the S unit from at least one of the seeding targets (the “IN” permutation), or from the seeding targets and the areas outside the seeding targets (the “INOUT” permutation, or only from areas outside the seeding targets (the “OUT” permutation) as long as the selected control unit was no more than 300 km from the S unit. Note that the 2 h match period was not done because suitable control matches could not be found in many cases. In making the matches it has been determined that at the time of initial seeding (time”0”) the correlations of the rain volume rate of the seed units ($RVR0_s$) with the average rain volume rate for the matched control units ($RVR0_c$ are excellent, typically $\geq$ 0.99. All seed units were matched for the $\pm$ 12 h time frame. When matching within $\pm$ 12 hours of the initiation of the seed units, however, only about 60% of the seed units could be matched. In order for more units to be matched in this time frame, the match criteria would have to be relaxed. This was not viewed as a good idea. Conversely, if the match criteria are made even more stringent, even fewer seed units would be matched in the $\pm$ 12 hour time frame.

Although the matches, making use of seasonal data provide the most conservative estimates of seeding effect, they are probably somewhat negatively biased against an effect of seeding, because most of the matching control units come on the wettest most strongly-forced days. Thus, there will be a disproportionate number of wet vigorous control units available to serve as matches for seed units on less convectively forced days. Thus, potential biases work both ways in the analysis.

Although the results of all past analyses have been subjected to statistical testing (re-randomization procedures), the resulting P values have been used merely to determine the relative strength of the various findings. This is the case with the current Texas evaluation

To set the stage for the results of the current analysis it is useful to take another look at the results of the earlier evaluation of the old HP and EA programs (see Woodley and Rosenfeld, 2004 in Appendix A. The apparent average effects of seeding per analysis unit in both the HP and EA programs were large even after accounting for selection biases and the convective cycle. The most conservative and credible estimates of seeding effects were obtained from control matches drawn from outside the operational target within 2 h of the time that each unit was seeded initially. Under these circumstances the percentage increase exceeded 50% and the volumetric increment was greater than 3,000 acre-feet (3,700 kilotons) per analysis unit with strong P-value support in both the HP and EA programs. The total project rain increment (average rain increment per unit times the number of units) was greater, however, for the HP program, because it had more than twice as many units as the EA program.

Using the HP project as an example because it had the largest sample, it is crucial to note that the apparent seeding effect was much larger when the control matches were drawn from the target than when the control matches were made for controls selected from outside the target. This is shown clearly in Figure 1, which has been excerpted from the JAM paper. This is a crude quantification of the biases that can confound the assessment of the effects of seeding. Clearly, such biases must be considered and eliminated whenever possible. No one would disagree that control matches made within the seeding target are to be preferred because the weather likely will be better matched when this is done. When such matching results in biases favoring a positive effect of seeding, however, it is better to do the matching with controls selected outside the seeding target but still close enough to have a good match of the attendant weather conditions.

Upon examining Figure 1, it can be seen that the assessment of seeding effect is greatest for matches made within the HP seeding target regardless of match period. At 2 h, however, the bias relative to matches drawn from outside the target is so large that one would have a hard time defending an assessment of seeding effect obtained from within-target matches within 2 h or the initial seeding. It is safest and most conservative, therefore, to use controls drawn from outside the seeding target whenever possible. These are the types of problems that must be addressed in assessing the effects of seeding in Texas. In this case, however, it is not necessary to select the "best" analysis. Of most importance a substantial positive effect of seeding is evident regardless of the specific analysis. This is the same approach that will be followed with the current analyses.

Further analysis provided additional insights into the effects of seeding. The apparent effect of seeding in both the HP and EA programs was strongly a function of the age of the unit when it was first seeded. Units more than 2 hours old when first seeded showed little to no response to seeding, while those less than an hour old when first seeded showed a strong positive response to seeding, ranging from +49% (EA) to +128% (HP). Because a disproportionate percentage of old cloud systems were seeded in the EA program as compared to the HP program (i.e., 67% vs. 46%), it is possible that the apparent seeding effects in the Edwards program were smaller because many of the clouds were seeded too late in their lifetimes. Speculating, this may have been due to weather differences 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.

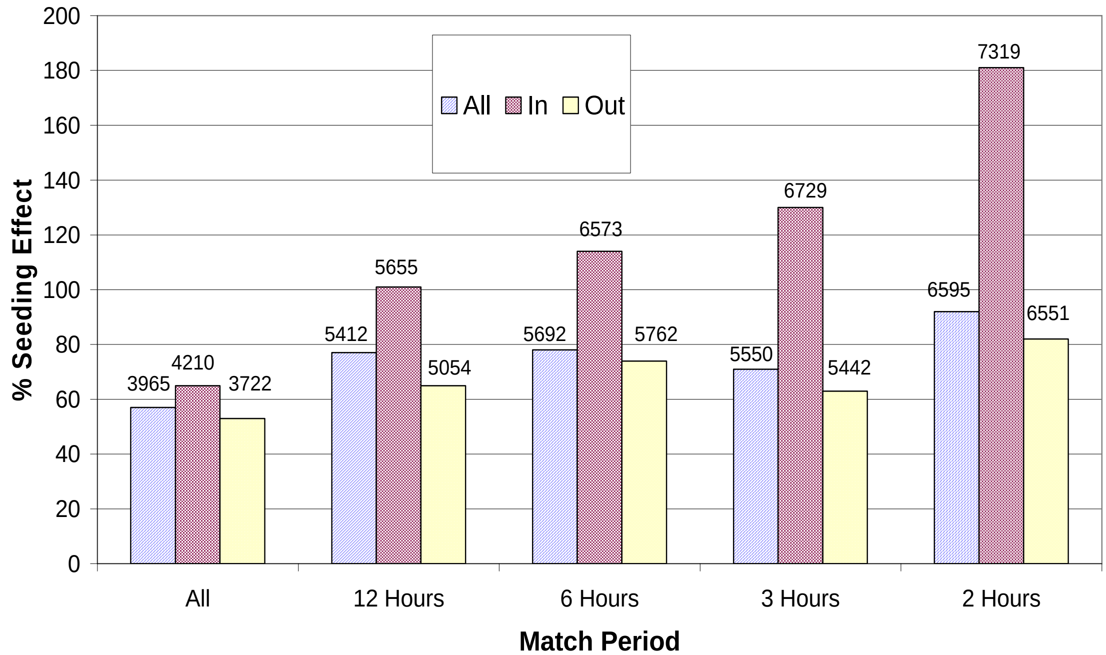

Figure 1. Apparent seeding effect (%) as a function of match period and match location for the High Plains Program in 1999 and 2000. The average rain increase (acre-feet) per unit is shown above each bar. Note that the apparent seeding effect increases as the time for the control matches is contracted. The large disparity between the estimated seeding effects when drawing control matches inside or outside the HP seeding target is quantification of the role that bias may have played in the assessment. The in-target matches result in "seeding effects" that are strongly biased in favor of a seeding effect.

Consistent with this result is the finding that the apparent effect of seeding also depends on the rain-volume rate (RVR) within the unit at the time of its initial seeding. If the unit is covered with heavy rain at the time of seeding, the apparent response of the unit to seeding intervention is small even though the unit itself may produce a large amount of rainfall in its lifetime. This agrees with the results as a function of unit age since old mature cloud systems at the time of initial seeding are more likely to be producing heavy rain than clouds that are young and growing. For maximum seeding effectiveness, therefore, it appears that relatively young but vigorous cloud systems producing only light to moderate rainfall are the best candidates for initial seeding.

The temporal response to seeding was 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 some cases for up to 10 hours. This was the case also for the randomized seeding in Thailand (Woodley et al., 2003a,b), where the seeded and control units were identical in size to those used in Texas. If the units are moving, this means that the effect of seeding is not limited to the boundaries of the fixed 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.

Attention then turned to all ten seeding programs of 2002 and then 2003 through 2006. The targets are depicted in Figures 2 and 3. Control matches were drawn from the total sample of S units within 300 km of the center of each unit in each project in several time periods relative to the time of initial unit seeding and from: a) within each operational target of interest and/or b) within each operational target of interest including any other operational targets immediately nearby and/or c) outside all operational targets. These various analysis permutations were made to determine the sensitivity of the results to match period and the location of the control matches.

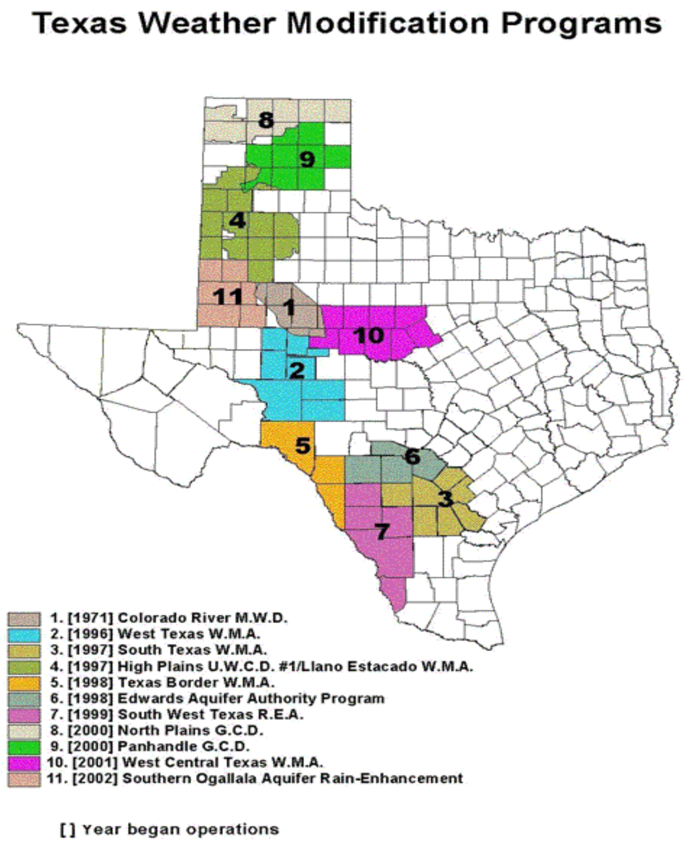

Figure 2. The ten seeding targets operative in Texas during 2002.

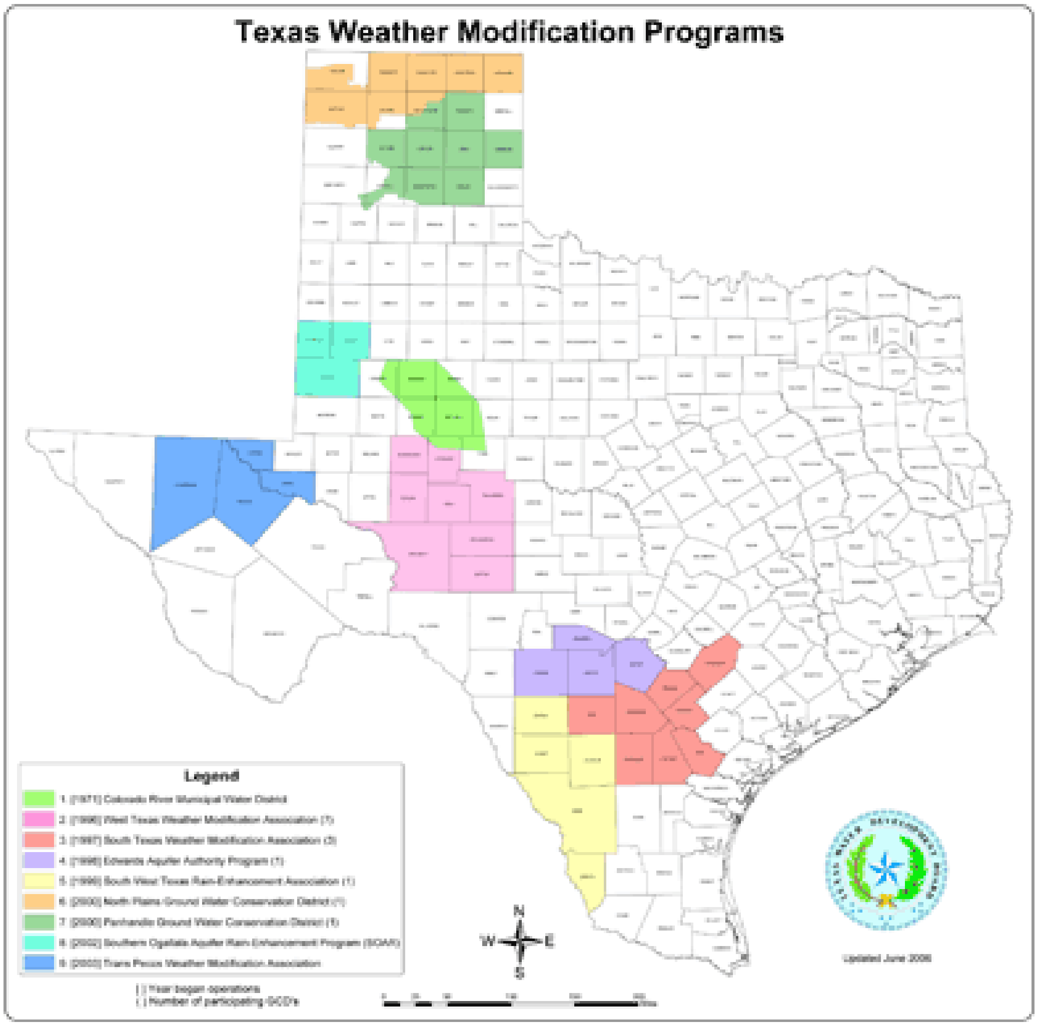

Figure 3. The Texas cloud seeding programs existent in 2006. Zapata County is no longer a part of the Southwest Texas seeding program.

During the analysis of the 2002 through the 2006 seasons 3,834 seed units were identified, tracked and matched during the 12 h match period when the control matches were drawn from within and outside the seeding targets. Fewer matches were made when the matching controls were selected from smaller areas over shorter match periods. A frequency plot of the total project sample of 3,834 S units as a function of time relative to the time of initial seeding is shown in Figure 4. Of the initial total sample, 2471 units or 63% existed 75 min prior to their seeding. The total unit total had dropped to about 50% of the initial total by 195 min or a little over 3 hours after their initial seeding. The unit total had decreased to 10% of the initial total by 555 min or a little over 9 hours. A single S unit was still being tracked at 2170 min (just over 36 hours) after its first seeding. The West Texas (WT) project produced 1040 S units or 27% of the total unit sample from the data provided to WWC. The unit sample would have been somewhat larger had all of the seeding data from all projects been available.

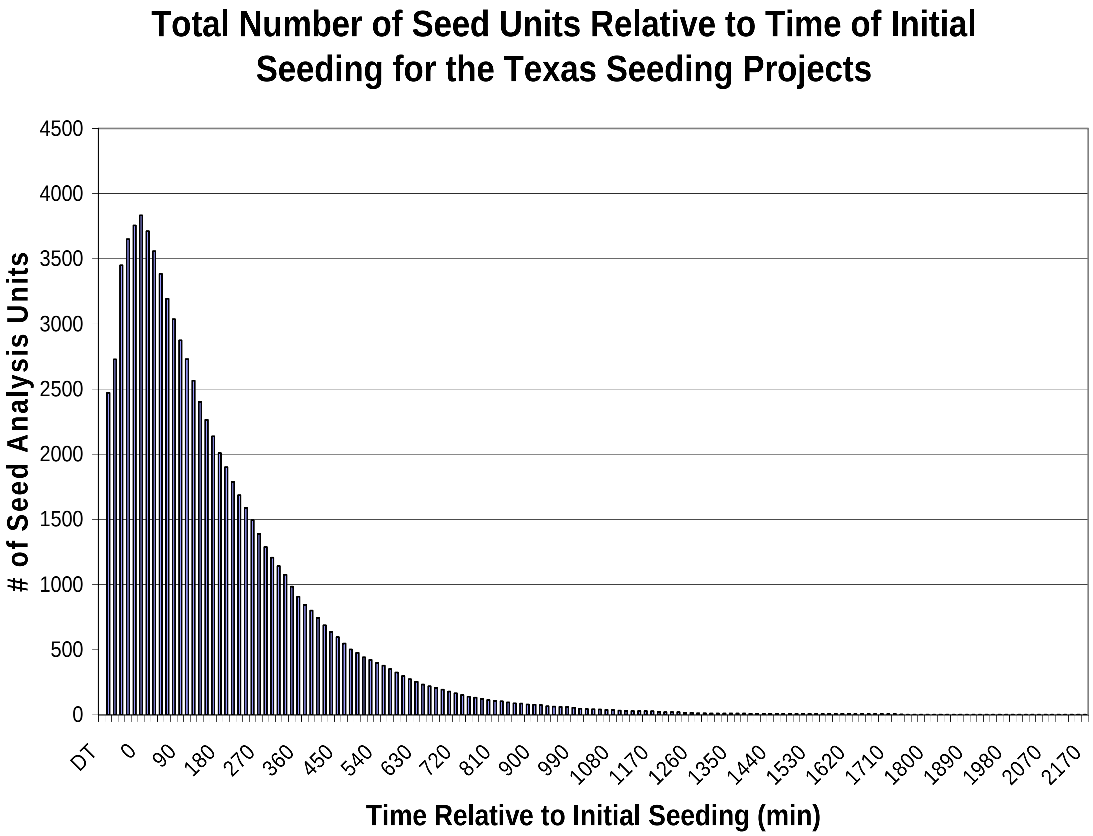

Figure 4. Total number of seed units relative to the time of initial seeding for the Texas seeding projects operative in the period 2002 to 2006.

The first pass through the 2002 data with the method caused renewed concern about the role of selection biases in the evaluations. In a few instances large "seeding effects" were noted only 15 minutes after initial seeding. Because there is no plausible mechanism for an area seeding effect in only 15 minutes subsequent to first seeding, especially when the nucleant is released at cloud base, a second analysis of the data was made by extending the restricted match criteria to 15 minutes <u>after</u> initial seeding. That is all matches in which the S and C values differed by more than 25% 15 minutes <u>after</u> the seeding were rejected. This eliminated both positive and negative selection biases, but it also decreased the match sample.

