"REVIEWED"

TESTING OF DYNAMIC COLD-CLOUD SEEDING CONCEPTS IN THAILAND
PART II: RESULTS OF ANALYSES

Daniel Rosenfeld[1], William L. Woodley[2], Warawut Khantiyanan[3],
Wathana Sukarnjanaset[3], Prinya Sudhikoses[3], and Ronit Nirel[4]

[1] Dept. of Atmospheric Sciences, Hebrew University of Jerusalem, Israel
[2] Woodley Weather Consultants, Littleton, Colorado
[3] Royal Rainmaking Research & Development Institute, Bangkok, Thailand
[4] Dept. of Statistics, Hebrew University of Jerusalem, Israel

Abstract. Part II provides the results of analyses of Thailand's randomized, exploratory, cold-cloud, seeding effort. The sample is small and caution should be exercised in interpreting the results of these analyses.

A total of 151 convective cells (87 seeded and 64 nonseeded) have been identified within the experimental units and their properties computed through analysis of three-dimensional, volume-scan, S-band radar data using cell tracking software. The results indicate that AgI seeding may have increased the maximum cell areas by 25%, durations by 14% and rain volumes by 69%. Little effect is indicated on maximum cell heights, which may be due in part to underestimation of the glaciated tops of AgI-treated clouds by the S-band radar. Additionally, within the height range of 7 to 11 km, seeded cells of a given maximum echo top produced more rain volume than unseeded cells of the same height. None of the results has strong statistical support.

Partitioning by cloud base temperature increased the apparent effect of seeding to 71%, 33% and 125% for cell areas, durations and rain volumes, respectively, within the warm base (T > 16°C) partition. The apparent effect on maximum cell height is on the order of +6%.

The results for the small sample (i.e., 7 Seed and & 7 NS) of experimental units also show more S than NS rainfall. All results are comparable to what has been reported by the first two authors for a similar program in Texas, and are discussed in the context of the conceptual model guiding both experiments.

This work was conducted under a contract with the Bureau of Reclamation as part of a program sponsored by the U.S. Agency for International Development to upgrade Thailand's weather modification capability.

1.0 INTRODUCTION

Part I presented the historical and conceptual framework for the exploratory randomized cold-cloud seeding experiments in Thailand, a discussion of their design and procedures, and a description of the aircraft and radar systems that were available to the effort. The operational summary then provided the context for the analyses of the radar data that are discussed in this paper. The sample is quite small, which complicates the search for evidence of effects of silver iodide (AgI) treatment. Nevertheless, past experience elsewhere suggests that inference of seeding effects might be possible despite the limited sample.

The philosophy or approach to the analyses for seeding effects and their interpretation has the following components:

a) The results cannot depend on the approach to the analyses.

b) Statistically significant results should be evident ultimately, if the sample is large enough and if some means are found to account for the natural variability.

c) Seeding effects should be indicated in most of the analyses, even when no individual indication is statistically significant.

d) The results should be consistent with the conceptual model, or, if not, suggest a plausible alternative explanation.

e) The outcomes should be compatible with the findings in similar experimentation conducted elsewhere, especially that in Florida and Texas where the conceptual model and the design and its implementation are comparable to what has been done in Thailand.

In essence, therefore, the analysis process must not boil down to an exercise in statistics. All results must be plausible, reasonable and physically consistent, if they are to be believed.

This work was conducted under a contract with the Bureau of Reclamation as part of a U.S. Agency for International Development-sponsored program to upgrade Thailand's weather modification capability.

2.0 ANALYSIS OF THE RADAR DATA

The three-dimensional structures of the convective rain cells were monitored and recorded by the Enterprise S-band radar which was located at Omkoi (see Part I for specifications). The radar scanned the whole volume of the troposphere in the target area every 5 minutes. The recorded radar data are the primary source of information for the scientific evaluation of the effect of seeding.

The three-dimensional matrices of radar reflectivity factor, which were used in the next steps to specify the history of the three-dimensional structures of the cells, were saved in 5-minute time intervals. The data were already recorded by the SIGMET radar processor in dBz units.

The initial focus of this study is on individual convective cells within clouds and cloud systems rather than on multi-cell echoes, because the cell is the fundamental building block of all convective weather systems. As in earlier work (Gagin et. al., 1985 and 1986; Rosenfeld, 1987, Rosenfeld and Woodley, 1989, 1993), convective cells are defined as entities with at least three closed radar reflectivity isolines, spaced at 1 dBZ intervals, at the cloud-base level. All the radar echoes greater than 12 dBZ are partitioned between these entities, with the division lines coinciding with the trough lines on the reflectivity map.

A special method, developed by Rosenfeld (1987), for the study of cells that compose convective rain systems. This method consists of a package of computer programs that use pattern recognition techniques on three-dimensional digital radar data to identify the rain cells, track them with time and calculate their properties. The product of the computations is a comprehensive data base of physically meaningful properties of rain cells, which can be used to infer the internal structure and the dynamics of convective rain systems. This includes the production of time-height reflectivity cross-sections of the tracked cells, which are very useful to obtain a physical understanding of the precipitation evolution in the clouds.

The cell tracking programs produce a data base of the tracked cells. Their data base consists of tables of cell properties during their lifetimes. There are 90 INSTANTANEOUS values for each scan at which the cell was scanned by the radar (usually 5 minutes apart). Each cell also has LIFECYCLE values, which contain cumulative cell properties or the life-cycle maximum of the instantaneous properties.

It is possible to analyze the cell data with both the "short track" and "long track" approaches. The "short track" approach follows the cells until they either dissipate or merge with neighboring cells at a particular reflectivity contour. The "long track" is an objective approach that allows for cell tracking after merger. It appears to be superior to "short track", because it permits a more complete history of each cell (Rosenfeld and Woodley, 1989). This is the analysis emphasized in this paper.

