

Results of On-Top Glaciogenic Cloud Seeding in Thailand. Part II: Exploratory Analyses

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ABSTRACT

Randomized, cold-cloud, rain-enhancement experiments were carried out during 1991–98 in the Bhumibol catchment area in northwestern Thailand. Exploratory experimentation in 1991 and 1993 was followed by a demonstration experiment, limited to A-type experimental units, to determine the potential of on-top silver iodide seeding for the enhancement of area (1964 km²) rainfall. Analyses in a companion paper (Part I) established that the Thai cold-cloud demonstration experiment, evaluated according to its original design, failed to reach statistical significance in the time allotted to the experiment, although the probabilities that the seeding effects were positive on the treated cells and units are 72% and 79%, respectively. The results of exploratory examination of the entire demonstration experiment, including both A- and B-type experimental units, are presented herein. The exploratory studies involved both cell [392 seeded (S) and 335 nonseeded (NS)] and unit (35 S and 35 NS) analyses, a bivariate analysis of the joint effects on cells and units, and the analysis of pooled results from the exploratory experiment and the entire demonstration experiment. The results of these exploratory studies strengthen the case for seeding-induced changes in rainfall that were indicated in the evaluation of the a priori demonstration experiment. A multiple regression analysis to account for some of the natural rainfall variability suggests, however, that the apparent seeding effect has been overestimated by about a factor of 2 (i.e., +92% versus +48%). Temporal plots and analyses of unit rain-volume rates and cumulative rain volumes for seeding effects revealed stronger statistical support for convective masses within the unit not having seeded ancestry, as determined by radar, than for convective clusters with seeded ancestry. This result suggests that the effect of seeding, which begins with the directly treated cells, is propagated to nonseeded clouds within the unit. Enhanced downdrafts and/or “secondary seeding,” as discussed herein, are posited as possible propagation mechanisms. Partitioning of the data by a crude aircraft measure of coalescence intensity revealed that the rain volume from NS units increased as coalescence intensity increased, whereas the greatest mean S rainfall was observed in the moderate coalescence category. The apparent seeding effects were >100% for units having clouds with weak to moderate coalescence and were nonexistent for units having clouds with strong coalescence. This was true also upon analysis of the cell sample. The implications of this and all results are discussed in the context of the conceptual model guiding the experimentation.

1. Introduction

Thailand’s Applied Atmospheric Resources Research Program (AARRP) was launched in 1988 as a joint project of the royal Thai government (RTG) (Bureau of Royal Rainmaking and Agricultural Aviation of the Ministry of Agriculture and Cooperatives) and the U.S. government (U.S. Agency for International Development). The goal of the AARRP was to provide the RTG

with the capability to conduct scientifically sound field experiments to quantify the water augmentation potential of warm- and cold-cloud rainmaking techniques in Thailand. It focused on theoretical and model studies and on randomized exploratory experiments to determine which of the physically plausible warm- and cold-cloud-seeding experiments warranted further testing and the design of a follow-on project (AARRP phase 2) to demonstrate their feasibility through proof-of-concept statistical experiments. Randomized exploratory cold-cloud experiments were conducted in Thailand for 1 week in 1991 and for 5 weeks in 1993 before the de-

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TABLE 1. Results of exploratory cell analyses for the demonstration sample (RVOL values in kilotons or 10^3 m^3). Dataset includes 392 AgI-seeded cells and 335 control cells.

Variable	Mean S	Mean NS	Seeding effect (%)	90% Confidence interval	
				Lower	Upper
RVOL	367.44	268.37	37	-8	104
HMAX	10.84	10.35	5	-14	27
ZMAX	49.73	46.39	7	-10	28
AMAX	66.57	54.19	23	-4	57
RVRMAX	759.13	581.76	31	-5	79
NCMAX	45.73	24.25	17	-1	38
DUR	58.04	47.94	21	-4	52

cision was made to proceed with a demonstration experiment. Fifteen experimental units were obtained during the 6 weeks of exploratory experimentation.

The demonstration experiment was carried out during portions of April, May, and June in 1994–98 in the Bhumibol catchment area in northwestern Thailand. Woodley et al. (2003, henceforth referred to as Part I) established that the experiment, evaluated according to its original design (henceforth referred to as the a priori demonstration experiment), failed to reach statistical significance in the time allotted to it. The proportional effect of seeding on unit rainfalls at 300 min after unit qualification for the sample of 62 experimental units [31 seeded (S) and 31 nonseeded (NS)] was 46% with a one-sided P value of 0.107. The proportional effect of seeding on cell rain volume (RVOL) for 353 silver iodide (AgI)-seeded cells and 289 control cells receiving simulated AgI (glaciogenic) treatment was 35%, with a one-sided P value of 0.139. Although the evaluation of units and cells fell short of the P -value threshold of 0.025 that was required for statistical significance, confidence that the seeding effect was positive was 79% and 72%, respectively.

The results of exploratory examination of the entire sample of units and cells in the demonstration experiment (henceforth referred to as the entire demonstration experiment), consisting of 35 S and 35 NS units, are presented here. The exploratory analyses are based on the maximum lifetime properties of the units and include 8 units (4 S and 4 NS) for which the supercooled cloud liquid water content (SLWC) requirement for unit qualification ($\text{SLWC} \geq 1.0 \text{ g m}^{-3}$) was eliminated and the 85 cells (39 S and 46 NS) in the 8 additional units. Confidence intervals are used as indicators of the apparent seeding effects, because they indicate at some specified level of confidence the range of the proportional effect of seeding (i.e., $\text{SR} - 1$, where $\text{SR} = \text{S}/\text{NS}$).

The analyses of the primary and secondary response variables begin with the convective cells, because it is the cells that receive the treatment, and continue with the unit analyses that also include multivariate analyses. This is followed by pooling of the RVOL results of the exploratory and demonstration experiments on the cell

and unit scales. Unit RVOL analyses also are made as a function of whether the unit radar echoes had a traceable connection to earlier treatment (the floating target vs its complement) and as a function of coalescence activity. Seeding effects are adjusted for natural rainfall variability through a multiple-regression relationship that incorporates two covariate variables. The interpretation of the seeding results in the context of the conceptual model guiding the experimentation and their implications are discussed.

2. Exploratory analyses of the demonstration experiment

a. Cell analyses

The exploratory cell data from the entire demonstration experiment (i.e., A + B units), which include 392 AgI-seeded cells and 335 control cells that received simulated AgI (glaciogenic) treatment during the unit experiments, were analyzed using the Rosenfeld long-tracking software. The results of the S and NS analyses for cells are presented in Table 1. Going from top to bottom in the table, the *mean* maximum lifetime cell parameters and their units are the (a) rain volume at cloud base (10^3 m^3), (b) maximum height of the 12-dBZ echo [HMAX (km)], (c) maximum radar reflectivity at cloud base [ZMAX (dBZ)], (d) maximum echo area at cloud base [AMAX (km^2)], (e) maximum rain volume rate through cloud base [RVRMAX ($10^3 \text{ m}^3 \text{ h}^{-1}$)], (f) maximum number of convective cells in the contiguous echo in which the subject cell is embedded (NCMAX), and (g) duration [DUR (min)]. RVOL, AMAX, and RVRMAX were measured at a height of 2 km (approximately cloud base) using a threshold reflectivity of 12 dBZ. The calculation of NCMAX is not limited by the boundaries of the moving target. From left to right are listed the S and NS averages of a particular cell property. The seeding effect [$100(\text{SR} - 1)$] expressed as a percentage comes next, where again SR is the single ratio of S to NS for a particular variable. This quantity is followed by the upper and lower bound of the 90% confidence interval.

