The Development and Testing of a New Method to Evaluate the Operational Cloud-Seeding Programs in Texas

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ABSTRACT

A method for the objective evaluation of short-term, nonrandomized 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 the Next-Generation Radar (NEXRAD) mosaic radar data to define fields of circular (25-km radius) floating-target analysis units with lifetimes from the 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 nonseeded (NS) analysis units. Objective criteria (quantified herein) 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 High Plains Underground Water Conservation District (HP) and Edwards Aquifer Authority (EA) programs during the 1999, 2000, and 2001 (EA only) seasons. 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 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 probability (P) values were 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 apparent effect of seeding in both programs was large—even after determining the effect of selection biases and the diurnal 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 exceeds 50% and the volumetric increment was greater than 3000 acre-feet (3700 kt) per unit with strong P-value support (i.e., <0.0001) in both the HP and EA programs. This is in good agreement with the apparent percentage effects of seeding for the randomized Texas and Thailand cloud-seeding programs, which were 43% and 48%–92%, respectively. The results and their P-value support after partitioning gave even stronger indications of positive seeding effects. Although the results of these and other analyses described herein make a strong case for enhanced rainfall by the operational seeding programs, such programs must not be viewed as substitutes for randomized seeding efforts that are conducted in conjunction with realistic cloud modeling and are followed by replication, preferably by independent groups for maximum credibility.

1. Introduction

Operational cloud seeding for precipitation enhancement continues worldwide even though scientific proof of the efficacy of seeding, according to the stringent ''proof of concept'' criteria set forth by Silverman (2001), is lacking. Those conducting these operational efforts have weighed the evidence and concluded that the potential benefits from precipitation augmentation in their programs outweighed the risks and costs involved. Many of the current operational cloud-seeding programs are being conducted in Texas, where 10 cloud-seeding projects were in operation during the 2001 and 2002 seasons (Fig. 1). The history of and the rationale for the Texas operational cloud-seeding programs are addressed by Bomar et al. (1999). Most of the individuals involved in these efforts agree with Silverman (2001) in that the evaluation of seeding effectiveness in all the programs should have high priority. They understand that seeding efficacy must be demonstrated or the projects ultimately will end in disillusionment and

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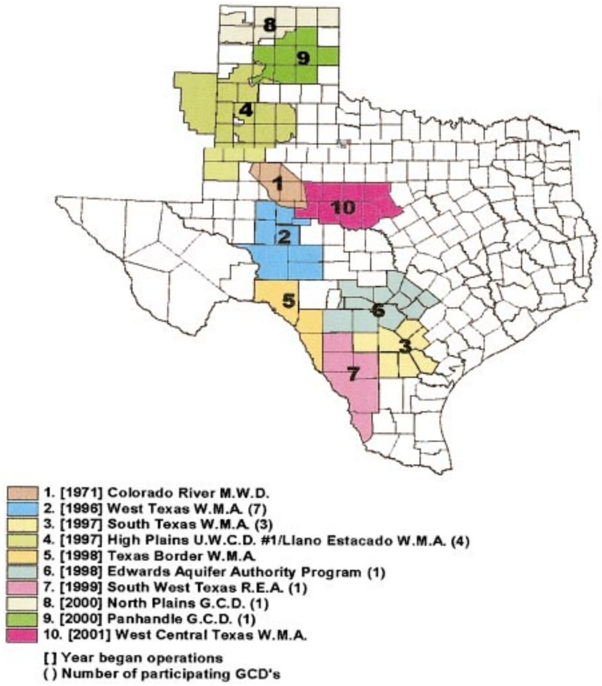

FIG. 1. Location of the 10 operational cloud-seeding programs operative in Texas during the 2001 and 2002 seasons.

controversy. Such a demonstration is difficult, however, because of the absence of treatment randomization.

The seeding programs to be examined here are those of the High Plains Underground Water Conservation District (HP) and the Edwards Aquifer Authority (EA). Typically in these programs, vigorous supercooled clouds were seeded at their bases and/or tops with silver iodide (AgI), the glaciogenic seeding agent used exclusively in Texas. When at cloud top, the seeding temperature ranged normally between −5° and −10°C. Typically, base seeding with generators and/or flares was done when the clouds were more mature and were precipitating, while top seeding was often done before the clouds were precipitating. Individual convective cloud towers usually received 20–60 g of AgI, while whole-target expenditures on active convective days totaled more than 2000 g of AgI. The intent of the nonrandomized seeding was to invigorate the clouds, induce the growth of new clouds, and promote the formation and fallout of more precipitation from large cloud systems, as evaluated by radar, than would have occurred without seeding intervention. The conceptual model for how this might take place has been addressed progressively over the years by the authors (see Woodley et al. 2003a,b). Whether precipitation enhancement took place in these Texas programs is the focus of this paper.

The purpose of this paper, therefore, is to describe and test a new methodology for the evaluation of nonrandomized operational cloud-seeding projects on a floating-target-area basis. This is an interim test of seeding effectiveness to serve as the basis for later whole fixed-target evaluations. Proof of seeding efficacy is lacking in the classical sense, but the results of the analyses and sensitivity tests suggest seeding-induced precipitation increases in these programs of at least 50%. Although the results of these and other analyses described herein make a strong case for enhanced rainfall by the operational seeding programs, such programs must not be viewed as substitutes for randomized seeding efforts conducted in conjunction with realistic cloud modeling that are followed by replication, preferably by independent groups for maximum credibility. Such activities are not normally the purview of operational programs and, in the current funding climate, should be undertaken by a partnership between the research and operational sectors.

2. Criteria for method development

Several realities had to be confronted prior to the development of a method for the evaluation of the operational cloud-seeding programs in Texas. First, project sponsors want insights regarding seeding efficacy now, even though all but the program of the Colorado River Municipal Water District (CRMWD) have been in existence for less than 6 yr. Second, the 10 seeding projects, which are nearly contiguous in space and time, get in each other's way during the analysis phase, because seeding in one area contaminates potential control areas elsewhere. Third, the evaluation of the projects cannot be based on rain gauge measurements, because rain gauges in sufficient density have been installed and maintained in only the High Plains seeding program. Even then, an assessment of the HP program based on its nonrecording gauge measurements can be made only on a seasonal basis. Fourth, the lack of gauge measurements dictates that the assessments be radar-based, with the attendant problems and uncertainties associated with radar estimation of rainfall.

When rain gauges are available, there are, in theory, a number of conventional options for the assessment of operational seeding projects, such as the derivation of target-control regressions based on historical rain gauge data. In practice, however, most are not possible. Evaluations using regressions based on historical data, such as that performed by Woodley and Solak (1990) for the evaluation of an operational seeding effort in San Angelo, Texas, are viewed as potentially biased because of a lack of stability in target-control ratios with time (Gabriel and Petrondas 1983). Further, even if this were not the case, the great extent of seeding in Texas compromises the conventional identification of long-term uncontaminated control areas. Clearly, an unconventional approach that recognizes these realities was needed for the project evaluations.

To be judged acceptable from our perspective, a method for the evaluation of the short-term operational cloud-seeding programs in Texas must

- minimize the possibility of human bias entering into the analyses;
- be radar-based for rainfall estimation, with checks on radar accuracies using rain gauge (G) versus radar (R) comparisons whenever possible;
- focus on the effect of seeding on an area basis rather than on individual clouds, because this is the scale of most interest to operational cloud-seeding programs;
- compensate for the absence of randomization by providing for the objective identification of fixed and/or moving uncontaminated ‘‘control’’ (C) areas;
- provide for the concurrent examination of all of the seeding programs both within and downwind of their targets;
- account for the confounding effects of ‘‘selection biases’’ and the diurnal convective cycle; and
- provide for the pooling of project data for an overall assessment of seeding effectiveness within various meaningful meteorological partitions.