Although such biases were found to be relatively infrequent, they could not be ignored. Thus, selection biases were addressed by extending the method match criteria at the time of initial seeding to 15 minutes afterward such that the S and C RVR values could not differ by more than 25%, the max reflectivity in the S and C units could not differ by more than 5 dBZ, and the correlation of the RVR values of the S and prospective C units from 75 min before initial seeding to 15 minutes subsequently had to be $\geq$ 0.60. In addition, it was required that at 30 minutes the S and prospective C RVR values could not differ by more than a factor of two (i.e., 3 dBZ), thereby allowing for a substantial effect of seeding, while still eliminating outlandish biases. The only disadvantage of these more stringent criteria for matching was the decreased number of matches that were possible, especially when matching within the day.

Rather than pin the evaluation on only one or two analysis permutation, it was decided to evaluate the projects with and without correction for selection biases. In doing this the following analysis permutations were used: a) the method as constituted originally (identified as 199) b) extending the seed-time match criteria to 15 min after seeding and allowing for a factor of two disparity at 30 min as discussed above (identified as 113), c) extending the seed-time match criteria to 15 min after initial seeding with no restraint on the S/C RVR ratio at 30 min (identified as 119) and d) extension of the seed-time match criteria to 30 min, allowing for only a 25% disparity in this time frame (identified as 111). The control matches under these scenarios were made for units within and outside the seeding targets for time periods within 12, 6, and 3 hours of initial seeding. With this approach of using multiple sensitivity analyses, the results cannot depend on a single analysis. Rather, it is the collective weight of the evidence from the multiple analyses that will be most persuasive of an effect of seeding.

Upon considering the complexity of the methodology, the many sensitivity analyses, and the massive amounts of data that are generated and then manipulated, it would be easy to become confused. The best way to combat this is to get into the data to see what is there. The first step is an examination of some of the tabulated output. Summary tables for each project are provided in Appendix B in the analysis Final Report that is available upon e-mail request through <williamlwoodley@cs.com>. An example for the West Texas (WT) project is brought forward here as Table 1 (immediately below). The WT project is one of the strongest in the sample in that the data were found to be in good shape for all years, operationally the program did a lot of seeding with strong evidence for positive effects.

It is instructive to examine the columns in Table 1 working from left to right. The first column (Area) is the project identifier (West Texas or WT). The second column (Cinout) tells the areas from which the matching control units were selected: 0 for in and outside of the seeding targets, -2 for controls selected from outside the seeding targets and 1 for controls selected from within the project seeding target and possibly other nearby targets). The third column (DBRV) gives the number of dBZ separation between the seed and the potential control match that is allowed at 0 minutes (seed time), 15 min after initial seed time and 30 min after initial seed time. Thus, a DBRV of 119 would require that the match have no more than a 1 dBZ separation at 0 and 15 minutes but permit at least a 9 dBZ separation at 30 minutes.

The fourth column (inday) tells whether the match occurred on the day of the unit seeding (a "0" value in the listing) or whether the match was made from the entire archive without regard to the day of actual seeding (a "1" value in the listing). Many units were matched under this matching scenario. The fifth column (DT) gives the time interval of the matches. Thus, a value of 6 means that all matches were made within 6 hours of the initial seeding of the units (obviously on the day of seeding). The sixth column (Crange) gives the maximum permitted range between a S unit and its matching control. It was 300 km in all cases. The seventh (Tbs1) and eighth (Tbs2) columns give the age intervals for the matching. If the values are 0 and 9999, the match is at the time of seeding (i.e., 0 time). If the two column values are 0 and 60, echo in the S unit had existed for up to 60 minutes prior to its seeding, and a prospective control match had to be of the same age. These are deemed "young" units. The other two age categories were 75 to 120 minutes ("middle age") and $\geq$ 135 minutes ("old"), where the S unit had existed more than 135 minutes prior to seeding in the unit. The ninth column (Nseed) gives the number of seed units that were matched within a particular category. Note that when matching from the archival data many (up to 996 for WT) units were matched. The tenth column (NCav) is the average number of matching control units for each S unit in each category. The value ranged typically between 1 and 3 units for the matches that were made 3 to 6 hours after initial seeding. When the matching took place within 12 hours of the seeding, the average number of matches was much greater, ranging up to 117.7 units for one category in which DBRV = 113 and DT = 12 h.

The next columns in Table 1 provide the radar-estimated rainfalls. The eleventh column gives the unit rain-volume rate of the S unit when it was first seeded (i.e., RVRs0). Although the matching unit could have had a RVRc0 value (not shown) that differed by as much as 25% from the RVRs0 value, typically the mean differences were only a couple of percent. This was to be expected based on the way the method is structured. The twelfth column (RVS600) gives the mean rain volume (in kilotons) produced by the S units by 600 minutes (10 hours) after their seeding and the thirteenth gives the comparable value for the matching control units (i.e., RVC600). The fourteenth column gives the S – C difference in mean values (i.e., column 13 minus column 14. The fifteenth, sixteenth, seventeenth and eighteenth columns give the ratio of S to C mean rain volumes at 0, 15, 30 and 600 minutes, respectively. Finally, the last or nineteenth column gives the statistical P-value significance of the S to C ratio at 600 minutes. The values are percentages. Although these are not statistical significances in the classical sense because of the lack of randomization, P values $\leq$ 5% indicate a strong result nonetheless.

There are 47 analysis permutations in this WT summary table. Of these, 40 had S/C ratios > 1 at 600 minutes and 35 had P values $\leq$ 5%. This strongly suggests a positive effect of seeding in this program. Comparable tables for the remaining programs can be found in Appendix B of the Final Report.

Table 1 Results for the West Texas Seeding Program for 2002 to 2006

Area	Cinout	DBRV	Inday	DT	Crange	Tbs1	Tbs2	NSEED	NCav	RVRs0	RVS600	RVC600	RVS600-RVC600	SR15	SR30	SR120	SR600	SIG
WT	0	199	0	3	300	0	9999	663	2.8	717.9	11463.5	9633.2	1830.3	1.02	1.02	1.14	1.19	0.03
WT	0	119	0	3	300	0	9999	361	1.5	808.8	13430	12099.1	1330.9	1.01	1.02	1.11	1.11	7.53
WT	0	119	0	6	300	0	9999	445	1.8	770.6	12398.3	10246.5	2151.8	1.02	1.04	1.16	1.21	0.53
WT	0	113	0	6	300	0	9999	340	1.6	848.2	13227	11402.6	1824.4	1.02	1.03	1.13	1.16	1.57
WT	0	111	0	6	300	0	9999	210	1.2	953	13630.8	12062.7	1568.1	1.02	1	1.11	1.13	4.7
WT	-2	199	0	3	300	0	9999	571	2.2	701.8	11368.5	9634.3	1734.2	1.01	1.02	1.14	1.18	0.07
WT	-2	119	0	3	300	0	9999	289	1.4	813.3	13577.1	11909.7	1667.4	1.01	1.03	1.13	1.14	2.17
WT	-2	119	0	6	300	0	9999	361	1.6	792	12492	10410.0	2082.0	1.01	1.04	1.16	1.2	0.73
WT	-2	113	0	6	300	0	9999	283	1.4	868.2	13116.7	11505.9	1610.8	1.01	1.03	1.14	1.14	4.7
WT	-2	111	0	6	300	0	9999	165	1.1	973.7	13852.6	12708.8	1143.8	1.01	1	1.08	1.09	7.67
WT	1	199	0	3	300	0	9999	124	1.2	671.8	11661.6	10898.7	762.9	1.17	1.14	1.1	1.07	23.5
WT	1	119	0	3	300	0	9999	39	1.1	531.8	8640.9	9819.2	-1178.3	1	0.92	1.02	0.88	62.67
WT	1	119	0	6	300	0	9999	63	1.1	525.9	8357.8	10192.4	-1834.6	1.02	0.96	1.03	0.82	83.5
WT	1	113	0	6	300	0	9999	36	1.1	554.8	9998.4	9998.4	0.0	1	1	1.28	1	43.7
WT	1	111	0	6	300	0	9999	12	1.1	640.1	10241.3	9571.3	670.0	0.98	1.02	1.09	1.07	44.9
WT	0	113	1	12	300	0	9999	996	86.6	718.5	10481.5	10587.4	-105.9	1	1	1.05	0.99	9.07
WT	0	111	1	12	300	0	9999	944	34.2	718.1	10411.9	10308.8	103.1	1	1	1.06	1.01	3.5
WT	-2	113	1	12	300	0	9999	979	55.4	722.2	10568.2	10361.0	207.2	1	1	1.06	1.02	2.53
WT	-2	111	1	12	300	0	9999	917	21.8	719.3	10557.6	10350.6	207.0	1	1	1.06	1.02	4.6
WT	0	199	0	6	300	0	9999	750	3.8	694.8	11101	8952.4	2148.6	1.04	1.04	1.18	1.24	0
WT	0	199	0	6	300	0	60	112	3.7	261.7	17701.9	7195.9	10506.0	1.11	1.15	1.78	2.46	0
WT	0	199	0	6	300	75	120	240	3.9	749.8	17871.2	10040.0	7831.2	1.02	1.04	1.32	1.78	0
WT	0	199	0	6	300	135	9999	402	3.7	777.5	10608.3	8695.3	1913.0	1.04	1.04	1.11	1.22	0.4
WT	-2	199	0	6	300	0	9999	660	2.8	691	10942.8	9119.0	1823.8	1.01	1.02	1.16	1.2	0
WT	-2	199	0	6	300	0	60	96	2.9	286	17564.8	8169.7	9395.1	1.12	1.16	1.68	2.15	0
WT	-2	199	0	6	300	75	120	214	2.8	743.8	18029	9589.9	8439.1	0.98	1.03	1.35	1.88	0
WT	-2	199	0	6	300	135	9999	353	2.8	764.5	9924.4	9022.2	902.2	1.02	1.02	1.07	1.1	9.93
WT	0	199	0	6	300	0	9999	399	3.4	138.6	8976	5374.9	3601.1	1.02	1.07	1.45	1.67	0
WT	0	199	0	6	300	0	9999	183	4.3	608.4	15175.7	9854.4	5321.3	1.13	1.14	1.27	1.54	0
WT	0	199	0	6	300	0	9999	171	4	2073.9	24710.9	16046.0	8664.9	1.02	1.01	1.16	1.54	0
WT	-2	199	0	6	300	0	9999	339	2.6	141.5	8629.5	5677.3	2952.2	1.01	1.05	1.34	1.52	0

WT	-2	199	0	6	300	0	9999	172	3.1	603.4	15628.4	10148.3	5480.1	1.08	1.12	1.35	1.54	0
WT	-2	199	0	6	300	0	9999	152	3	2004.8	23813.6	15265.1	8548.5	1	1	1.14	1.56	0
WT	0	113	1	12	300	0	9999	996	86.6	718.5	10481.5	10587.4	-105.9	1	1	1.05	0.99	8.17
WT	0	113	1	12	300	0	60	147	81.8	276.9	17103.3	10001.9	7101.4	1.02	1.03	1.33	1.71	0
WT	0	113	1	12	300	75	120	308	94.3	759.8	16673.4	11115.6	5557.8	1.01	1.02	1.22	1.5	0
WT	0	113	1	12	300	135	9999	545	83.3	809.6	10253.6	10793.3	-539.7	0.99	1	0.98	0.95	26.23
WT	-2	113	1	12	300	0	9999	979	55.4	722.2	10568.2	10361.0	207.2	1	1	1.06	1.02	3
WT	-2	113	1	12	300	0	60	146	50.3	278.7	16972.6	8980.2	7992.4	1.02	1.04	1.41	1.89	0
WT	-2	113	1	12	300	75	120	301	60.2	773.3	16969	11237.7	5731.3	1.01	1.02	1.24	1.51	0
WT	-2	113	1	12	300	135	9999	537	53.9	809.1	10250.6	10250.6	0.0	0.99	1	1	1	19.83
WT	0	113	1	12	300	0	9999	541	64.9	130.7	8491.2	7076.0	1415.2	0.97	0.99	1.15	1.2	0.07
WT	0	113	1	12	300	0	9999	228	117.7	608	14599.1	10656.3	3942.8	1.02	1.02	1.12	1.37	0
WT	0	113	1	12	300	0	9999	231	106.3	2193.2	23716.5	19281.7	4434.8	1	1.01	1.1	1.23	0.07
WT	-2	113	1	12	300	0	9999	532	41.3	131.2	8468.5	6616.0	1852.5	0.98	1.01	1.23	1.28	0
WT	-2	113	1	12	300	0	9999	225	74.1	609.8	14660.7	10110.8	4549.9	1.02	1.02	1.13	1.45	0
WT	-2	113	1	12	300	0	9999	228	69.2	2198.3	23912.4	19441.0	4471.4	1	1.01	1.09	1.23	0.03

3.0 PRESENTATION OF THE RESULTS

3.1 Results as a Function of Match Interval and Location

The major challenge in preparing this report was the presentation of the results of the evaluation without getting lost in its details. The best approach seemed to be present a results overview of all projects in order to get overall impression of the apparent effects of seeding. More detailed information by project has been relegated to Appendix C of the Final Report. In all of the materials it should be noted that the results are presented for all seasons (2002-2006) instead of for individual seasons, because of the limited sample size. As it is, the working sample is only as large as the number of valid unit matches. Shrinking the sample matches in space and time around the position and time of seeding of each unit should make for excellent matches, provided selection biases can be avoided. Such restrictions will, however, decrease the size of the match sample. The R/W method also makes it possible to make matches with S units without restrictions in space and time by drawing the matches from the entire unit archive. When selecting matches from the entire unit archive virtually all units can be matched many times, thereby maximizing the unit sample. The challenge is to find a "happy medium" between the two extremes. Too restrictive a match process will eliminate most of the sample whereas matches without space and time restrictions will produce a result that is biased against an effect of seeding because the unit archive is dominated by the strongest convective days from which most of the C matches will be chosen.

The evaluation produced a staggering amount of information. An overview of these results is presented here. Details are given in Appendices B and C of the Final Report. Making sense out of all of it was a challenge.

It was instructive first to examine the tables in Appendix B of the Final Report to determine how many of the 48 analyses for each project (see Table 1 and the tables in) produced S/C ratios at 600 minutes > 1 and how many of these ratios have P values $\leq$ 0.05 or 5%. This is done in Figure 5. Note that some of the old seeding projects are included in this plot including the High Plains (HP) program that ended after the 2002 season, the CRMWD program that was not able to provide useable seeding data after the 2002 season, the Abilene (AB) program that ended after the 2003 season and had little useable documentary seed data for that season, the Texas Border project that ended after the 2002 season. In addition, the Pecos program appears in the plot even though not all of the needed documentary seeding data in all seasons could be secured prior to the analysis. As a start, let's arbitrarily define a successful project as one that had S/C values > 1 for 40 of the 48 total analyses and P values $\leq$ 0.05 (i.e., 5%) for 25 of these 40 analyses. On that initial basis the PH, WT, SW and ST projects would have to be deemed successful with the SOAR project following closely behind. The Texas Border (TB) project would appear to have been the least successful. Although the tables for the TB project can be found in Appendices B and C, this project has been dropped from the rest of the presentations in the body of the text. Before jumping to any definitive conclusions, however, it is important to look closer at the results for the individual projects.

The next step was an examination of the results of the original method (i.e., RVR199) after making control matches within 3 hours of each seeding event as shown in Figure 6. The ordinate of the plot is seeding effect expressed as a percentage (SR-1) x 100%) and the abscissa gives the project identifiers. There are three bars for each project. The first corresponds to the apparent seeding effect based on control matches selected from within the seeding target or a nearby target. The second is for matches selected from within and outside the project target and the third is the apparent effect for control matches selected only from outside the seeding target. All matches were selected within 300 km of each seeded unit. The single or double asterisk that appears above some of the results bars gives the P-value support for a particular result. A single asterisk represents a P-value $\leq$ .05 (or 5%) while the P-value represented by the double asterisk represents a P-value $\leq$ 0.01 (or 1%). The largest apparent seeding effect in 5 of the 10 projects represented was produced by control matches made within the seeding target. This could be due to chance or it could be due to a bias whereby the seeding in the target left only inferior units to serve as controls. This is a continuing risk when selecting matches from within a seeding target. This appears to have been a problem for the Pecos seeding project that shows a very large (> 160%) "seeding effect" with strong P-value statistical support but negative effects for matches drawn from INOUT and OUT of the seeding target. This lack of consistency and dependency on where the matching control units were selected suggests that the large positive seeding effect is more likely due to selection biases. The Abilene project is inexplicably negative. The result for the CRMWD (CR) project that has since been discontinued is surprisingly positive. The average seeding effect on rainfall for the strongest (PH, HP, SR, CR, WT, SW and ST) programs is around +20%).