Note that the proportional effect of seeding on cell RVOL is 37%. The lower and upper bounds of the corresponding 90% confidence interval are -8% and +104%, respectively. Further, there is 81% confidence that the seeding effect is positive, with the true effect being in the range from 0% to 88%. Thus, the results for the entire demonstration experiment are only slightly stronger than the results for the a priori demonstration experiment reported in Part I.

The other cell parameters suggest positive effects of seeding, but their 90% confidence intervals include the null effect. If seeding augmented the rain volume from the convective cells, it was likely produced by increasing their radar reflectivities, areas, rain-volume rates (RVR), clustering with other clouds, and/or their du-

TABLE 2. Results of exploratory unit analyses for the demonstration sample (RVOL values in kilotons or 10^3 m^3). Dataset includes 35 seeded and 35 nonseeded units.

Variable	Mean S	Mean NS	Seeding effect (%)	90% Confidence interval	
				Lower	Upper
(a)					
TT					
RVOL	11 787.8	6097.7	93	2	267
HMAX	10.04	10.27	-2	-11	7
ZMAX	37.98	41.02	-7	-15	0
AMAX	804.91	620.81	30	-4	75
RVRMAX	6059.91	3828.25	58	3	144
TNCELL	39.4	30.51	29	1	66
DUR	311.97	253.46	23	5	44
(b)					
FT					
RVOL	5318.2	3168	68	-13	223
HMAX	12.42	11.56	7	-2	18
ZMAX	51.89	50.87	2	-2	6
AMAX	396.64	305.25	30	-10	87
RVRMAX	4014.1	2821.6	42	-8	121
TNCELL	11.2	8.51	32	-4	80
DUR	191.34	166.29	15	-6	39
(c)					
TT - FT					
RVOL	6469.6	2929.7	115	4	345
HMAX	8.81	8.51	3	-7	15
ZMAX	28.95	30.44	-5	-17	8
AMAX	697.26	518.79	34	-4	87
RVRMAX	4456.39	2536.17	76	5	194
TNCELL	30.34	24.49	24	-5	61
DUR	311.97	253.46	23	5	44

ration. As noted in Part I, increased vertical growth of the seeded cells, as inferred by measuring their echo heights with radar, does not appear to have played a major role in the apparent seeding-induced rainfall increases. This was the case also in Texas (Rosenfeld and Woodley 1993). This finding, which is contrary to the dynamic-mode seeding hypothesis, is discussed later.

b. Unit analyses

The results of unit analyses are given in Table 2. Examination of the rainfall from all echoes in the entire moving experimental unit is called the total target (TT), whereas the examination of the rainfall from those unit echoes known to have seeded ancestry is called the floating target (FT). The complement of the FT, which is the difference between the TT and the FT, contains the unit echoes that did not have treated ancestry. The other unit response variables listed in Table 2 are comparable to those listed in Table 1 for the cells, except that number of cells in the experimental unit (TNCELL) replaces NCMAX.

Analysis of the 70 experimental units over their lifetimes gave mean S and NS TT rain volumes of $11\,787.8 \times 10^3$ and $6097.7 \times 10^3 \text{ m}^3$, respectively, and a pro-

portional effect of seeding of +93% on unit rain volume (Table 2a). The lower and upper bounds of the corresponding 90% confidence interval are +2% and +267%, respectively. There is 91% confidence that the seeding effect is positive, with the true effect being in the range from 0% to +274%. The results for the entire demonstration experiment are considerably stronger than the results for the a priori demonstration experiment reported in Part I.

The apparent effects of seeding on the secondary response variables for the units are similar to those calculated for the convective cells, except for the HMAX and ZMAX variables, which are positive for the convective cells and negative for the experimental units. Although the results for HMAX between cells and units differ in sign, they are small and well within the statistical variability. The results for ZMAX cannot be dismissed as easily because the negative ZMAX result for the units is strong. A possible reason for this strength is presented in the discussion section.

Complicating the interpretation of the Thai cold-cloud-seeding experiment are year-to-year differences in rainfall, which might have natural or artificial causes (e.g., radar miscalibration that survived the clutter recalibration), and the disproportionate draw of a particular treatment decision within an overly wet or dry year. To account for such imbalances, the yearly unit RVOL values were normalized to the mean NS RVOL for all years. Although this procedure changes the unit values within each year, it preserves the intrayear-seed-versus-no-seed relationships and makes it possible to account for year effects. The mean S and NS unit RVOL values after normalization are $10\,157 \times 10^3$ and $5403 \times 10^3 \text{ m}^3$, respectively, giving a proportional seeding effect of +88%. This exercise suggests that the assessment of the effect of seeding is insensitive to year effects.

c. Multivariate analyses

A bivariate analysis on the simultaneous effects of seeding on units and cells was conducted for the entire demonstration experiment, as was done for the a priori demonstration experiment in Part I. To satisfy comparability of the unit and cell data, the cell dataset was again limited to only those cells that were determined upon postanalysis to have been treated within the confines of the experimental units. It was found that the Hotelling T square = 2.93. Because this value is less than $\chi^2_{(2,0.95)} = 5.99$, the result is not significant at the 0.05 level and the null hypothesis cannot be rejected. There is only about 30% confidence that the seeding effect on both units and cells is simultaneously positive. Thus, the results for the entire demonstration experiment are only slightly stronger than the result for the a priori demonstration experiment reported in Part I.

TABLE 3. Results of pooled cell and unit RVOL analyses for the exploratory and demonstration samples (RVOL values in kilotons or 10^3 m^3).

Dataset	N	Mean S	Mean NS	Seeding effect (%)	90% Confidence interval	
					Lower	Upper
Convective cells						
Exploratory sample	126	132.23	96.25	37	-44	240
Demonstration sample	727	367.44	268.37	37	-8	104
Pooled sample	853			37	-7	102
Experimental units						
Exploratory sample	15	4321.9	1936.7	123	-28	593
Demonstration sample	70	11 787.8	6097.7	93	2	267
Pooled sample	85			95	7	257

d. Pooled cell and unit analyses

To complete the overall cell and unit analyses, the RVOL results for 15 units (8 S and 7 NS) obtained from the exploratory tests in 1991 and 1993 were pooled with the results from the entire demonstration experiment. The results of each analysis were weighted according to the sample size and inversely weighted with respect to the variance. This approach should be contrasted conceptually with the combination of datasets that are then subjected to a single analysis. Because of the weighting, the pooled RVOL results (Table 3) are little different from those for the entire demonstration experiment. The proportional effect of seeding on cells is +37%, with lower and upper bounds of the 90% confidence interval of -7% and +102%. Likewise, pooling of the unit RVOL results produced a slightly more positive proportional seeding effects of +95%, with lower and upper bounds of the 90% confidence interval of +7% and +257%, respectively.

3. Analyses of the floating target and its complement

a. Floating-target analyses

The uncertainty concerning the propagation of seeding effects within and outside the units was addressed using analysis comparable to the floating-target analysis that was developed for the Florida Area Cumulus Experiment (FACE; Woodley et al. 1982). In the original analysis all treated echoes and those echoes with which they merged at the 30-dBZ contour were tracked manually as the echo mass "floated" within the fixed FACE target. This FT analysis was viewed as a more sensitive measure of the effect of seeding than the TT analysis, because it kept track of echo entities that were known to have treated ancestry by virtue of direct treatment or through merger with treated echoes.