3. Selection of a radar-based system for precipitation estimation

All of the Texas cloud-seeding projects make use of the 1974 C-band Weather Surveillance Radar (WSR-74C) radars in conjunction with Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN) hardware and software. The initial intention was to base the development of a new method to evaluate the operational cloud-seeding programs on these C-band project radars. This did not prove possible, because none of the projects consistently operate their radars around the clock, meaning that there is not a common 24-h database for thorough evaluation of all of the projects. Further, the project C-band radars were found to suffer from attenuation in heavy precipitation and from ground clutter. Attenuation in rain is inherent to C-band radars and can be avoided only by using a radar with a longer wavelength. (Even then, attenuation by a wet radome during heavy rain is still a problem.) The ground clutter, resulting in ‘‘false rainfall,’’ could not be removed without Doppler, making it a major source of potential error in estimating the unit rainfalls and for the comparison of gauge and radar rainfalls. Last, there was no way to normalize the calibration of all project radars to a common standard.

Because of these problems, a decision was made to use merged Texas S-band Next-Generation Weather Radar (NEXRAD) data, which are produced for the entire United States through a partnership between the National Weather Service (NWS) and private industry. These are S-band (10 cm) radars, which do not attenuate appreciably in heavy rain, although attenuation by a wet radome during very heavy rain can reach about 5 dB or more, and they are operated continuously unless they are down for maintenance. In addition, NEXRAD has a clutter-removal algorithm that ostensibly eliminates most of the ground clutter and false rainfall produced during periods of anomalous propagation. The NEXRAD processing subsystem has been addressed fully by Fulton et al. (1998). The NEXRAD locations and coverage circles for the continental United States are shown in Fig. 2. Texas has among the densest radar coverage in the United States because of the overlapping of many radars. This should result in integrated data of better quality than in states with sparser radar coverage.

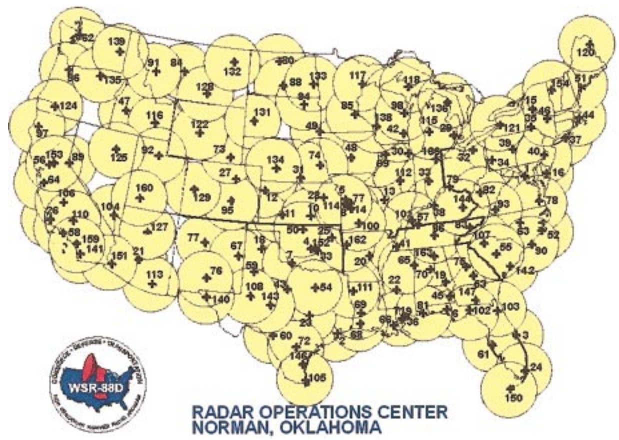

FIG. 2. Map showing all of the NEXRAD sites in the continental United States.

The National Aeronautics and Space Administration (NASA)’s Global Hydrology Resource Center (GHRC) provided the authors with merged 15-min base-scan reflectivity data that it had received from Weather Services International (WSI) for all of the NEXRAD sites in the United States. WSI has developed its own quality control process to remove radar signal artifacts manifested from ground clutter, anomalous propagation, and malfunctioning radars while maintaining the echoes and their intensity caused by real weather. Automated algorithms using signal-processing techniques are applied to the raw WSR-1988 Doppler (WSR-88D) data from all 154 National Weather Service sites as the data are received at WSI. In each 15-min period the most recent reflectivity data in polar coordinates to a range of 230 km are interpolated to a 2 km $\times$ 2 km Cartesian grid. This information is then automatically mosaicked into continental United States, Alaskan, and Hawaiian sectors, using proprietary decision-based algorithms, which determine the validity of the single-site information. During this processing the echo intensities from each radar are accepted as recorded. In regions of overlapping radar scans the common base-scan (2 km $\times$ 2 km) pixels having the greatest reflectivity become part of the mosaic. Lesser values from the other radars contributing to the overlap are rejected. Under this scheme, the accepted base-scan data are not generally at the same height. In the worst-case situation the radar beam would be about 4 km AGL for a radar having the strongest common pixel at the maximum quantitative range of

230 km. Because of the dense radar coverage in Texas, however, this should not be an issue.

At this point degreed meteorologists, who have been thoroughly trained in recognizing various meteorological and operational conditions that impact the validity of the radar data, use advanced tools to perform the third step in the WSI quality control process. When the data from a particular radar obviously are in error, the meteorologist can go so far as to remove and replace them. If there are no alternatives, the data from the ''offending'' radar can be deleted altogether with a notation in the radar product that this has been done. Thus, there is provision for human intervention in the automated process on a constant basis for the most recent of the three scans made every 15 min throughout the 24 h of the day. This human intervention is unique to WSI, which feels strongly that it improves the quality of the products produced from the radar data. In addition, this routine daily process is augmented by seasonal and technical updates to the algorithms employed. Although one might find fault with certain aspects of the WSI radar data processing, especially considering the subjective aspects of the third step, its main advantage for the study of seeding efficacy is the knowledge that the authors played no part in doing it. This precluded inadvertent biases on their part, which might have influenced the outcome of the study. More specific information about the WSI procedures were not made available by WSI because of proprietary considerations.

With this as background, the secured NEXRAD 15-min base-scan mosaicked reflectivity data were used to generate the rainfalls needed for this study. This was done using the relationship $Z = 300R^{1.4}$ to convert radar reflectivity (Z) to rainfall rate (R), which was synthesized from other studies by Woodley et al. (1975) and is used now as standard practice by the National Weather Service. If R was >120 mm h^{-1}, R was set to 120 mm h^{-1} to avoid too much contamination by hail. The initial work involved a test run of the data, and this was followed by the generation of the needed rainfalls for the 1999, 2000, and 2001 seasons.

Because a ''sore point'' in the evaluation of cloud-seeding programs is always the accuracy of the radar-rainfall estimates in representing rainfall at the ground, the next step was comparison of the radar-rainfall estimates with those provided by rain gauges. The first comparison involved 505 nonrecording rain gauges installed in the High Plains target. These gauges were read over a 3–5-day period at the end of each month. Unfortunately, this necessary practice compromised the accuracy of the monthly network gauge averages, when it rained during the period that the gauges were being read. It was still possible, however, to make valid comparisons on a seasonal basis with the finding that the combined seasonal radar-rain estimates, obtained from the default Z–R relationship (i.e., $Z = 300R^{1.4}$) used by the National Weather Service (Woodley et al. 1975), were within between 4% and 8% of the gauges in 1999 and 2000, respectively (Woodley et al. 2001). Of considerable importance is the fact that at least 25% of the rainfall in the High Plains target in this period was from seeded clouds (documented later). Thus, the notion that radar cannot represent the rainfall from seeded clouds on the ground accurately is unfounded, at least for seasonal rain estimates. This should not be a surprise, because Cunning (1976) has shown that the raindrop size distributions at the bases of AgI-seeded and nonseeded supercooled clouds do not differ appreciably.

The second comparison involved an extensive network of recording rain gauges. After the 2001 season it was possible to compare the daily radar-rainfall estimates with those provided by 96 recording rain gauges distributed over an 11 000 km^2 area in the northern portion of the EA target. The period of comparison was 4 May through 20 September 2001. The correlation between the G and R daily estimates was 0.922 and the ratio of G to R for the period was 1.56, indicating radar underestimation of the gauge rainfall. These results suggest that the Z–R equation (i.e., $Z = 300R^{1.4}$), which performed well on a seasonal basis for the High Plains target in 1999 and 2000, underestimated the unit radar-estimated rain volumes by a factor of 1.56 in at least the 2001 season in the Edwards Aquifer program. Whether this was true for the 1999 and 2000 seasons is unknown, because G versus R comparisons were not possible until the 2001 season.

