Results of the Thailand Warm-Cloud Hygroscopic Particle Seeding Experiment

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ABSTRACT

A randomized, warm-rain enhancement experiment was carried out during 1995–98 in the Bhumibol catchment area in northwestern Thailand. The experiment was conducted in accordance with a randomized, floating single–target design. The seeding targets were semi-isolated, warm convective clouds, contained within a well-defined experimental unit, that, upon qualification, were selected for seeding or not seeding with calcium chloride particles in a random manner. The seeding was done by dispensing the calcium chloride particles at an average rate of 21 kg km^{-1} per seeding pass into the updrafts of growing warm convective clouds (about 1–2 km above cloud base) that have not yet developed or, at most, have just started to develop a precipitation radar echo. The experiment was carried out by the Bureau of Royal Rainmaking and Agricultural Aviation (BRRAA) of the Ministry of Agriculture and Cooperatives as part of its Applied Atmospheric Resources Research Program, Phase 2.

During the 4 yr of the experiment, a total of 67 experimental units (34 seeded and 33 nonseeded units) were qualified in accordance with the experimental design. Volume-scan data from a 10-cm Doppler radar at 5-min intervals were used to track each experimental unit, from which various radar-estimated properties of the experimental units were obtained. The statistical evaluation of the experiment was based on a rerandomization analysis of the single ratio of seeded to unseeded experimental unit lifetime properties. In 1997, the BRRAA acquired two sophisticated King Air 350 cloud-physics aircraft, providing the opportunity to obtain physical measurements of the aerosol characteristics of the environment in which the warm clouds grow, of the hydrometeor characteristics of seeded and unseeded clouds, and of the calcium chloride seeding plume dimensions and particle size distribution—information directly related to the effectiveness of the seeding conceptual model that was not directly available up to then.

The evaluation of the Thailand warm-rain enhancement experiment has provided statistically significant evidence and supporting physical evidence that the seeding of warm convective clouds with calcium chloride particles produced more rain than was produced by their unseeded counterparts. An exploratory analysis of the time evolution of the seeding effects resulted in a significant revision to the seeding conceptual model.

1. Introduction

In 1988, Thailand's Applied Atmospheric Resources Research Program (AARRP) was launched as a joint project of the Royal Thai government (RTG, Bureau of Royal Rainmaking and Agricultural Aviation, Ministry of Agriculture and Cooperatives) and the U.S. government [U.S. Agency for International Development (USAID)]. AARRP was patterned after a program recommended in the report commissioned by USAID entitled ''Weather Modification Assessment for the Kingdom of Thailand'' (Silverman et al. 1986). The goal of AARRP was to provide 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. The program involved the conduct of field research and studies leading to the development of a design and operations plan for promising rainmaking experiments the provision of equipment, and technology transfer training and technical assistance to carry out the experiments. Therefore, AARRP focused on design feasibility studies and exploratory experiments, that is, theoretical and model studies and randomized exploratory experiments, to determine which of the physically plausible warm- and cold-cloud seeding concepts warranted further testing. It also focused on the design of a follow-on project (AARRP Phase 2) to demonstrate their feasibility through proof-of-concept statistical experiments.

A randomized, single-target, warm-rain enhancement experiment was designed and performed during 1995–

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98 in the Bhumibol catchment area in northwestern Thailand as part of the AARRP Phase 2 (Fig. 1). The experiment was designed to test whether the seeding of warm, tropical convective clouds with calcium chloride particles can produce statistically significant increases in rainfall. It was postulated that the introduction of the relatively large-size calcium chloride particles would improve the precipitation efficiency of the cloud by accelerating the coalescence process through the initiation of the collision–coalescence process earlier in the life of the cloud and, thereby, would lead to an augmentation of the rainfall produced by the cloud.

The design of the warm-cloud seeding experiment is briefly described; see Woodley et al. (1999) for a more detailed discussion of the original experimental design. Then, the results of the statistical evaluation of the experiment in accordance with the experimental design are presented, followed by some exploratory statistical analyses. Last, results of some preliminary warm-cloud physical studies are presented, studies that provided physical measurements of the aerosol characteristics of the environment in which the warm clouds grow, of the hydrometeor characteristics of seeded and unseeded clouds, and of the calcium chloride seeding plume dimensions and particle size distribution—measurements of convective clouds in Thailand that were not directly available up to then.

2. Physical design

a. Physical basis of the design

The physical design of the warm-cloud seeding experiment was guided by the results of numerical model experiments. The numerical cloud model provided an inexpensive means of screening numerous candidate warm-cloud seeding strategies to identify those that are most promising scientifically. A one-and-one-half-dimensional, time-dependent, detailed microphysical model originally developed by Silverman and Glass (1973), as extended by Nelson (1979) to include ice processes and further updated by Silverman (Silverman et al. 1994) to include ice multiplication processes and a variety of hygroscopic chemical seeding options, was used to test the relative effectiveness of a wide range of seeding scenarios. This model is most realistic in simulating the initiation of precipitation in clouds and, because of its dimensionality limits, becomes less realistic in simulating the further evolution of the precipitation process; nevertheless, the difference between seeded and unseeded precipitation is believed to be a realistic index of the relative effectiveness of seeding scenarios.

The results of the numerical model experiments (Rasmussen et al. 1989; Silverman et al. 1994; Silverman and Sukarnjanaset 1996) indicated that large hygroscopic particle seeding leads to increased precipitation by producing microphysical effects that improve the precipitation efficiency of the warm convective clouds. Of the four hygroscopic chemicals investigated (calcium chloride, ammonium nitrate, sodium chloride, and urea), seeding with dry calcium chloride particles produced the largest effects. For clouds of limited duration, the largest seed–no-seed ratios were achieved with 50-μm-radius calcium chloride particles. For clouds of longer duration, the best results were achieved with smaller-size calcium chloride particles of 10–30-μm radius depending on where in the cloud the seeding particles are injected. It was found that seeding near cloud base with calcium chloride particles produced larger seed–no-seed ratios than did near–cloud-top seeding and that the seed–no-seed ratios increase with increasing concentration or dosage; logistical considerations will place an upper limit on what is possible, however. Of importance to the warm-cloud seeding experiment, it was found that seeding with readily purchased, inexpensive, relatively large–size calcium chloride particles produced smaller seed–no-seed ratios than did seeding with more-optimum–sized monodisperse particles; nevertheless, experimentally observable seed–no-seed ratios still were produced. It was also found that seeding with calcium chloride particles is most effective when conducted early in the life of a growing cloud, before the development of a natural radar echo, when the precipitation process still can be influenced. These model results agree in principle with the model experiments of Tzivion et al. (1994), who used a three-dimensional axisymmetric model to simulate hygroscopic particle seeding in a convective cloud.

b. Seeding conceptual model

Considering the fact that economic and logistic factors require that the seeding be done with commercially available, relatively large, polydisperse calcium chloride particles (in effect, precipitation embryos), the conceptual model for the warm-cloud seeding experiment is based on accelerating the coalescence process by initiating the collision–coalescence process earlier in the life of the cloud. It is postulated that, by reducing the time required for the precipitation process to evolve with respect to the time available, rain efficiency will increase such that clouds that would not naturally rain will rain, and clouds that would naturally rain will rain more. According to the results of the numerical model experiments, the increase in rain volume from seeding is due primarily to an increase in rain volume rate.

c. Physical experimental units

The experimental units are warm, semi-isolated, convective cloud entities that occur during the summer monsoon months from June through September each year. The experimental units have a hard, cauliflower appearance with a cloud top of at least 3350 m but not higher then the freezing level (about 4900–5500 m).