This is the same rationale for making FT analyses in the Thai cold-cloud experiment, where again the FT is the portion of unit echoes known to have seeded ancestry. If the S FT persists within the moving experimental unit long after seeding has ceased, it would be

easier to argue for long-lasting seeding effects than if the floating target dies shortly after seeding has ceased.

The Thai floating-target analysis was accomplished by first writing the software needed to specify the treatment ancestry versus time of all cells within the experimental unit. Once written, the cell tracking was objective and was not subject to unintentional human biases. The analyses gave mean S and NS floating-target rain volumes of 5318.20×10^3 and $3168 \times 10^3 \text{ m}^3$, respectively, and a proportional effect of seeding of +68% on unit RVOL (Table 2b). The lower and upper bounds of the corresponding 90% confidence interval are -13% and +223%, respectively. The apparent seeding effect for the FT is smaller than the overall apparent effect in the TT. Thus, unit cloud masses without treated ancestry must have contributed to the overall seeding effect if seeding caused the differences.

It is instructive to examine the results for the secondary-response FT variables as listed in Table 2b. Note first that the sign of the effect for all of the FT secondary-response variables is the same as those for the cells (Table 1). This includes the results for HMAX and for ZMAX, which had the opposite sign for the TT (Table 2a). This result makes sense because both the S cells and the S unit FT actually received the glaciogenic nucleant.

The analysis was carried one step farther by quantifying the rainfall from FT echoes within and outside of the moving experimental unit. The floating-target calculations for the experimental unit and beyond gave an S-to-NS ratio of 2.22 at a *P* value of 0.125. The ratio is much larger than the FT calculations limited to the target boundaries, suggesting that the propagation of echoes with treated ancestry outside of the unit boundaries was more prevalent when the treatment was silver iodide. However, the *P* value does not allow for much confidence in this result.

b. Analysis of the floating-target complement

For ease of discussion, those unit echo masses without treated ancestry are called the "FT complement," or TT - FT. This analysis of the FT and its complement

is similar to the kind of analysis that was used by Silverman and Sukarnjanaset (2000) in exploratory analyses aimed at understanding the physical processes that led to enhanced rainfall in the Thai warm-cloud hygroscopic particle-seeding experiment.

The results for the FT complement are presented in Table 2c. The analyses for the FT complement gave mean S and NS total-target rain volumes of 6469.6×10^3 and $2929.7 \times 10^3 \text{ m}^3$, respectively, and a proportional effect of seeding of +115% on unit RVOL. The lower and upper bounds of the corresponding 90% confidence interval are +4% and +345%, respectively. These are large apparent effects, which can only be explained by communication of the apparent seeding effect in the FT to its complement, if indeed seeding caused the differences. This possibility is not out of the question, because the conceptual model indicates that seeding effects need not be limited to clouds having seeded ancestry as determined from radar observations. Propagation of seeding effects to nonseeded clouds might occur through downdraft interactions and “secondary seeding,” a new element in the conceptual model to be addressed later.

Comparison of the secondary-response variables for both the S and NS FT with their complements revealed large differences. The S FT contains taller-more reflective convective cells than its complement, whereas the S FT complement has much greater rain-volume rates, areas, and number of convective cells, and it is 63% longer in duration. The same is true for the NS FT with respect to its complement, although the differences are not as large. The FT complements produced about 20% more S RVOL and about 7.5% less NS RVOL than their corresponding FT values, thereby causing the single ratio of S/NS RVOL (and the corresponding proportional effect of seeding) to be much greater for the FT complement than it is for the FT. The S FT complement would appear to have the properties of long-lasting light-to-moderate, mainly stratiform rainfall as might be produced by thick “anvil” debris from the earlier intense convection. As postulated by the conceptual model as early as 1982 (Woodley et al. 1982), seeding might enhance the rainfall from such clouds through the slow growth of ice crystals in the anvil mass, which is continually fed from below by penetrative glaciated convection, and through the development of a direct vertical circulation with rising motion in the thick anvil shield with sinking on its periphery. As postulated later, these processes are enhanced through secondary seeding. Although all of these processes are now addressed in the conceptual model, the evidence supporting their existence is weak and circumstantial.

c. Relative effects on RVR and RVOL

Plots of mean S and NS unit RVR for the TT, FT, and FT complement (TT – FT) are provided in Figs. 1a–c, respectively. As discussed in Part I, the S RVR

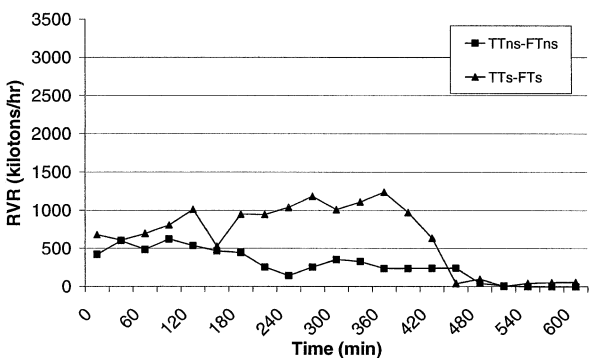
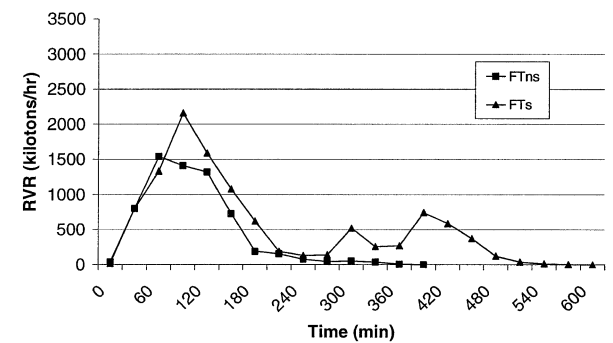
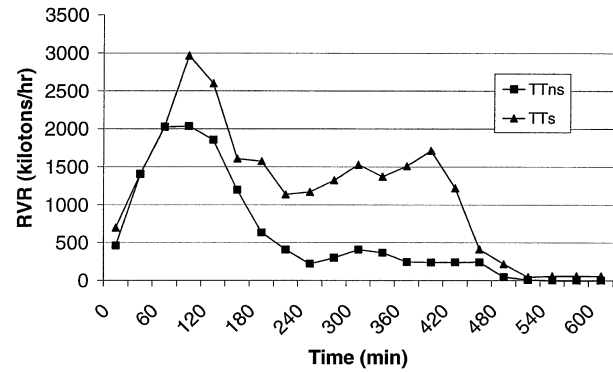


FIG. 1. Plots vs time of mean S and mean NS RVR for the (top) TT, (middle) FT, and (bottom) TT – FT for the entire Thai demonstration experiment.

exceeded the NS RVR before treatment in the TT, but covariate analysis to determine the potential impact of prequalification unit rainfall biases favoring the S sample revealed no effect on the results of the experimentation. The RVR disparity had diminished greatly by the time of unit qualification and, as Fig. 1a shows, there were virtually no differences out to 80 min after unit qualification. The S plot subsequently exceeds the NS plot out to 480 min, reaching a secondary peak at 400

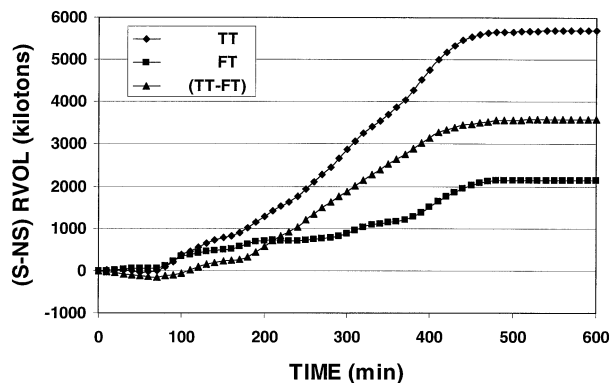


FIG. 2. Plots vs time of S - NS cumulative RVOL differences for the TT, FT, and TT - FT.

min. Although the conceptual model clearly calls for the propagation of seeding effects in space and time, it is unclear to what extent the time plots represent real effects of seeding, because the average and longest treatment periods were 122 and 197 min, respectively.