The 2001 results did not come as a big surprise, because the NWS Z–R relationship, which performs well for deep convection, is known to underestimate rainfall from clouds with a maritime structure by as much as a factor of 2. Considering the flow of tropical air from the Gulf of Mexico into the EA target on some days, one would have expected the radar to underestimate the rainfall from clouds growing in that air mass. Under strongly tropical conditions the NWS recommends that the tropical Z–R equation, derived by Rosenfeld et al. (1993) and adopted by the NWS (i.e., $Z = 250R^{1.2}$), for tropical clouds be used for radar-rain estimation. This ''tropical'' Z–R gives about double the value of R for the same Z when compared with the standard Z–R of $Z = 300R^{1.4}$. If used, the tropical Z–R equation would more than compensate for the actual radar underestimates. Only the single Z–R relationship ($Z = 300R^{1.4}$) was used in our study, however, although we reserved the option of later adjustment of the radar-rainfall estimates based on the gauge versus radar comparisons. In any case, radar biases should not affect the estimates of the seeding effect, because such biases should apply equally to both the seeded (S) and C units, based on the study of Cunning (1976).

Although the measure of the success of an experiment ultimately must be the effect of seeding on the entire fixed target, the evaluation could not start there. Whole-target (Fig. 1) evaluations of seeding operations require a suitable control area, but this in turn requires that the rainfall in the target and control areas be highly correlated for the development of target versus control regression relationships. It is very difficult, however, to satisfy this requirement in regions where convective clouds produce most of the rainfall with high spatial variability. In addition, whole-target evaluations require that the rainfall in the control area not be contaminated by seeding elsewhere. This is a condition that is nearly impossible to satisfy in Texas at the present time.

4. The new methodology

With the above as background, evaluation on the scale of circular (25-km radius) floating-target analysis units (FTAUs) was chosen as the alternative to the full-target assessment. This was the choice also for the randomized experimentation in Texas (Rosenfeld and Woodley 1989, 1993; Woodley and Rosenfeld 1996) and Thailand (Woodley et al. 2003a,b). In the current case, however, the FTAUs are always seeded, necessitating the identification of suitable FTAU control matches for the seeded FTAUs for the evaluation. New software was written to define and track these FTAUs, containing seeded echoes, and to match their contents objectively with comparable nonseeded FTAUs. This was done in several steps:

1) Define FTAUs continuously over the entire area of interest irrespective of actual seeding, using the NEXRAD radar composite for Texas.
2) Each FTAU is defined when an echo first reaches 40 dBZ within a 25-km radius that contained only weaker echoes in the previous radar scan. The FTAU is centered at the 40-dBZ maximum, its radius is 25 km, and its area coverage is 1964 km^2.
3) A new FTAU can be defined just outside, that is, >25 km from the center of a preexisting FTAU, when a new echo reaches 40 dBZ. Thus, FTAUs are allowed to overlap in order to make sure that no echoes escape analysis.
4) All FTAUs are tracked backward and forward with time, and unit histories of maximum reflectivity (Zmax) and rain volume rate (RVR) are established. The motion vector of each FTAU is determined using cross-correlation maximization within a radius of 50 km.
5) A master treatment file is produced using the aircraft track and seed information provided by the individual projects, and the treatment file is used to determine which of the defined FTAUs were seeded. Any FTAU receiving any AgI is considered seeded, regardless of how the AgI was delivered to the unit.
6) Although its complete history is known, the preseeding history of a seed (S) FTAU is defined for the 75 min prior to treatment in terms of RVR, rain volume (RVOL), and maximum unit reflectivity (Z_{max}). The history of the FTAU following its initial seeding is determined until 1 h elapses without an echo in the unit.
7) A potential C FTAU is defined as one that never received any AgI and its perimeter never approached to within 25 km of the perimeter of an S FTAU.
8) Control FTAUs should be selected from a region that is meteorologically representative of the S FTAUs. Thus, the S and C FTAUs should come from the same region and on the same day whenever possible.
9) Potential C FTAUs must not be contaminated by seeding in other projects. Consequently, it is necessary to consult with the surrounding projects to determine when and where seeding was conducted in their project areas. If the times and locations are not known exactly, a buffer must be defined in order to avoid the selection of contaminated C FTAUs.
10) A prospective C FTAU matches an S FTAU when the following three conditions are met: 1) its RVR is within 25% [i.e., $\log|(RVR_S/RVR_{NS})| < 0.1$] of the seed RVR at seed time, 2) the maximum unit reflectivities at seed time do not differ by more than 5 dBZ, and 3) the correlation between the S and C RVR values for the period of common rainfall in the 75 min before seeding must be $>+0.60$ (as many as six point pairs enter into the calculation).
11) Multiple C FTAUs can be matched with each S FTAU as long as they satisfy the match criteria. Comparisons of S FTAU rainfalls are then made with the average C FTAU values for matching units.
12) The effect of seeding is evaluated on the whole population in various time frames (e.g., ±2, 3, 6, and 12 h of the initial seeding, or it can be done on a seasonal basis). The evaluation can also be done within various partitions such as the age of the S unit when it was first seeded.

5. Processing the data

The new software was used to track FTAUs throughout the state of Texas for the 1999, 2000, and 2001 (EA only) seasons. After the unit tracking had been completed, the aircraft seeding and tracking information were superimposed on the unit track maps to determine which of the FTAUs in the HP and EA seeding programs during the three seasons had been seeded. Once that had been completed, the seeded units were matched with control units for the match areas shown in Fig. 3, using the criteria and procedures discussed in the previous section. It should be noted that both match areas overlap other seeding targets. The High Plains match area includes portions of the CRMWD and Panhandle targets and the Edwards Aquifer match area includes portions of the south Texas, southwest Texas, and Texas border operational targets. It was crucial, therefore, to know when and where seeding was done in these areas in

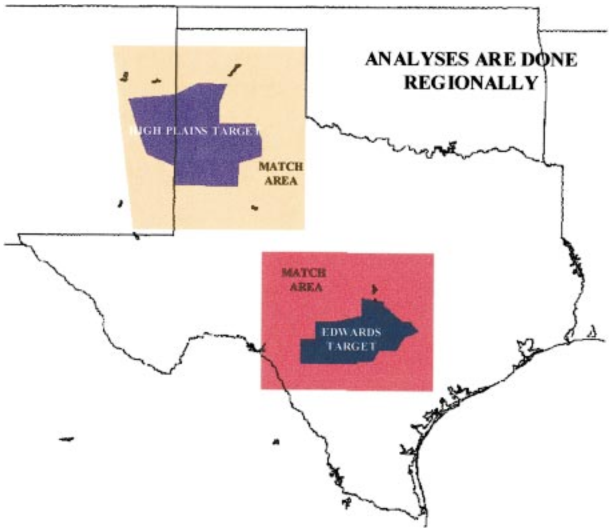

FIG. 3. Depiction of the match areas and targets for the Edwards Aquifer and High Plains seeding programs.

order to avoid the selection of contaminated units to serve as controls for the programs of current interest.

Partitioning played a major role in the analyses of apparent seeding effect, because it was felt that no single analysis would prove seeding efficacy. It is the collective weight of all of the evidence that would make the case for seeding. The partitions included (a) the effects of seeding for unit matches made from the entire archive and within 2, 3, 6, and 12 h of initial unit seeding, both within and outside the FTAU, (b) the age of the unit when it was first seeded, and (c) the unit RVR at the time of its initial seeding. It would have been interesting also to have partitioned the data based on whether the seeding took place near the cloud top or at the cloud base. On most days, however, seeding took place at both the cloud top and cloud base, either at different times by the same aircraft or when two aircraft were seeding simultaneously, one at base and the other near cloud top.

The matching was done only on days when seeding was done in the subject target. The rationale for this restriction was that if the project meteorologist rejected a day for seeding, his/her decision should be respected, and C matches should not be selected from days when the aircraft were not seeding. This is only an issue when the matches are drawn from the complete archive. Many matches can be made when drawing from the entire archive, but the seed units will not be nearly as well matched meteorologically as the matches from the restricted match periods within the day of seeding. Further, a bias against a seeding effect is built into the archival match period, because most of the C matches for individual seed units will come from the most active convective days. On the other hand, the primary disadvantage of matching within the day is that not all units can be matched from the more limited control pool, especially when the match period around the time of initial seeding is contracted.