A total of 151 cells were treated (AgI or simulated AgI) in 1991 and 1993 and subsequently tracked in the long-track analyses. These are the input data for the ensemble cell analyses that follow. All rainfalls were calculated from the reflectivity (Z) Rainfall Rate (R) relationship: $Z = 300R^{1.4}$, which was used by Woodley (1970) for radar estimation of rain from convective clouds over south Florida.

No analysis was possible for 18 April 1993 on which AgI seeding was done. The radar was not operated properly on this day, resulting in the loss of the data necessary to track the cells and calculate their properties. Thus, there are 14 experimental units (7 S and 7 NS) available for the inference of treatment effects. These are discussed in the next section.

3.0 SEARCH FOR EFFECTS OF COLD-CLOUD SEEDING

3.1 Statistical Significance Tests

The probability that the AARRP cell results are due to chance was calculated by a refinement of the Monte Carlo rerandomization test (Gabriel and Feder, 1969). This was done in the following steps:

a) A randomization reallocation of the experimental random cases to seeded (S) and non-seeded (NS) was made. All the treated cells in an experimental random case were assigned the same treatment which was drawn for the case.

b) The single ratio (SR) between all the S and NS cells, pulled together from all the S and NS randomized cases was calculated.

c) Steps a) and b) were repeated for 3000 permutations and a sorted vector of the SR's, obtained in the permutations, was produced.

d) The fraction (P, in %) of the randomly obtained SR's, which are larger than the observed one in the real experimental allocation, is the chance that the experimental result is due to the natural variability. This chance is referred to as the "significance level."

3.2 Results of the Cell Analyses

The mean cell properties for the Thailand data set are provided in Table 1. NS refers to cells that were not seeded and S to cells that received AgI treatment. NCLMAX is the mean maximum number of cells within each cell cluster. S/NS is the single ratio of S to NS cell properties and the significance of each observed SR was calculated using rerandomization procedures.

Examination of the presentation in Table 1 suggests that the S cells produced more rainfall than the NS cells by virtue of covering more area and having greater durations and larger rain volume rates. This result, while physically plausible and in agreement with the results in Texas (Rosenfeld and Woodley, 1989; 1993), could well be due to chance because of the small sample. No single result can be seen to have a significance value anywhere near 5%.

The next step was to examine only those cases having warm cloud bases, when coalescence would be more active and rainwater would be present in vigorous updrafts above the freezing level. It can be seen from Table 3 in Part I that the sample had rather variable cloud-base temperatures, ranging from 11°C to 22°C.

The cool cloud bases might strike the uninitiated scientist as rather odd, considering the tropical location of the experimentation. As discussed by Woodley and Rosenfeld (1993), however, high, cool, cloud bases are fairly typical of Thailand during the pre-monsoon period, when conditions are relatively dry. It is during the monsoon itself that cloud bases are lower and warmer. Woodley and Rosenfeld (1993) estimate that the onset of the monsoon at Chiang Mai in 1993 took place on 19 May. Both random units obtained after this date have base temperatures > 20°C.

The Thai cell results for those 10 cases in which the cloud base temperature was > 16°C are provided in Table 2. (The 16°C cutoff is purely arbitrary, but, in examining the data in Table 1 of Part I, it seemed as logical as any other.) Note that the ratio of S to NS has increased for every listed parameter, except for the number of cell mergers, which stayed the same. The apparent effect on cell rainfall has increased to 2.25, which is comparable to what has been observed in Texas (Rosenfeld and Woodley, 1993). All significance values have improved as well, but they are still far short of what is needed for high confidence in ascribing the results to AgI seeding.

It is interesting to note from the presentations in Tables 1 and 2 that the apparent 100% increases in mean cell rainfall have taken place without an appreciable increase in mean cell heights.

This too was the case in Texas, where the increase in mean cell height was < 10%. In Florida, on the other hand, the mean increase in cell height was on the order of 20%. A potential explanation for these results, involving the expenditure of the seeding-induced buoyancy to sustain the increased water mass and leaving little left over for increased vertical growth of the cloud, has been addressed by the conceptual model that was discussed in Part I.

At this point, however, one cannot discount the possibility that AgI seeding may have made the clouds less reflective near cloud top than comparable unseeded clouds. This would result in underestimation of the growth of the seeded clouds by the S-band radar.

These Thai results were the impetus for re-examining the Texas cell results (Rosenfeld and Woodley, 1993) as a function of cloud base temperature. It was found that even in the cold base partition (i.e., T $\leq$ 16°) the SR of S to NS rainfalls is a factor of 2.08, but the SR of S to NS echo top heights is only 0.95. Thus, in the cooler cloud base situation there is still a 100% increase in cell rainfall, but increased vertical cloud growth is apparently not associated with the rain increases.

In the warm base partition (i.e., T > 16°C), the apparent effect of treatment in west Texas is even larger at a factor of 2.85, and the SR of echo top heights is 1.23, which is comparable to what has been observed in Florida. This suggests that in the warm base situation, when the concentration of rainwater at the level of treatment should be greater, the seeding-induced buoyancy is large enough both to sustain the increased water mass and to increase echo top height.

Further quantification of the apparent seeding effect as a function of cloud-base temperature is provided in Figure 1, which shows plots of the ratio of mean S to NS values (the Seeding Effect Ratio) versus cloud-base temperature for echo height and rain volume in Texas and in Thailand. The plots were constructed by including cases cumulatively, beginning with the case with the coldest cloud-base temperature. The right edge of each plot, therefore, represents the S/NS ratio of cell height and rain volume for all cases. Note that the plots for both regions show increasing S/NS values for cell heights and rain volumes as cloud base temperature increases.