It can be seen in Fig. 1b that the plots of the S and NS RVR values for the FT show an initial burst of convective rainfall in the period 60–120 min. This is followed by resurgence of the S FT rainfall that peaks at 400 min after unit qualification, whereas the NS FT dies out without a secondary surge. Thus, the finding that apparent seeding effects are evident to 400 min in the unit plots is not as unrealistic as first believed, because echoes with S ancestry still existed at that time.

Even then, as noted earlier, the FT complement made a major contribution to the apparent seeding effect. The plots of the S and NS FT complement (Fig. 1c) show the S FT complement surging as the S FT decreases, suggesting communication of seeding effects from the directly treated clouds to those that were not seeded. This transition appears to begin at about 160 min after unit qualification.

Additional insights are provided by plots of mean cumulative S - NS TT, FT, and TT - FT unit rain volume differences (Fig. 2). The TT S - NS differences is near zero from 0 to 90 min, followed by a steep increase subsequently. It levels out by 480 min after unit qualification, and by 600 min the cumulative S - NS RVOL difference is about 5800 kilotons.

The same picture is evident in the plot of mean cumulative S - NS FT unit rain volume difference. Note that the FT RVOL difference plot is coincident with the TT difference plot to 105 min after unit qualification, indicating that treated clouds were producing virtually all of the apparent enhancement of the rainfall in this time frame. Both difference plots are in positive territory. The lines depart subsequently as the TT difference plot shows a strong increase while the FT RVOL difference plot shows a much smaller rate of growth.

The plot of mean cumulative S - NS RVOL difference for the TT - FT illustrates the strength of its

contribution to the overall effect on the TT. Until 105 min after unit qualification, the difference is slightly negative. Note that the crossover point for the FT and TT - FT S - NS difference plots takes place at 210 min after unit qualification. This marks the end of the dominance by the directly treated clouds and the beginning of the extended period during which rainfall in the FT complement is dominant.

4. Analyses of seeding effect as a function of coalescence intensity

a. Finding a measure of coalescence intensity

During the Texas randomized-seeding experimentation, Woodley and Rosenfeld (1996) noted that "The apparent seeding effects were larger for clouds having base temperatures $>16^{\circ}\text{C}$ in which coalescence is probably active, suggesting clouds with at least some coalescence may be more responsive to seeding than clouds without coalescence." This was factored into the revised dynamic-mode seeding conceptual model (Rosenfeld and Woodley 1993), which indicates that the optimal cloud structure for seeding intervention is a strong updraft containing low concentrations of raindrops generated from below by coalescence interspersed within high quantities of cloud water. Supercooled clouds without raindrops are not viewed as optimal because glaciation and the growth of graupel to precipitation size proceeds more slowly in such clouds, even with seeding intervention (Rosenfeld and Woodley 1993, 1997). In converse, clouds low in cloud water and laden with raindrops are not optimal either because such clouds usually glaciate at -10°C or even warmer through natural droplet freezing and ice multiplication, resulting in the early formation of precipitation. The seeding "window" is closed in such circumstances.

Because of the guiding conceptual model, there was considerable interest in investigating the effect of seeding as a function of coalescence activity in the Thai cold clouds. This interest was manifested first in the design of the experiment. As discussed in Part I, all experimental units were randomized in two blocks as a function of cloud-base temperature (CBT) (i.e., $\text{CBT} \leq 16^{\circ}\text{C}$ and $\text{CBT} > 16^{\circ}\text{C}$), which was measured by the aircraft in the afternoon on its climb into the target area. The randomization blocks were set as proxies for weak ($\text{CBT} \leq 16^{\circ}\text{C}$) and stronger ($\text{CBT} > 16^{\circ}\text{C}$) coalescence. Upon looking at the RVOL results for the Thai units, the larger apparent effect of seeding, expressed as a percentage (519% vs 71%) and as a rain difference (8589 vs 5019 kilotons) was found in the cooler CBT partition. This is the reverse of the findings in Texas where the largest apparent effect was noted in the warmer CBT partition. This clearly calls for a closer look with a more direct measure of in-cloud coalescence.

In the absence of particle-measuring probes in Thailand, coalescence intensity was "quantified" using ob-

servations of the presence or absence of detectable raindrops on the windshield of the project Aero Commander seeder aircraft as it penetrated the updrafts of growing convective towers at about the -8°C level (about 6.5-km above mean sea level). The window coalescence assessment was done by two Thai scientists after adequate training for all cloud passes on the 85 days of randomized cold-cloud experimentation in Thailand by viewing the flight videotapes made by a camera mounted in a forward-looking position on the right-hand side of the cockpit in the seeder aircraft. The autofocus feature of the camera ensured that it focused on the windshield during the cloud penetration and outside on the cloud field when the aircraft exited the cloud.

Because the cloud penetrations were made in strong updrafts (often $>5\text{ m s}^{-1}$), about 200–600 m below cloud top, the visible impacts on the aircraft windshield were interpreted as raindrops originating below the aircraft. The strong updrafts assured that at least the smaller raindrops formed below the penetration level would rise with the updraft. Later comparisons with the cloud physics instruments on the Thai cloud physics aircraft that arrived in late May of 1997 showed that these impacts were associated with two-dimensional cloud (2DC) images of particles larger than about $150\text{-}\mu\text{m}$ diameter. The rounded spherical shapes of these images and the penetration level temperature suggested that they were supercooled raindrops, or at most unrimed frozen drops.

Rosenfeld and Woodley (2003) used this approach for quantifying coalescence intensity in a study of the role of coalescence in determining the rainfall from natural (unseeded) clouds. This approach was extended for the purposes of this paper by calculating for each unit the percentage of cloud passes having observable drop impacts on the aircraft windshield. From these, three supercooled rainwater (SCR) coalescence categories were defined: 1) weak coalescence (category 1), when 0% of the cloud passes had detectable raindrops; 2) moderate coalescence activity (category 2), when $0\% < \text{SCR} < 90\%$; and 3) strong coalescence (category 3) when $\text{SCR} \geq 90\%$. Category 1 was defined as having weak, rather than no, coalescence, because the absence of detectable impacts on the windshield could not be interpreted as proof there was no coalescence. Three coalescence categories were chosen, because the conceptual model indicates that there should be three levels of response to glaciogenic seeding—positive in clouds without obvious coalescence activity, positive and larger in clouds with some coalescence, and much smaller, possibly even negative, in clouds with strong coalescence.