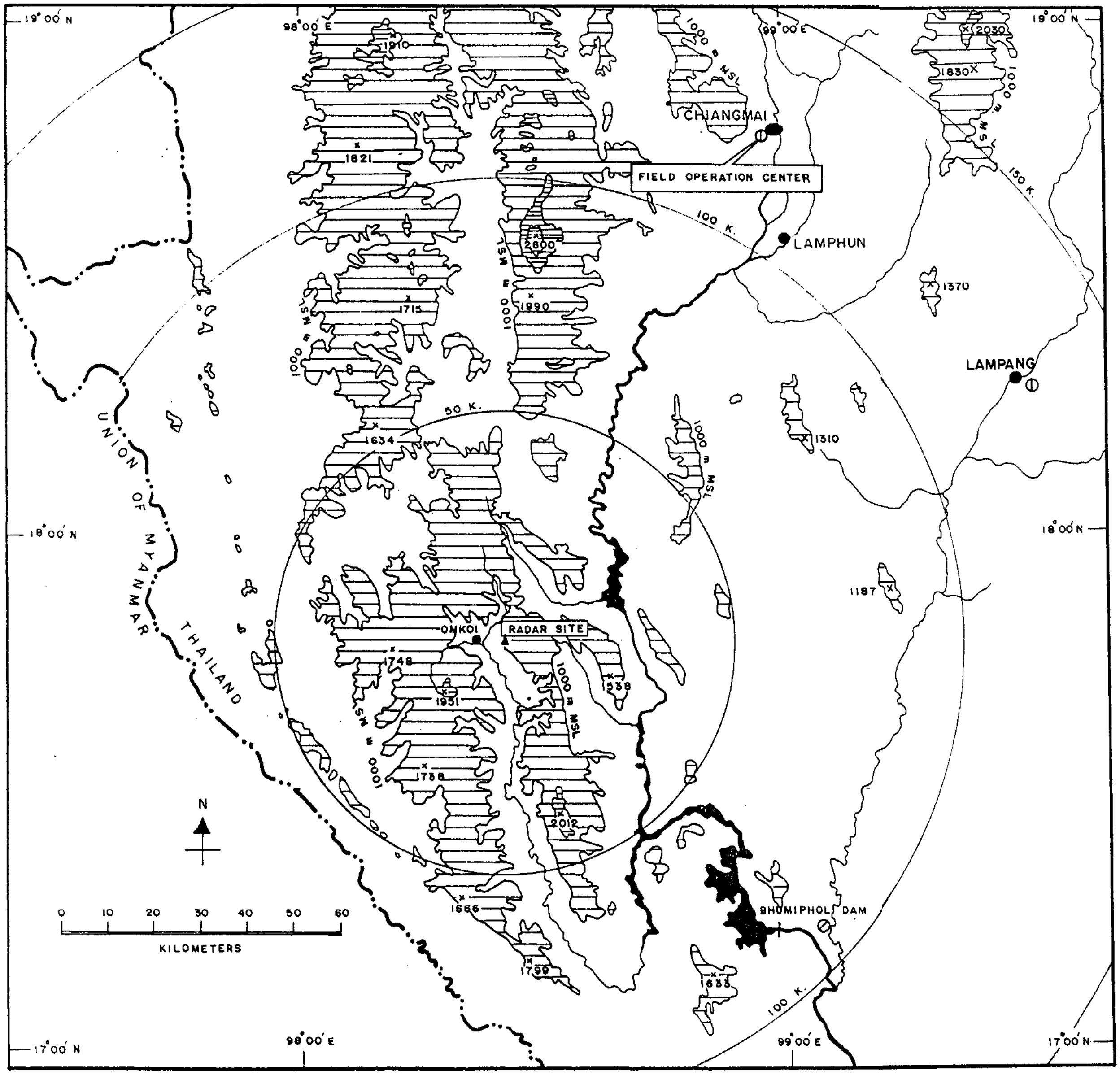

FIG. 1. Map of the AARRP project area. The target area for the warm-cloud calcium chloride seeding experiment is the area bounded by the 100-km range circle of the project radar at Omkoi.

Upon penetration at about 3200 m during a qualification pass, to be selected as an experimental unit the cloud must have a liquid water content of at least 0.5 g m^{-3}, an updraft maximum of at least 2.5 m s^{-1}, and a cloud penetration length of at least 2 but no more than 6 km in length. The experimental units are relatively small convective cloud entities that contain few convective cells; so, for all practical purposes, the experimental units and treatment units are identical at the time of qualification.

The numerical model experiments indicate that the best results of seeding are expected for clouds that are seeded while they are in the active growing stage and prior to the time they develop a natural radar echo. Because the time window for seeding such clouds is very small, the time it takes to qualify a unit after penetration and the time it takes to implement the treatment decision should be kept as short as possible. Because it is time-consuming to establish confidently that a radar echo does not exist at the precise location of the qualification pass, the requirement for no radar echo was not made a formal part of the measurement qualification criteria. Rather, the presence or absence of a radar echo at the time of selection was stipulated as a stratification parameter, and the evaluation of experimental units be made so as to exclude those experimental units that had an appreciable radar echo history (in time and intensity) prior to their selection, that is, that had a preexisting radar echo of more than 10 min and an accumulated radar rain volume greater than 5000 m^3.

It is emphasized that seeding with hygroscopic particles is not limited to warm clouds that satisfy the experimental unit qualification criteria defined above. These experimental units were chosen for this experiment to maximize the seeding signal and minimize the natural variability so that the effectiveness of the seeding could be evaluated with a relatively small sample size—a sample size that could be obtained within the planned 4-yr duration of the experiment. As such, the warm-cloud calcium chloride seeding experiment was primarily a proof-of-concept experiment. Once the seeding conceptual model is proven, it will be possible to determine the range of warm- and cold-cloud conditions on which it is likely to be effective.

d. Treatment strategy

In accordance with the results of the numerical model simulations, treatment was specified to be carried out as soon as the experimental unit qualification criteria were deemed to be met. Treatment also was specified to be carried out as low in the cloud as possible consistent with good flight-safety practices, which, in the mountainous target area, was about 2900 m. The Construcciones Aeronauticas S.A. (CASA) seeding aircraft was instructed to make repeated treatment passes as long as the cloud was observed still to be growing, dispensing seeding material when the randomized treatment decision was seed and dispensing nothing when the decision was not to seed. Considering that the maximum payload of a CASA aircraft is 1200 kg, that the CASA aircraft customarily fly at 120 kt, and that the seeding material cannot be dispensed in less than 15 min, the average seeding dosage during each seed-treatment pass of the aircraft is 80 kg min^{-1}, or about 21 kg km^{-1}.

This treatment strategy was simulated in the warm-cloud numerical model for seeding passes using sized calcium chloride particles. The sized calcium chloride seeding particles, as purchased, were delivered in 25-kg sealed bags. Measurements of the calcium chloride particle size distribution were made soon after its delivery from the manufacturer and then were made again sometime later from samples of the calcium chloride particles taken on the CASA seeder aircraft when the bags were first opened just prior to dispersal during a seeding mission. As expected, the particle size spectrum of the highly hygroscopic calcium chloride degraded during storage and handling, with clumping causing a shift in the particles to larger sizes and a corresponding decrease in particle concentration (see Table 1). The size spectrum of calcium chloride particles as measured on the aircraft was used in the model simulations of seeding effectiveness.

The seeding with calcium chloride particles in the model was patterned after the seeding procedures to be used in the randomized warm-cloud seeding experiment. Accordingly, seeding was simulated by dispensing 1200 kg of calcium chloride particles over 15 min from a CASA aircraft flying at 120 kt through the target cloud at 2900 m. The seeding concentration was determined by these parameters, assuming that the calcium chloride particles were distributed in a cross-sectional area defined by the wing-tip vortices of the aircraft. This calculation yielded a calcium chloride particle seeding concentration in the cloud of 0.0343 g m^{-3} on each seeding pass. Model experiments were conducted to determine the effectiveness of seeding dosage by seeding the cloud with one, two, and three seeding passes. Seeding was started when the cloud top was approximately 215 m above the seeding level of 2300 m, with subsequent seeding passes every 3 min thereafter.

TABLE 1. The size distribution of calcium chloride particles taken from samples obtained just after delivery from the manufacturer and just prior to dispensing from the seeder aircraft.

Particle diameter (μm)	Percent of total mass	
	On delivery	On aircraft
88	27.0	0.8
152	6.0	6.6
302	44.0	61.1
700	23.0	31.5

The results of the model simulations are shown in Fig. 2. It can be seen that the effectiveness of the calcium chloride particle seeding increased as the number of seeding passes increased and as the continentality of the simulated warm cloud increased. It was concluded that the magnitudes of the simulated seeding effects indicated here were sufficiently large that they should be detectable in the statistical warm-cloud calcium chloride particle seeding experiment.

Not shown in Fig. 2 but important to note are the model results for the unseeded clouds as a function of initial cloud condensation nuclei (CCN) concentration. Using the rain amount produced by the unseeded cloud with a CCN concentration of 100 cm^{-3} as a reference, the unseeded clouds with CCN concentrations of 600 and 1100 cm^{-3} produced 75% and 40% of that rain amount, respectively, demonstrating the influence of environmental aerosols on natural rain production of convective clouds.