One of the more interesting Thai analyses is the presentation in Figure 2, which is a semi-log plot that shows the mean S and NS rainfalls by height interval. Note that in the interval

Table 1: Means, single ratios and the rerandomization significance levels of the ratios for the various cell properties for the 14 experimental units obtained in Thailand through 1993. The data are for the long-tracked cells.

Variable	No. of Cells		S	NS	S/NS	Rerand. Sig. (%)
	S	NS				
R_{vol} (10^3 m^3)	87	64	190.6	113.1	1.69	38.4
H_{max} (km)	87	64	9.6	9.8	0.98	59.6
Z_{max} (dBZ)	87	64	43.1	42.7	1.01	47.0
A_{max} (km^2	87	64	69.6	55.8	1.25	21.0
DUR (min)	87	64	43.1	37.8	1.14	30.8
RVR_{max} (10^3 m^3/h)	87	64	413.8	290.5	1.42	33.1
NCLMAX	87	64	19.5	11.9	1.64	27.5
MERGERS	87	64	1.9	1.7	1.07	40.5

Table 2 Means, single ratios and the rerandomization significance levels of the ratios for the various cell properties for the 10 experimental units obtained in Thailand whose cloud base temperatures were > 16°C. The data are for the long-tracked cells.

Variable	No. of Cells		S	NS	S/NS	Rerand. Sig. (%)
	S	NS				
R_{vol} (10^3 m^3)	61	47	261.1	115.9	2.25	30.0
H_{max} (km)	61	47	10.0	9.4	1.06	34.1
Z_{max} (dBZ)	61	47	46.4	42.2	1.10	16.2
A_{max} (km^2	61	47	82.4	48.1	1.71	3.2
DUR (min)	61	47	52.4	39.4	1.33	11.9
RVR_{max} (10^3 m^3/h)	61	47	535.4	256.4	2.09	19.8
NCLMAX	61	47	24.5	13.7	1.78	23.6
MERGERS	61	47	1.9	1.7	1.07	38.0

between 7 and 11 km the S cells produce more rainfall than NS cells of the same height. This suggests a more efficient microphysical process in the S cells whereby more water mass is accumulated within its interior than exists within NS cells of the same height. This is very similar to the results that were obtained in Texas (see Figure 4 in Rosenfeld and Woodley, 1993).

Plots of the mean properties of the S and NS cells as a function of time for all cells and for those cells in units with base temperatures > 16°C are provided in Figures 3 and 4, respectively. The means are for those cells that existed at each time interval.

Examination of the plots for all cells (Figure 3) shows somewhat greater echo areas and rainfalls for the S cells both before and after the initial treatment. The S and NS reflectivity plots are little different, while the S and NS height plots suggest slightly taller NS cells. By one hour after initial treatment, all differences favor the NS cells, although less than one-third of the cells remain in the sample at this time.

Examination of the plots for all cells with warm bases (Figure 4) shows essentially the same picture, although the S and NS differences before and after treatment are somewhat larger. Again, the few NS cells remaining in the sample by one hour after initial treatment are stronger than the S cells. This is different from the Texas results that showed the S vs NS differences increasing with time (Rosenfeld and Woodley, 1993).

A more representative picture of the effect of seeding on mean cell areas and rainfall flux is the calculation by time interval that includes the zero (0) values of those cells that had already dissipated. The plots for all cells are provided in Figure 5 and for only those cells with warm bases in Figure 6.

The all cells plots (Figure 5) show smaller pre-treatment and post-treatment differences, with the S cell areas and rain fluxes generally exceeding the NS values until 60 min after initial treatment. The plots for only the warm-based cells (Figure 6) show essentially the same picture as in Figure 5, although the S-NS differences are substantially greater.

Many readers might feel intuitively that the somewhat higher mean rainfall for the S cells prior to treatment represents a bias favoring the S sample. This does not appear to be the case for this sample, however, as can be seen in the scatter plot for the NS and S cells of total pre-treatment cell rainfall vs the total rainfall produced by the cell in its lifetime (Figure 7). The scatter is large in both plots. Note that all but one of the cells in both samples, producing > 10^6 m^3 in rain volume, had zero pre-treatment rainfalls. The one exception in the S sample had a modest pre-treatment rainfall and its position in the plot could well be a function of the seeding intervention. Note further that all cells having pre-treatment rainfalls $\geq 40 \times 10^3$ m^3 had very small lifetime rainfalls. If these cells are eliminated from both samples, the new ratio of mean S to NS post-treatment cell rainfalls is 1.77 vs the original value of 1.69 shown in Table 1. It appears, therefore, that it is a liability to a cell's post-treatment rainfall for it to have a large pre-treatment rainfall.

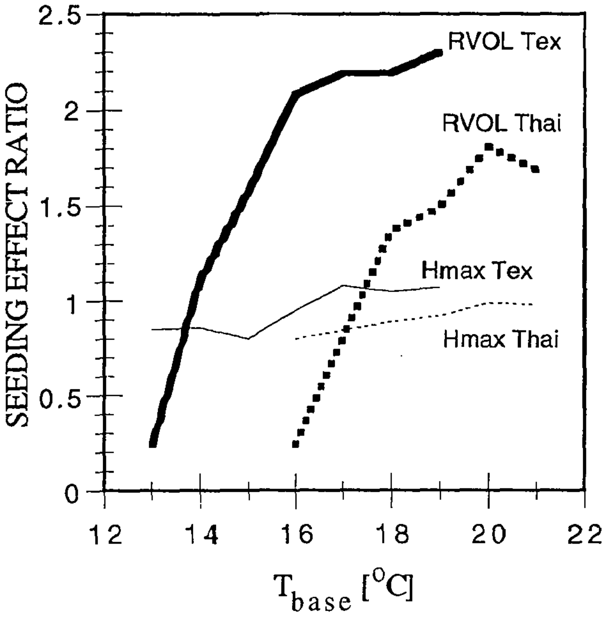

Figure 1. The indicated seeding effects on cell rain volume and maximum echo top height in Texas and Thailand as a function of cloud-base temperature. The cases are considered cumulatively beginning at the coldest observed cloud-base temperature. The right terminus of each line provides the overall effect from all cases.