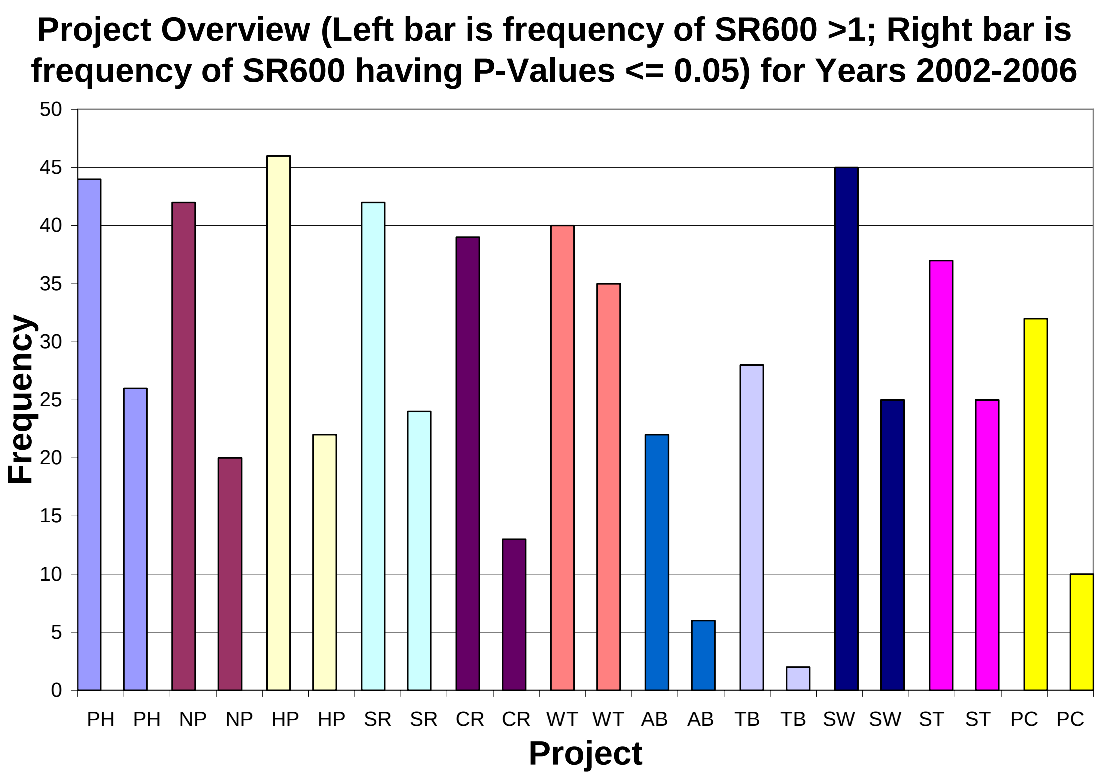

Figure 5. Results overview by project, where the left bar for each project is the frequency of SR600 > 1 and the right bar is the frequency of SR600 values that have P-values $\leq$ 0.05. All project results such as those presented in Table 1 for the WT project are reflected in this plot.

The next step was the expansion of the analysis to a 6 hour match period for the original method (RVR199) (Figure 7). The format and presentation is the same as in Figure 6. Because of

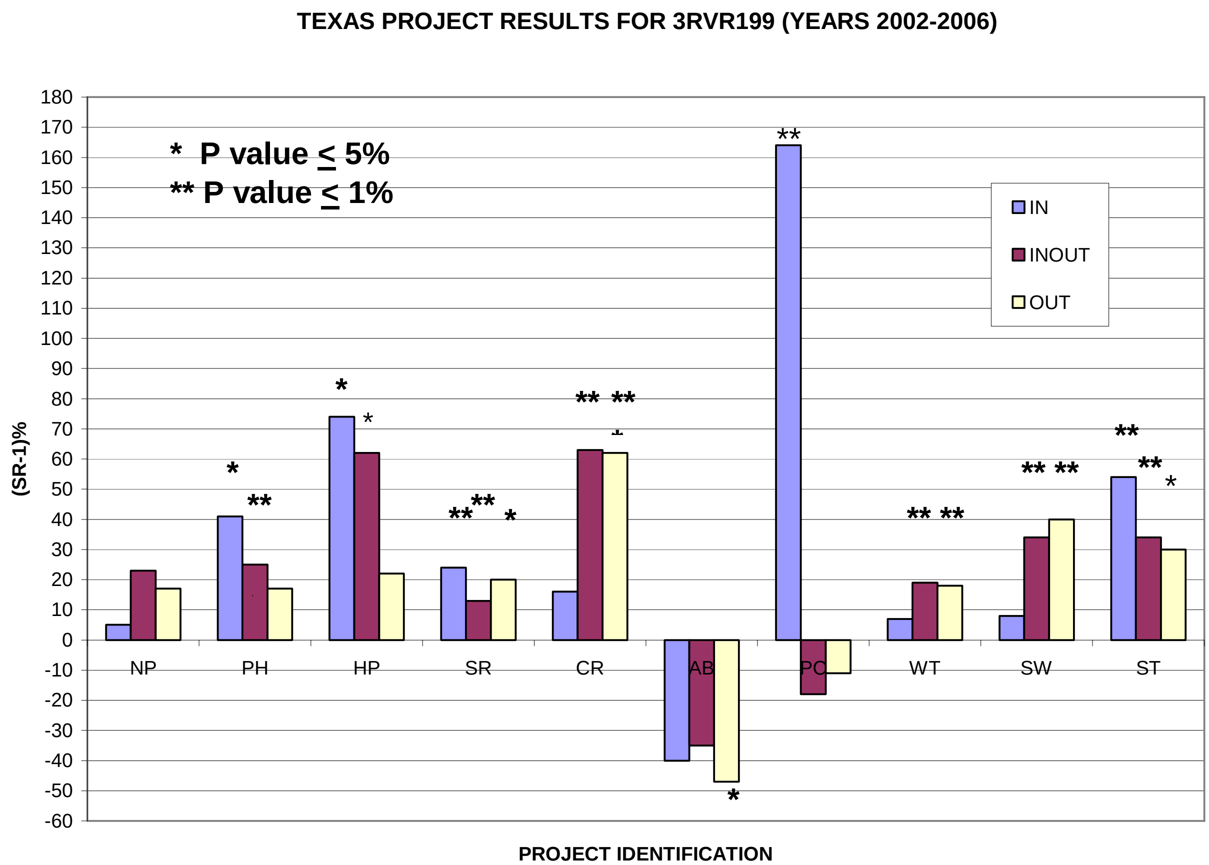

Figure 6. Bar plot of seeding effect (SR-1)100% by project for control matches made IN, IN&OUT and OUTside the seeding target within 3 h of each seeding event using the RVR199 version of the R/W analysis methodology.

the increased (6 h vs. 3 h) period of matching, more units could be matched. In this instance only the INOUT and OUT match permutation is shown because the within target matching appears to lead to results biased in favor of a seeding effect. The apparent seeding effects are roughly the same as with the 3 h match period and those projects showing fairly strong P-value support are the PH, HP, SR, CR WT and ST. Note that the HP project is being carried along through the analyses, because it was apparently the most successful through 2002, the year that it was terminated. Its apparent seeding effect was on the order of 50%, which is larger than the other projects. This is a matter for scientific curiosity since the apparent seeding effects in this project in 1999 and 2000 were quite large as well (See Woodley and Rosenfeld, 2004). It would be interesting to know why this was the case. Again, the Abilene project continues inexplicably negative.

The third step involved an attempt to account for possible selection biases by resorting to the RVR113 version of the method. Recall that one of the match provisions of the original R/W method requires that the radar-derived rain-volume rate (RVR) of each S unit and its matching C unit not differ by more than 1 dBZ (25% in rainfall rate) at the time of the initial seeding and not more than 9 dBZ (essentially unrestricted in rainfall rate) at 15 and 30 minutes after seeding. Thus, there was no way to account for run away matches whereby the S and C unit matches could differ enormously by 15 and 30 min after initial seeding. To address this potential problem the match requirements were extended to 15 and 30 min after initial seeding. In one version of the method (RVR113) the S and C matches could differ by 1, 1 and 3 dBZ at 0, 15 and 30 min after the initial seeding. Under this sensitivity version of the method all matches that did not satisfy these sequential criteria were discarded, resulting in a decreased match sample, especially when the matches were drawn from the seeding target (Table 2). The results of the Texas evaluation using the RVR113 version of the method are given in Figure 8.

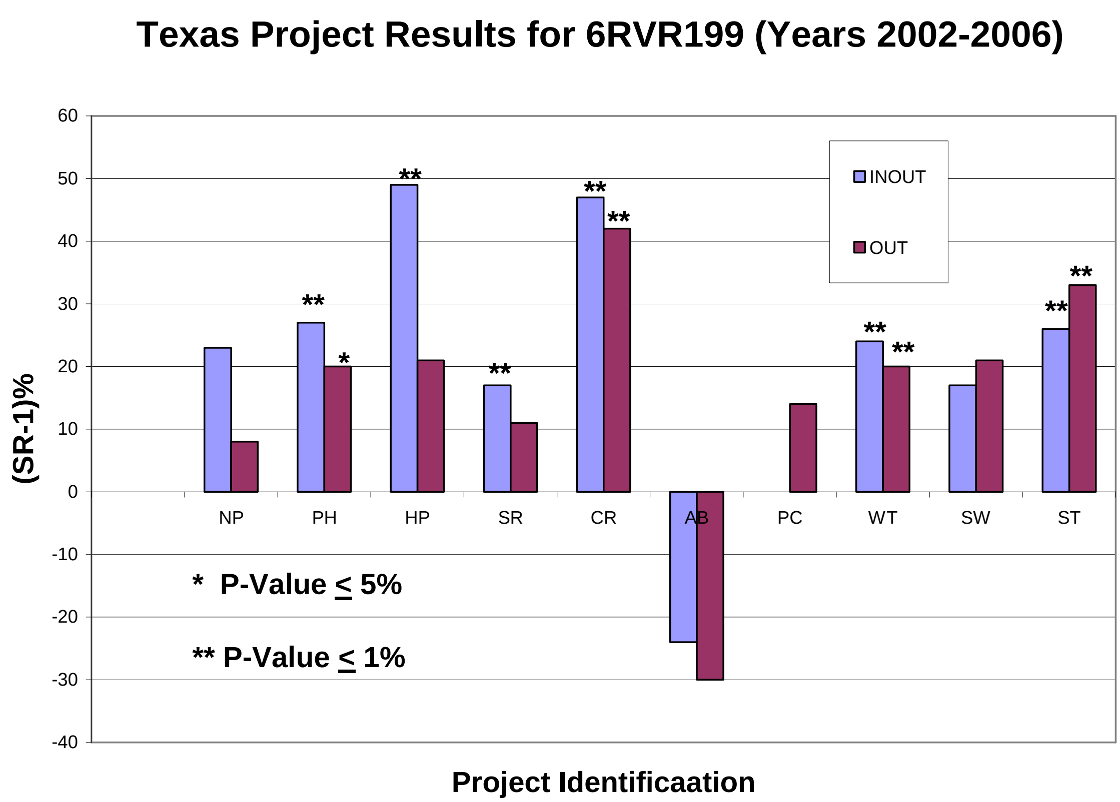

Figure 7. Bar plot of seeding effect (SR-1)100% by project for control matches made IN&OUT and OUTside the seeding target within 6 h of each seeding event using the RVR199 version of the R/W analysis methodology.

TABLE 2 RVR113 SAMPLE SIZE BY PROJECT AND MATCH LOCATION

PROJECT	IN	INOUT	OUT
	#	#	#
NP	2	60	47
PH	37	169	98
HP	7	31	19
SR	18	92	65
CR	5	28	19
AB	1	25	10
PC	12	42	30
WT	36	340	283

SW	20	110	78
ST	36	139	104

The presentation in Figure 8 is similar to that in Figures 6 and 7. Upon considering the content of Figure 7, one first has to look at the sample sizes given in Table 2. The sample for the in-target matches (IN) is too small for the results of this partition to be taken seriously, especially for the NP, HP, CR and AB projects. The samples are much larger for matches selected within and outside the target and outside the target and the results are likely more reliable. On that basis the plot suggests a positive seeding effect for the PH, HP, SR, PC, WT, SW and ST projects. The evidence is strongest for the WT and ST projects.

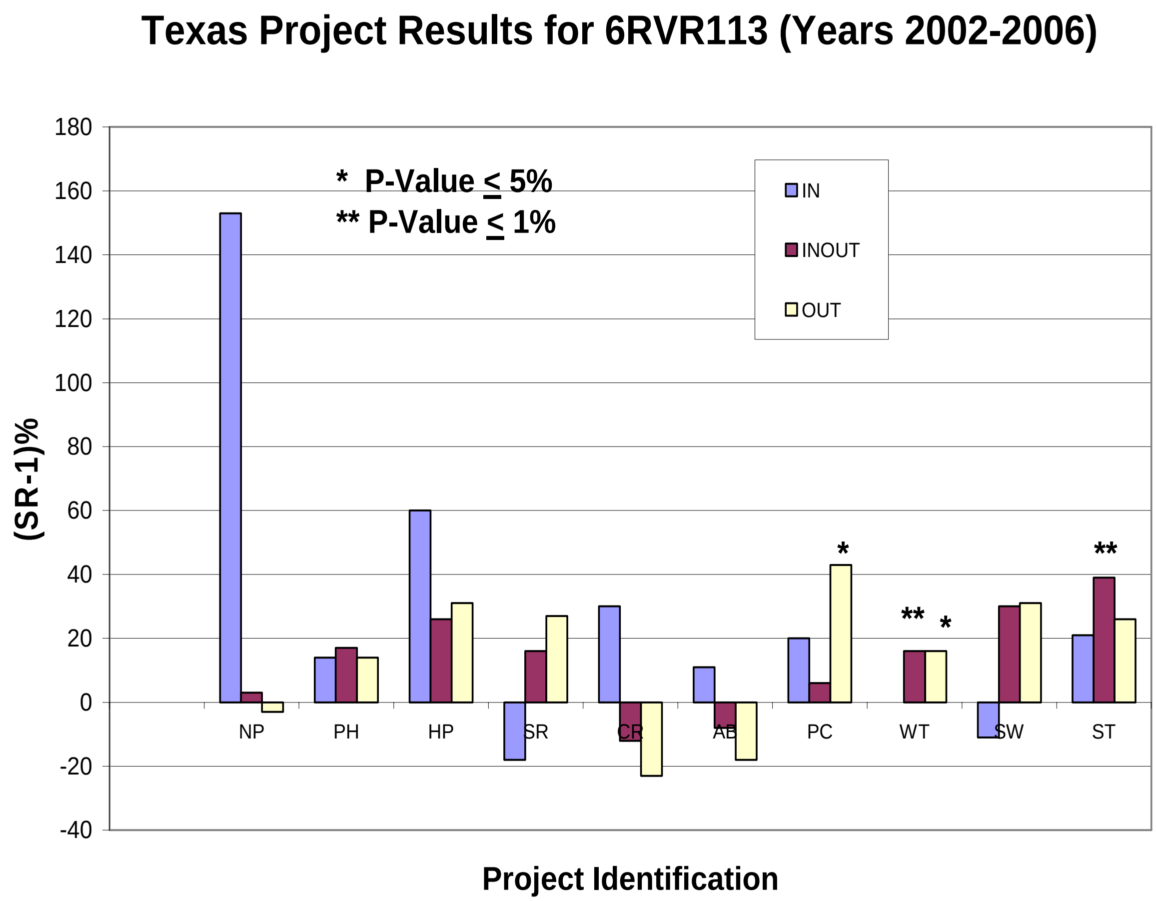

Figure 8. Bar plot of seeding effect (SR-1)100% by project for control matches made IN, IN&OUT and OUTside the seeding target within 6 h of each seeding event using the RVR113 version of the R/W analysis methodology.

The next analysis iteration involved 12 h matches IN&OUT and OUT of the seeding targets for the RVR113 version of the methodology. Matching over 12 hours is actually equivalent to archival matching whereby C matches are drawn from the entire unit archive. When this is done virtually all of the S units, shown in the bar frequency plot in Figure 9, can be matched many times. Note that there is more than a factor of 10 variability in the number of S units from project to project for the full period from 2002 through 2006 (e.g., 1040 for WT vs. 94 for AB). Although the capability of matching all units is a major plus for the method, archival matches have major disadvantages, because they are not likely to match the weather conditions under which the S units existed. Further, 12 h matches from the unit archive are biased against the S units because the majority of the matching controls will be drawn from the most active convective days that will overwhelm the S units obtained on less active convective days. The results of the archival matches are shown in Figure 10.

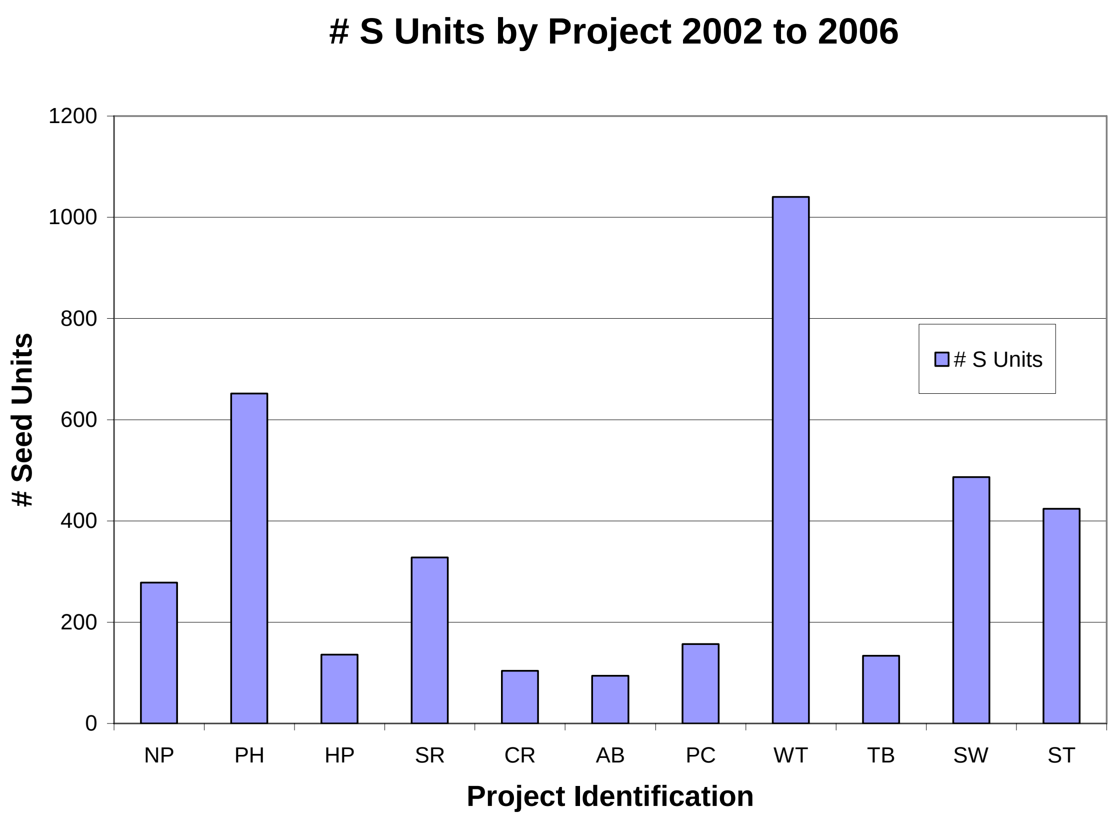

Figure 9. The number of Seed units by project for the 2002 through the 2006 seasons.