3. Statistical design

a. Experimental design

Using 3 yr of radar data, the warm-cloud seeding experiment was originally designed as a randomized crossover between two pairs of target areas with control and downwind areas selected for each target pair (Silverman et al. 1994). During the summer of 1995, the execution of this design was practiced and difficulty was

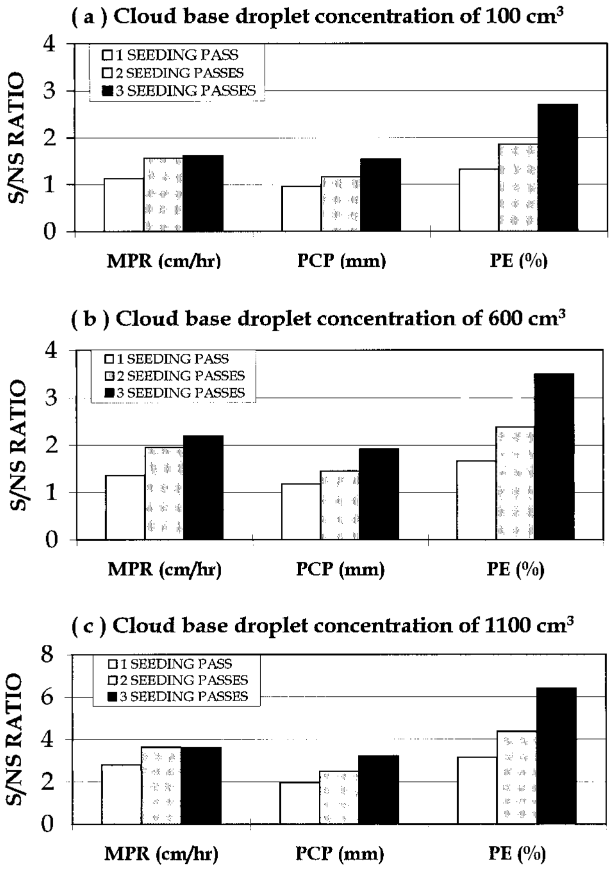

FIG. 2. The results of model simulations on the effect [seeded: nonseeded (S/NS) ratio] of calcium chloride seeding amount (number of seeding passes) on the maximum precipitation rate (MPR), total precipitation (PCP), and precipitation efficiency (PE) of a typical warm convective cloud of radius 2 km having a cloud-base droplet (CCN) concentration of (a) 100 cm^{-3}, (b) 600 cm^{-3}, and (c) 1100 cm^{-3}.

encountered in identifying cases when suitable clouds were present simultaneously in a target pair. As the practice missions continued, it became apparent that suitable experimental units would occur far less frequently than was indicated by the design-study radar analyses, which provided the basis for the crossover design; in fact, none had occurred yet. In view of this fact, the crossover design was replaced by a randomized single-cloud, floating-target design for the type of clouds described in section 2c, which were observed to occur fairly frequently in the target area.

b. *Statistical experimental units*

For the purposes of the statistical evaluation, the experimental unit consisted of all the convective clouds and entities, whether actually treated or not, within a circle having a radius that is two times [radius multiplication factor (RMF)] the radius of the unit as measured during the pretreatment qualification pass prior to its selection for randomized treatment.

An RMF of two was selected in advance as the one that provides an area of analysis that best encompasses all the experimental units most compactly. Because it is based on a parameter that was measured prior to making the randomized treatment decision, the evaluation results are not biased by this choice. The selection of the value of RMF to use was a balance between not making RMF so small that it does not encompass all of the larger-area experimental units and thereby does not capture a significant portion of any potential seeding effects, and not making RMF so large that it encompasses too large an area around the smaller experimental units and thereby significantly dilutes any potential seeding effect by including untreated clouds. The decision was made to use an RMF value equal to 2.

c. *Seeding hypotheses*

The warm-cloud seeding experiment was designed to test the following null hypotheses.

H01: Calcium chloride seeding does not alter the total rainfall volume per experimental unit 30 min after terminating treatment of the units.

H02: Calcium chloride seeding does not alter the total rainfall volume per experimental unit over the lifetime of the units.

d. *Radar response variables*

The AARRP 10-cm, Doppler radar at Omkoi monitored and recorded the three-dimensional structure of the convective rain cells during its scan of the whole troposphere in the target area every 5 min. These data were the primary source of response variables for the scientific evaluation of the effect of seeding on warm clouds in this experiment. Because the evaluation relied on rainfall measurements by radar, it was very important to keep the radar calibrated to the same reference throughout the experiment. Therefore, in addition to the electronic calibration, a recalibration of the radar data was done by bringing it to the same level as the intensity of the ground clutter during daytime periods of clear weather with well-mixed boundary layer, to avoid anomalous propagation. Reference to solar intensity was also used in the recalibration process, mainly to check its validity and stability.

Convective cells in the seeded and nonseeded experimental units were identified and tracked by the method of Rosenfeld (1987) in three dimensions. The analysis focused on all cells within the circle encompassing the experimental unit that is twice the qualification pass radius of that experimental unit. The time history of the experimental unit is obtained by advecting the center of the unit at the time of qualification backward and forward in time with the mean cell-motion vector, as determined by the cell-tracking programs. Properties of each cell within the experimental unit are calculated for each 5-min radar scan for as long as a radar echo exists within the experimental unit circle. These properties include radar-estimated rain volume RVOL, rain flux RVR, echo area *A*, peak reflectivity *Z* at 2-km altitude (cloud base), and echo-top height *H*.

Rain intensities *R* were calculated by using the *Z–R* relationship, $Z = 300R^{1.5}$, on the 2-km-altitude (cloud base) reflectivities. This *Z–R* relationship was obtained during the design phase of the experiment from a comparison of data from the radar with that from a rain gauge network installed in the project area. Note that it is very similar to the *Z–R* relationship of $Z = 283R^{1.43}$ obtained by Sims et al. (1963) from raindrop photographs taken during showers in Miami, Florida. Because the same *Z–R* relationship is applied to both the seeded and unseeded experimental data, the evaluation results should represent the differences between the seeded and unseeded response variables as long as seeding does not alter the natural raindrop size distribution appreciably. In the extreme case, there is a possibility that hygroscopic particle seeding merely shifts the existing rain volume into a narrow spectrum of fewer but much larger drops, which yields a large radar return with no actual rain increase. Although the numerical model results do not support such a possibility, experimental evidence that rules out this possibility would provide reassurance that the evaluation results are real.

The properties of the experimental units at any given time were calculated from the respective cell properties, summing or averaging them as appropriate. For example, the experimental unit rain flux at a given time was determined by the sum of the rain fluxes of the cells whose peak occurred within the circle of the experimental unit. The number of cells in each experimental unit at each 5-min volume scan was included as a property of the experimental unit. The maximum value of each of these experimental unit properties during any specified time interval yielded the radar response variables of interest. The maximum values of these radar response variables over the lifetime of the experimental units are referred to as its lifetime properties and are denoted as such by adding MAX to the variable name.

In accordance with the null hypotheses, the statistical evaluation of the experimental units was based on the maximum value of the integrated rain flux (radar-estimated rain volume RVOL at the end time of the period, because RVOL is cumulative) during two experimental time periods, that is, from qualification time until 1) 30 min after the flight scientist on the Aerocommander officially terminated the treatment of the experimental unit (RVOL 30), and 2) the time when the radar echo ceased to exist within the experimental unit circle as determined by the radar cell-tracking programs (the lifetime property RVOLMAX). Analyses were done also on the secondary response variables, that is, the experimental unit's lifetime properties of rain volume rate (RVRMAX), area (AMAX), echo-top height (HMAX), peak reflectivity (ZMAX), number of cells (NCMAX), and duration (DUR).

4. Results of the statistical evaluation of the experiment

a. Experimental summary

The experiment was conducted on warm, semi-isolated convective cloud entities that occurred during the summer monsoon months from June through September each year from 1995 through 1998. The seeding targets were well-defined experimental units that, upon qualification, were selected in a random manner for seeding or nonseeding with calcium chloride particles. An Aerocommander aircraft, equipped to make state-parameter and limited cloud-physics measurements, was used for surveillance, experimental unit qualification, and cloud measurements; and a CASA aircraft was used for seeding operations. A second CASA aircraft replaced the first CASA in the seeding missions when the first CASA had used all its seeding chemicals. The floating-target design coupled with the use of two seeding aircraft made it possible to obtain more than one experimental unit per day when convective conditions were favorable.