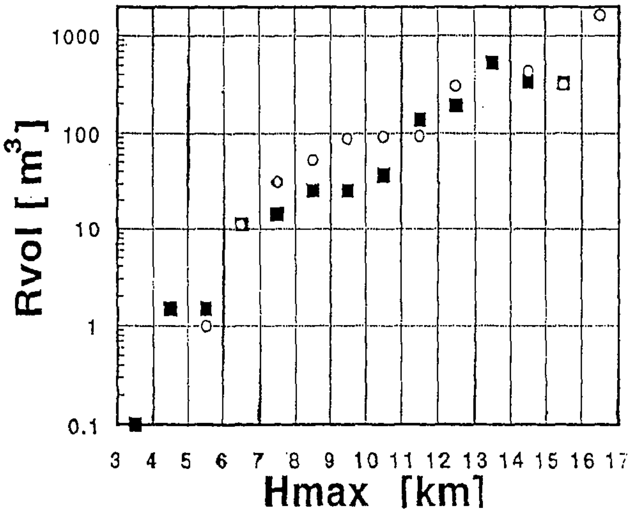

Figure 2. Semi-log plots of mean S and mean NS cell rain volumes within 1 km height intervals. The open circles represent S data and the solid squares represent NS data.

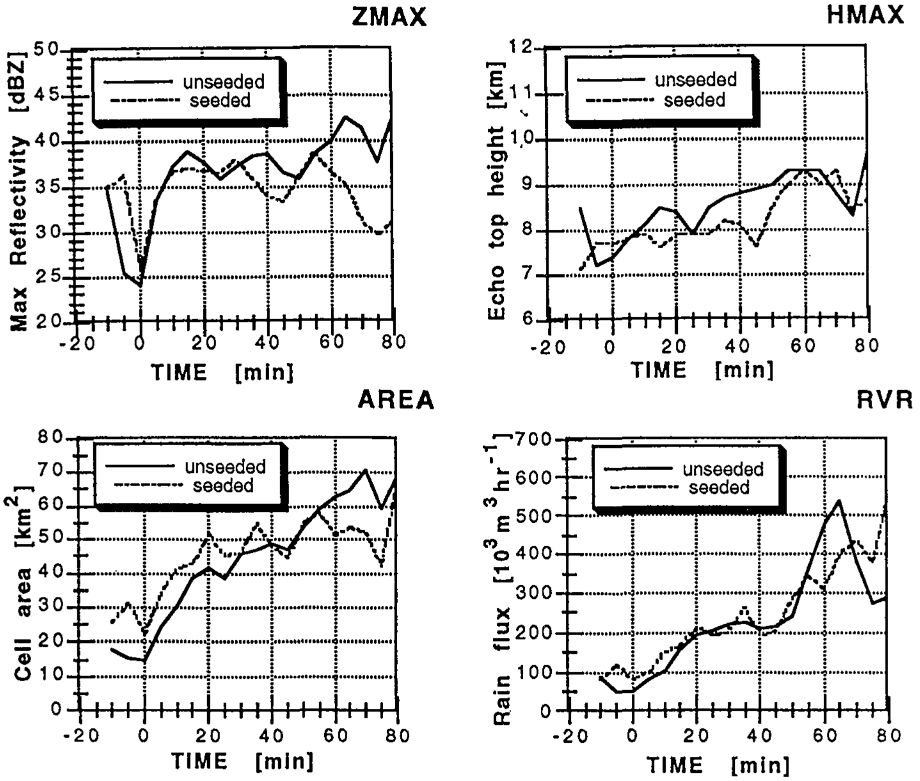

Figure 3. Line plots of mean S and mean NS reflectivities (upper left), cell heights (upper right), areas (lower left) and rain volume rates (lower right) for all of the cell data. The means have been calculated at each interval based on the number of cells in the sample at that time.