Some projects (i.e., NP, HP, WT and SW still are showing positive seeding effects, but the apparent effects are smaller and less significant except for the old HP project. This is as to be expected for the reasons given above. The main value of this analysis is to show off the power of the methodology in that it can make matches with S units using the entire archive. It is not particularly useful in this case, however, because of the inherent biases against an effect of seeding.

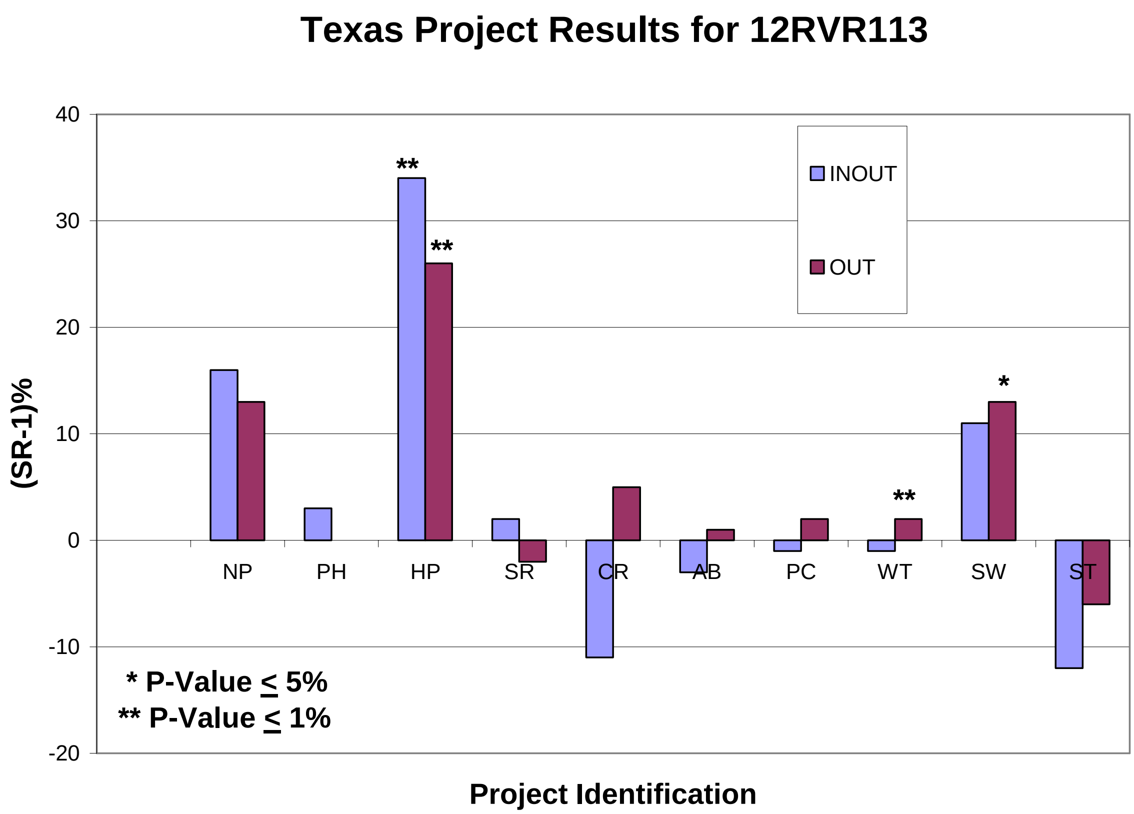

Figure 10. Bar plot of seeding effect (SR-1)100% by project for control matches made IN&OUT and OUT of the seeding targets within 12 h of each seeding event using the RVR113 version of the R/W analysis methodology.

To complete this section it is useful to summarize the results to determine which projects provide the strongest evidence for an effect of seeding, expressed either as a percentage change or as a volumetric rain increment in kilotons (divide by 1.23 to convert kilotons to acre-feet). This is done in Table 3. In preparing the table the results obtained by using the original RVR199 version of the method for 3h and 6h matches selected from within and outside each project seeding target were considered. In addition the results for the RVR113 method iteration that takes into account potential biases were examined for consistency with the RVR199 results.

The tabular results indicate that the PH, SR, CR, WT, and ST projects are the strongest of the 10 examined. The RVR113 results for these projects are also positive except for the CR project result, which is negative, making it somewhat weaker than the other four. Overall, these projects provide very strong evidence for positive seeding effects in Texas. The SW and HP projects are also quite positive for both the RVR199 and RVR113 method iterations, although their P-value support is a little weaker than the first five projects. Typically, the sizes of the effects range between 20 and 25%, although the CR and HP projects are greater. The volumetric rain increment ranges between 2,000 and 3,000 kilotons. Again, the increments for the CR and HP projects are larger. The results for the AB and PC projects appear negative although they are based on a small sample and have very weak P-value support. Considering that the seeding in these projects was conducted around other "positive" projects, the negative results are difficult to understand. Further analysis is needed. Partitioning is usually helpful in this regard.

TABLE 3
SUMMARY OF PROJECT RESULTS BASED ON RVR199 3H AND 6H INOUT MATCHES

PROJECT	% CHANGE	AVG. RAIN INCREMENT KILOTONS	P-VALUE SUPPORT	6RVR113 RESULTS
PROJECTS WITH STRONGEST EVIDENCE FOR SEEDING INDUCED RAIN INCREASES				
PH	23 TO 27	3,583	VERY STRONG	POSITIVE
SR	12 TO 17	2,056	VERY STRONG	POSITIVE
CR	47 TO 61	5,297	VERY STRONG	NEGATIVE
WT	23 TO 26	1,990	VERY STRONG	POSITIVE
ST	26 TO 32	2,370	VERY STRONG	POSITIVE
PROJECTS WITH WEAKER EVIDENCE FOR SEEDING INDUCED RAIN INCCREASES				
NP	22 TO 23	2,699	WEAK	POSITIVE
HP	49 TO 61	8,257	STRONG	POSITIVE
SW	17 TO 32	1,970	STRONG	POSITIVE
PROJECTS WITH NO EVIDENCE FOR SEEDING INDUCED RAIN INCREASES				
PC	-18 TO 0	-874	WEAK	POSITIVE
AB	-35 TO -24	-4,034	WEAK	NEGATIVE

3.2 Results as a Function of Unit Age and Initial Unit Rain-Volume Rate (RVR0)

Timing is a major consideration in the conduct of a cloud seeding operation. Thus, the next step in the analysis involved an examination of the project seeding effects as a function of the age of the unit when it was first seeded, because the results reported in JAM showed that the size and sign of a seeding effect is dependent partially on unit age at seeding. In doing the analysis it was required that the prospective control match be of the same age at the time in its history when it was matched with the seed unit. The results by unit age for the RVR199_6h_INOUT (i.e., original method, 6 h matches from within and outside the seeding targets) was used to study the effect of unit age. Other analysis permutations produced essentially the same result. The preference here is on the original method (i.e., RVR199) for matches selected from within and outside the seeding targets within 6 hours of the initial seeding of each seeded unit.

In this analysis a young unit was one that had existed no longer than 60 minutes at its time of first seeding while a middle-age unit had an age of 75 to 120 minutes at its first seeding. An old unit was one that had existed on radar 135 minutes or longer. The results shown in Figure 11 are highly revealing. In all ten projects the percentage seeding effect was greatest for the young seeded units and smallest, even negative for the AB project, for the old seeded units. This consistency suggests that seeding was operative even in the two weak projects (AB and PC) even though the overall seeding effects were negative in both projects. The percentage seeding effects in young units exceeded 100% in 6 of the 10 projects studied even exceeding 200% in 2 (HP and SW) of these 6 projects.

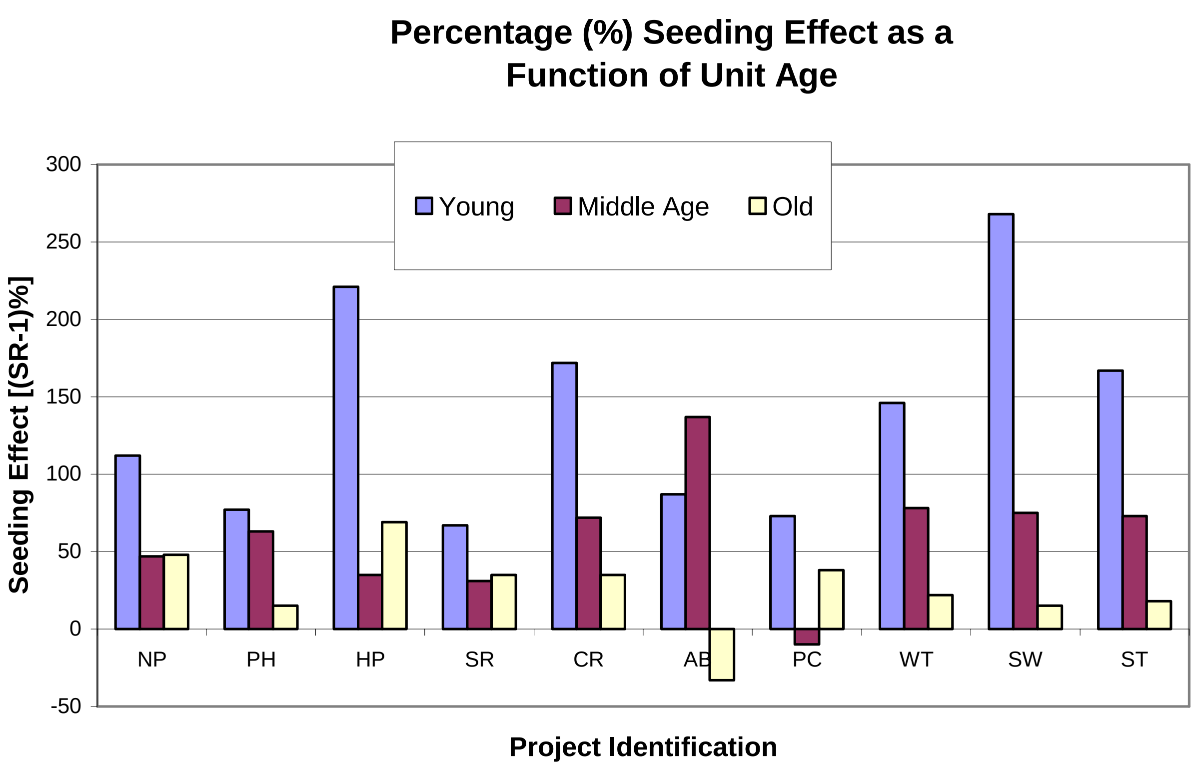

Figure 11. Bar plot showing the unit seeding effect [(SR-1)100%] for each project as a function of the unit age at seeding relative to the time that radar echo first appeared in the unit. Young, middle age and old units have time frames of 0-60, 75-120 and $\geq$135 minutes, respectively, after echo first formed in the unit.

The rain increments (in kilotons) for the units as a function of age are also of intense interest (Figure 12). As one would expect, the volumetric rain increments are greatest for the young seeded units, reaching a staggering 25,000 kilotons (i.e., 20,325 acre feet) per young unit for the old HP program. In 4 of the other 9 projects the seeding increment exceeded 10,000 kilotons. Even when seeding older units, however, there was still a positive payoff except for the AB and PC programs that had small negative increments. The obvious lesson here is that a project is better off seeding convective units early in their lifetimes.

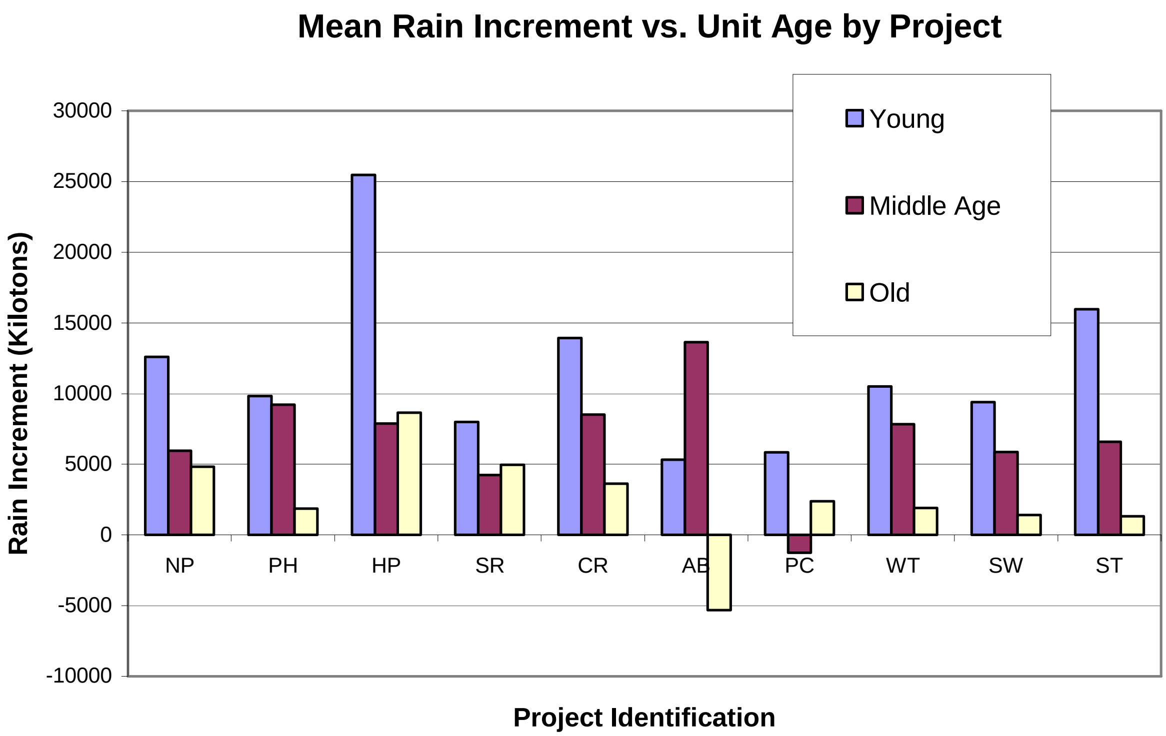

Figure 12. Bar plot showing the seeded rainfall increment in kilotons for each project as a function of the unit age at seeding relative to the time that radar echo first appeared in the unit. Young, middle age and old units have time frames of 0-60, 75-120 and ≥135 minutes, respectively, after echo first formed in the unit. To convert kilotons to acre-feet divide by 1.23.

An obvious uncertainty to be addressed at this point is whether some of the seeding projects had a disproportionate number of young or old units. This is addressed in Figures 13 and 14, respectively. Figure 13 is a bar plot of the percentage of young (i.e., ≤ 60 minutes old) seeded units and the percentage seeding effect [(SR-1)%] produced by these young units for the Texas seeding projects. Again, the percentage seeding effect is positive and large for all projects even for the AB and PC projects. Of the project unit total, the percentages of young units ranged between 10 and almost 30%. The overall mean was 20%, the mean seeding effect at 600 minutes was 139% and the mean increment was 11,686 kilotons. The percentages of young units for the AB and PC projects were 12% and 22%, respectively. A few other more productive projects (i.e., WT, SW and ST) had even lower maximum young percentages. Thus, one cannot blame the weak seeding results in the AB and PC projects on the lack of young seeded units.

Figure 14 is a bar plot of the percentage of old (i.e., ≥ 135 minutes) seeded units and the percentage seeding effect [(SR-1)%] produced by these old units for the 10 Texas seeding projects. In comparing Figure 14 with Figure 13, note that all of the projects had a higher percentage of old seeded units than young seeded units. The overall mean was 50%. The percentage seeding effects average 26%, producing a mean rain increment of 2,562 kilotons.

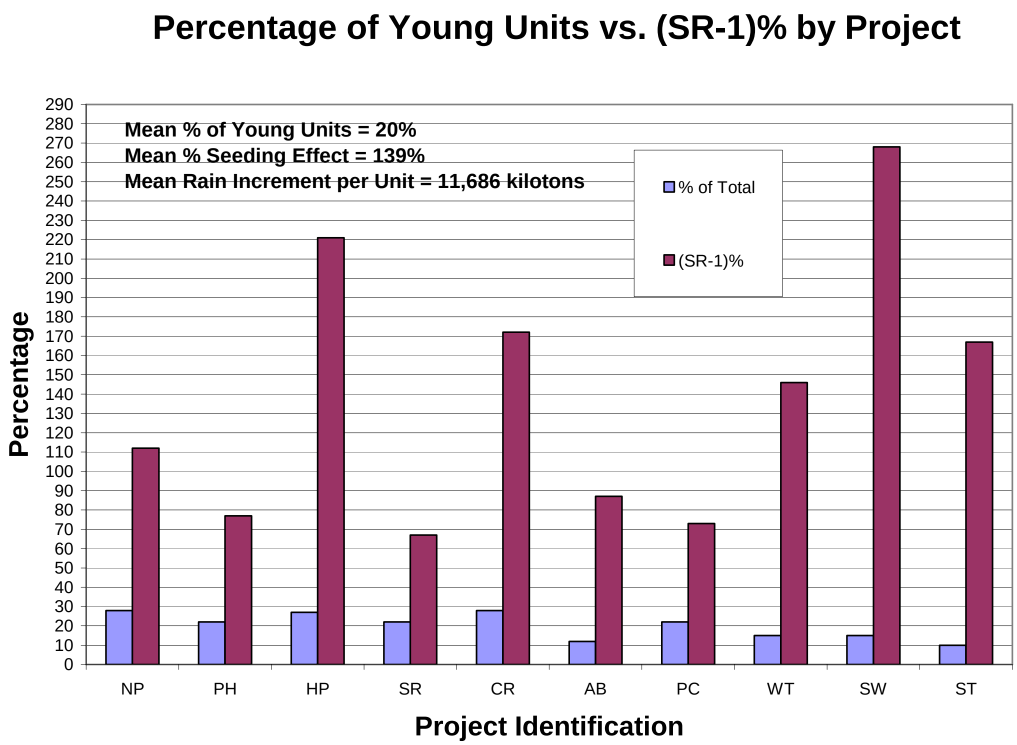

Figure 13. Bar plot by project of the percentage of young (i.e., ≤ 60 minutes old) seeded units and the percentage seeding effect [(SR-1)%] produced by these young units.