The seeding of each experimental unit was done by dispensing calcium chloride particles from the CASA aircraft at an average rate of 21 kg km^{-1} per seeding pass into the updrafts of growing warm convective clouds (about 1–2 km above cloud base) that had not yet developed or, at most, had just started to develop a precipitation radar echo. The CASA made repeated treatment passes, seeding or not seeding according to the randomized decision, until the flight scientist on the Aerocommander terminated the treatment of the unit because the cloud was deemed to be no longer active. If the treatment decision was to seed and the CASA ran out of calcium chloride during its treatment passes, treatment passes were continued until terminated by the Aerocommander flight scientist. Regardless of the treatment decision, the flight patterns were the same.

Once the decision on a particular unit was made, it was irrevocable and could not be changed; failure of the radar, however, could result in elimination of a unit from the sample because without the radar no rainfall data would be available to evaluate the unit. The unit also could be eliminated from the sample if it was found, on subsequent analysis, to have an appreciable radar echo prior to its selection.

Table 2 shows the number of experimental units that were qualified during the 4-yr duration of the experiment. It can be seen that a total of 76 experimental units were obtained (38 seeded and 38 nonseeded) of which 69 (35 seeded and 34 nonseeded) qualified for analysis according to the experiment design. Three of the units (one seeded and two nonseeded) were eliminated because of radar failure, and four of the units (two seeded and two nonseeded) were eliminated because they sub-

TABLE 2. Experimental units qualified during the 4-yr duration of the warm-cloud calcium chloride particle seeding experiment.

	Units meeting the a priori criteria	Units not meeting the a priori criteria: Inoperative radar	Units not meeting the a priori criteria: Preexisting radar echo	Total
Seeded	35	1	2	38
Not seeded	34	2	2	38
Total	69	3	4	76

sequently were found to contain a radar echo prior to qualification that exceeded the limits of acceptability set in the experimental design. It is noteworthy that the 76 experimental units were obtained on 52 experimental days. More than one unit was obtained on 17 days, with as many as five units on one of these days.

There was, on the average, 7.4 treatment passes per seeded experimental unit, lasting an average of 29.14 min, and 6.7 treatment passes per unseeded experimental unit, lasting an average of 25.65 min. For 10 of the seeded experimental units, the CASA seeder aircraft ran out of calcium chloride before the Aerocommander flight scientist terminated the treatment of the experimental unit. Consequently, the average number of treatment pases on which calcium chloride was actually dispensed into the cloud was 6.0. The amount of calcium chloride chemical dispensed per seeded experimental unit ranged from 100 to 1200 kg, the average being 690 kg.

b. Checking for ''compromising covariates''

Before starting the statistical evaluation, relevant characteristics of the seeded and unseeded experimental units (Table 3) were examined to see if the randomization produced a ''bad draw'' [termed as inadvertent bias by Mather et al. (1997)] during the experimental unit qualification process that could affect the evaluation. For the primary response variables RVOL30 and RVOLMAX, there could be no direct effect because by definition only experimental units without a radar echo were included in the dataset. However, there could be a compromising covariate [called ''culprit covariates'' by Gabriel (1999a)] that might explain away an otherwise statistically significant result as a type-I error. It can be seen from Table 3 that, although there were some differences in the cloud characteristics of the seeded and unseeded samples, none were significantly different except, perhaps, the cloud liquid water content, which favored the unseeded sample.

TABLE 3. Characteristics of the average seeded and unseeded experimental units at the time of qualification. LWC is liquid water content.

	Seed (S)	Nonseed (NS)	S/NS
Cloud area (km^2)	10.57	11.30	0.93
LWC (g m^{-3})	1.33	1.48	0.90
Updraft (m s^{-1})	7.55	6.92	1.09
Cloud-base temperature (°C)	22.63	22.58	1.00
Cloud-top height (ft)	12,120.00	12,250.00	0.99

In addition, the topography underlying each experimental unit at the time of qualification was examined to determine if this influence on natural cloud development favored either the seeded or unseeded experimental units. The experimental units were found to develop over a variety of topographic conditions that included mountains, river valleys, semi-isolated ridge lines, and the downwind side of mountains and ridge lines in the transition zone to river valleys. Because the frequency of occurrence of topographic conditions was about the same for the seeded and unseeded experimental units, there was no reason to suspect that orographic influences favored the subsequent development of either.

Because there was no indication of a bad draw in either the qualification or treatment processes, the evaluation was conducted without concern that the results might be affected by a compromising covariate.

c. Results of the evaluation

The primary method used in the statistical evaluation of the warm-cloud seeding experiment was the single-ratio (SR) rerandomization test. From this test, the proportional effect of seeding, SR-1, was estimated along with its one-sided P value and 90% confidence interval. The ratio statistics approximation to the rerandomization test (Gabriel 1999b) was used to calculate the power of detection of the observed result.

The results of the evaluation of the two null hypotheses set forth in the original design is given in Table 4. It can be seen that H01, that is, calcium chloride particle seeding does not alter RVOL30, cannot be rejected at the 5% significance level. On the other hand, null hypothesis H02, that is, calcium chloride particle seeding does not alter RVOLMAX, can be rejected at the 5% significance level at a power of detection of 65%. In fact, the true value of the proportional effect of seeding based on RVOLMAX was estimated with 90% confidence to be between 27% and 180%. It was reassuring to find that the evaluation results for H02 were virtually the same for the sample that included the four units with the preexisting radar echo.

Because the experiment includes two null hypotheses, it could be argued that rigorous statistical practice requires that the 5% level of significance be partitioned

TABLE 4. Results of the evaluation of the warm-cloud calcium chloride particle seeding experiment. Values of SR-1 with *P* values ≤ 0.05 are shown in italics.

	Avg S ($\times 10^3$ m^3)	Avg NS ($\times 10^3$ m^3)	SR-1	*P* value	90% confidence interval
H01 (RVOL30)	33.48	30.46	0.10	0.439	−1.11 to 0.63
H02 (RVOLMAX)	*137.10*	*65.61*	*1.09*	*0.020*	*0.27 to 1.80*

among the two null hypotheses. Given that H02 includes H01 suggests that the partitioning could be weighted in favor of H02. Because this approach was not specified in advance, however, we are obliged to partition equally and assign a level of significance of $P = 0.025$ to each. In that case, it can be seen that the results of the evaluation remain unchanged: H02 can be rejected and H01 cannot.

d. Evaluation of the secondary response variables

According to the numerical model results, it was expected that the increase in the lifetime property RVOLMAX would be accompanied by an increase in RVRMAX. The numerical model results did not indicate that seeding will have a significant effect on either HMAX, ZMAX, or DUR, and the nature of the numerical model readers it incapable of simulating effects on AMAX or NCMAX. Table 5 gives the results of the evaluation of these secondary response variables.

It can be seen that the statistically significant increase in RVOLMAX is accompanied by a statistically significant increase in AMAX, a strongly suggested increase in RVRMAX that was not statistically significant, and a strongly suggested decrease in ZMAX that was not statistically significant. No significant changes in HMAX, NCMAX, and DUR are indicated.

5. Some exploratory analyses

What follows are exploratory analyses that were conducted to gain a better physical understanding of the results of the seeding experiment and, perhaps, to gain some insight as to how the seeding produced the effects indicated by the statistical analyses. Toward that end, use will be made of *P* values, not as measures of statistical significance, but as measures of the strength of the suggested evidence.

a. Radius multiplication factor

In accordance with the experimental design, the experimental unit was a floating circle with a radius that was two times (RMF) the initial radius of the experimental unit as measured during the qualification pass. The a priori selection of this value of RMF to use was a balance between not making RMF so small that it does not encompass all of the larger-area experimental units and not making RMF so large that it encompasses too large an area around the smaller experimental units. To assess how well this balance was achieved by the a priori choice of RMF, a series of exploratory evaluations were conducted in which RMF was varied from a value of 1 to 8.

It can be seen from Fig. 3 that exploratory evaluation results with *P* values ≤0.05 were obtained with RMF values from 1.5 through 3.0, with the maximum value of the proportional effect of seeding, SR-1, peaking at 1.23 for an RMF value of 2.5. Thus, the value of 2 was a good but not the best choice for RMF; it produced a statistically significant evaluation result but not the best possible result.

b. Evolution of the seeding effect

Since null hypothesis H01 could not be rejected at the 5% level of significance but null hypothesis H02 could, the data were examined to determine how the

TABLE 5. Evaluation of the secondary response variables in the warm-cloud calcium chloride particle seeding experiment. Values of SR-1 with *P* values ≤ 0.10 are shown in boldface; those with *P* values ≤ 0.05 are italicized.