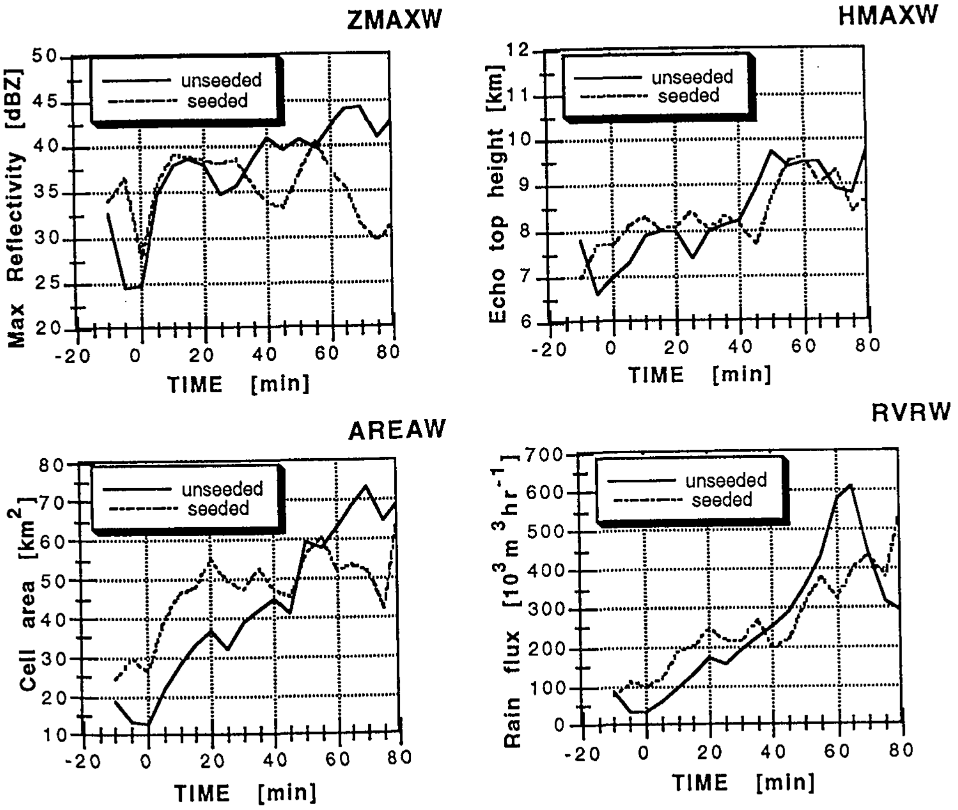

Figure 4. As in Figure 3, but for the cell data when cloud-base temperatures exceeded 16°C.

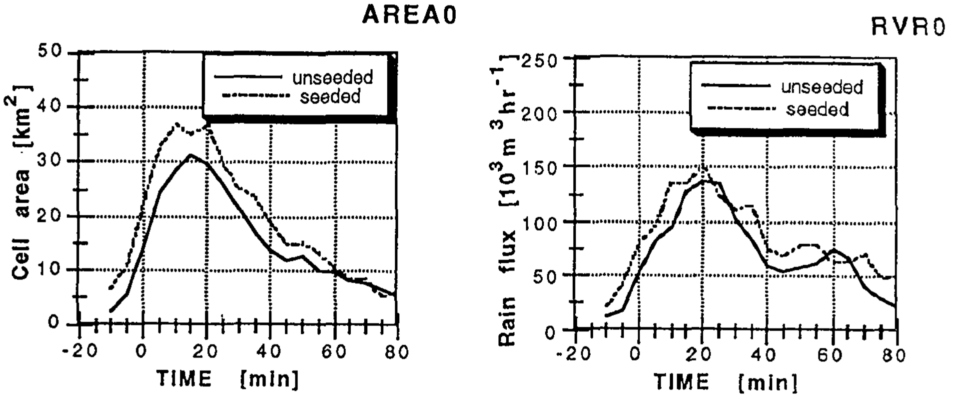

Figure 5. Line plots of mean S and mean NS cell areas (A) (at top) and rain and rain volume rates (R) (at bottom) for all of the cell data. The mean A and R values for each time interval were calculated by inputing zero values for those cells that had dissipated previously.

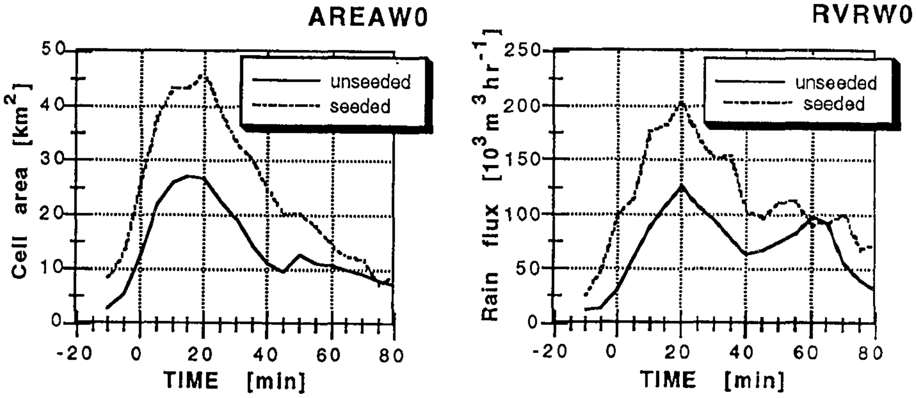

Figure 6. As in Figure 5, but for the cell data when cloud-base temperatures exceeded 16°C.

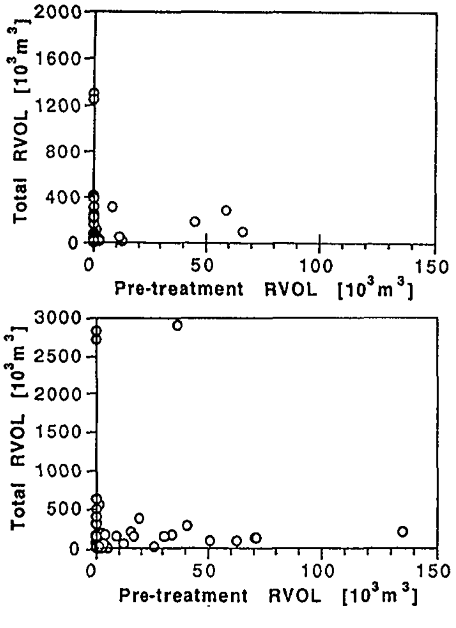

Figure 7. Scatter plot of the total rainfall produced by the NS (top) and S (bottom) cells (units: m^3 x 10^3) prior to real or simulated treatment vs the total rainfall produced by the cells in their lifetimes.

Further physical insight into the cell results was provided by the construction of time-height reflectivity cross sections for the entire cell data set (not shown), and for the cells having base temperatures > 16°C in Figure 8. The numbers above the abscissa indicate the number of cells that contributed to the composite versus time. The S cross-section for the cells with warm cloud bases (top) appears to be more stratified than the comparable NS cross-section (bottom), beginning 30 minutes after initial seeding. The NS cells left in the sample at that time are also taller than the S cells that remain, in contrast with the results obtained in Texas.