The next step was comparison of calculated mean first-echo depths as a function of inferred coalescence activity, where the mean first-echo cloud depth (FED) is defined as the difference between mean first-echo heights (FEH) and measured cloud-base height (CBH) for the day. This was done with the expectation that

TABLE 4. Mean properties of first-echo depth vs coalescence category for treated echoes meeting the selection criteria. FED = FEH – CBH; the one-tail P values were obtained from a t test assuming unequal variances.

N	SCR	FEH (km)/ Temperature ($^{\circ}\text{C}$)	CBH (km)/ CBT ($^{\circ}\text{C}$)	FED (km)	P value for FED diff
19	1	6.36/–8	2.21/16.4	4.15	1 vs 2: $P = 0.039$
38	2	5.48/–2	1.87/19.9	3.61	2 vs 3: $P = 0.05$
15	3	4.76/+2	1.77/20.5	2.99	

mean first-echo depths would be smaller for clouds with rapid onset of coalescence as compared with clouds with slower coalescence activity.

To qualify for inclusion in the assessment, each treated convective cell on a given day had to be within 80 km of the radar and relatively isolated from other already precipitating clouds at the time of its first echo at the 12-dBZ threshold level. The first-echo height was taken as the most intense echo within the first-echo interval, or midpoint, when no identifiable maximum occurred. All treatment passes were made through new cloud towers, and only the corresponding cells that existed at the time of the first aircraft pass were considered for the analysis. Clouds seeded with AgI also are included because the coalescence (cloud pass) discrimination was made before the ejection of any flares.

The results for the three coalescence categories are presented in Table 4. It can be seen that the mean first-echo depth is inversely proportional to the intensity of coalescence activity. The results are supportive of the coalescence partitioning, thereby verifying our expectations and supporting our search for apparent seeding effects as a function of coalescence intensity.

b. Seeding results as a function of coalescence activity

Assessment of the apparent effects of seeding on the cell and unit scales was then made for SCR categories 1, 2, and 3, defined above. Results are presented in Table 5. First for the NS results, note that the cell rain volumes increase as the coalescence activity increases. Although other factors may be involved, category-3 clouds with intense coalescence likely produce more rain volume because of more efficient rain-forming processes. On the other hand, the apparent seeding effects are smallest in category 3 and are greatest in category-1 clouds, which have weak coalescence. The latter is readily understood, because clouds with intense coalescence are probably highly efficient microphysically and do not need seeding intervention. The former is somewhat of a surprise because the largest effect was expected in category-2 clouds.

The same picture is evident for the experimental units (Table 5). Because of the very small sample sizes, the results for the 90% confidence interval should be viewed

TABLE 5. Results of exploratory cell and unit analyses for the demonstration sample (RVOL values in kilotons or 10^3 m^3): results after partitioning by SCR.

Variable	Mean S	Mean NS	Seeding effect (%)	90% Confidence interval	
				Lower	Upper
Convective cells					
Cells SCR category 1	257.42	123.07	109	-9	382
Cells SCR category 2	350.22	217.21	61	-4	172
Cells SCR category 3	479.68	433.7	11	-44	118
Experimental units					
TT SCR category 1	6185.57	1994.18	210	20	698
TT SCR category 2	14 828.87	6075.63	144	0	494
TT SCR category 3	8009.15	8193.59	-2	-47	82
FT SCR category 1	3449.12	973.88	254	5	1093
FT SCR category 2	6256.89	3323.65	88	-26	378
FT SCR category 3	4256.15	3953.76	8	-49	125
TT - FT SCR category 1	3054.83	1235.84	147	18	420
TT - FT SCR category 2	8770.29	2862.11	206	12	737
TT - FT SCR category 3	4095.13	4611.91	-11	-58	88

with caution. Again, NS units with strong coalescence produce the most total target rain volume. They also have greater lifetime RVR values as can be seen in the NS RVR plots in the top panel of Fig. 3. Note that the NS RVR plots for category-1, -2, and -3 plots stack up from driest to wettest, respectively, and that category-3 units show a second weaker surge of rainfall about 3 h after the initial unit maximum.

The picture is reversed for the S units (bottom panel of Fig. 3). The wettest S units by far are category-2

units, and category-3 units are only slightly wetter than those of category 1. It appears that seeding may have changed the natural tendencies. Note that category-2 and -3 units also show a second surge of rainfall. This implies that the primary convection communicates somehow to the rest of the unit to generate a second (usually weaker) surge of rainfall 3–5 h after the first burst of convection. If this is so, the communication mechanism appears to be more pronounced in the S units.

Examination of the TT, FT, and TT - FT RVR plots for the S and NS units in Fig. 1 provide additional insights. The NS plots suggest that the complement to the FT accounts for the secondary surge in the TT RVR plot. This is true also for the S RVR plots, although the FT also makes a significant contribution.

As with the cells, the largest percentage effect of seeding in the experimental units with the strongest statistical support was noted in units with weak coalescence, followed closely by units with moderate coalescence activity (Table 5). The largest absolute increase in rain volume, however, is produced in the category-2 units. No seeding effect is evident in clouds with intense coalescence. This is in good agreement with the seeding conceptual model.

The results were qualitatively similar when this exercise was repeated after defining three CBT partitions (i.e., $12^\circ < \text{CBT} < 17^\circ\text{C}$, $16^\circ < \text{CBT} < 23^\circ\text{C}$, and $22^\circ < \text{CBT} < 26^\circ\text{C}$) to approximate weak, moderate, and intense coalescence, as inferred using the SCR. Both approaches showed the smallest apparent seeding effects in the SCR and CBT partitions indicative of intense coalescence. In the CBT exercise, however, the largest apparent seeding effect in terms of percentage and absolute RVOL differences was noted in the coolest CBT category. Although the SCR should be a better indicator of coalescence than CBT, because the former was obtained through direct “measurement” in the clouds, one should not dismiss this disparity out of hand. The truth is that we do not yet have a solid understanding of the

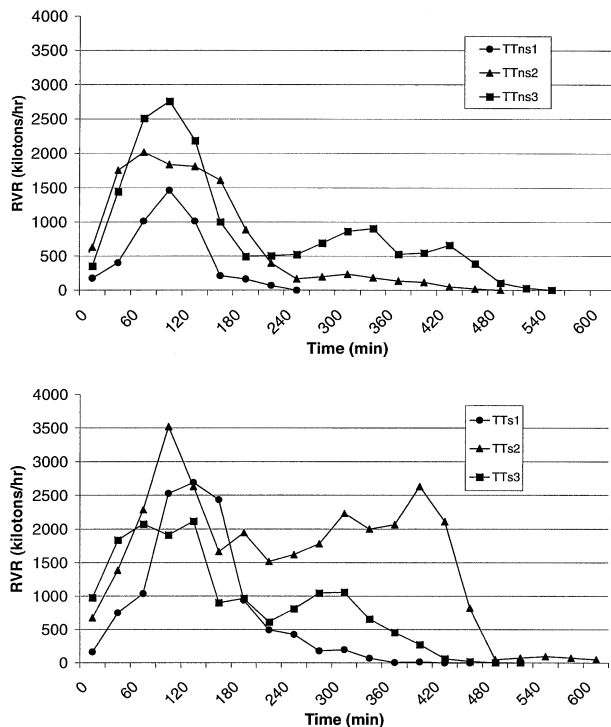


FIG. 3. Plots vs time of mean total target (top) NS and (bottom) S RVR for SCR categories 1, 2, and 3 for the entire Thai demonstration experiment.

effects of seeding under varying intensities of in-cloud coalescence. Direct measurement of coalescence using particle measurement probes is needed to resolve this important uncertainty. Until then, one is safest concluding only that dynamic-mode glaciogenic seeding of clouds with intense coalescence is unlikely to be effective.