Variable	Avg S	Avg NS	SR-1	*P* value	90% confidence interval
RVRMAX ($\times 10^3$ m^3 h^{-1})	315.76	196.47	**0.61**	**0.07**	**−0.07 to 1.16**
HMAX (km)	7.68	7.65	0.00	0.47	−0.23 to 0.21
ZMAX (dBZ)	38.98	43.93	**−0.11**	**0.08**	**−0.28 to 0.02**
DUR (min)	152.71	136.85	0.12	0.29	−0.28 to 0.45
AMAX (km^2)	49.13	29.92	*0.64*	*0.03*	*0.11 to 1.14*
NCMAX	2.20	2.53	−0.13	0.23	−0.47 to 0.13

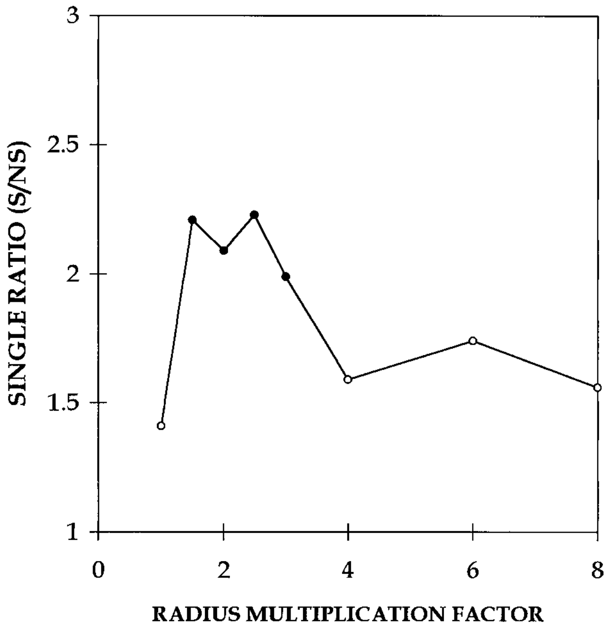

FIG. 3. The single ratio of RVOLMAX as a function of radius multiplication factor. Values represented by black circles are associated with P values ≤ 0.05.

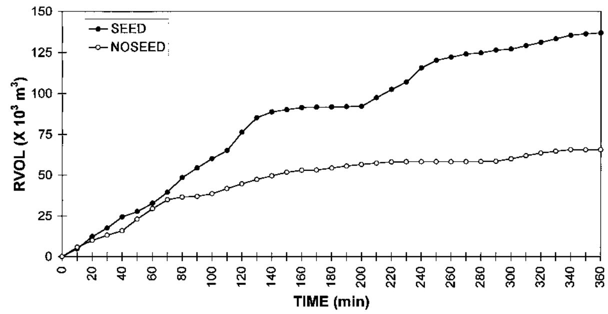

FIG. 4. The cumulative values of average RVOL for the seeded (black circles) and nonseeded (open circles) cases as a function of time.

seeding effect developed over time. Figure 4 shows the average accumulated RVOL for the seeded and nonseeded experimental units as a function of time after qualification. It can be seen that the average rain volume of the seeded experimental units first started to exceed that of the nonseeded experimental units about 20 min after qualification. The difference between seeded and nonseeded experimental unit rain volume remained relatively small (and not statistically significant) until about 70 min after qualification, after which time the difference became successively greater until statistical significance was achieved. That this significance started to occur about 45 min after treatment of the units was terminated suggests that the calcium chloride seeding is affecting the dynamics of the experimental units.

To gain insight into the evolution of the seeding effect, the radar data for the experimental units were reprocessed through the cell-tracking programs, producing one data subset that includes only those cells that were directly treated, hereinafter called the treated-cell component of the experimental units, and a second, complementary data subset that includes all cells except those that were directly treated, hereinafter called the untreated-cell component of the experimental units. Figure 5 shows the average accumulated RVOL for the seeded and unseeded experimental units as a function of time after qualification for the treated- and untreated-cell components of the experimental units, respectively. Table 6 gives the results of a statistical assessment of the radar response variables associated with the treated- and untreated-cell components of the experimental units.

Almost all of the rain volume from both the seeded and unseeded experimental units was produced by the treated-cell component during the first 70 min after qualification, by which time the clouds in the treated-cell component had completely dissipated. During this period, the treated cells were the primary cells in the experimental units. In comparing seeded and unseeded treated-cell components, it was found that their rain volume production was nearly the same, accounting for 18% and 36% of the lifetime rain volume accumulation of the experimental units, respectively. They generally were similar in other respects as well, except for their DUR and ZMAX, for which statistically suggested decreases are indicated. The suggested decrease in ZMAX with no appreciable increase in RVOLMAX indicates that the rain from the seeded treated-cell component of

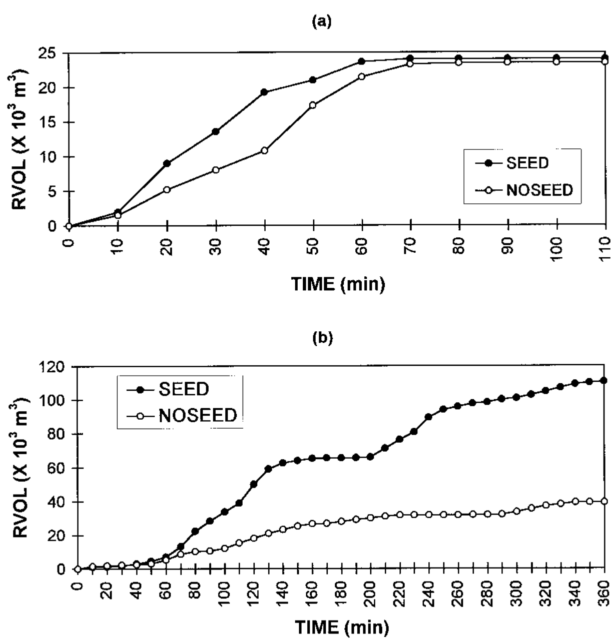

FIG. 5. The cumulative values of average RVOL for the seeded (black circles) and unseeded (open circles) cases as a function of time for (a) the treated-cells component and (b) the untreated-cells component of the experimental units.

TABLE 6. Assessment of seeding effects on the portion of the experimental units containing only treated cells and only untreated cells.

Variable	Only treated cells			Only untreated cells		
	Avg S	Avg NS	SR-1 (*P* value)	Avg S	Avg NS	SR-1 (*P* value)
RVOLMAX ($\times 10^3$ m^3)	24.05	23.47	0.02 (0.480)	110.81	39.10	1.83 (0.019)
RVRMAX ($\times 10^3$ m^3 h^{-1})	90.82	117.86	−0.23 (0.258)	267.16	126.13	1.12 (0.048)
HMAX (km)	5.20	5.75	−0.10 (0.220)	6.79	6.81	−0.00 (0.495)
ZMAX (dBZ)	33.19	40.19	−0.17 (0.034)	30.37	36.92	−0.18 (0.083)
DUR (min)	23.94	31.53	−0.24 (0.046)	149.43	131.06	0.14 (0.287)
AMAX (km^2)	17.45	18.71	−0.07 (0.394)	44.35	22.05	1.01 (0.026)
NCMAX	1.09	1.24	−0.12 (0.167)	1.86	2.09	−0.11 (0.318)

the experimental units consisted of somewhat smaller but more numerous raindrops than that from the unseeded treated-cell component. These results provide some assurance that seeding is not shifting the existing rain volume into a narrow spectrum of fewer but much larger drops; rather, it is increasing the number of precipitation embryos as predicted by the numerical model.

It can be seen from Table 6 that the statistically significant results for the lifetime properties of the experimental units shown in Tables 4 and 5 are due essentially to the seeding effects on the untreated-cell components of the experimental units. In comparing the seeded and unseeded untreated-cell components, there is a strong statistical suggestion of increases in RVOLMAX, RVRMAX, and AMAX, as was the case for the lifetime properties of the experimental units.