Bias is a major issue for the analysis. To the extent that the match criteria quantify the rain potential of the matching C units relative to the S units, the results to be presented will be representative of the effects of operational seeding. Based on our experience, however, it is likely that selection bias will confound these assessments unless it is addressed, where selection bias is defined as real-time pilot seeder and radar meteorologist recognition of the best cloud and weather conditions for seeding (e.g., especially hard looking towers, strong cloud organization, obvious outflow boundaries, absence of upper cloud, etc.), which may not be quantified adequately by the current match criteria. Assuming that this is the case, this bias was addressed by selecting control matches from both within and outside the operational target. If bias exists, the inferred apparent effect of seeding for a given match period will be larger for controls selected within the target than for controls selected from outside. In the former instance, the seeding may be so extensive that only inferior unseeded clouds exist within the operational target to serve as controls, especially as the match period is contracted progressively around the time of seeding. For matches selected from the outside, however, the bias should be minimal because all clouds outside the fixed operational target are off-limits to the seeder pilots, and there is, therefore, no reason to expect the potential controls here to be inferior to the seeded clouds within the fixed operational target.

Another source of potential bias is the daily convective cycle. If all seeding in the two projects took place at the peak of the convective cycle and the corresponding matches were selected at times of lesser convective activity, a spurious seeding effect would be ''detected'' due solely to the convective cycle. If the reverse were true, it might appear that seeding had actually decreased the rainfall. The size of this potential bias can be quantified by progressively contracting the match period and then comparing the inferred seeding effect. In order to do this, one must assume that the 2-h match period is least affected by the daily convective cycle—a reasonable assumption. Then, if the apparent effect of seeding decreases as the match period is contracted, the bias due to the daily convective cycle favors the seed units. Conversely, if the inferred effect increases with contraction, the bias has worked against an effect of seeding.

All results were subjected to a one-tailed ''*t*'' test for paired comparisons to determine the relative strength of the various results. Such tests cannot be used as proof of seeding efficacy because they are reserved for results from randomized experimentation. In addition, such testing is vitiated when biases are present. A one-tailed test was used to calculate the probability (P) values. Entries recorded as 0.000 indicate that the P values were <0.001, indicating strong results in the absence of biases. In addition, it should be recalled that some of the

TABLE 1. Results for the High Plains and Edwards Aquifer programs.

In/out	DT	Age at first seed	Ns	Avg No. of matches per unit	RVRs0 (kt h^{-1})	RVRc0 (kt h^{-1})	SR0	RVOLs10 (kt)	RVOLc10 (kt)	S − C (kt)	*P* value	SR10
						High Plains program						
All	All	All	635	97.7	629	621	1.01	13 412	8517	4895	0.000	1.57
In	All	All	635	39.0	605	604	1.00	13 140	7943	5197	0.000	1.65
Out	All	All	635	60.2	626	617	1.01	13 330	8734	4596	0.000	1.53
All	12	All	376	2.9	693	689	1.01	15 345	8663	6682	0.000	1.77
In	12	All	233	2.0	617	614	1.00	14 865	7383	7482	0.000	2.01
Out	12	All	325	2.0	709	710	1.00	15 788	9549	6239	0.000	1.65
All	6	All	342	2.2	713	714	1.00	15 981	8954	7027	0.000	1.78
In	6	All	203	1.6	601	597	1.01	15 227	7112	8115	0.000	2.14
Out	6	All	278	1.8	753	758	0.99	16 764	9650	7114	0.000	1.74
All	3	All	288	1.7	724	724	1.00	16 544	9692	6852	0.000	1.71
In	3	All	154	1.4	581	565	1.03	14 686	6379	8307	0.000	2.30
Out	3	All	233	1.4	744	746	1.00	17 880	10 662	7218	0.000	1.63
All	2	All	247	1.5	650	647	1.00	17 006	8864	8142	0.000	1.92
In	2	All	123	1.3	592	578	1.02	14 036	5000	9036	0.000	2.81
Out	2	All	193	1.2	615	621	0.99	17 953	9870	8083	0.000	1.82
						Edwards Aquifer program						
All	All	All	306	96.9	476	473	1.01	7598	6680	918	0.063	1.14
In	All	All	301	27.0	476	471	1.01	7626	5925	1701	0.004	1.29
Out	All	All	305	69.4	478	473	1.01	7622	6853	769	0.103	1.11
All	12	All	194	2.4	469	475	0.99	8344	5388	2956	0.000	1.55
In	12	All	89	1.4	446	442	1.01	10 294	5513	4781	0.001	1.87
Out	12	All	177	2.0	471	479	0.98	8710	5529	3181	0.001	1.58
All	6	All	182	2.0	469	478	0.98	8317	4920	3397	0.000	1.69
In	6	All	76	1.3	471	468	1.01	10 298	5320	4978	0.001	1.93
Out	6	All	161	1.8	474	483	0.98	8867	4990	3877	0.000	1.78
All	3	All	157	1.7	486	499	0.97	8950	4755	4195	0.000	1.88
In	3	All	57	1.1	506	506	1.00	11 645	5801	5844	0.001	2.01
Out	3	All	135	1.6	498	508	0.98	9298	5020	4278	0.001	1.85
All	2	All	133	1.5	481	494	0.97	9494	4676	4818	0.000	2.03
In	2	All	44	1.1	514	514	1.00	12 243	5858	6385	0.014	2.09
Out	2	All	114	1.5	590	506	1.17	9583	4638	4945	0.000	2.07

units overlap and are, therefore, not independent. Unit overlap is addressed further later in the manuscript.

6. Results of analyses

a. As a function of match period and location

The results of analyses for seeding effects 10 h after initial seeding as a function of match period and the source of the C match (i.e., inside or outside the fixed operational target) in the HP (top) and EA (bottom) targets are tabulated in Table 1. The columns from left to right in the Table 1 are (a) C source (in, out, or both), (b) match period (all archive and within 12, 6, 3, and 2 h of the initial seeding), (c) age of unit at first seeding (all ages for this table), (d) number of S units (Ns), (e) average number of matching C per seeded unit, (f) the mean rain volume rate for the S units at the time of their initial seeding (RVRs0), (g) the mean rain volume rate for the matching C units at the time they were found to match the S units (RVRc0), (h) the ratio of f to g (i.e., SRO = RVRs0/RVRc0), (i) the mean total S rainfall in the 10-h period beginning with the initial seeding (RVOLs10), (j) the mean rain volume total for the matching C (RVOLc10), (k) the difference in mean S and mean C rain volumes, (l) the *P* value for the rain volume differences, and (m) the single ratio (SR) of the mean S and mean C rain volumes by 10 h after initial seeding (SR10).

Examination of the table entries reveals that the number of matched S cases in each program decreases as the match period decreases from all seasons (the entire archive) to within 2 h of the initial seeding for each unit. From this it follows that the average number of matches per S unit decreases as the match period is decreased. Thus, one trades sample size for focus as the match period is contracted. On average, the S and C units are well matched in terms of RVR0, especially when there are many matches. This must be the case, of course, because each NS unit had to pass stringent match criteria in order to qualify as a match.