5. Addressing the natural rainfall variability

One of the challenges faced by cloud-seeding experiments, especially those with small samples, is the natural rainfall variability, which can confound the interpretation of the results. The natural rainfall variability was taken into account by identifying covariate variables that could serve as predictors of the natural rainfall. Only the mean precipitable water (PW) and the mean control cell rainfall ($RVOL_{CC}$), calculated external to the units, using the "short track" software, proved to be useful covariates for the experimental unit rainfall ($RVOL_U$).

The criteria for the selection of the control cells are discussed at length by Rosenfeld and Woodley (1989). In defining the cells to be used as controls, several factors had to be considered. First, the prospective clouds had to conform as much as possible to the selection criteria for the clouds in the actual experimental units that received S or NS (simulated) treatment. Second, the control cells had to be separated from the S and NS cells by 35 km to minimize the possibility of contamination. Third, each set of control cells had to be as far from the radar as the experimental cells that resided within each experimental unit to minimize range biases.

The multiple-regression equation using these covariates was $RVOL_U = -26\,938.19 + 129.304\,RVOL_{CC} + 5364.664\,PW$. The multiple correlation is 0.526, indicating that 28% of the natural rainfall variability is being taken into account. The overall regression is highly significant as are the intercept and the coefficients for the covariates. The ratio of the predicted S to predicted NS rainfalls [SR(pred)] is 1.3, indicating that the estimate of the seeding effect after taking natural variability of rainfall into account is reduced to +48% [i.e., $SR(obs)/SR(pred) = 1.93/1.30 = 1.48$] with a 90% confidence interval from -14% to +154%.

This covariate analysis suggests that any effect of seeding on the unit scale has been overestimated by about a factor of 2. Even then, the 48% apparent effect of seeding on the unit scale in Thailand is comparable to the result (+45%) in Texas that was obtained from a sample of only 38 units (Woodley and Rosenfeld 1996) before the experiment was terminated. Neither the Thai nor Texas results have strong statistical support.

6. Discussion

Although the Thai cold-cloud demonstration experiment did not prove the efficacy of dynamic-mode seed-

ing for the enhancement of convective rainfall, the probability that the results were positive is at least 80%, depending on the analysis. This is important information for water managers who typically make probabilistic benefit-versus-cost estimates before embarking on a program of operational cloud seeding for rainfall enhancement. Proof of seeding effectiveness, however, must come from an independent confirmatory experiment.

a. Uncertainties and inconsistencies

Although the results on the cell and unit scales suggest a positive effect of seeding, there are a number of troublesome uncertainties and inconsistencies in the results relative to the guiding conceptual model. For example, all early versions of the conceptual models guiding on-top glaciogenic seeding experiments have called for increased vertical growth of the seeded clouds. Statistically significant increases in cloud growth averaging about 20% have been documented for clouds over the Caribbean and Florida (Simpson et al. 1967; Simpson and Woodley 1971). Clouds seeded in Texas (Rosenfeld and Woodley 1993; Woodley and Rosenfeld 1996) and Thailand, however, have shown much less vertical growth, with weak statistical support.

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

This is not a problem for the estimate of the effect of seeding on cloud growth, however, as long as the radar "sees" seeded and nonseeded clouds the same way. This is not likely the case. Seeding changes the microphysical structure of the clouds, causing glaciation at higher temperatures (Sudikoses et al. 1998). As such, they resemble natural, more maritime clouds (Rosenfeld and Lensky 1998), which are characterized by early glaciation and fallout of precipitation-sized particles. The reflectivity of these clouds falls off faster with height above the 0°C-isotherm level than more continental clouds (Zipser and Lutz 1994). Thus, if seeded clouds are made to resemble glaciated natural maritime clouds, it follows the radar is going to underestimate their tops at 12 dBZ more than nonseeded clouds, which do not glaciate until colder temperatures.

Additional supporting evidence is provided in Figs. 10c and 11c (not reproduced here) in an article by Rosenfeld and Woodley (2003) in the American Meteo-

rological Society meteorological monograph honoring Dr. Joanne Simpson. Reflectivity profiles for clouds with active coalescence and early glaciation show reflectivity maxima below the freezing level and a rapid falloff of reflectivity above the maximum to echo top. In contrast, clouds with little coalescence and delayed glaciation have reflectivity maxima well above the freezing level, in many cases to near echo top. It was noted further that for the same echo top, the difference between cloud top and echo top was up to 3 km greater for clouds with strong coalescence and early glaciation. Because AgI seeding produces glaciation in seeded clouds that is comparable to the highly glaciated natural case, these results suggest that the growth of the seeded clouds has been underestimated substantially relative to the clouds that did not receive AgI treatment.

Thus, the seeded clouds in Texas and Thailand were likely taller physically than the nonseeded clouds by more than the calculated factor of 1.05, but that cannot be known through the radar measurements. This statement is, of course, highly speculative. Measurements of cloud tops using aircraft and/or infrared satellite imagery are necessary to resolve this important uncertainty, which has created doubts in some quarters (e.g., Silverman 2001) concerning the dynamic-mode seeding conceptual model and the role that the vertical growth of a seeded cloud plays in the apparent rainfall enhancements.

Despite the indications of positive seeding effects, it was difficult initially to reconcile the Thai cell results with those published for Texas (Rosenfeld and Woodley 1993; Woodley and Rosenfeld 1996) that suggested seeding effects on RVOL of greater than 100%. Reconciliation came upon considering two factors. First, the supercooled clouds of western Texas typically are microphysically continental, having weak to at most moderate coalescence activity. Virtually none of the Texas experimental units were qualified under conditions of strong coalescence. Thus, the Thai cell RVOL results for SCR categories 1 and 2, with apparent seeding effects ranging between +61% and 109%, are most comparable to those of western Texas. Second, the published results for Texas were generated without the deletion of cell duplications as was done for Thailand (see Part I). To facilitate the Thai-versus-Texas comparisons, therefore, the Texas dataset published by Rosenfeld and Woodley (1989, 1993) was reanalyzed after the cell duplications had been deleted. In doing so, the apparent seeding effect dropped from 131% to 72%. This brings the apparent seeding effect on convective cells in Texas into good agreement with that quantified for Thai clouds having weak to moderate coalescence.

On the other hand, the cell results in Texas indicated larger apparent effects of seeding for $CBT \geq 17^{\circ}\text{C}$, which made sense in the context of the conceptual model because clouds with warm bases are more likely to develop coalescence and, therefore, to be more responsive to seeding. In Thailand, however, the larger apparent

effect of seeding was noted for $CBT \leq 16^{\circ}\text{C}$ on both the cell and unit scales. This is true also for the SCR partition that is suggestive of the least coalescence.