That the seeding effect is primarily associated with the untreated-cell component of the experimental units is also a further indication that the calcium chloride seeding is affecting the dynamics of the experimental units. To gain insight into how the microphysical seeding might be producing these dynamic effects, the time evolution of the seeded and unseeded treated- and untreated-cell component radar response variables were plotted; specifically, maximum values of the average seeded and unseeded response variables for the treated- and untreated-cell components in 10-min intervals after qualification were plotted as a function of time in Figs. 6a and 6b, respectively. Looking first at Fig. 6b, it can be seen that both the seeded and unseeded untreated-cell components of the experimental units consist of several secondly cells, presumably second-, third-, and fourth-generation cells initiated by the rain-induced downdrafts from the seeded and unseeded treated-cell components of the experimental units, respectively. The secondary cells produced by the seeded untreated-cell component of the experimental units, however, are substantially greater in RVRMAX, AMAX, HMAX, and ZMAX than those in the unseeded untreated-cell component. The difference between the seeded and unseeded treated-cell components of the experimental units that might have dynamically influenced the development of the second-, third-, and fourth-generation cells can be found by examining Fig. 6a. Although the seeded treated-cell component of the experimental units produced only a little more rain than the unseeded treated-cell component (Fig. 5), the rain formed earlier, consisted of somewhat smaller but more numerous raindrops, and fell out sooner and somewhat harder in the seeded untreated cells than in the unseeded treated cells. In fact, except for not producing more rain in the seeded treated-cell component of the experimental units, the seeding appears to have acted as postulated by the seeding conceptual model. The changes in the timing (and probably location), character, and intensity of the rain, however, appear to have produced a change in the timing (and probably location) and intensity of the downdraft, one or both of which appears to have triggered the successive development of more vigorous second-, third-, and fourth-generation cells that produced much more rain than their unseeded counterparts. That the seeding effect is associated primarily with the component of the units that were untreated, resulting from invigorated dynamic forces that were triggered by the microphysical effects of seeding, provides further assurance that the seeding effects are real and are not the result of altering the raindrop spectra to produce a large radar return with little or no additional water.

Mather et al. (1997) obtained a similar result in the South African hygroscopic flare seeding experiment. They reported that the difference between the seeded and unseeded storms became statistically significant some time after the termination of seeding, suggesting that the hygroscopic seeding was affecting the dynamics of the storms. Bigg (1997) proposed an addition to the South African hygroscopic flare seeding conceptual model, postulating that the hygroscopic seeding produces rainfall earlier and at a lower level in the seeded clouds, which causes a stronger and more localized downdraft to form much closer to the updraft, and the resulting gust front interacts with the low-level inflow to trigger new and more vigorous cloud growth on the

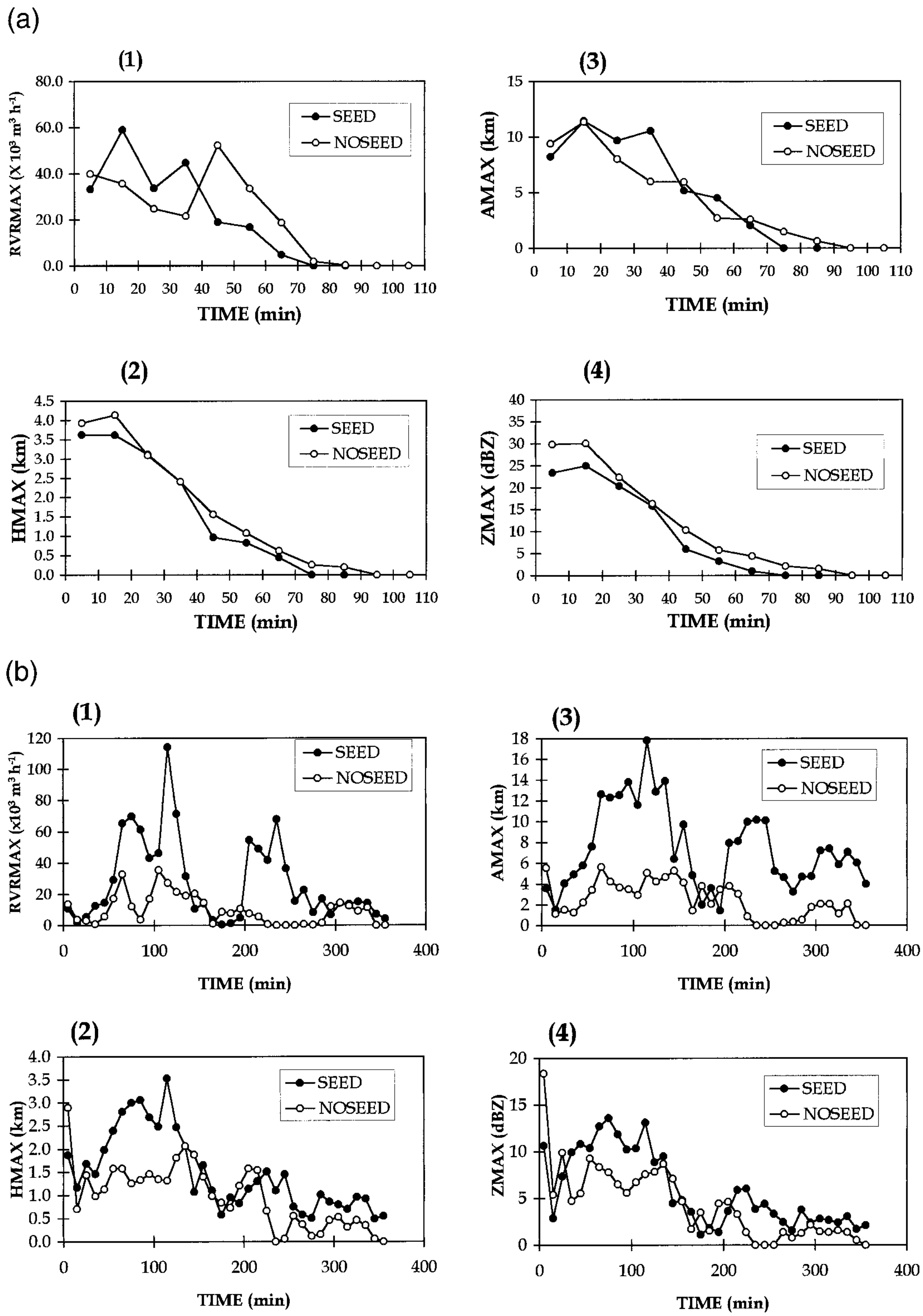

FIG. 6. (a) The average maximum value of 1) RVRMAX, 2) HMAX, 3) AMAX, and 4) ZMAX in 10-min intervals after qualification for the seeded (black circles) and unseeded (open circles) cases as a function of time for the treated-cells component of the experimental units. (b) Same as (a) but for the untreated-cells component of the experimental units.

flanks of the treated storms. Simpson (1980) emphasized the importance of stage II in the dynamic cold-cloud-seeding conceptual model, postulating that enhanced downdrafts below convective towers seeded with silver iodide result in convergence at the interface between the downdraft and the ambient flow, causing the growth of secondary towers and the expansion of the treated cloud system. Cotton and Anthes (1989) discuss the role of downdrafts and gust fronts in the autopropagation of large convective storms.

6. Results of preliminary physical evaluation studies

During the 1997 field season, Thailand's Bureau of Royal Rainmaking and Agricultural Aviation (BRRAA) acquired two King Air B-350 cloud-physics aircraft. The instrumentation on the King Air cloud-physics aircraft included, among other things, Forward-Scattering Spectrometer Probes (FSSP) and two-dimensional cloud (2DC) and precipitation (2DP) probes for the measurement of cloud hydrometeors, a King hot-wire device for the measurement of cloud liquid water content; a Ball variometer for the estimation of cloud updrafts, temperature and dewpoint probes, and a global positioning system for navigation; the data from all of which were recorded on a data acquisition system with real-time display capabilities. In addition, the aircraft was equipped with a forward-looking video camera. During 1997, one of the aircraft also contained a Passive-Cavity Aerosol Spectrometer Probe (PCASP) and University of Wyoming CCN counter, which the National Center for Atmospheric Research provided on a short-term loan. During 1998, BRRAA acquired University of Wyoming CCN counters for both aircraft.