Only after subtracting the patterns of Figure 8 (i.e., S time height profile minus NS time height profile) does something of interest appear (Figure 9). Note that there is a positive reflectivity difference of up to 11 dBz centered between 6 and 8 km at the time of initial treatment which persists until about 30 minutes thereafter.

Such a difference pattern was observed also in Texas, although the differences were initially smaller in

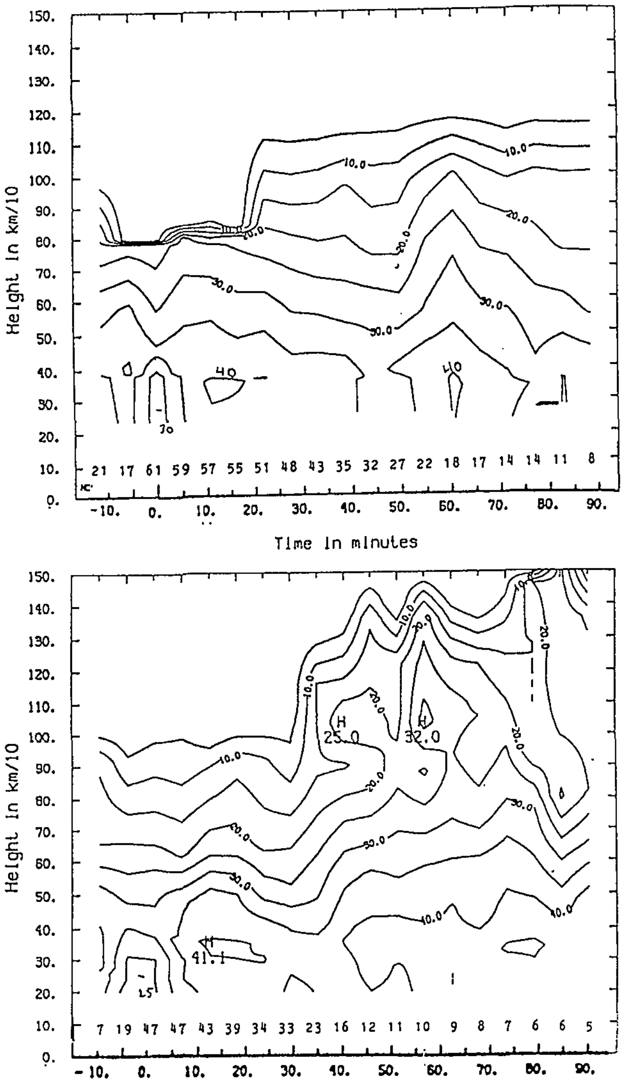

Figure 8. Composite time-height reflectivity plots of the cells with cloud-base temperatures > 16°C that were treated with AgI (top) or received simulated AgI treatment (bottom). The numbers above the abscissa refer to the number of cells (NC) in the sample at that time interval. The "0" time refers to the time of real or simulated treatment.

Texas than in Thailand (See Figure 3c in Rosenfeld and Woodley, 1993). Such positive reflectivity differences are consistent with the formation of graupel particles following AgI seeding as postulated in the conceptual model. Beyond that, however, the difference patterns in Thailand and Texas are quite disparate. The S-NS reflectivity differences in Thailand become slightly negative (below 10 km) with time, indicating that the few NS cells that remain in the sample are stronger than the few S cells that persist. In Texas, on the other hand, the differences become strongly more positive with time, indicating stronger S than NS cells long after the initial treatment.

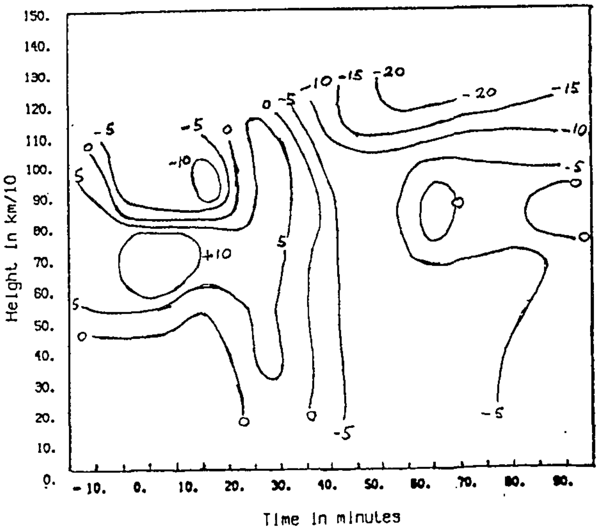

Figure 9. Difference (i.e., S-NS) composite time-height reflectivity plots for the cells having cloud-base temperataures > 16°C. The "0" time marks the time of initial treatment (AgI or simulated AgI).

3.3 Results for the Experimental Units

The last step in the analysis progression was an investigation of the effect of treatment on the experimental units themselves. Fourteen (7 S and 7 NS) experimental units were available for analysis. A listing of the input data by case, presented cumulatively in 30 min intervals relative to the time of initial treatment is provided in Table 3.

Examination of Table 3 reveals enormous case-to-case variability in the recorded values. It is imperative, therefore that the sample be increased and that predictors be found that can account for some of the natural rainfall variability that is inherent in the Thai experiments.

The mean cumulative rainfalls by time period for the S and NS samples and the ratios of the former to the latter are provided in Table 4. There are two listings in the table. The first provides the mean S and NS rainfalls and the ratios of the former to the latter. The second provides the same information but with the wettest day in each sample deleted. This is done to see how sensitive the results are to outliers. No significance testing of the ratios has been done, because such an exercise would have little meaning at this point in the Thai experiments. The sample is still much too small.