Another apparent inconsistency is the difference between the effect of seeding on the maximum radar reflectivity—positive on the cell scale and negative on the scale of the experimental units. This apparent inconsistency is resolved when one notes that the S cells actually received AgI treatment, whereas not all of the cells in the overall S unit received AgI treatment. When one examines the FT unit variable, however, the apparent effect of seeding on the maximum cloud-base radar reflectivity is positive because it is for the treated cells. This makes physical sense, because the FT cells have direct seeded ancestry. The TT results for the maximum radar reflectivity were, however, dominated by the results for the FT complement that had values of the average maximum radar reflectivity that were 40% lower than those for the FT and were affected by seeding in a negative sense.

A perplexing inconsistency in the Thai dataset is the finding that the apparent effect of seeding is larger with greater statistical support on the unit scale rather than the cell scale, as required by the conceptual model. This is not easily explained away. If both effects are real, it means that some mechanism is operative to communicate and amplify the effect of seeding on the scale of the individually treated cells to convective cells within the unit that did not receive direct treatment. The conceptual model has identified downdrafts as a mechanism for the propagation of seeding effects in space and time. Simpson (1980) and Woodley et al. (1982) have long argued that the main manifestation of enhanced downdrafts would be the generation of new cells and their eventual merger. The data in Table 1 for the cell analyses, which show more clustering of the S cells, suggest that this may have happened in Thailand. In addition, the finding that echoes with treated ancestry persist for as much as 7 h after unit qualification (or about 5 h after cessation of seeding) lends support to the arguments for the propagation of seeding effects with time.

We do not pretend, however, to understand how seeding might act to enhance downdrafts. The conceptual model calls for the RVR of the S cells to peak later in time than the RVR of the NS cells, because the seeding-induced enhanced buoyancy should act to support the growing precipitation mass longer before it plummets to earth as heavy rain with its attendant downdraft. It makes sense physically perhaps, but the data do not support this expectation. The commencement of rain and its peak are in phase for the S and NS cells, but the rain from the S cells is somewhat greater than that from the NS cells (see Fig. 4).

b. Modification of the conceptual model

It is time to consider two deletions, a modification, and one addition to the conceptual model as put forth

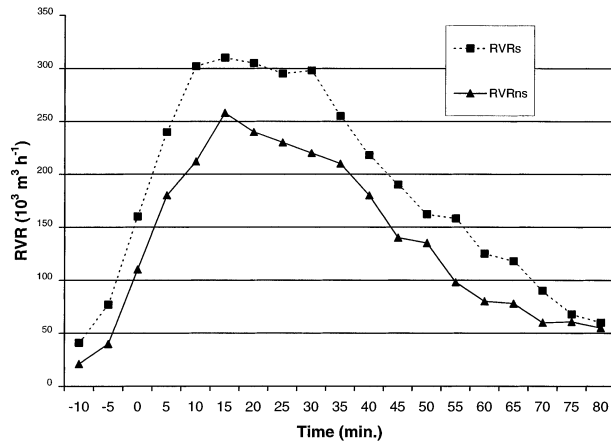


FIG. 4. Plot vs time of mean S (dashed) and NS (solid) RVR of cells for the Thai demonstration experiment.

by Rosenfeld and Woodley (1993). The first deletion is the requirement that the S RVR peak later than the NS RVR. That this does not occur suggests that we do not understand totally the response of individual cells to treatment. Realistic cloud modeling would be helpful in this regard. The second deletion, which is related somehow to the first, is the requirement that the apparent seeding response on the cell scale be larger with stronger statistical support than the apparent seeding response on the unit scale. Although this still seems like a reasonable requirement in that the seeding is done on the cell scale, the data do not support its retention in the conceptual model. Deletion of this link in the conceptual chain has implications for the manner in which the seeding effect, which begins on the cell scale, is communicated to the overall unit. Downdraft outflows and the exchange of hydrometeors from the seeded clouds to those not seeded (secondary seeding) would appear to be prime candidates for the communication of seeding effects. Both mechanisms could take place close in space and time to the seeded clouds or they could be operative quite separately in space and time from the seeded clouds, especially secondary seeding, which in principle could take place hours after seeding has ceased. Again, cloud modeling would be helpful in understanding the relative importance of these processes.

The modification of the conceptual model involves the manner in which seeding effects are communicated from the directly treated cells to the overall unit. Since its inception, the model has identified downdrafts as the likely mechanism for communication, but it was expected implicitly that this effect would be traceable through the floating target as has been defined here. Although an effect of seeding is suggested in the floating target, the larger apparent effect is evident in the floating-target complement, which had no traceable seeded ancestry. Although this came as somewhat of a surprise, it is consistent with the results of the Thai warm-cloud hygroscopic particle-seeding experiment reported by

Silverman and Sukarnjanaset (2000) that showed the apparent seeding effect was associated primarily with the untreated-cell component of their experimental units. Both experiments suggest that at least the initial communication mechanism involves dynamics, presumably enhanced downdrafts, leading to regions of convergence and new cloud growth at the interface between the outflowing air and the ambient flow. Mather et al. (1997) apparently obtained a similar result for the South African hygroscopic flare seeding experiment in that the seeding effects did not reach significance until some time after seeding had ceased. Although these comparisons are legitimate as an illustration of the apparent occurrence of dynamic effects in the hygroscopic seeding experiments when none were expected, the differences in the nature and complexity of these effects relative to those apparently operative in the Thai glaciogenic seeding experiment are readily acknowledged.

With respect to at least dynamic-mode glaciogenic seeding experiments, it appears that the conceptual model also should be revised to address secondary seeding, whereby unseeded clouds ingest ice particles from clouds that earlier had received direct glaciogenic (e.g., silver iodide) treatment. This thought to be a mechanism for the propagation of seeding effects in space and time (Woodley and Rosenfeld 2002). It is hypothesized that the ingested ice particles, after experiencing some growth in the donor clouds, act to glaciolate the receptor clouds during their active growth phase and to provide them precipitation embryos. These embryos give the receptor clouds a head start on precipitation development because the hydrometeors grow further as graupel to precipitation size in the updraft that is laden with high quantities of supercooled cloud water.

Secondary seeding is not unique to seeded clouds nor is it a rare event. Further, it need not be limited to ice particles. Rosenfeld and Woodley (1997) discuss a case, showing that clouds that existed in a clustered environment and had ingested embryos from decayed clouds contained large raindrops on the initial pass through active cloud towers. Ice subsequently formed faster and the supercooled cloud water decayed more rapidly in these clouds. On the other hand, clouds (on the same day) that were relatively isolated during their growth phases retained their cloud water longer than clustered clouds. Rain drops were rare during the initial cloud passes and increased only slightly later. This readily illustrates the importance of the exchange of hydrometeors in the development of precipitation in clouds that could not otherwise develop precipitation on their own.

The finding that the rainfall in the complement to the FT occurs later in time and is much less convective than that in the FT itself suggests that secondary seeding could also play an important role in the transmission of seeding effects within the experimental unit. Further, it may not be possible to track the effects of secondary seeding on radar when the exchange of hydrometeors

produced by the initial seeding occurs long after seeding has ceased and the FT echoes have dissipated.

The relative importance of downdrafts and secondary seeding in the transmission of seeding effects is unknown, if indeed either process is operative in the apparent seeding-induced rainfall enhancements. There is simply too little information at present to reach a conclusion. These issues serve to emphasize the importance of cloud modeling in conjunction with a state-of-the-art cloud-seeding research effort. Cloud models have now progressed to the point at which they address most cloud processes explicitly and realistically. The recent realistic simulation by Khain et al. (2001) of a case of extreme supercooling in Texas, as documented by Rosenfeld and Woodley (2000), is a case in point. It is time now to give more emphasis to the modeling component of weather-modification research efforts.