The cloud-physics aircraft were incorporated into the warm-cloud seeding experiment and were assigned to various missions related to the physical evaluation of the experiment. These missions were intended to obtain plausible physical evidence of the effect of seeding to support the positive statistical evidence that already was becoming apparent in the experimental results; both types of evidence are needed to establish scientific proof of the effectiveness of the hygroscopic particle seeding methodology. The results of three kinds of these aircraft missions are presented, that is, missions to obtain physical measurements of 1) the aerosol characteristics of the environment in which the warm clouds grow and the associated cloud-base droplet concentrations, 2) the calcium chloride particle plume dimension and particle size distribution, and 3) the rain spectra below natural and seeded clouds.

a. *FSSP CCN and aerosol measurements*

The variability of the CCN measurements and aerosol particles over Thailand are reported by Bruintjes et al. (1999); here we confine our interest to the measurements in the experimental area as they pertain to their influence on the effectiveness of hygroscopic particle seeding in a numerical model. In the absence of site-specific measurements, model simulations were carried out for a variety of cloud-base droplet concentrations ranging from maritime (100 cm^{-3}) to highly continental (1100 cm^{-3}). The concentrations and spectral shape of CCN were extrapolated from measurements taken in similar meteorological and geographical regimes. The CCN spectrum was represented by a Junge-type spectrum, the slope of which was assumed to be a function of the cloud droplet concentration that increased with increasing concentration.

Typical of the general characteristics of the CCN spectra that were measured during 1997 in the warm-cloud experimental area is the spectrum that was measured below cloud base on 15 June 1997 over the Bhumibol reservoir area, the area over which many of the warm-cloud experimental units were qualified. It was found that the supersaturation spectra, expressed in the usual form of $N = cS^k$, had values of $c = 652$ and $k = 1.447$. Here, N is the number concentration of CCN (cm^{-3}) activated at a given supersaturation S (%), and c and k are coefficients. Measurements of the droplet concentrations about 50–100 m above cloud base during 1997 ranged from about 200 to 400 cm^{-3}, indicating that the critical supersaturation for CCN activation was from 0.5% to 0.7%.

It was assumed that CCN had about the same spectral shape as the PCASP aerosol particles, so the PCASP aerosol measurements on 15 June 1997 were used to estimate the slope of the spectrum of activated cloud condensation nuclei. It was found that the PCASP aerosol particle size distribution was fitted well by a Junge-type spectrum with a slope of -3.01 (see Fig. 7). This result agreed well with the previously conducted model simulations that were based on spectral slopes of -2.7 and -3.1 for cloud droplet concentrations of 200 and 400 cm^{-3}, respectively.

b. *Calcium chloride particle spectra and plume measurements*

The CASA seeder aircraft flying at 120 kt dispensed 1200 kg in 15 min. It was assumed that the calcium chloride particles were initially dispersed in the wing-tip vortices, producing a seeding concentration of 0.0343 g m^{-3}. This was the seeding dosage per seeding pass used in the model simulations. It was, however, recognized that this concentration probably was somewhat high because the particles in the wing-tip vortices plume would spread farther by diffusion. A model of the plume therefore was constructed in which the particles initially were dispersed through the wing-tip vortices, then dispersed by diffusion according to a two-stage dispersion approximation (WMO 1980). During stage one, the calcium chloride particles diffused as a function of time to the power of 1.5 times the square

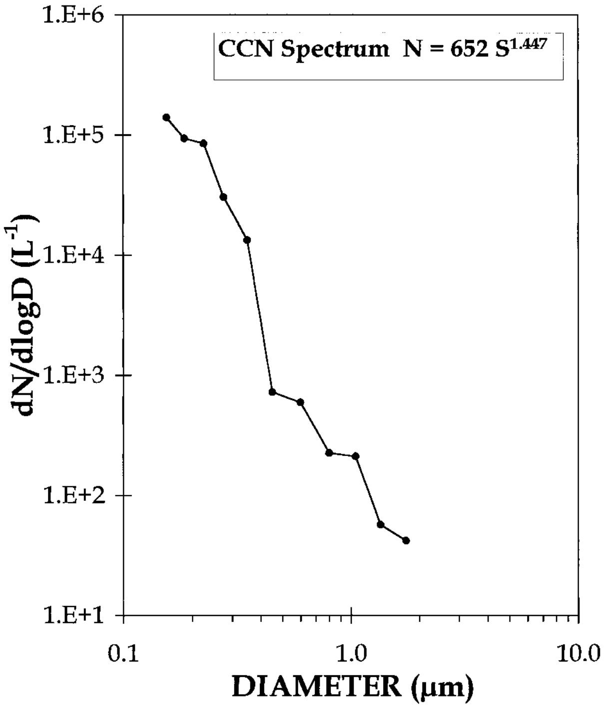

FIG. 7. The size distribution of aerosol particles in the environment below cloud base over Bhumibol Dam. Also shown is the result of the concommitant measurement of the CCN supersaturation spectrum (N and S are defined in the text).

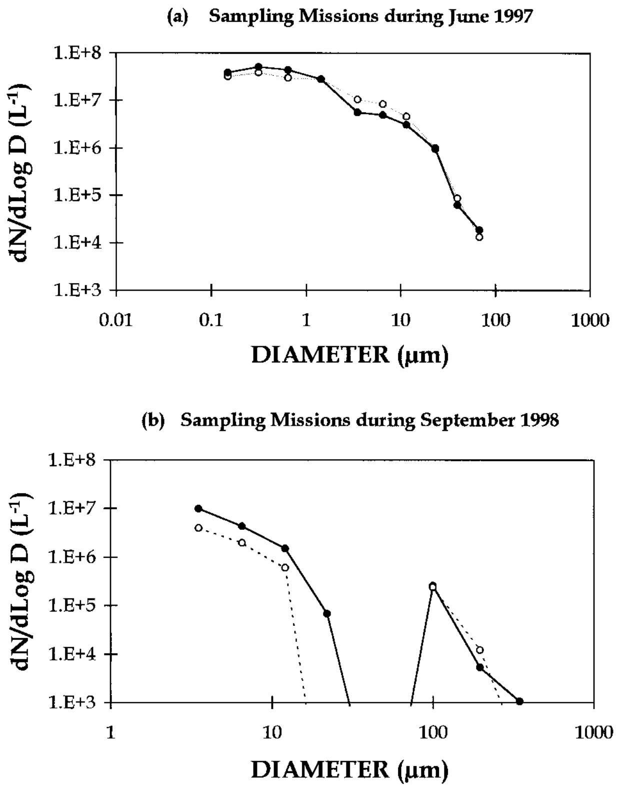

FIG. 8. Size distribution of calcium chloride particles measured in the seeding plumes as measured on sampling flights during (a) 1997 and (b) 1998.

root of the turbulent dissipation rate until the plume spread to about 200 m and then, during stage two, as a function of the square root of the quantity two times the eddy diffusion coefficient times time.

The King Air cloud-physics aircraft was used to determine the actual size distribution and concentration of calcium chloride being emitted from the CASA seeding aircraft. Toward this end, a clear-air mission was conducted with the King Air during 1997 to make measurements of and in the calcium chloride particle plume emanating from the CASA seeding aircraft. The King Air cloud-physics aircraft trailed close behind and to one side of the CASA aircraft until the calcium chloride particles were released and the plume passed it; then the King Air penetrated the plume at a very shallow angle, passing through it from one side to the other. On a second measurement pass, the King Air zigzagged through the calcium chloride particle plume, staying in it for many minutes. The size distribution of the calcium chloride particles was calculated from the King Air measurements on its two passes through the plume. The plume dimensions could not be calculated with any degree of accuracy from the first measurement pass data because of the uncertainties in resolving the magnitude of the very shallow transect angle given the uncertainties in the wind direction and speed and the accuracy of the aircraft-heading information. Therefore, two additional calcium chloride missions were conducted in 1998 that were designed to measure the plume dimensions more accurately. On these missions, the King Air transected the plume at steeper angles, both horizontally and vertically, to resolve the plume dimensions better; because the time in plume was now very short, however, resolution of the size spectrum of calcium chloride particles suffered.

The results of the 1997 and 1998 measurements indicated that the measurements of plume dimensions and calcium chloride particle concentrations were consistent with the plume model, considering the uncertainty in the measurements, the accuracy of the two-stage dispersion approximation, and the uncertainty in knowing what values of the turbulent dissipation rate and eddy diffusion coefficient to use under these circumstances. The measurements also were consistent internally in that the plume dimensions increased and the concentrations decreased the farther behind the CASA the King Air made its measurements.