In examining the data presented in Tables 3 and 4, a reader's first impression is that a bias favored the S units, because the mean S rainfalls exceed the mean NS rainfalls by about a factor of

Table 3

Cumulative Rainfall from the Experimental Units in Time Intervals Relative to the Time of Initial Treatment
(Units: $m^3 \times 10^3$)

SEED CASES

Date	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
8/7/91	829.3	518.8	879.3	1723.9	2077.1	2302.0	2595.0	3712.1	5452.0	7548.0	9673.3	11312.0
4/21/93	18.6	5.0	3.9	25.8	48.4	69.0	69.4	74.7	782.5	2200.7	3208.2	3761.5
4/22/93	44.9	42.2	238.1	916.2	1625.3	2338.0	4248.7	6321.5	6730.9	6763.1	6769.1	
4/25/93	18.6	16.3	48.3	189.3	533.4	991.7	1092.2					
5/7/93	0.1	0.1	33.8	250.3	700.5	2301.3	6001.8	7872.1	8225.9	8330.0	8375.8	
5/9/93	170.3	139.1	233.3	890.8	1556.9	1630.6	1644.4	1792.0	2197.3	2197.5		
5/27/93	351.1	196.5	265.0	519.3	656.1	763.1	888.5	979.7	987.2			

NO SEED CASES

Date	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
4/15/93	161.1	132.9	145.9	380.2	488.7	494.3						
4/20/93	1.4	1.2	19.6	559.1	985.1	1102.5						
4/23/93	27.3	27.3	518.9	1894.9	3469.3	4635.5	5139.6	5904.4	6957.5	7081.4		
4/29/93	343.1	248.7	292.9	636.2	1048.5	1380.7	1535.4	1541.9				
5/4/93	88.8	45.7	19.1	23.7	23.8	23.9						
5/8/93	0.1	0.1	151.8	429.7	755.6	883.8	887.9					
6/4/93	20.9	16.9	34.7	136.1	315.9	543.5	757.5	854.8	890.1	1020.2	1310.2	1487.5

Table 4

Mean Cumulative Rainfalls for the Experimental Units Relative to the Time of Initial Treatment
(Units: $m^3 \times 10^3$)

All Data

	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
S	204.7	131.1	243.1	645.1	1028.2	1485.1	2362.8	3120.6	3638.3	4159.8	4586.2	4927.9
NS	91.8	67.5	169.0	580.0	1012.4	1294.8	1420.2	1544.2	1730.5	1736.0	1777.4	1802.8
S/NS	2.23	1.94	1.44	1.11	1.02	1.15	1.66	2.02	2.10	2.40	2.58	2.73

Data with Wettest Unit from the S and NS Samples Deleted

	0 to -60	0 to -30	0 to 30	0 to 60	0 to 90	0 to 120	0 to 150	0 to 180	0 to 210	0 to 240	0 to 270	0 to 300
S	100.6	66.5	137.1	465.3	853.4	1349.0	2324.1	3022.0	3336.0	3595.1	3771.7	3863.9
NS	102.6	74.2	110.7	360.9	602.9	738.0	800.3	817.5	859.3	845.1	893.4	923.0
S/NS	0.98	0.90	1.24	1.29	1.42	1.83	2.90	3.70	3.88	4.25	4.22	4.19

two in the hour <u>prior</u> to initial treatment. This impression may not be correct, because there appears to be no correlation between the pre-treatment rainfalls and the rainfalls that are produced by the experimental units subsequently. This can be seen in the log-log plot for the NS cases of the rainfall in the hour before initial treatment vs the rainfall in the two hours after initial treatment (Figure 10). (The S units were not used in this exercise, because AgI treatment is postulated to have altered the natural rainfalls.) The scatter is great and there is no evidence from this limited sample that the pre-treatment unit rainfalls are a predictor of the rainfall that will be produced subsequently within the unit. If anything, the limited sample suggests a negative correlation (i.e., more rainfall prior to treatment means less rainfall afterwards). This is virtually the same result that was obtained for individual cells.

The presentation in Table 4 and the plot of the S to NS ratios in Figure 11 show that the sample is quite sensitive to the deletion of the wettest unit from the and NS samples. First, note that the

"REVIEWED"

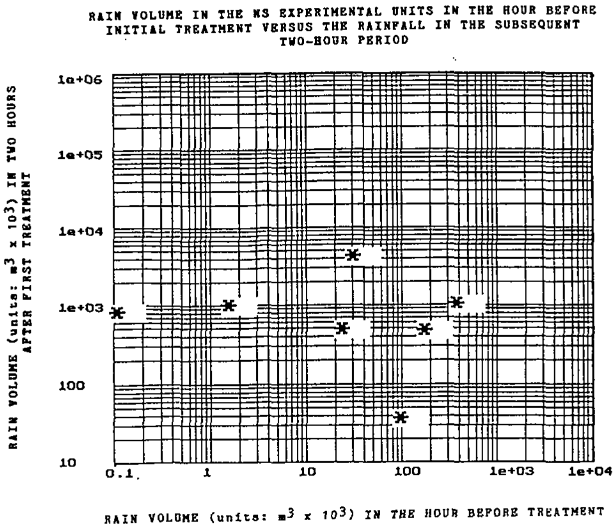

Figure 10. Log-log plot of the rain volume for the NS experimental units in the hour prior to initial simulated treatment versus the unit rain volume in the subsequent two hours.

apparent pre-treatment bias in the S sample totally disappears after deleting the wet case on 7 August 1991. Second, notice that the ratio of S to NS mean rainfalls increases continuously after the initial treatment when the wettest S and the wettest NS units are deleted.

The reader is urged to be cautious with the interpretation and dissemination of these results. Although they do provide the impetus to continue with the Thai experiments, no unequivocal argument that AgI treatment produces large increases in rainfall within the experimental units is justified at this time. With patience and a lot of hard work to increase the sample, such an argument might have some basis in the future.