To facilitate interpretation of the seeding results as a function of match location and period they are summarized in Figs. 4 and 5 for the HP and EA programs, respectively. The number above each bar is the average rain increment (i.e., S − C) per unit, expressed deliberately in units of acre-feet for those unable to think in ''kilotons.'' (To convert acre-feet to kilotons, multiply by 1.233.) Upon examining the results for the HP pro-

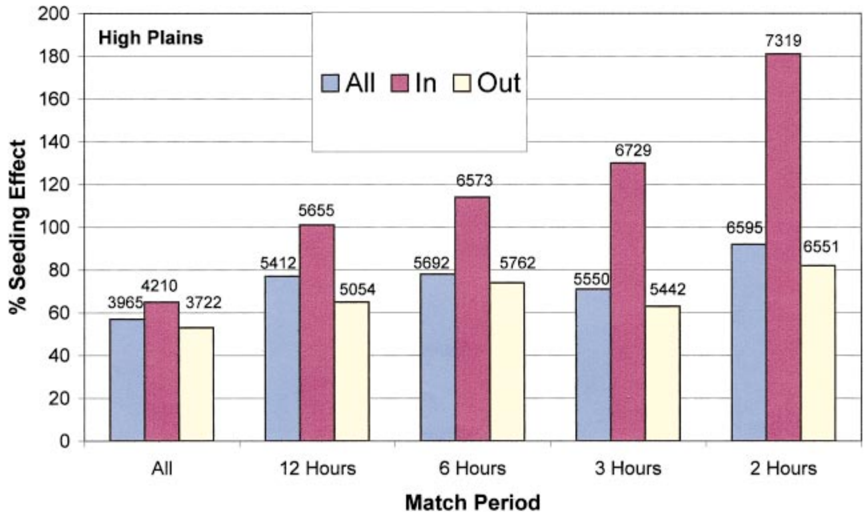

FIG. 4. Apparent seeding effect (%) as a function of match period and match location for the High Plains program in 1999 and 2000. The average rain increase (acre-feet) per unit is shown above each bar.

gram (Fig. 4), it is obvious that the match period and location are very important. Looking first at match location, note that the apparent effect of seeding is larger when objectively drawing control matches from within the operational target than from outside the operational target. The difference is quantification of the selection bias, which is a factor, as expected, despite the strict match criteria. This bias is seen to increase as the match period is contracted. This makes perfect sense because the number of "good" control clouds available for matching will decrease as the search period is contracted.

Upon looking next at the change in apparent effect as a function of match period, it can be seen that the apparent effect of seeding increases as the time interval from which a matching control is selected decreases. This will come as somewhat of a surprise to those who were concerned that the diurnal convective cycle might account for most of the apparent seeding effect. By shrinking the match period to within 2 h of the time of seeding the importance of the diurnal cycle is diminished, because the selected controls are temporally close to the seeded units. That the apparent seeding effect increases as this match period decreases means that there were more control than seed units available at the time of the convective peak. This makes sense because a seeding program normally will seed as long as there are suitable clouds somewhere in the operational target.

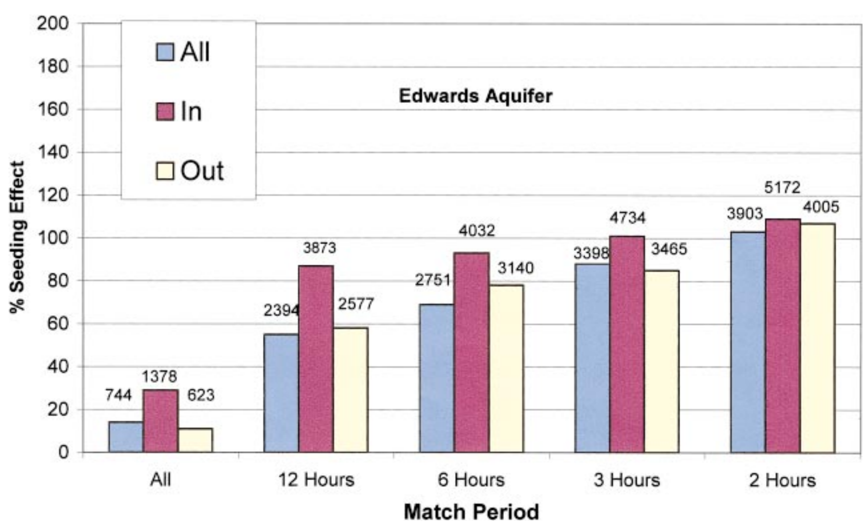

FIG. 5. Apparent seeding effect (%) as a function of match period and match location for the Edwards Aquifer program in 1999, 2000, and 2001. The average rain increase (acre-feet) per unit is shown above each bar.

Sometimes seeding will extend well into the evening hours, whereas most of the control matches will come at the time of the convective peak unless the match period is constrained.

Thus, the most realistic estimate of seeding effect is obtained from matches drawn from the most contracted match period from outside the operational target that is off-limits to the seeder pilots. Even with these restrictions, however, Fig. 4 suggests that the percentage rain volume increase exceeded 50% and the volumetric increment was greater than 3000 acre-feet per unit (about 2 mm in rain depth over the unit area) in the HP program in 1999 and 2000. This is true also even if the matches are drawn from the entire archive. Although these are large apparent percentage effects of seeding even after accounting for the various potential biases, they are no larger than the 92% apparent effect of seeding that was determined for the Thai randomized cold cloud-seeding experiment prior to linear regression, which decreased the apparent seeding effect to 48% (Woodley et al. 2003b).

This learning experience continues with examination of the results for the EA program (Fig. 5). Although there is the same increase in apparent seeding effect with contraction of the match period, the selection bias is much less here than that quantified for the HP program. This might be due to the fact that the seeding was pursued much more aggressively in the HP than the EA program. This means that more good clouds in the operational target were seeded in the HP program on a given day than in the EA program, leaving primarily rejected clouds to serve as controls, which is especially the case when the match period was contracted to within 2 h of the seeded units. The irony here is that the debilitating effects of the selection bias in any program is going to be proportional directly to the level of effort expended in seeding—the more the seeding the greater the bias. Fortunately, one can circumvent this bias by limiting one's selection of matches to the vast reservoir of candidates existing immediately outside the fixed operational target. Without that, it would be difficult to make a credible case for an effect of seeding.

Another interesting feature of the EA results is the finding that archival matches give a smaller apparent effect than the matches made within the day. For example, when limiting all of the matches to outside the operational target, the archival matches give an apparent seeding effect of 11%, as compared with $>$50% for matches made within the day. Although this disparity is much less in the HP program, there is good reason to expect archival matches to give a lower seeding effect than the matches made within the day. The archive is dominated by the most convectively active days, and most C matches for the S units will come from these active days. Thus, this puts the S units on weak convective days at a disadvantage when their matching is done from the archive.

b. *After partitioning*

The next issue was the effect of seeding in both projects as a function of the age of the unit when it was seeded. In selecting the matches it was required that the prospective match be of the same age at the time in its history when it was matched with the seed unit. The results for three match periods (i.e., all, 6, and 3 h) for only matches selected from outside the targets are provided in Table 2 and in Figs. 6 and 7 for the High Plains and Edwards Aqueduct projects, respectively. The results are very strong within each match period for the HP program with huge apparent seeding effects ($>$100%) and seeded increments ($>$10 000 acre-feet) for young units (i.e., from 0- to 75-min old when seeded) and virtually no effect of consequence evident for units $\geq$180-min old. This result is consistent with the conceptual model that calls for the greatest seeding response in young vigorous clouds.

This same picture is evident for the EA program (Fig. 7) for the all and 6-h match periods, although the magnitudes of the apparent effects are smaller than those for the High Plains program. Further, the pattern is not evident for the 3-h match period. Why this should have been the case is unknown, although the sample of cases is quite small for this partition. Once again one should remember that the EA rain volumes have not been adjusted upward by a factor of 1.56 to correct for radar underestimation of the rainfall. Once this is done, the S and C rain volumes and the seeded increments are comparable to those inferred for the HP program.

The seeding results as a function of the RVR at the time of seeding are presented in Fig. 8 for the High Plains program. The apparent seeding effects are largest for the seeded units having little rainfall at the time of initial seeding and smallest for those units that were full of rainfall at the time of initial seeding. These results are consistent with the results partitioned by age. This picture is not evident, however, in the EA program.

c. *Time plots*

Plots of the mean S and C rain volume rates versus time for the HP program are provided in Fig. 9. The matching C values were obtained from outside the operational target within 2 h of the initial seeding in each unit. Included also in Fig. 9 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 semiarid 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 (60–90 min) 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 prescreen-

TABLE 2. Results for the High Plains and Edwards Aquifer programs partitioned by the age of the unit at the time of its initial seeding.