The big surprise was the size distribution of the calcium chloride particles in the plume; the particle sizes were very much smaller than those measured on the ground or in the aircraft (see Table 1). The size distribution of the calcium chloride particles in the seeding plume measured during 1997 is given in Fig. 8a. It can be seen that there were high concentrations of particles of less than about 3-μm diameter, the concentration de-

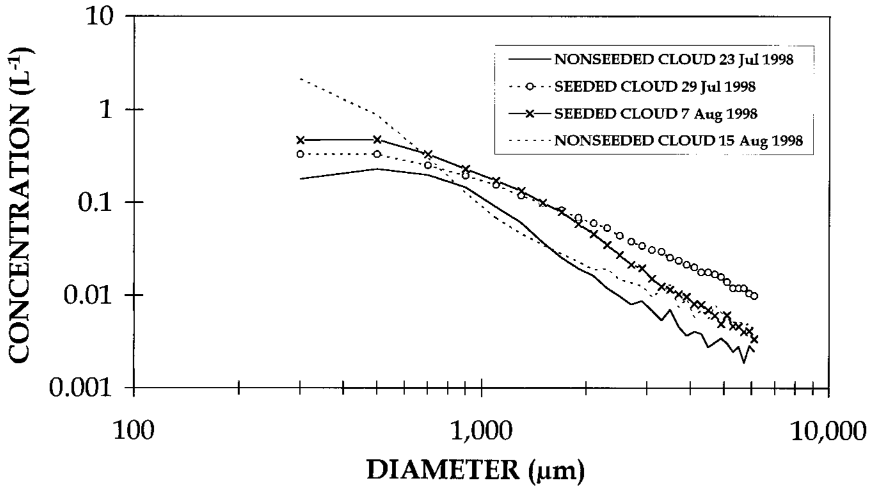

FIG. 9. Comparison of rain spectra measured below two seeded and two unseeded case-study clouds.

creasing with increasing particle size. There were no particles of greater than about 150-μm diameter. The results of the 1998 measurements are given in Fig. 8b. The 1998 calcium chloride particle measurements exhibit a pronounced bimodal distribution with one peak at about 3-μm diameter (it may have peaked at a smaller size but there was no PCASP to measure it) and a second peak at about 100-μm diameter, with virtually no particles between about 25- and 75-μm diameter. There were no particles of greater than 425-μm diameter. Our best guess at this time is that the calcium chloride particles, which likely clumped during storage, were blasted apart as they entered the airstream upon being ejected out the venturi tube of the aircraft. The calcium chloride particle size distribution resulting from the airstream's effects will vary somewhat, depending on how long and under what conditions the bags of calcium chloride were stored.

A qualitative analysis of the effect of the results of the calcium chloride plume measurements indicates that the seeding should be more effective than previously calculated in the numerical model experiments. Many more of the particles are in sizes that are much closer to those predicted to be optimum, and the number of artificial precipitation embryos injected into the cloud is greater. A quantitative analysis was performed by running the model (seeding run 1) on a typical warm-cloud case that is seeded with the size distribution of calcium chloride particles as measured on the aircraft (see Table 1) and comparing it with the results of running the model (seeding run 2) on the same cloud that is seeded with the size distribution of calcium chloride particles measured by the King Air (see Fig. 8a), the seeding concentrations being held constant. It was found that seeding run 1 increased the precipitation from the cloud over that of the unseeded cloud by 13%, causing the rain to fall earlier, in a short time interval, and with greater intensity and associated downdraft than in the unseeded cloud. Seeding run 2 increased the precipitation from the cloud over that of the unseeded cloud by 25%, causing the rain to fall even earlier, in a shorter time interval, and with even greater intensity and associated downdraft than in the cloud from seeding run 1.

c. Rain spectra below seeded and unseeded clouds

During the 1998 warm-cloud field season, a number of warm clouds were selected as physical case studies for using the King Air cloud-physics aircraft to investigate whether there are any differences between the rain spectra from clouds seeded with calcium chloride particles and clouds that were not seeded. Four of the case-study clouds (two seeded and two unseeded) contained sufficient 2DP data to be included in this study. On 29 July and 7 August seeded case-study clouds were obtained in which rain shafts were penetrated 26 and 19 times, respectively. The rain shafts of the unseeded case study clouds obtained on 23 July and 15 August were penetrated 19 and 18 times, respectively.

One difference between the rain shafts of seeded and unseeded clouds immediately became apparent. It was found that the average transit time through the rain shafts of the seeded clouds was significantly greater than that through the unseeded cloud. The average pass time through the rain shafts of the seeded clouds was 40.9 and 41.3 s, but the average pass times through the rain shafts of the unseeded clouds were 22.3 and 6.9 s.

On comparing the rain spectra from the seeded and unseeded clouds (see Fig. 9), it was found that they are fundamentally similar in shape. Some differences between the rain spectra of the seeded and unseeded clouds are suggested, but these differences must, at this time, be viewed with caution, because each of the clouds occurred on a different day on which the environmental conditions were somewhat different. For example, it can be seen that the number concentration of raindrops

(drops ≥500 μm in diameter) was greater in the seeded clouds than in the unseeded clouds, especially in the size range from 1000- to 3000-μm diameter. The net result was that the rain mass per unit volume in the seeded clouds was greater than that from the unseeded clouds, and, when the larger area of the seeded-cloud rain shafts is taken into account, the total rain mass produced by the seeded clouds was considerably greater. These findings, although based on a limited sample of physical observations, tend to provide additional assurance that the radar-measured increases in rain volume are real—that it is not an apparent effect caused by shifting the existing rain volume into a narrow spectrum of fewer but larger drops that gives a large radar return with little or no additional water.

7. Conclusions

The warm-cloud seeding experiment has provided strong statistical evidence that the precipitation characteristics of clouds that were seeded with calcium chloride particles are significantly different from those of their unseeded counterparts. It was found that the average maximum rain volume over the lifetime of the seeded clouds (RVOLMAX) is 109% greater than that of the unseeded clouds, the average maximum radar echo area over the lifetime of the seeded clouds (AMAX) is 64% greater than that of the unseeded clouds, and the average maximum radar rain volume rate over the lifetime of the seeded clouds (RVRMAX) is 61% greater than that of the unseeded clouds. There is both statistical and physical evidence that the radar-estimated increases in rain volume are, in fact, real and not an apparent effect caused by a seeding-produced shift in the existing rain volume into a narrow spectrum of fewer but larger drops that yields a large radar return with little or no actual rain increase.

The statistically significant differences between the seeded and unseeded experimental units were not manifest in the relatively short-lived clouds in the experimental units that were treated directly as envisioned by the seeding conceptual model. Instead, the seeding effects were found in the untreated clouds in the experimental units that subsequently were spawned by the treated clouds. Exploratory analyses of the time evolution of the seeding effects revealed that the seeding conceptual model, as originally stated, needed to be revised to explain the cause–effect relationship between the seeding intervention and the observed results.

It now is postulated that seeding warm convective clouds with relatively large polydisperse calcium chloride particles will accelerate the coalescence process by initiating the collision–coalescence process earlier in the life of the cloud. By reducing the time required for the precipitation process to evolve with respect to the time available, rain efficiency will increase such that the treated clouds will precipitate earlier and with greater intensity than they would naturally but may not necessarily produce more rain than they eventually would naturally. The change in the timing (and location) and/or intensity of the rain will produce an enhanced downdraft, the gust front from which will trigger the successive development of more vigorous second-, third-, and fourth-generation cells than those from unseeded clouds, and they will produce more rain than their unseeded counterparts.

The warm-cloud seeding experiment has provided preliminary physical evidence that is consistent with the strong statistical evidence, evidence that supports but does not yet corroborate the physical plausibility that the effects of seeding suggested by the results of the statistical experiment were, in fact, caused by the seeding intervention in accordance with the revised seeding conceptual model. Additional physical studies need to be conducted to clarify, confirm, and extend the physical–statistical findings from this experiment. In general, a better understanding is needed of how the timing (and location) and/or intensity of the downdraft affects the autopropagation of a cloud system. In particular, it must be determined how seeding can be used to modify the downdrafts in a way that enhances the autopropagation of the cloud system. Doppler radar observations and three-dimensional mesoscale cloud model simulations of seeded and unseeded clouds will be valuable assets in this regard.

It is unlikely that the application of this seeding methodology to individual convective clouds will be economically viable. It will be necessary to adapt the seeding methodology for application on an areawide basis and to demonstrate that it is equally effective on the larger scale. This demonstration undoubtedly will require the satisfactory resolution of additional scientific issues and logistical challenges. Knowing precisely how the seeding conceptual model works is the proper scientific basis for applying this seeding concept on an areawide basis.. It also will provide the scientific basis for transferring the seeding technology, when it becomes warranted, to other areas and to other types of clouds.

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