4.0 SUMMARY AND CONCLUSIONS

Scientific progress with the Thai cold-cloud seeding effort has been substantial. It is now known that Thailand presents a rich harvest of supercooled clouds that are suitable for seeding intervention for the enhancement of their rainfalls. Thai pre-monsoon clouds are different from those that exist typically during the monsoon over the region of study. Cloud-base temperature is the major determinant of cloud conditions. When bases are high and cool, as is often the case in the pre-monsoon period, much of the water within the cloud apparently is concentrated in small cloud drops. Seeding of these clouds appears to result in rather slow glaciation and a rather weak vertical growth response of the cells. This is in agreement with the predictions of Lamb et al. (1981) that glaciation in clouds with small supercooled drops will proceed rather slowly. When the bases are low and warm, as is the usual case during the monsoon, a substantial amount of the water that is encountered within the cloud at temperatures of about -8°C is apparently in raindrops. Seeding of these clouds appears to result in rapid glaciation and in explosive vertical growth in some circumstances. Although rainfall increases may be produced in both cloud types, the largest increases are likely produced in the clouds with warm cloud bases. This is consistent with the conceptual model as presented and discussed in Part I. Having such a model to guide the effort has been a major plus for the program.

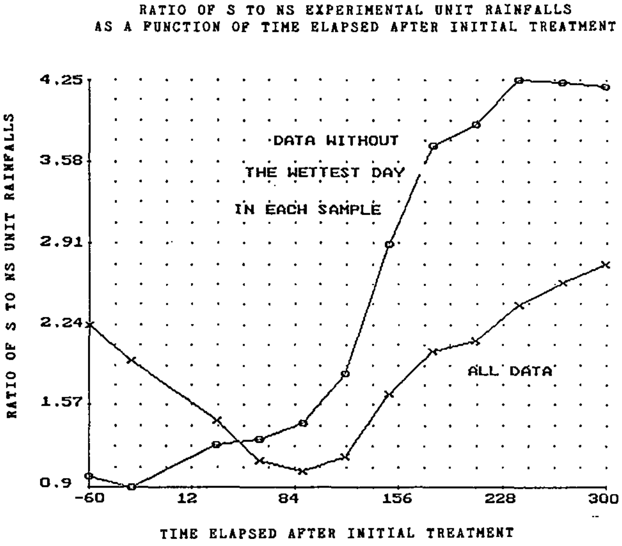

Figure 11. Plot of ratios of S to NS unit rain volumes by 30-min time intervals relative to the time of initial treatment. The solid line is for all data. The dashed line plot is for the ratios that were calculated after the wettest day in the S and NS samples had been deleted.

The results of cold-cloud seeding to date are consistent in most respects with the results that have been published previously for Florida and Texas (Gagin et al., 1986; Rosenfeld and Woodley, 1989; 1993). Initial results suggest that AgI seeding may have increased the cell rainfalls by as much as 100% or more for cells having cloud bases > 16°C. As is the case in Texas, these increases have been produced by broader cells with longer durations. Vertical cell growth of the S cells has been small relative to the growth of the NS cells and does not, therefore, appear to be a requirement for the rain increases. An important finding is that AgI-treated cells in both Texas and Thailand produce more rainfall than non-seeded cells having the same echo top height. How this might take place is addressed extensively in the conceptual model (see Part I).

It is also possible, however, that the vertical growth of the S cells may have been underestimated by the S-band radar operative in Thailand. Visual inspection of the clouds in real time and on video tape suggests a more stratified glaciated structure of the tops of the S cells relative to those that have not been seeded. This might mean lesser reflectivity near the tops of the AgI seeded clouds. Further study is needed to resolve this uncertainty.

The results for the 14 experimental units (7 S and 7 NS) for which analysis is possible are consistent with a positive effect of seeding. The natural variability is great and the results are highly sensitive to removal of the wettest unit from each of the S and NS samples.

The Thai cold-cloud experiments appear to be on the right track, and the obvious recommendation is that they continue. The present design appears to be well suited for the continuation, considering the progress that has been made so far.

5.0 REFERENCES

Gabriel, K.R., and P. Feder, 1969: On the distribution of statistics suitable for evaluating rainfall stimulations. Technometrics, 11, 149-160.

Gagin, A., D. Rosenfeld and R.E. Lopez, 1985: The relationship between height and precipitation characteristics of summertime convective cells in South Florida. J. Atmos. Sci., 42, 84-94.

Gagin A., D. Rosenfeld, W.L. Woodley and R.E. Lopez, 1986: Results of seeding for dynamic effects on rain cell properties in FACE-II. J.of Climate and Appl. Meteor., 25, 3-13.

Lamb, D., R.I. Sax and J. Hallett, 1981: Mechanistic limitations to the release of latent heat during the natural and artificial glaciation of deep convective clouds. Quart. J. Roy. Meteor. Soc., 107, 935-954.

Rosenfeld, D., 1987: Objective method for tracking and analysis of convective cells as seen by radar. J. Atmos. Sci., 4, 422-434.

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

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

Woodley, W.L., 1970: Precipitation results from a pyrotechnic cumulus seeding experiment. J. Appl. Meteor., 9, 242-257.

Woodley, W.L. and D. Rosenfeld, 1991: Testing Dynamic Seeding in Thailand. A Report to the U.S. Bureau of Reclamation on Contract No. 1-CS-81-17780. 78 pp.

Woodley, W.L. and D. Rosenfeld, 1993: Analysis of Randomized Experiments in Thailand. A Report to the U.S. Bureau of Reclamation on Contract No. 1425-3-CS-81-19050, 62 pp.

Woodley, W.L., D. Rosenfeld, B. Silverman, and C. Hartzell, 1991: Design and Operations Plan for a Randomized Cold-Cloud Seeding Experiment Focused on Individual Convective Cells. July 1991, 126 pp.