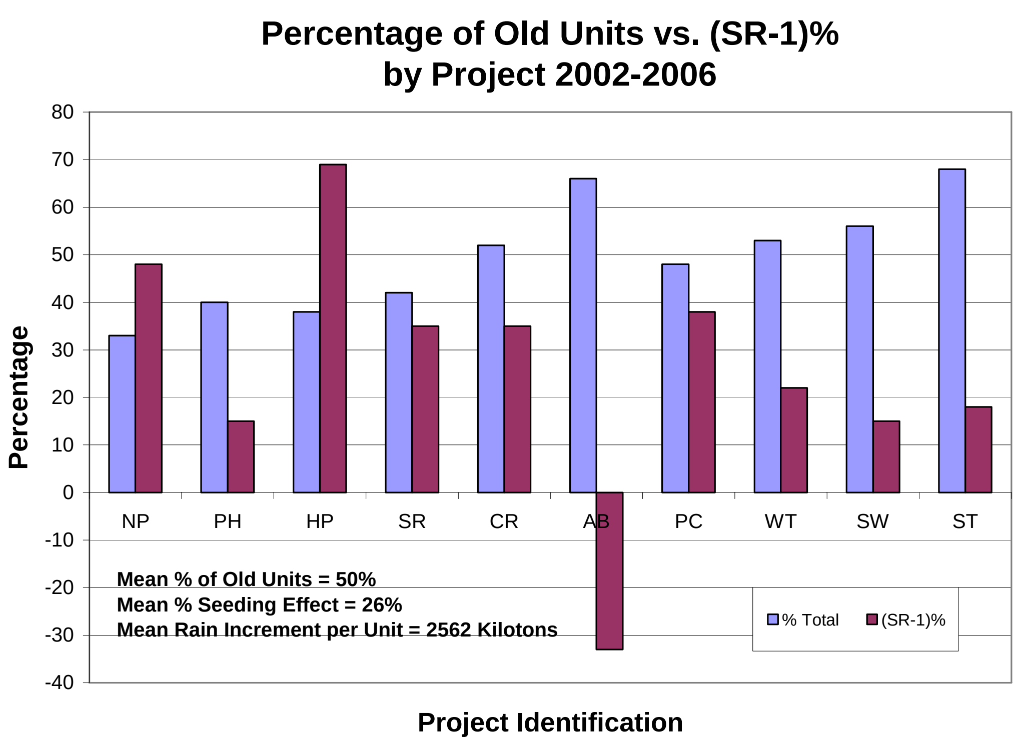

Figure 14. Bar plot of the percentage of old (i.e., ≥ 135 minutes old) seeded units and the percentage seeding effect [(SR-1)%] produced by these old units for the 10 seeding projects.

The unit rainfall results were partitioned further by rain-volume rate (RVR) into three RVR categories (light; 0 to 350 kilotons/h, medium; 350 to 1,000 kilotons/h and heavy; > 1,000 kilotons/h) by the unit rain volume rate at the time of first seeding (RVR0). This partitioning variable is related to unit age because a young unit will usually have correspondingly light RVR0 values whereas an old unit is more likely to have a heavy unit RVR0 at the time of seeding. This is exactly the case as is shown in Figure 15, depicting the project percentage seeding effects as a function of RVR0.

Note that in most cases the percentage seeding effect is greatest in units having light precipitation at the time of initial seeding, somewhat less for units with medium RVR0 values and least for heavy RVR0 values. The obvious exceptions are the AB and PC projects that show little to negative effects of seeding.

All is not lost, however, if one has seeded heavy-rain units as shown in Figure 15. Although the percentage rain increases are least with the old units, the mean S-C rain increments are still quite large for the heavy-rain units because a small percentage increase of a large initial number is still a lot of water (Figure 16). Note that 7 of the 10 projects analyzed had mean rain increases for the heavy-rain units exceeding 10,000 kilotons (Figure 16).

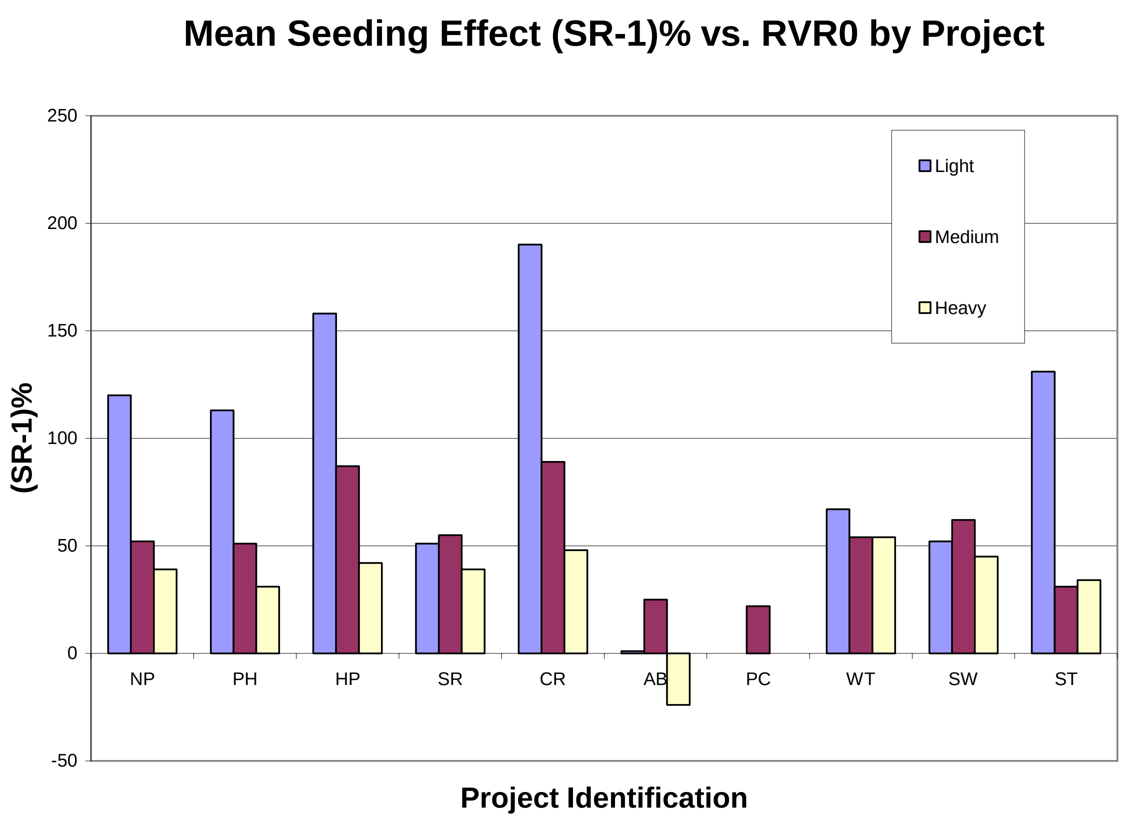

Figure 15. Bar plot of the mean percentage seeding effect [(SR-1)%] as a function of the rain volume rate at the time of initial seeding (RVR0)

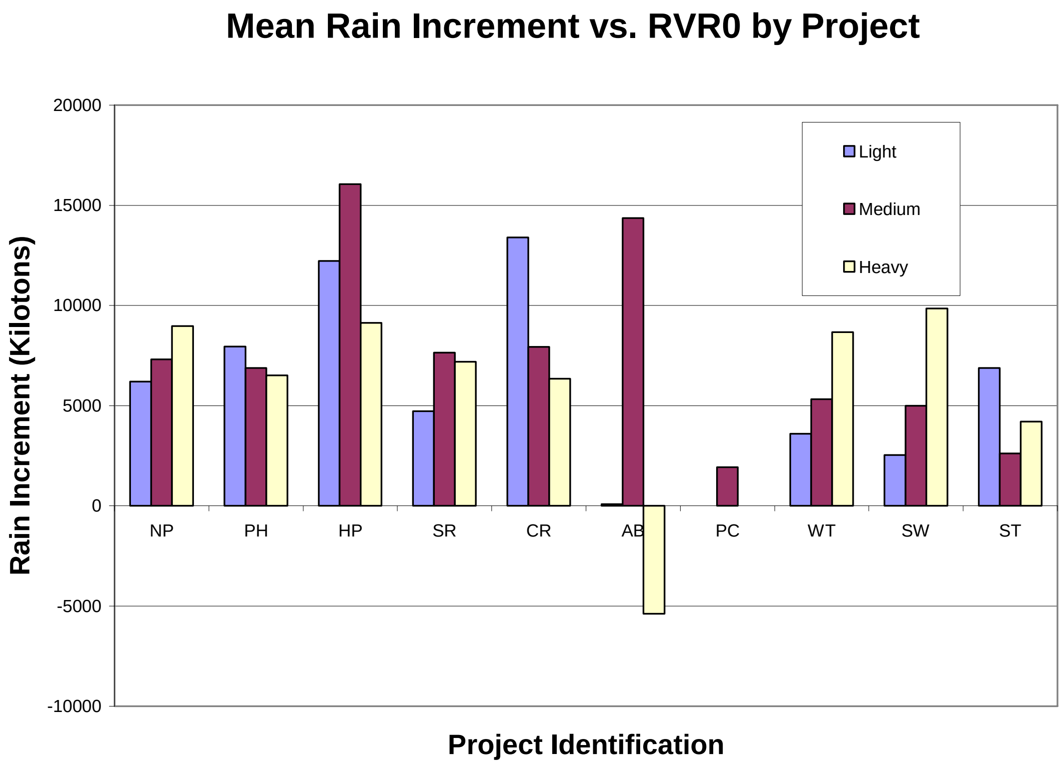

Figure 16, Bar plot of the mean rain increment (S-C) in kilotons as a function of the rain volume rate at the time of initial seeding (RVR0)

3.3 Results as a Function of the Index of Coalescence Activity

A major component of the assessment was the calculation of parameters such as the Index of Coalescence Activity (ICA) that was used to partition the results where the ICA = 8.6 – T_{CCL} + 1.72(PB) and T_{CCL} is the temperature at the convective condensation level and PB is the potential buoyancy at 500 mb for a saturated parcel raised from the convective condensation level (CCL) to 500 mb. If the parcel temperature at 500 mb is greater than the ambient 500 mb temperature, the potential buoyancy is positive and equal to the temperature difference. Conversely, if the 500 mb lifted parcel temperature is less than the ambient 500 mb temperature, the potential buoyancy is negative and equal to the temperature difference. The purpose of this exercise was to determine whether the apparent seeding effects are smaller in clouds with rampant coalescence (i.e., large negative values of the ICA) than in clouds without coalescence (i.e., positive values of the ICA). Resolving this uncertainty is crucial to understanding the results of seeding and it may affect how the projects conduct their seeding operations.

ICA calculations were made for each day of seeding for each seeding project using the 1200 GMT sounding. On days when the seeding went into the night hours, the 0000 GMT sounding for the next day was used. This and the PB and CCL were calculated from the relevant atmospheric sounding that is best matched spatially and temporally to the seeding events. The Amarillo sounding was used as representative of the NP, PH and HP projects. The Midland sounding was used for the SR, CR, AB, PC and WT projects. The Del Rio sounding was used for the SW and TB projects and the Corpus Christi sounding was used for the calculation of the ICA for the ST project.

The results of the ICA calculations by project are provided in Table 4 that has 6 ICA partitions. The heading of each partition gives the range of the ICA values. The top two panels are ICA between 0 and -5 (left) and 0 to 5 (right). The middle two panels are ICA ranging between -5 to -99 (left) and 5 to 99 (right). The bottom two panels give the entire ICA range from 0 to -99 (left) and 0 to 99 (right). Within each partition for each project is the sample size N, the mean seeding effect (i.e., SR-1 where SR is the single ratio of S to C rainfalls) expressed as a percentage and the P-value significance for each result, where the P values were obtained through 3,000 rerandomizations. The line within each partition appears blue if the P value for a given project is $\leq$ 5%, and it appears red if the P-value is $\leq$ 1%. An overview of Table 4 revealed the most coloration within the partitions for which the ICA > 0, especially for ICA > 5. Eleven of the cells in the table have P-values $\leq$ 5% for ICA partitions > 0, while two of the cells in the table (both for the South Texas project) have P-values $\leq$ 5% for ICA partitions < 0 Thus, the indications for seeded rain increases were noted mostly for the ICA partitions > 0. Note that there is the suggestion of positive seeding effects for the partition when ICA ranges between 5 and 99 but no evidence for rain increases when the ICA ranges between -5 and -99.

The South Texas project (and to a lesser extent the Southwest Texas project) is a special case. It is the only project for which positive seeding effects are indicated (based on the P-value significance values) on days when the ICA was < 0. This was somewhat of a surprise because clouds are typically not suitable for glaciogenic seeding intervention on days with strong in-cloud coalescence (i.e., days with ICA < 0). This analysis does not, however, take into account convective forcing due to convergence along outflow boundaries or in sea-breeze convergence zones. These complicate matters. Under conditions of such forcing the in-cloud updrafts will be stronger than under non-forced conditions. This means that the cloud water will be transported higher into the clouds and take longer to convert to precipitation-sized drops. When this happens the clouds will appear visually harder over a longer time period. Radar meteorologists and seeding pilots usually focus their seeding actions on these more suitable clouds that would not have existed without the forcing. With respect to the South Texas and Southwest Texas projects, therefore, it is suspected that sea breeze forcing has played a role in the apparent seeded rainfall increases.

These overall results make good physical sense, because the clouds on days on which ICA >> 0 should have had little coalescence, increased quantities of supercooled water, and been slow to glaciate. Such clouds should have been responsive to glaciogenic seeding intervention. The positive seeding results for the ICA range -5 to +5 are not too surprising because it is questionable how well the ICA quantifies coalescence intensity either side of the 0 demarcation. The lesson to be learned here is that days with ICA values > 0 are to be preferred for cloud

Texas Seeding Effects as a Function of the Index of Coalescence Activity (ICA)
ICA = 8.6 - Tccl +1.72(PB)

TABLE 4

	ICA -5_0			ICA 0_5		
Project	N	(SR-1)%	SIG	N	(SR-1)%	SIG
North Plains	2	-19	NA	45	18	25.7
Panhandle	30	-21	71.6	118	47	0.6
High Plains	7	-35	63.5	24	28	24.2
SOAR	**6**	**-45**	**NA**	**62**	**-9**	**70.4**
Pecos	5	NA	NA	51	29	10.2
CRMWD	2	-28	NA	17	3	45.1
Abilene	1	NA	NA	12	-32	86.2
West Texas	**38**	**15**	**35.1**	**302**	**3**	**37.9**
Texas Border	**30**	**61**	**9**	**27**	**-7**	**54.1**
Southwest	101	10	33	94	21	14.5
South Texas	**173**	**46**	**0.1**	**29**	**19**	**27.2**

	ICA -99_-5			ICA 5_99		
Project	N	(SR-1)%	SIG	N	(SR-1)%	SIG
North Plains	0	NA	NA	112	27	7.8
Panhandle	0	NA	NA	280	24	3
High Plains	0	NA	NA	47	-24	74.4
SOAR	**0**	**NA**	**NA**	**111**	**29**	**3.1**
Pecos	0	NA	NA	280	24	3
CRMWD	0	NA	NA	61	67	1.6
Abilene	0	NA	NA	41	-25	85.4
West Texas	**0**	**NA**	**NA**	**328**	**32**	**0.2**
Texas Border	**5**	**NA**	**NA**	9	-21	63.3
Southwest	21	75	25	54	14	29.8
South Texas	**44**	**7**	**37.7**	**1**	**NA**	**NA**

	ICA -99_0			ICA 0_99		
Project	N	(SR-1)%	SIG	N	(SR-1)%	SIG
North Plains	2	NA	NA	156	25	6.1
Panhandle	32	-22	71.7	395	30	0.2
High Plains	7	-35	66	79	57	1
SOAR	**6**	**NA**	**NA**	**173**	**17**	**9.2**
Pecos	5	NA	NA	98	1	48.8
CRMWD	2	NA	NA	78	49	2.1
Abilene	1	NA	NA	57	-24	89.7
West Texas	**38**	**15**	**35.9**	**625**	**19**	**0.9**
Texas Border	**35**	**46**	**14.2**	**36**	**-10**	**60.3**
Southwest	122	17	24	148	17	18.7
South Texas	**217**	**39**	**0.2**	**30**	**12**	**32.6**

Bold entries are 3 h matches. All others are 6 h matches.

seeding because of the higher probability for positive seeding effects. Apparent positive seeding effects were noted on some days with ICA < 0 and these had some P-value statistical support. These were probably on days with strong convective forcing as occurs in sea-breeze convergence zones. There is, however, no P-value support for positive seeding effects on days when the ICA was < -5. Such days probably should be avoided for cloud seeding.

3.4 Plots of Mean Seed and Mean Matching Control Unit Rain-Volume Rates vs. Time

Plots of the mean S and C rain-volume rates vs. time for the Texas seeding programs are usually quite informative. The plot for the old HP program, which was excerpted Woodley and Rosenfeld (2004) is provided in Figure 17. The matching C values were obtained from outside the operational target within 2 hrs of the initial seeding in each unit. Included also in Figure 17 are comparable S and NS plots from the Thai randomized glaciogenic cloud seeding program (Woodley et al., 2003a,b). Considering that one set of curves was generated for an operational cloud seeding project in a semi-arid region of the United States and the other set was generated for a randomized cloud seeding project in Southeast Asia, the plots are surprisingly similar. Both S and C plots peak at roughly the same time after the initial seeding (60 to 90 minutes) with the Texas plots showing greater amplitude than in Thailand, even though Northwest Thailand is by far the wetter location. This “anomaly” is the result of pre-screening in Thailand to eliminate the wettest days before the randomized instructions were drawn whereas in Texas the operational seeding took place on virtually all days, including those on which there was heavy shower activity. Note also that the mean S RVR values exceed the mean C RVR values out to 8 h after initial seeding in both programs. That the apparent seeding effect persists for so long means that some of the rainfall from the S units likely falls outside the operational target as the analysis units drifted across the target boundaries. The persistence of seeding effects also raises questions as to how this came about in both programs.