In/Out	DT	Age at first seed (min)	Ns	Avg No. of controls per unit	RVRs0 (kt h^{-1})	RVRc0 (kt h^{-1})	SR0	RVOLs10 (kt)	RVOLc10 (kt)	RVOLs10 − RVOLc10 (kt)	*P* value	SR10
High Plains program. No adjustment need be applied to the radar-estimated rain volumes.												
All	All	0–75	188	162.4	317	305	1.04	20 072	7316	12 756	0.000	2.74
All	6	0–75	105	3.2	364	360	1.01	21 520	6374	15 146	0.000	3.38
All	3	0–75	93	2	379	376	1.01	22 195	6766	15 429	0.000	3.28
All	All	90–165	267	76.5	713	711	1.00	16 537	8938	7599	0.000	1.85
All	6	90–165	155	1.9	805	795	1.01	18 837	9542	9295	0.000	1.97
All	3	90–165	130	1.5	841	821	1.02	19 380	9438	9942	0.000	2.05
All	All	190–9999	166	58.5	848	836	1.01	11 360	9200	2160	0.020	1.23
All	6	180–9999	82	1.7	984	1015	0.97	12 873	11 144	1729	0.168	1.16
All	3	180–9999	65	1.6	983	1027	0.96	13 446	14 387	−941	0.350	0.93
In	All	0–75	188	66	317	307	1.03	20 072	6653	13 419	0.000	3.02
In	6	0–75	73	2	295	293	1.01	21 145	7551	13 594	0.000	2.80
In	3	0–75	58	1.6	294	289	1.02	21 094	7864	13 230	0.000	2.68
In	All	90–165	265	28.8	679	686	0.99	16 049	8496	7553	0.000	1.89
In	6	90–165	85	1.4	755	753	1.00	17 397	5683	11 714	0.000	3.06
In	3	90–165	65	1.3	779	762	1.02	15 988	4519	11 469	0.000	3.54
In	All	190–9999	163	22.1	833	827	1.01	11 384	8955	2429	0.021	1.27
In	6	180–9999	45	1.4	809	795	1.02	10 837	9101	1736	0.167	1.19
In	3	180–9999	31	1.4	703	672	1.05	11 517	7500	4017	0.045	1.54
Out	All	0–75	188	85.8	317	307	1.03	20 072	7709	12 363	0.000	2.60
Out	6	0–75	82	2.5	380	380	1.00	22 927	7118	15 809	0.000	3.22
Out	3	0–75	72	1.6	401	399	1.01	23 481	7562	15 919	0.000	3.11
Out	All	90–165	263	47.6	719	716	1.00	16 571	9287	7284	0.000	1.78
Out	6	90–165	127	1.5	801	794	1.01	19 084	10 554	8530	0.000	1.81
Out	3	90–165	107	1.3	812	798	1.02	19 599	10 397	9202	0.000	1.89
Out	All	190–9999	165	36.4	848	838	1.01	11 375	9492	1883	0.038	1.20
Out	6	180–9999	69	1.3	1110	1143	0.97	13 871	10 994	2877	0.096	1.26
Out	3	180–9999	54	1.3	1065	1106	0.96	14 529	15 338	−809	0.391	0.95
Edwards Aquifer program. All rain volumes should be adjusted upward by a factor of 1.56 to bring them into better agreement with rain gauges.												
All	All	0–75	45	173.7	158	157	1.01	13 684	5285	8399	0.000	2.59
All	6	0–75	31	2.2	196	192	1.02	12 910	5743	7167	0.003	2.25
All	3	0–75	28	1.8	177	177	1.00	12 824	5731	7093	0.006	2.24
All	All	90–165	110	100.9	476	472	1.01	12 058	6734	5324	0.000	1.79
All	6	90–165	58	2.4	581	595	0.98	13 238	5536	7702	0.000	2.39
All	3	90–165	48	2	631	645	0.98	14 059	5175	8884	0.001	2.72
All	All	190–9999	151	71.1	571	567	1.01	7371	7056	315	0.330	1.04
All	6	180–9999	93	1.7	490	500	0.98	7415	4262	3153	0.001	1.74
All	3	180–9999	81	1.5	508	524	0.97	7769	4168	3601	0.000	1.86
In	All	0–75	45	55.9	158	154	1.03	13 684	4610	9074	0.000	2.97
In	6	0–75	16	1.4	156	133	1.17	15 365	5862	9503	0.005	2.62
In	3	0–75	13	1.1	105	94	1.12	15 863	7825	8038	0.049	2.03
In	All	90–165	108	26.1	484	482	1.00	11 992	5994	5998	0.000	2.00
In	6	90–165	20	1.5	618	616	1.00	15 799	5035	10 764	0.003	3.14
In	3	90–165	15	1.1	755	751	1.01	19 007	6417	12 590	0.008	2.96
In	All	190–9999	148	18.8	566	560	1.01	7415	6274	1141	0.073	1.18
In	6	180–9999	40	1	523	529	0.99	8216	5246	2970	0.055	1.57
In	3	180–9999	29	1.1	557	564	0.99	8551	4575	3976	0.012	1.87
Out	All	0–75	44	119.2	162	161	1.01	13 992	5661	8331	0.000	2.47
Out	6	0–75	26	1.8	166	173	0.96	13 638	5810	7828	0.004	2.35
Out	3	0–75	23	1.7	175	183	0.96	12 695	7014	5681	0.023	1.81
Out	All	90–165	110	74.2	476	474	1.00	12 058	6929	5129	0.000	1.74
Out	6	90–165	54	2.1	567	577	0.98	13 337	5785	7552	0.001	2.31
Out	3	90–165	45	1.9	590	596	0.99	13 356	4953	8403	0.001	2.70
Out	All	190–9999	151	51.5	571	563	1.01	7371	7146	225	0.378	1.03
Out	6	180–9999	81	1.5	511	518	0.99	7990	4197	3793	0.000	1.90
Out	3	180–9999	67	1.4	547	560	0.98	8718	4380	4338	0.000	1.99

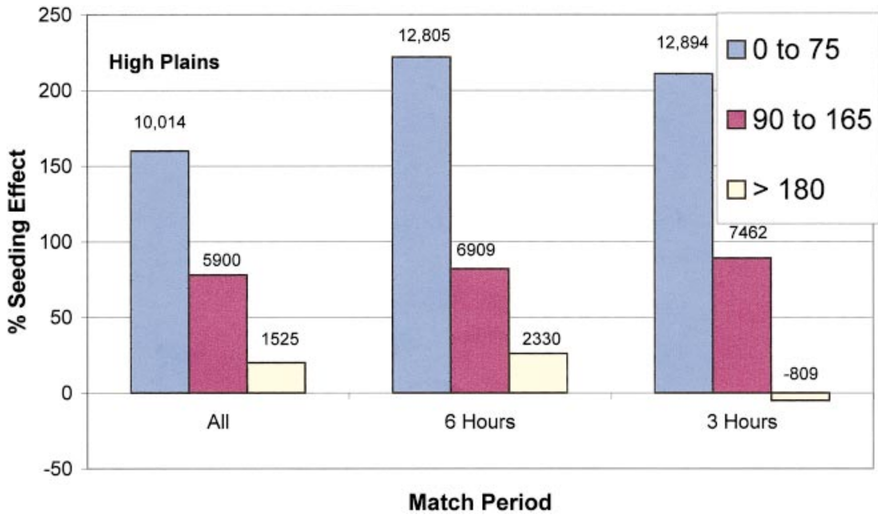

FIG. 6. Apparent seeding effect (%) as a function of pretreatment age at initial treatment and match period for matches made outside the operational target for the High Plains program in 1999 and 2000. The average rain change (acre-feet) per unit is shown above each bar.