7. Conclusions

Part I established that the Thai cold-cloud demonstration experiment failed to reach statistical significance in the time allotted to the experiment, although the probabilities that the seeding effects were positive on the treated cells and units are 72% and 79%, respectively. The results of exploratory examination of the entire demonstration experiment, consisting of 35 seeded and 35 nonseeded units, strengthen the case for seeding-induced changes in rainfall.

The exploratory evaluation involved both cell and unit analyses. The cell dataset includes 392 AgI-seeded cells and 335 nonseeded cells that received simulated AgI (glaciogenic) treatment. The proportional effect of seeding on cell rain volume is +37%. The lower and upper bounds of the corresponding 90% confidence interval are -8% and +104%, respectively. There is 81% confidence that the seeding effect is positive, with the true effect being in the range from 0% to 88%.

Analysis of the 70 experimental units over their lifetimes gave a proportional effect of seeding of +93% on unit RVOL. The lower and upper bounds of the corresponding 90% confidence interval are +2% and +267%, respectively. There is 91% confidence that the seeding effect is positive, with the true effect being in the range from 0% to +274%.

A bivariate analysis on the simultaneous effects of seeding on units and cells was also conducted for the entire demonstration experiment. There is 30% confidence that the seeding effect on both units and cells is positive. Thus, the results of the analysis for the entire demonstration experiment on cells, units, and cells and units jointly, are slightly stronger than the result for the a priori demonstration experiment reported in Part I.

To complete the picture, the RVOL results from the 15 units (8 S and 7 NS) from the exploratory tests in 1991 and 1993 were pooled with the results for the demonstration sample. The pooled results gave slightly more positive proportional seeding effects of +95%,

with lower and upper bounds of the 90% confidence interval of +7% and +257%, respectively. Comparable pooling was done also for the exploratory and demonstration cell samples. The results for the pooled cell sample are indistinguishable from those obtained by analysis of the demonstration cell sample.

A major effort was made to understand the apparent effects of seeding, which was larger with stronger statistical support for convective masses within the unit not having seeded ancestry, as determined by radar, than for convective clusters with seeded ancestry. If real, it means that the effect of seeding, which begins with the directly treated cells, is propagated to nonseeded clouds within the unit.

Partitioning of the data by a crude aircraft measure of coalescence intensity (i.e., weak, moderate, and intense) was helpful in understanding the apparent effects of seeding. The rain volume from NS units increased as coalescence intensity increased. This natural tendency was reversed for the S units. Further, the apparent seeding effects were >100% for units having weak to moderate coalescence and were nonexistent for units with strong coalescence. This was true also for the cell analyses. Because clouds with strong coalescence are known to glaciate naturally at temperatures of $\geq -10^{\circ}\text{C}$, the ineffectiveness of glaciogenic seeding in such clouds is not surprising.

Covariate analysis to account for the natural rainfall variability in the experiment suggests a smaller apparent effect of seeding. The apparent seeding effect after accounting for about 28% of the natural rainfall variability with multiple linear regression is 48%, with a 90% confidence interval from -14% to +154%.

Further progress in specifying the effects of dynamic-mode, glaciogenic seeding is contingent upon a coordinated research effort involving randomized physical/statistical field experiments and numerical modeling, virtually the same type of effort recommended by Simpson (1980) but not yet accomplished satisfactorily. The passage of time has not obviated the need for such an effort, which also would include directed but basic research observations.

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REFERENCES

- Khain, A. P., D. Rosenfeld, and A. Pokrovsky, 2001: Simulation of deep convective clouds with sustained supercooled liquid water down to -37.5°C using a spectral microphysics model. *Geophys. Res. Lett.*, **28**, 3887–3890.
- Mather, G. D., D. E. Terblanche, F. E. Steffans, and L. Fletcher, 1997: Results of the South African cloud-seeding experiment using hygroscopic flares. *J. Appl. Meteor.*, **36**, 1433–1447.
- Rosenfeld, D., and W. L. Woodley, 1989: Effects of cloud seeding in west Texas. *J. Appl. Meteor.*, **28**, 1050–1080.
- , and —, 1993: Effects of cloud seeding in west Texas: Additional results and new insights. *J. Appl. Meteor.*, **32**, 1848–1866.
- , and —, 1997: Cloud microphysical observations of relevance to the Texas cold-cloud conceptual seeding model. *J. Wea. Modif.*, **29**, 56–69.
- , and I. M. Lensky, 1998: Spaceborne sensed insights into precipitation formation processes in continental and maritime clouds. *Bull. Amer. Meteor. Soc.*, **79**, 2457–2476.
- , and W. L. Woodley, 2000: Deep convective clouds with sustained supercooled liquid water down to -37.5°C . *Nature*, **405**, 440–442.
- , and —, 2003: Spaceborne inferences of cloud microstructure and precipitation processes: Synthesis, insights and implications. *Cloud Systems, Hurricanes, and the Tropical Rainfall Measuring Mission, Meteor. Monogr.*, No. 51, Amer. Meteor. Soc., 59–80.
- Silverman, B. A., 2001: A critical assessment of glaciogenic seeding of convective clouds for rainfall enhancement. *Bull. Amer. Meteor. Soc.*, **82**, 903–923.
- , and W. Sukarnjanaset, 2000: Results of the Thailand warm-cloud hygroscopic seeding experiment. *J. Appl. Meteor.*, **39**, 1160–1175.
- Simpson, J., 1980: Downdraft as linkages in dynamic cumulus seeding effects. *J. Appl. Meteor.*, **19**, 477–487.
- , and W. L. Woodley, 1971: Seeding cumulus in Florida: New 1970 results. *Science*, **173**, 117–126.
- , G. W. Brier, and R. H. Simpson, 1967: Stormfury cumulus seeding experiment 1965: Statistical analysis and main results. *J. Atmos. Sci.*, **24**, 508–521.
- Sudikoses, P. W., W. Sukarnjanaset, N. Tantipubthong, W. L. Woodley, and D. Rosenfeld, 1998: Cold-cloud microphysical observations in seeded and non-seeded Thai clouds. Preprints, *Conf. on Cloud Physics 14th Conf. on Planned and Inadvertent Weather Modification*, Everett, WA, Amer. Meteor. Soc., J40–J43.
- Woodley, W. L., and D. Rosenfeld, 1996: Testing cold-cloud seeding concepts in Texas and Thailand. Part I: Results in Texas to date. Preprints, *13th Conf. on Planned and Inadvertent Weather Modification*, Atlanta, GA, Amer. Meteor. Soc., 60–67.
- , and —, 2002: Secondary seeding as a means of propagating seeding effects in space and time. *J. Wea. Modif.*, **34**, 31–38.
- , J. Jordan, J. Simpson, R. Biondini, J. A. Flueck, and A. Barnston, 1982: Rainfall results of the Florida Area Cumulus Experiment, 1970–76. *J. Appl. Meteor.*, **21**, 139–164.
- , D. Rosenfeld, and B. A. Silverman, 2003: Results of on-top glaciogenic cloud seeding in Thailand. Part I: The demonstration experiment. *J. Appl. Meteor.*, **42**, 920–938.
- Zipser, E. J., and K. R. Lutz, 1994: The vertical profile of radar reflectivity of convective cells: A strong indicator of storm intensity and lightning probability? *Mon. Wea. Rev.*, **122**, 1751–1759.