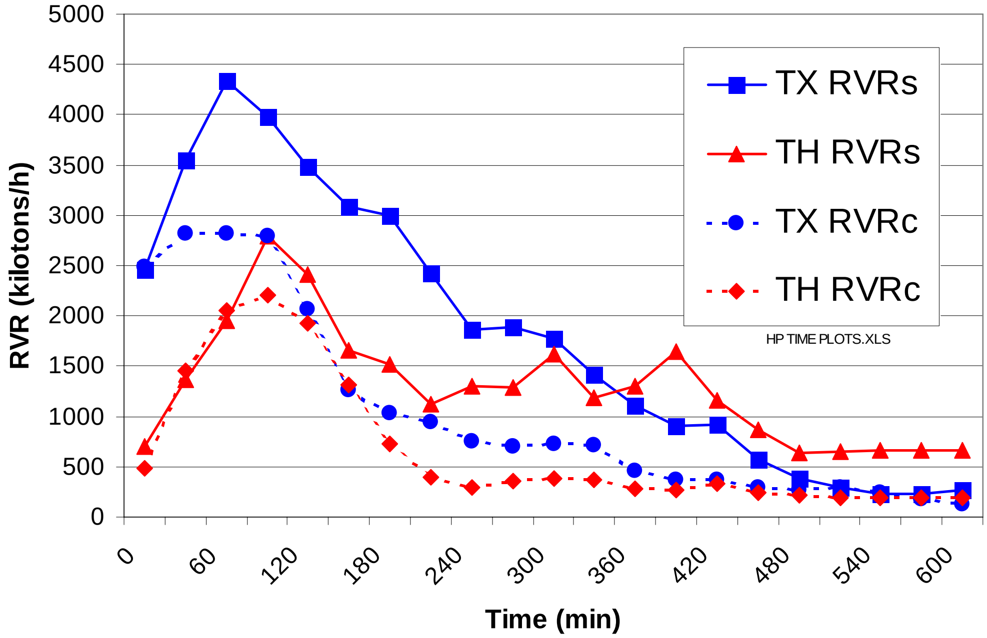

Figure 17. Time plots of mean S and C unit rain volume rates (RVR) in the Texas High Plains Program (Out, 2 hr match) and in Thailand (randomized). Comparable time plots were generated for selected projects for the Texas 2002-2006 analyses. These were done with the original method (i.e., RVR199) for matches drawn from within and outside the seeding targets within 300 km of the seeded unit. The match periods were typically 3 and 6 hours. Time plots were done also for those units that were seeded within 60 min of their appearance on radar since the earlier presented results indicate this is the partition with the strongest positive effect of seeding.

The first plot of the mean S and C RVR vs. time (130 units)) is for the North Plains project for the original method for 3 h matches made within and outside the seeding target (Figure 18). Note how well the S and C means are matched through 60 min after seeding. This is as it should be considering the requirements for a unit match. After that the S value increases to 105 min while the C value had begun its decrease at 45 min., so the S units reach their peak later and rain more than the C units. The comparable time plot for young units in the North Plains project is given in Figure 19. In this instance the plots are very different after nearly a perfect match up to the time of seeding. Subsequently, the S plot continues to grow, reaching a maximum of nearly 1,300 kilotons/h at 225 minutes is on a strong downward trend. If this plot were valid across the board in the North Plains project, it would be a spectacular result indeed.

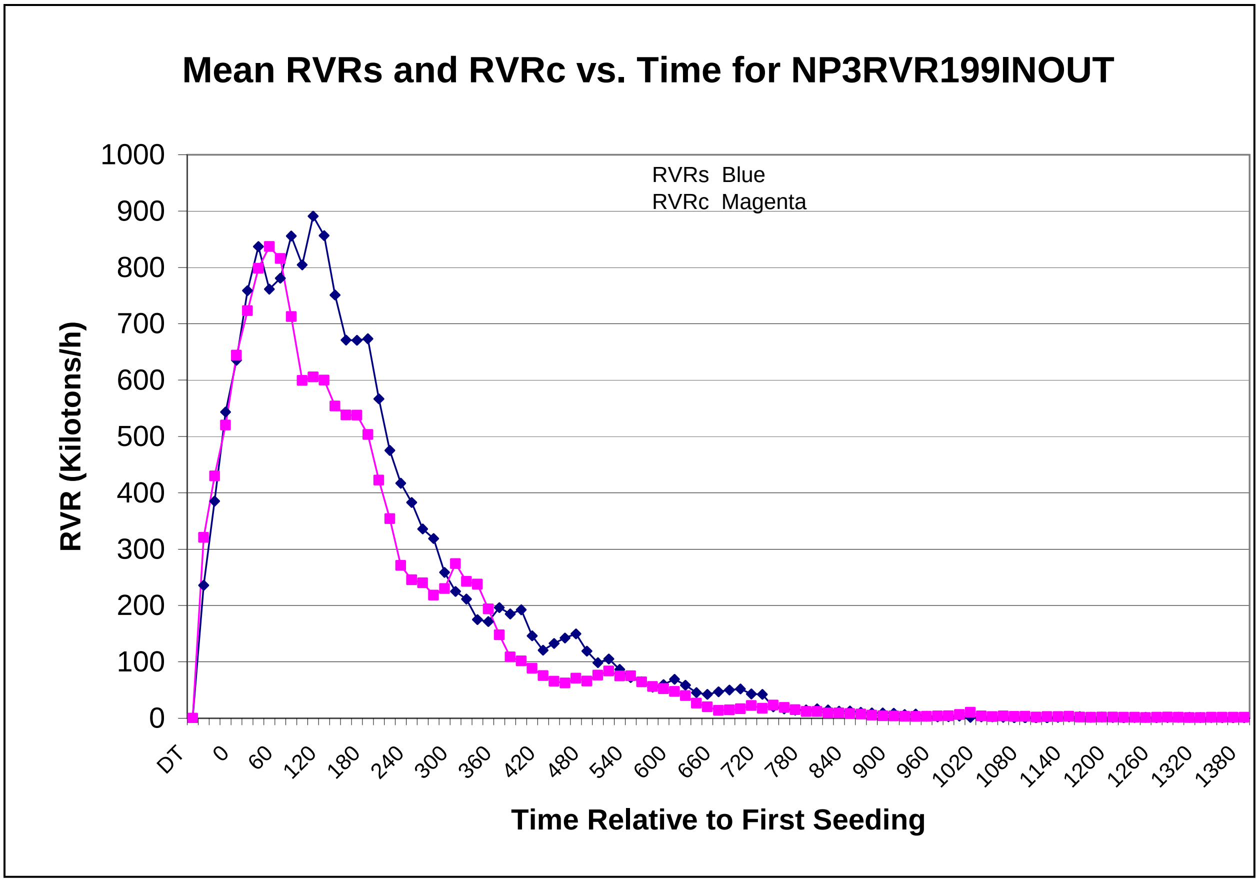

Figure 18. Plot (130 units) of mean S and C RVR obtained from the original method (i.e., RVR199) for 3 h matches selected from within and outside the seeding target for the North Plains project.

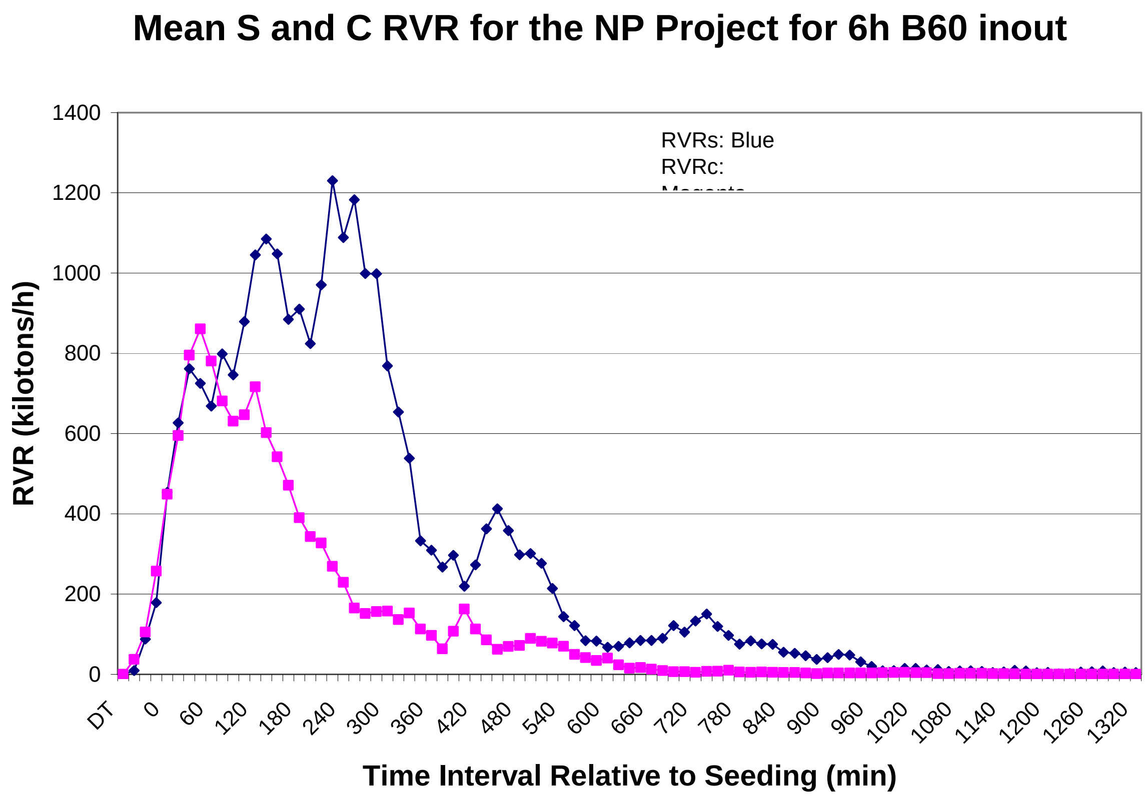

Figure 19. Plot (45 units) of mean S and C RVR obtained for young units from the original method (i.e., RVR199) for 6 h matches selected from within and outside the seeding target for the North Plains project.

Attention then turned to the Panhandle project with the presentation of the mean RVRs and RVRc time plots for the RVR199 method iteration for INOUT matches within 3 h of the unit seedings (Figure 20). The plots are similar to those for the North Plains project (Figure 18), although the apparent seeding effect appears smaller. When looking at the plots for young units (Figure 21), however, the PH and NP plots look very similar. The rain production from seeded young units in both the NP and PH projects was much greater than the rain production by the matching control units.

Comparable paired plots (all and young units) for the SOAR (SR) project are given in Figures 22 and 23, respectively. Note that the S-C RVR differences are small in the overall plot but quite large again in the RVR plots for the young units. This has proven to be characteristic of all of the seeding projects examined so far.

The situation for West Texas is not much different with relatively small overall differences and huge differences when comparing young S to C units head-to-head (Figures 24 and 25). The plots for the SW project are given in Figures 26 and 27. The overall 3 h plot is based on 221 units while the plot for the young units (Figure 27) is based on only 40 units and the plot looks noisy.

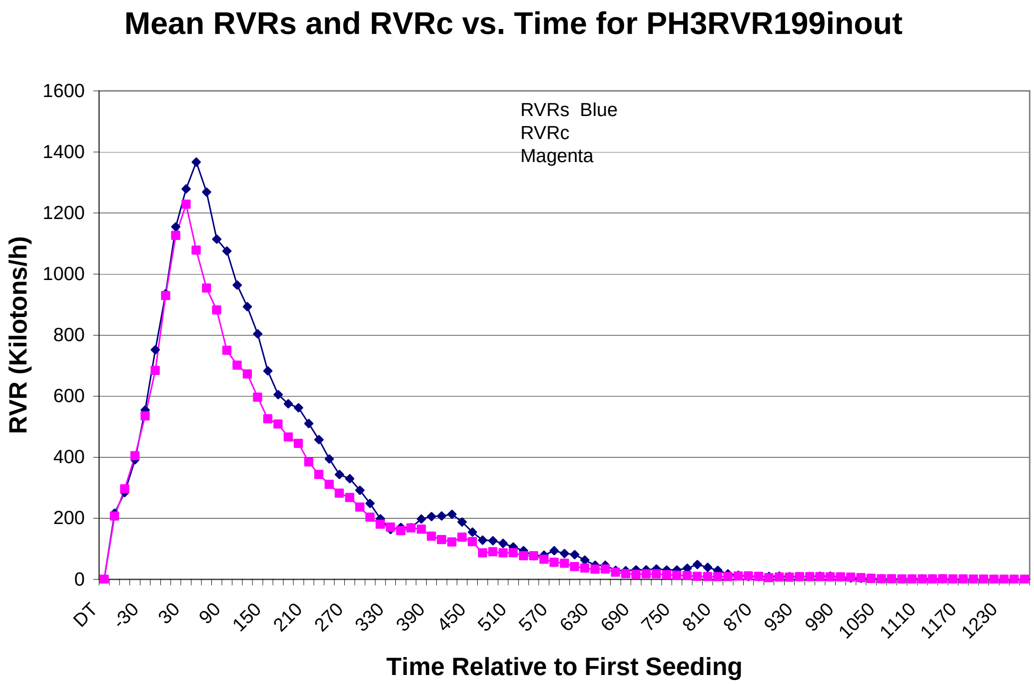

Figure 20. Plot (366 units) of mean S and C RVR obtained from the original method (i.e., RVR199) for 3 h matches selected from within and outside the seeding target for the Panhandle project.

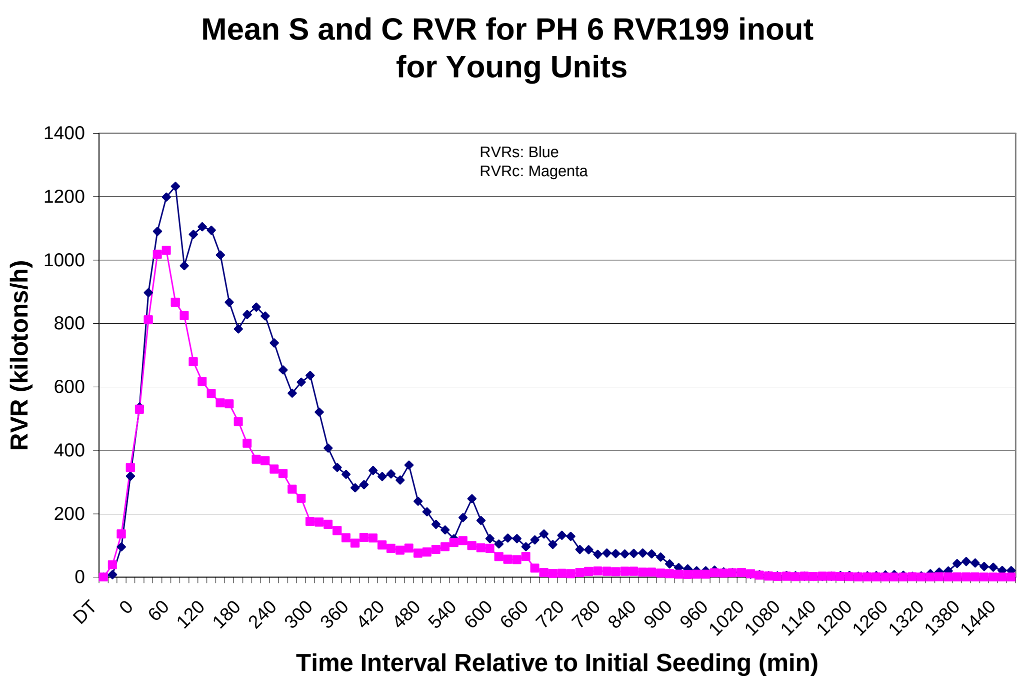

Figure 21. Plot (93 cases) of mean S and C RVR obtained for young units from the original method (i.e., RVR199) for 6 h matches selected from within and outside the seeding target for young units in the Panhandle project.

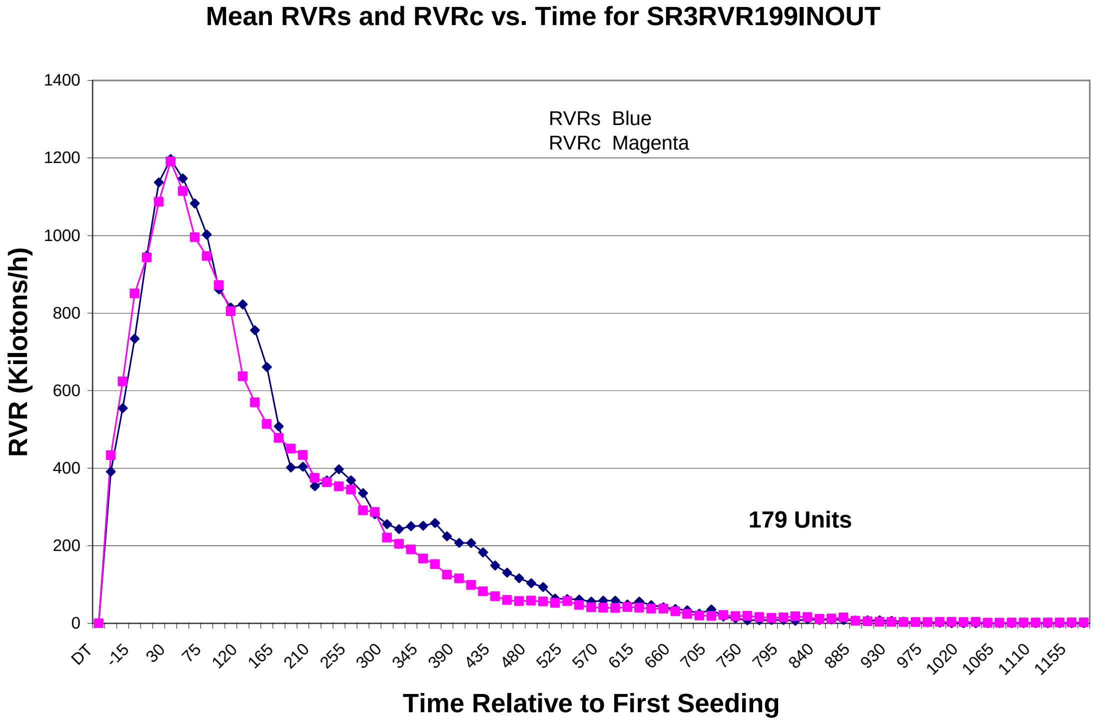

Figure 22. Plot (179 units) of mean S and C RVR obtained from the original method (i.e., RVR199) for 3 h matches selected from within and outside the seeding target for the SOAR (SR) project.