ing in Thailand to eliminate the wettest days before the randomized seeding 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 fell 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.

d. The effect of unit overlap

Because the analysis allowed for the definition of overlapping seed units in order to include all of the precipitation echoes, an obvious sensitivity test is the recalculation of the effect of seeding as a function of unit overlap. This was investigated by obtaining the seeding effect versus unit overlap for the HP and the EA programs and then averaging the results by overlap interval. A 12-h match interval (all locations) was used in this exercise and the rain volume, seeding-effect results were expressed as a percent for each of seven unit overlap intervals, also expressed as a percentage. The

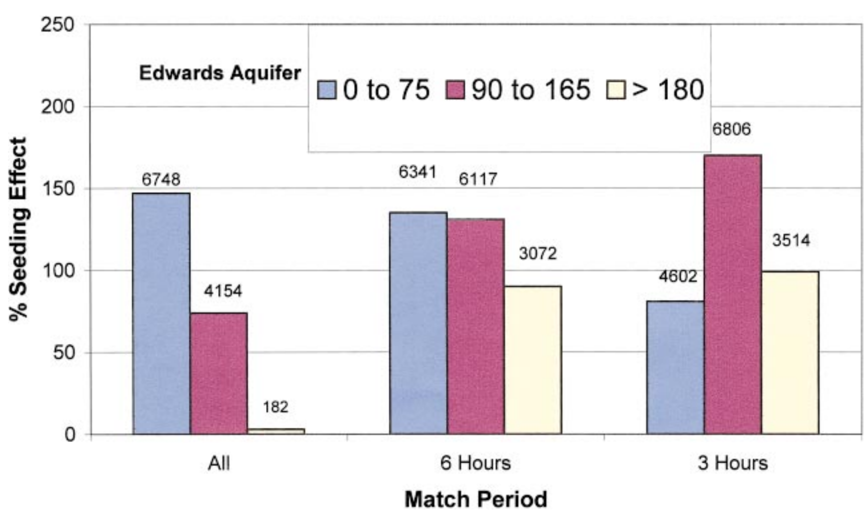

FIG. 7. Apparent seeding effect (%) as a function of pretreatment age at initial treatment and match period for matches made outside the operational target for the Edwards Aquifer program in 1999, 2000, and 2001. The average rain change (acre-feet) per unit is shown above each bar.

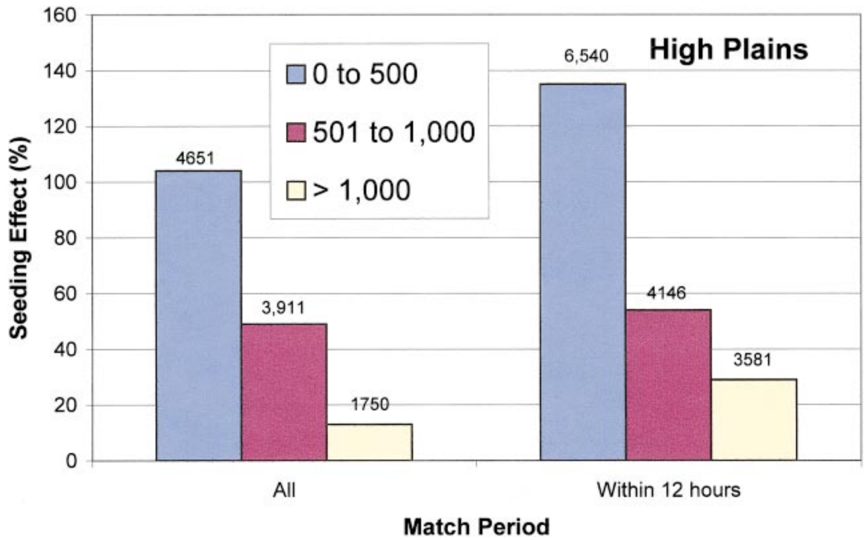

FIG. 8. Apparent seeding effect (%) as a function of initial unit RVR (kt h^{-1}) and match period for the High Plains program in 1999 and 2000. The average rain increase (acre-feet) per unit is above each bar.

results are provided in Fig. 10 where (as before) the percentage seeding effect is [(SR − 1)100] and SR = S/C. The summed unit seed sample is given above each bar. For no unit overlap (i.e., 0%) the apparent seeding effect for the HP and EA programs combined is +56%. Thus, if one had insisted on no unit overlap, the apparent seeding effect would not be much different from the current results. The apparent combined seeding effect reaches a maximum of +140% at 10%–20% unit overlap and decreases to an effect of +39% for those units that overlapped by more than 40%. One could speculate why the apparent seeding effect for strongly overlapping units is less than the overall average, but such speculation does not appear appropriate here. The essential point that the overall results do not hinge on unit overlap is sufficient.

7. Discussion

The analyses presented here make a strong case for seeding-induced rain increases in the HP and EA operational cloud-seeding programs of Texas, at least on the scale of the analysis units. Although the apparent seeding effect of at least 50% clearly is larger than would have been expected in some quarters, it is consistent with what was determined in the Thai randomized glaciogenic seeding experiment (Woodley et al. 2003a,b) in which the analysis unit was identical to that used in the previous Texas randomized seeding experiments (Woodley and Rosenfeld 1996) and in the current study. Further, the claims for such effects in the Texas HP and EA programs are stronger now than previously because of negation of the arguments that selection bias

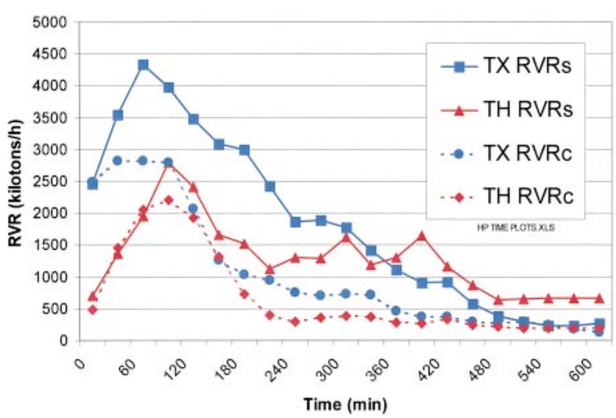

FIG. 9. Time plots of mean S and C unit RVR in the Texas (TX) High Plains program (out, 2-h match) and in Thailand (TH) (randomized).

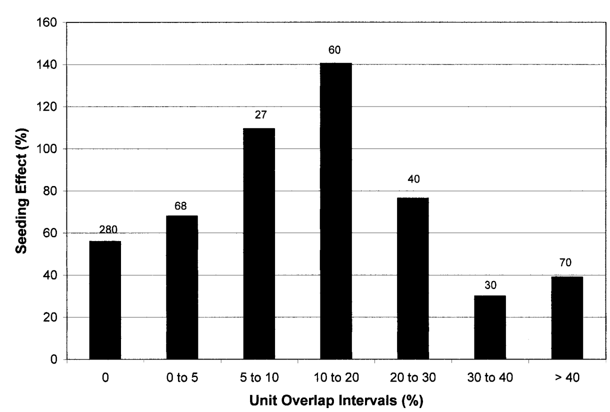

FIG. 10. Seeding effect [(SR − 1)100%] where SR = S/C vs percent of unit overlap for a 12-h match period for the High Plains and Edwards Aquifer programs combined. The total sample per interval appears above each bar.

TABLE 3. Comparisons by year and overall of seed unit RVOLS with target RVOLS during the operational season (RVOL values are in kilotons). All rain volumes in this table are unadjusted.