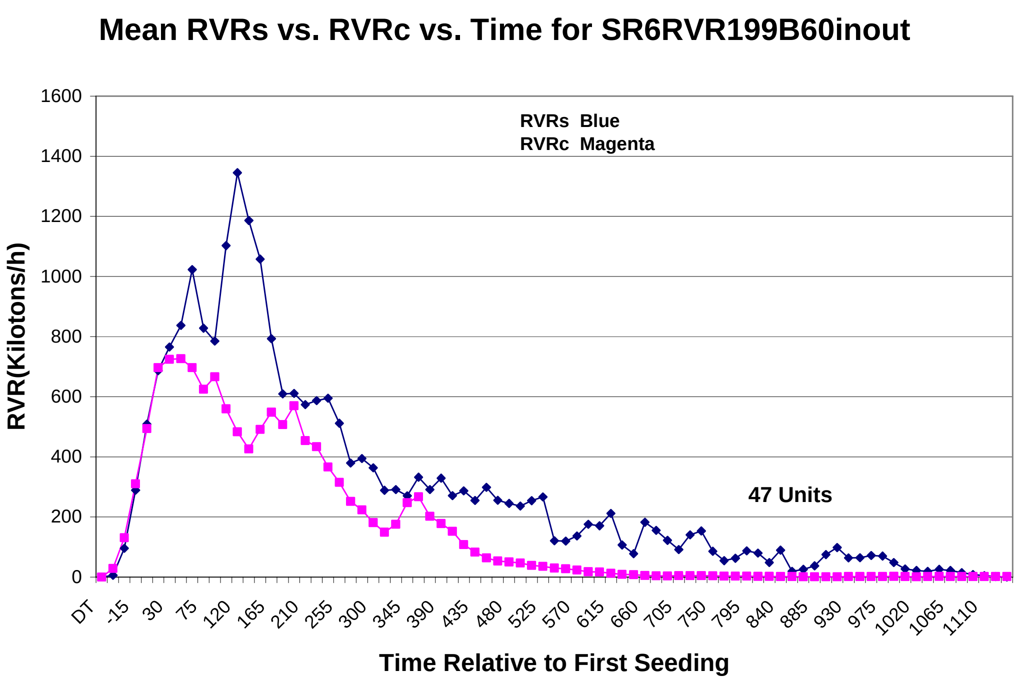

Figure 23. Plot (47 units) of mean S and C RVR obtained for young units from the original method (i.e., RVR199) for 6 h matches selected from within and outside the seeding target for the SOAR (SR) project.

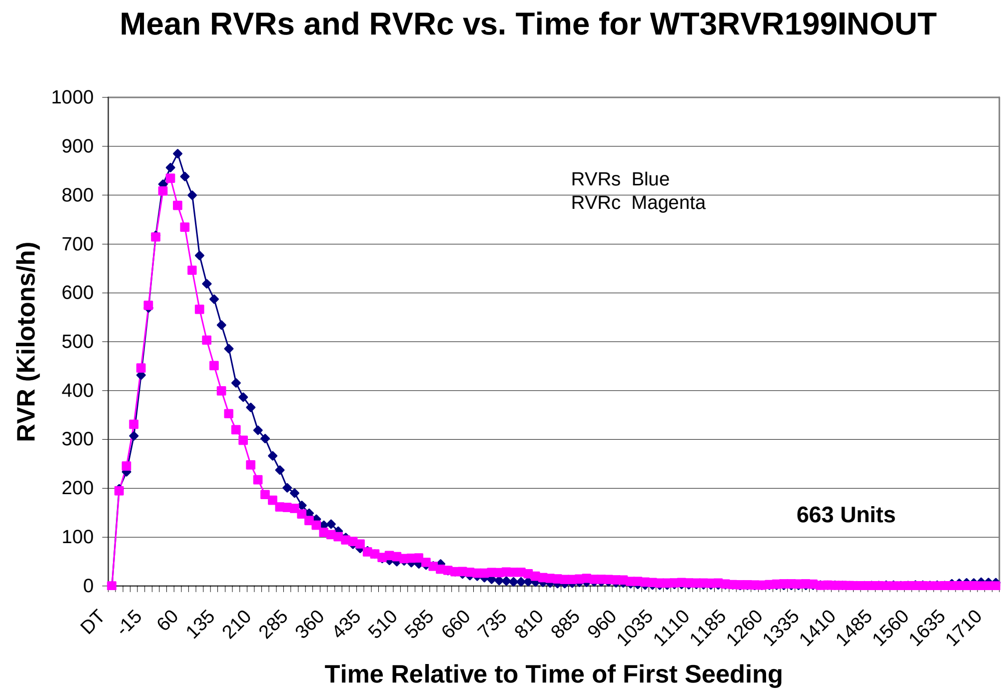

Figure 24. Plot (663 units) of mean S and C RVR obtained from the original method (i.e., RVR199) for 3 h matches selected from within and outside the seeding target for the West Texas project.

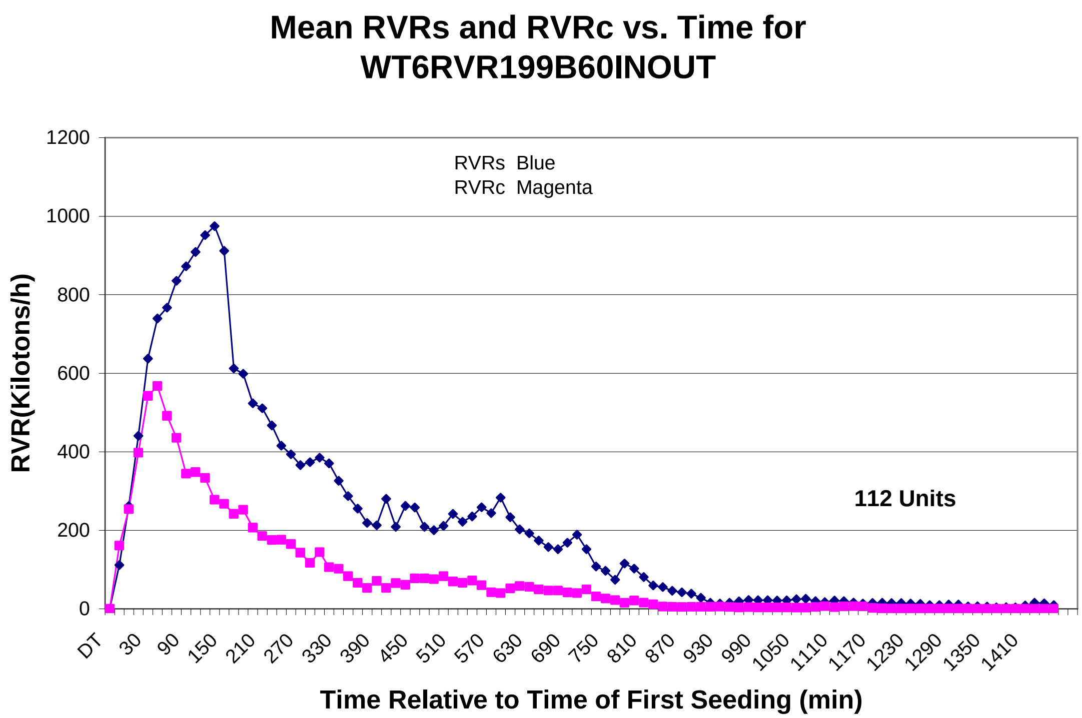

Figure 25. Plot (112 units) of mean S and C RVR obtained for young units from the original method (i.e., RVR199) for 6 h matches selected from within and outside the seeding target for the West Texas (WT) project.

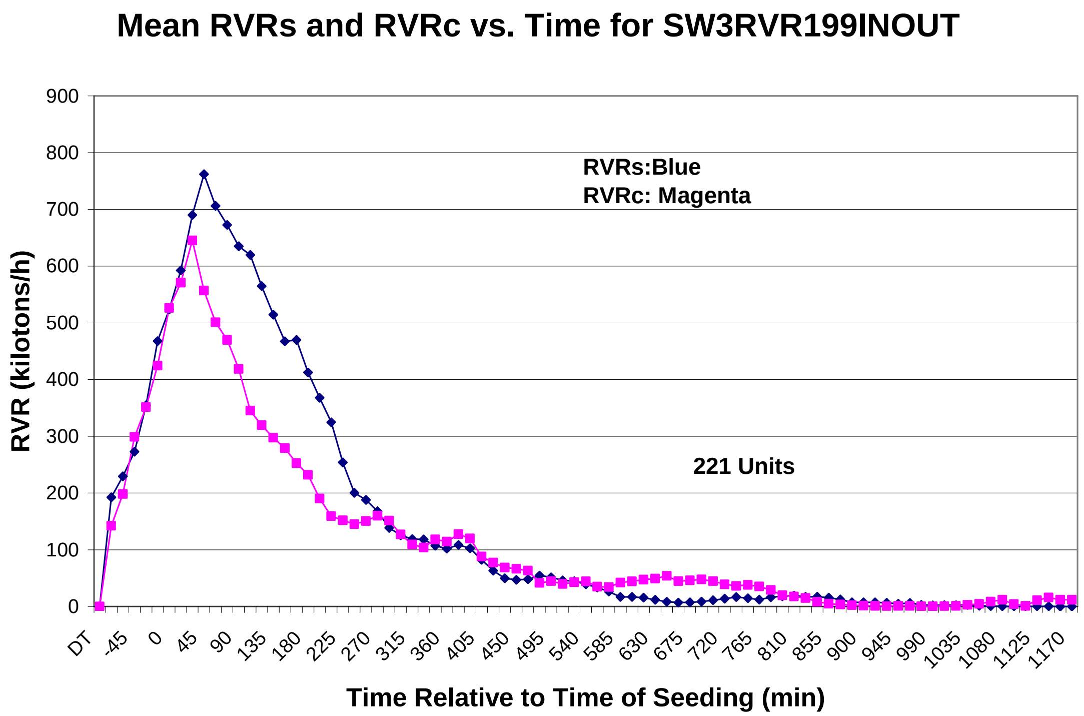

Figure 26. Plot (221 units) of mean S and C RVR obtained from the original method (i.e., RVR199) for 3 h matches selected from within and outside the seeding target for the Southwest (SW) seeding project.

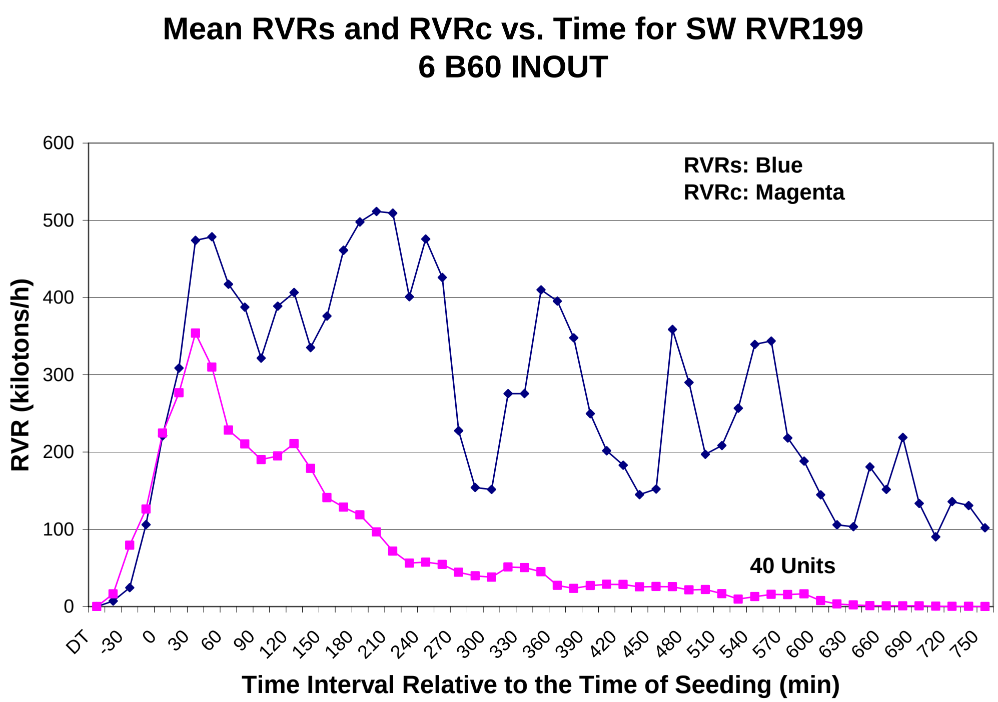

Figure 27. Plot (40 units) of mean S and C RVR obtained for young units from the original method (i.e., RVR199) for 6 h matches selected from within and outside the seeding target for the Southwest (SW) seeding project.

The last project to be examined with RVR time plots is the ST project. The plot for the 3 h matches for the RVR199 version of the method drawn from in and outside the seeding target (Figure 28) shows near coincidence of the RVRs and RVRc lines through and immediately after the initial time of seeding. This near perfect initial coincidence of the plots is highly gratifying. As is typical for the other projects, the lines diverge thereafter with the S units peaking later and higher than the matching C units. This pattern is enhanced in the RVR plots for the young S and C units (Figure 29) where the differences, although based on a rather small sample, are quite dramatic. If this consistent pattern is real, it implies that seeding works quite effectively on young units.

Comparable plots could have been generated for the remaining seeding projects, but the sample sizes were generally too small to warrant reaching any conclusions regarding the outcomes. Those that were generated for the NP, PH, SR, WT, SW and ST projects are justified by the strong evidence for positive seeding effects in these projects.

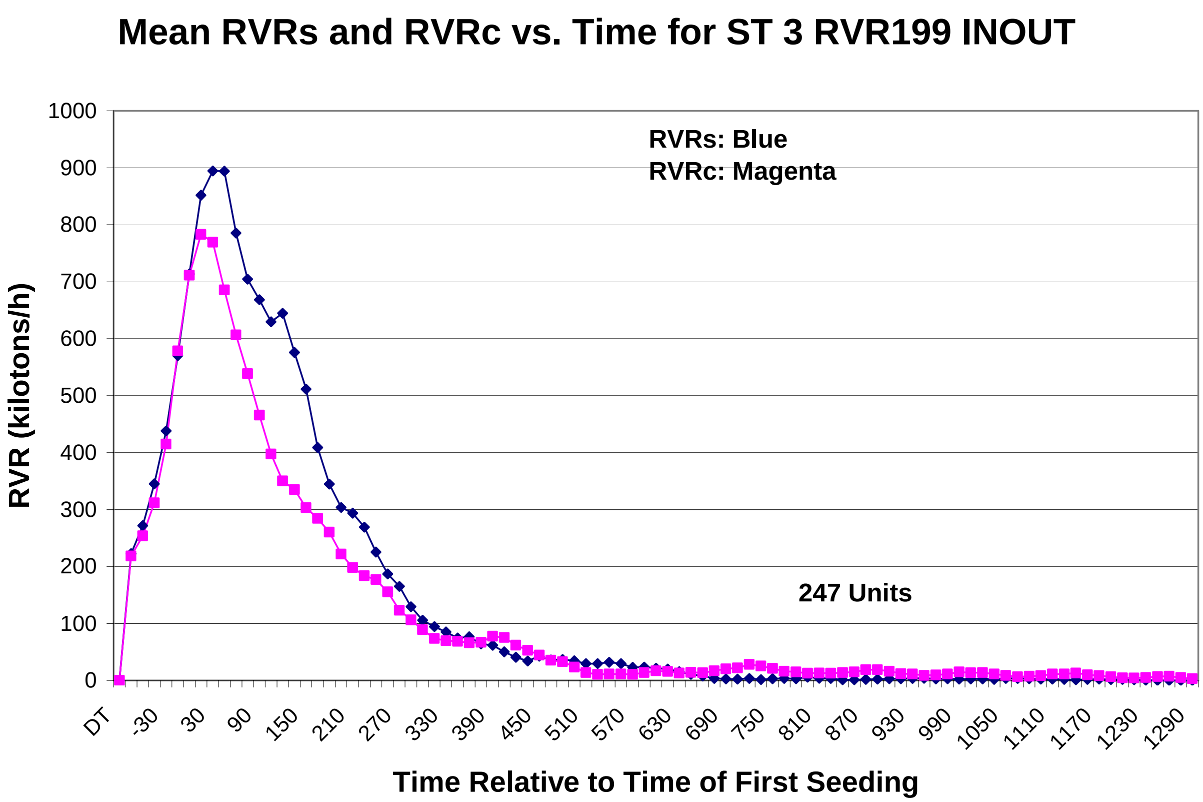

Figure 28. Plot (247 units) of mean S and C RVR obtained from the original method (i.e., RVR199) for 3 h matches selected from within and outside the seeding target for the South Texas (ST) seeding project.

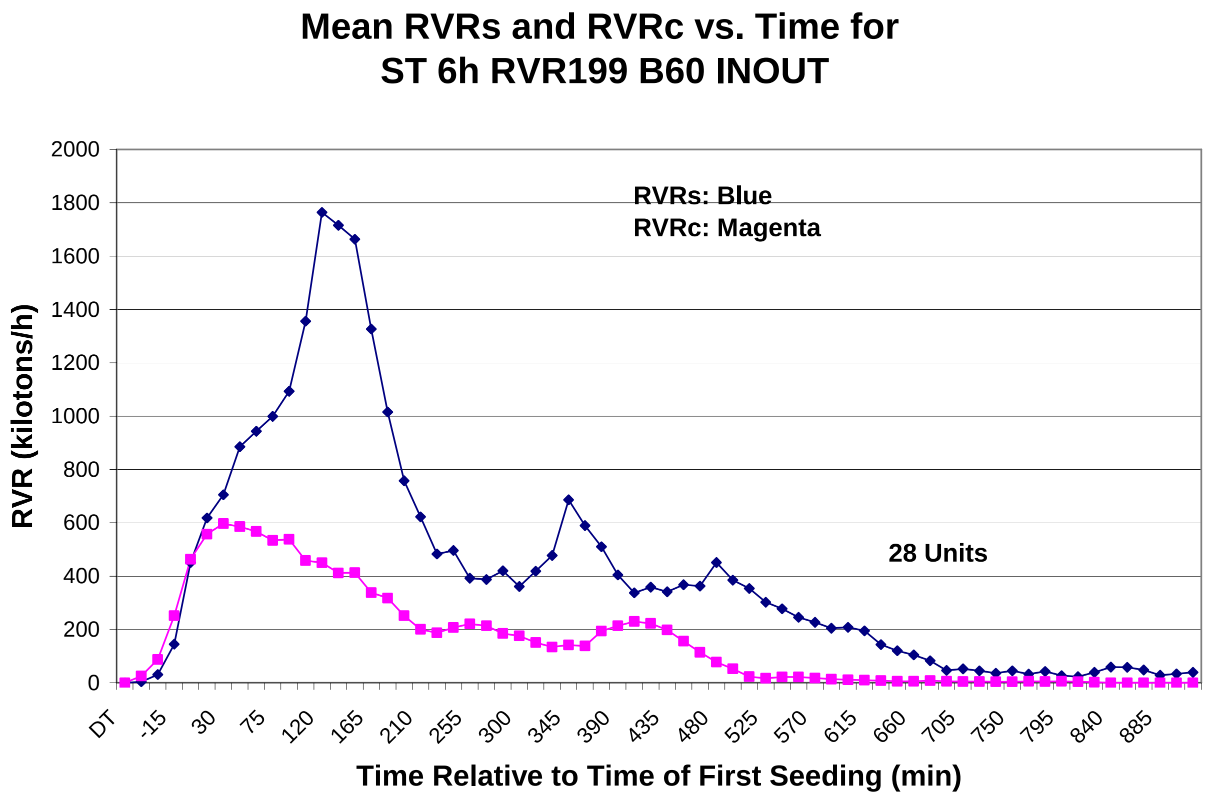

Figure 29. Plot (28 units) of mean S and C RVR obtained for young units from the original method (i.e., RVR199) for 6 h matches selected from within and outside the seeding target for the South Texas (ST) seeding project.

The time plots of the mean rain-volume rates for the S and matching C units are strongly supportive of a positive effect of seeding. Typically, the plots are nearly coincident up to and immediately after the time of initial seeding. Subsequently the S and C plots diverge with the S units peaking later and producing more rainfall than the C units. Positive seeding effects persist in most cases for 5 h or more. This pattern is enhanced greatly in young units that were seeded before they reached an age of 1 hour. Such units are apparently highly responsive to seeding intervention.

This shows even for the Pecos project that provided little evidence for seeding-induced precipitation increases. The time plots for young seeded units in Pecos for 12h matches for the RVR113 version of the R/W version of the method (Figure 30) suggest a positive effect of seeding. It is, however, based on only 26 cases. This may represent a real effect of cloud seeding even though the other presentations do not indicate a positive effect of seeding. It is best to be cautious at this point and wait for more unit data for further analyses. At this point in its history, the evidence does not suggest a positive effect of seeding in the Pecos project.

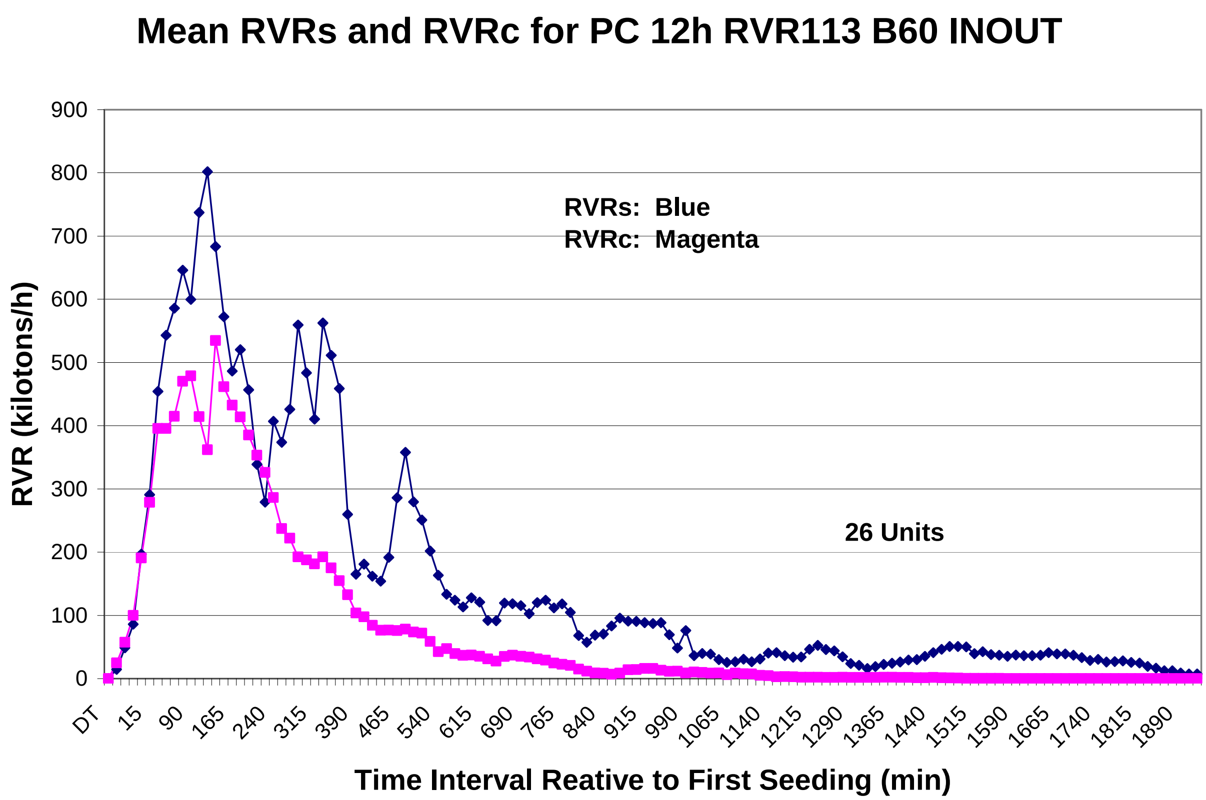

Figure 30. Plot (26 units) of mean S and C RVR obtained for young units from the version of the method that accounts for biases (i.e., RVR113) for 12 h matches selected from within and outside the seeding target for the Pecos (PC) seeding project.

4.0 ESTIMATION OF TOTAL PROJECT RAIN VOLUME INCREMENTS

Because all of the Texas seeding projects are focused on enhancing the precipitation, there is an obvious interest in how much additional precipitation might have been produced in the period 2002 to 2006. A crude way to approach this is to determine the average unit rain increase by project and then to multiply this number by the number of seeded units that were obtained during the 2002 to 2006 period of operation and evaluation. This will work for some projects that provided a complete seeding record, but it will underestimate the amount of additional rainfall for those projects that provided an incomplete seeding record, resulting in an underestimate of the number of seeded units and their rainfalls. In any case this is a very crude estimate of total project seeding effects, because there is no way of knowing the effect of seeding beyond the unit boundaries. The details of the calculations are given in Table 5. It is best not to take them too seriously because of the assumptions involved. This is intended as an internal estimate, primarily for the benefit of project management.

The first column identifies the individual projects. The second column gives the "best" estimate of the mean amount of additional rainfall (in kilotons) that was generated for the seeded units in each project. It represents an average of the estimates obtained from the original method (RVR199) for 3 and 6 h matches drawn from within and outside the seeding target. These estimates are highly variable and they are negative for two projects (AB and PC). The rain increment is large in the old HP program relative to the others but only had one years worth of data which was included in this analysis.

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TABLE 5
ESTIMATED ADDITIONAL SEEDED RAINFALL
BY PROJECT

PROJECT	Avg. Rain Inc./unit (kilotons)	# Seed Units 2002-2006	Total Rain Volume (kilotons)	Total Rain Volume (acre-feet)
NP	2,699	278	750,322	610,018
PH	3,583	652	2,336,116	1,899,281
HP	8,257	136	1,122,952	912,969
SR	2,056	328	674,368	548,267
CR	5,297	104	550,888	447,876
PC	-374	157	-58,718	-47,738
WT	1,990	1,040	2,069,600	1,682,602
AB	-4,034	94	-379,196	-308,289
SW	1,970	487	959,390	779,992
ST	2,370	424	1,004,880	816,976

The third table column provides an estimate of the total number of seeded units in the period 2002 through 2006. The largest total by far was obtained in the WT program. Based on data availability the unit total is likely low for the NP, CR, PC and AB projects. The total for the HP is probably fairly accurate since this program ended in late August 2002, the only year in the 2002-2006 period that data were acquired for this analysis..

The fourth column gives an estimate of the total rain increment obtained by taking the product of the estimated additional rainfall per seeded unit and the total number of units. The fifth column gives the estimates converted to acre-feet, where 1 acre foot = 1.23 kilotons. In doing this it was assumed that the rain increment that was determined from 3 and 6 h matches is valid for the entire project unit sample, even though it was not possible to match some of the units in the 3 and 6 h time frame. In two of the projects (PH and WT) the total increment substantially exceeds one million acre-feet, and in two others (SW and ST) the total is near

800,000 acre-feet. Remarkably, the total exceeds 900,000 acre-feet in the HP project, which is the product of a modest number of units and a large unit rain increment. Again, the table numbers are low for those projects that were unable to provide complete seeding records. It is difficult to know what to make out of the PC and AB negative totals that are based on a small incomplete input sample. The P-value support for the negative increments is weak, so it is best not to make too much out of the negative totals. Virtually the same seeding materials and procedures were used in these two projects as in the others that showed highly positive results. There is little reason to expect, therefore, that the precipitation losses are real and are most likely the result of an inadequate sample.

5.0 SUMMARY AND CONCLUSIONS

Although the assessment of seeding efficacy in Texas must be a work in progress, much has been learned by the current exhaustive analysis that warrants continuation of this effort. The findings and conclusions, which include the initial studies published in Woodley and Rosenfeld (2004), include the following:

Results Obtained Prior to the Current Study (from Woodley and Rosenfeld, 2004)

- The R/W method of matching seeded units with control units, 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 in the selected parameters, works as intended.

- The R/W methodology was used initially to evaluate seeding effects in the High Plains (HP) and Edwards Aquifer (EA) programs during the 1999, 2000 and 2001 (EA only) seasons. Objective unit control (C) matches were selected from within and outside each operational target within 12, 6, 3 and 2 h of the time on a given day that seeding of a particular unit took place in order to account for selection biases and the diurnal convective cycle. Matches were drawn also from within and outside each target using the entire archive of days on which seeding was done. The apparent effect of seeding in both programs was large (i.e., > 50%) even after accounting for selection biases and the diurnal convective cycle.

- Although the results of all analyses were subjected to statistical testing, the resulting P-values were used only to determine the relative strength of the various findings. In the absence of treatment randomization P-values cannot be used as proof of seeding efficacy.

- The most conservative and credible estimates of seeding effects were obtained from control matches drawn from outside the operational target within 2 h of the time that each unit was seeded initially. Under these circumstances the percentage increase exceeded 50% and the volumetric increment was greater than 3,000 acre-feet (3,700 kilotons) per unit with strong P-value support (i.e., < 0.000) in both the HP and EA programs.

- The matching of seed units with control units drawn from within the seeding targets likely biases the result in favor of seeding. This is one manifestation of selection bias.

- The results and their P-value support after partitioning by unit age and initial rain-volume rate (RVR) gave even stronger indications of positive seeding effects. Those Texas seeding projects with the smallest positive seeding effect had a disproportionate percentage of old units in their samples. Those projects with the greatest percentage of young seeded units had the largest apparent seeding effect on the scale of the analysis units..

- Time plots of S and C RVR indicate that seeding effects persist for at least 8 h in some instances and that up to 35% of the rainfall from the moving analysis units fell outside the fixed target areas downwind during the course of a seeding season.

- It is questionable whether enough seeding was done in both the HP and EA programs to affect most of the suitable clouds over the target areas, giving considerable room for improvement both in the amount of seeding, its areal extent and its timing. Until then, an effect of seeding on the seeded units cannot be equated to the effect over the entire fixed target.

Results of the Current Study

- The analysis of the Texas seeding projects existent in the period 2002 to 2006, using the original R/W method with 3 and 6 h control matches selected from within and outside the seeding targets, confirmed the early results for the HP and EA programs and greatly strengthened the case for seeding induced increases in precipitation. This was achieved despite the loss of some documentary seeding data from some projects. The evidence for rain increases on the scale of the seeded units is quite strong for the PH, SR, WT, SW, ST and HP projects. Virtually all of the evidence for seeding effects in the HP project came from the 2002 season, the year it was terminated. The evidence also indicates positive seeding effects for the NP and CR projects, both of which were terminated after the 2006 seasons. All of these results did not change appreciably after attempting to account for selection biases.

- The results for the PC and AB projects are inexplicably negative, but without statistical support for the apparent rain decreases. This is probably due to losses of some documentary seeding data, since other projects nearby that employed similar seeding materials and procedures showed positive effects of seeding.

- The apparent precipitation increases were documented throughout Texas and showed no regional preference, despite expectations that the effects would be smaller in the east because of more intense coalescence in the clouds, resulting in early warm rain and glaciation and closure of the seeding window. Most of the positive seeding effect was, however, confined to days when the Index of Coalescence Activity (ICA) was positive (ICA > 0) or only slightly negative, suggesting minimal in-cloud coalescence activity. No increases in precipitation were noted when the ICA was highly negative (i.e., ICA $\leq$

-5), indicating that clouds with intense coalescence are not suitable for glaciogenic seeding.

- Unit age at seeding was a major predictor for positive seeding effects. Those units seeded within an hour of their appearance on radar showed a huge positive effect of seeding as contrasted with the older seeded units. This was true in virtually all projects and emphasized the importance of timing when conducting seeding operations. There was also the tendency for positive seeding effects when the rain in the unit was light at the time of its first seeding. Even so, unit age at seeding was the dominant factor.

- Although these results were generated using archival radar data, the results are credible despite the uncertainties associated with radar estimation of precipitation, because the analysis has focused on S and C differences and ratios and not on absolute values. As long as the radar "sees" S and C clouds similarly, the rain differences should be a valid measure of seeding efficacy. Earlier research by Cunning (1976) did not find appreciable differences in the raindrop size distributions from seeded and non seeded clouds, meaning that a radar should "see" S and C clouds similarly.

6.0 RECOMMENDATIONS

The results of this exhaustive investigation provide a stronger basis for the continuation of the Texas seeding projects than existed previously and that is our major recommendation. In doing this, it is recommended further that the projects strive to be better stewards of their documentary seed data compiled in TITAN. Data lapses were a serious problem for a few projects. It is recommended further that the projects find a way to incorporate randomization of treatment into their projects. This was our recommendation to the State of Texas many years ago, and we provided a suggested means of doing so. We are pleased to learn that some projects apparently are considering this course of action.

We have not provided all of the answers with our analyses. There is just so much that could be done in the six-month allotted time frame with the funds that were available. There are still analyses that could be done with existing data. For example, we would like to see a cleaner relationship between the ICA and seeding effects. This should be examined further. In addition, it would also be interesting to seek a relationship between AgI dosage and seeding effect. This might be done for individual projects by examining the individual seeded units. The input seeding data are too crude in many cases for all this to be done across-the-board for all projects. It would also be of interest to provide an estimate of the fraction of the unit rainfalls that fell outside of the project fixed targets.

7.0 REFERENCES

Cunning, J.B., Jr., 1976: Comparison of the Z-R relationship for seeded and non-seeded Florida cumuli. J. Appl. Meteor., **15**, 1121-1125.

Rosenfeld, D. and W.L. Woodley, 1989: Effects of cloud seeding in west Texas. J. Appl. Meteor., **28**, 1050-1080.

Rosenfeld, D., and W. L. Woodley, 1993: Effects of cloud seeding in west Texas: Additional results and new insights. J. Appl. Meteor., **32**, 1848-1866.

Woodley, W.L., D. Rosenfeld, and B.A. Silverman, 2003a: Results of on-top glaciogenic cloud seeding in Thailand: Part I. The demonstration experiment, J. Appl. Meteor., **41**, 920-938

Woodley, W.L., D. Rosenfeld, and B.A. Silverman, 2003b: Results of on-top glaciogenic cloud seeding in Thailand: Part II. Exploratory analyses, J. Appl. Meteor., **41**, 939-951.

W. L. Woodley and D. Rosenfeld, 2004: The Development and Testing of a New Method to Evaluate the Operational Cloud Seeding Programs in Texas. *J. Appl. Meteor.*, **43,** 249-263.

ACKNOWLEDGEMENTS

Funding from the Texas Weather Modification Association and from the Sandyland Underground Water Conservation District to conduct this exhaustive study of the effects of operational cloud seeding in Texas is gratefully acknowledged. We also thank the project meteorologists and managers for their assistance with various aspects of this study, especially Todd Flanagan of the South Texas cloud seeding project for his input to the ICA calculations.