	High Plains program			Edwards Aquifer program			
	1999	2000	All years	1999	2000	2001	All years
A Tot unit RVOL	5 268 763	3 059 899	8 328 662	812 143	884 424	628 322	2 324 889
B Unit RVOL in target	3 961 105	2 251 145	6 252 250	535 222	453 580	550 184	1 538 986
C Ratio B/A	0.75	0.74	0.75	0.66	0.51	0.88	0.66
D Target RVOL	15 060 446	9 829 639	24 890 085	4 992 421	4 750 854	8 550 439	18 239 714
E Ratio B/D	0.26	0.23	0.25	0.11	0.10	0.06	0.08

and/or the diurnal cycle likely accounted for the apparent effects of seeding.

Some might retort that, if the apparent effects of seeding are >50%, they should have been evident over the entire operational target. This appears reasonable until one examines the seeding in each program relative to the total rainfall in each operational target during the period of analysis. This is done in Table 3 and in Figs. 11 and 12. Beginning with the HP (Fig. 11), note that the rainfall in the target from seeded systems in the two years is 25% of the target total. This small percentage might make it difficult to detect an effect of seeding, especially so when one realizes that only about one-half of that 25% might reasonably be ascribed to seeding. The situation is worse for the EA program (Fig. 12) where the seeded systems contributed only 8% of the target total for the three seasons. Under these circumstances it would be nearly impossible to detect an effect of seeding for the whole target. Thus, what was done in the two seeding programs was apparently done well, but it is speculated that too little seeding was done to produce a detectable effect over the entire operational targets. Whole-target analyses are necessary to address this issue.

The duration of apparent seeding effects in both Texas and Thailand is worthy of note for several reasons. First, the effects appear to persist for as much as 8 h after initial seeding, indicating that the enhanced rainfall propagates out of the fixed operational target area downwind. A crude estimate, assuming that the effect of seeding is confined solely to the seeded floating target analysis units (not very likely), is provided in row 3 of Table 3. In the HP program about 25% of the seed unit rain volumes fell outside the fixed target. In the EA program the corresponding value is 34%.

Second, the persistence of apparent seeding effects begs for an explanation. This was addressed in the Thai cold-cloud experiment (Woodley et al. 2003a,b) with the speculation that enhanced downdrafts, as postulated by Simpson (1980), and ''secondary seeding'' were probably causal, where secondary seeding (Woodley and Rosenfeld 2002) is defined as a process whereby unseeded clouds ingest ice particles from clouds that earlier had received direct glaciogenic (e.g., silver iodide) treatment. Although it is unlikely that secondary seeding affected the control units, if such contamination did take place, it would work against the inference of positive seeding effects.

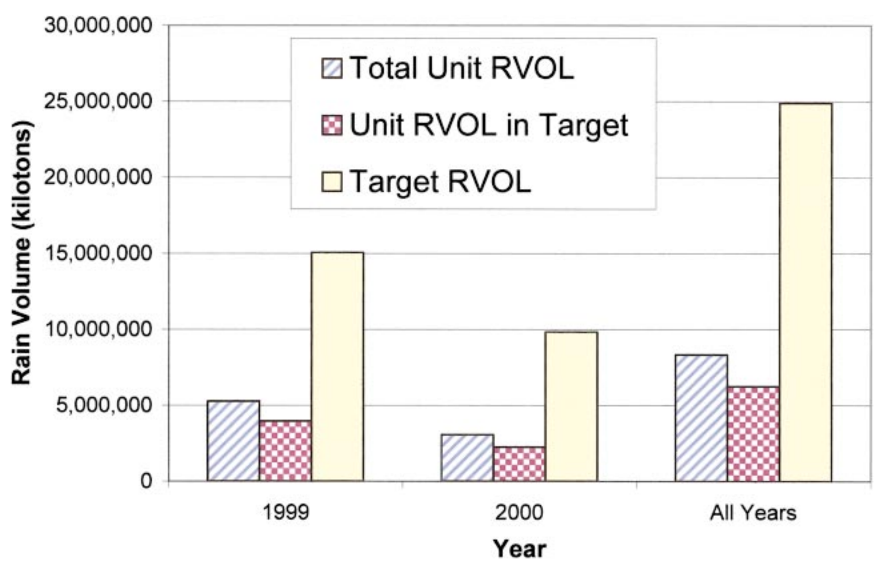

FIG. 11. Comparisons by year and overall of seed unit rain volumes with target rain volumes during the operational seasons. The High Plains target covers 44 755 km^2.

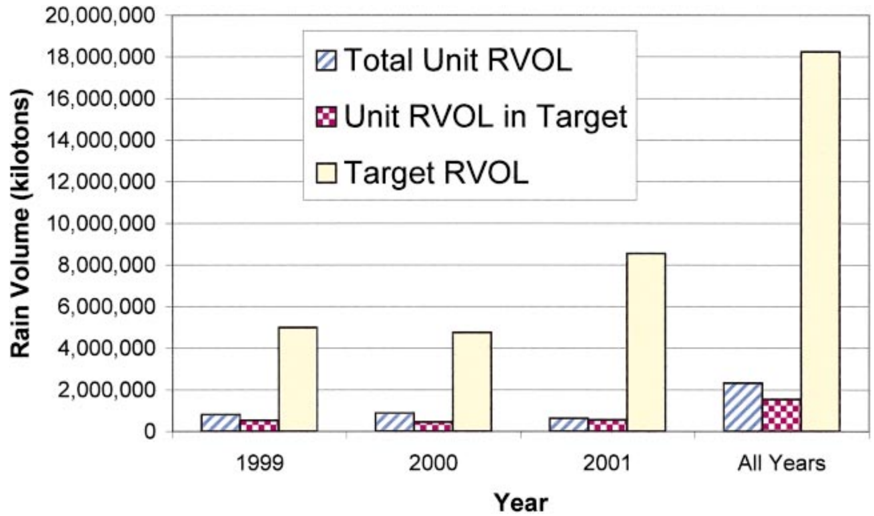

FIG. 12. Comparisons by year and overall of seed unit rain volumes with target rain volumes during the operational seasons. The rain volumes shown are unadjusted. The Edwards Aquifer target covers 22 658 km^2.

8. Conclusions

The work to date using the new computer-based method to evaluate operational cloud seeding has led to the following conclusions:

- The 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 pretreatment biases in the selected parameters, works as intended. A major plus for the new method is the compilation of an echo archive that will grow to enormous size with time such that multiple matching of seeded units will be possible within virtually any meteorological partition.
- The methodology was used to evaluate seeding effects in the High Plains Underground Water Conservation District (HP) and Edwards Aquifer Authority (EA) programs during the 1999, 2000, and 2001 (EA only) seasons. Objective unit 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, even after accounting for selection biases and the diurnal convective cycle.
- Although the results of all analyses are subjected to statistical testing, the resulting *P* values were 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 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 exceeds 50% and the volumetric increment was greater than 3000 acre-feet (3700 kt) per unit with strong *P*-value support (i.e., <0.0001) in both the HP and EA programs. This is in good agreement with the apparent percentage effects of seeding for the randomized Texas (Woodley and Rosenfeld 1996) and Thailand (Woodley et al. 2003a,b) cloud-seeding programs, which were 43% and 48%–92%, respectively.
- 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. Time plots of S and C RVR indicate that seeding effects persist for at least 8 h and that between 25% and 34% of the rainfall from the floating target analysis units fell outside of the fixed target areas downwind. As with the results of the Thailand randomized glaciogenic seeding experiments, which are consistent with those reported herein, it is postulated that enhanced seeding-induced downdrafts and/or ‘‘secondary seeding’’ are responsible primarily for the rainfall enhancements.
- 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 and its timing.

This is a work in progress. The foundation has been laid for the evaluation of all of the operational cloud-seeding programs in Texas on a floating-target basis. Ultimately, attention must be given to the extension of these results to the full-target areas.

Although the results of these and other analyses described herein make a strong case for enhanced rainfall by the operational seeding programs, such programs must not be viewed as substitutes for randomized seeding efforts that are conducted in conjunction with realistic cloud modeling and are followed by replication, preferably by independent groups for maximum credibility. In view of the current funding climate, such programs might be done as a partnership between the research and operational weather modification sectors.

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