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TESTING OF DYNAMIC COLD-CLOUD SEEDING CONCEPTS IN THAILAND
PART I: EXPERIMENTAL DESIGN AND ITS IMPLEMENTATION

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Abstract. Dynamic, cold-cloud, seeding concepts are being tested in Thailand in the context of the Applied Atmospheric Resources Research Program (AARRP). 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. The AARRP is a component of Thailand's national program of weather modification under the direction of the Royal Rainmaking Research Development Institute (RRRDI). Part I focuses on the design and execution of the Thai, exploratory, randomized, cold-cloud experiments and on the conceptual model that is guiding these investigations. The treatment units for these experiments are the convective cells, which contain cloud towers that meet the liquid water and updraft requirements. In the Thai design, it is the cell that receives the on-top silver iodide treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells. The experimental unit consists of the small multiple-cell convective system located within a radius of 25 km and centered at the location of the convective cell that qualifies the unit for the first treatment. Evaluation of the experiments is to be accomplished using an S-band (10-cm) radar that is located near Omkoi in northwestern Thailand.

Fifteen experimental units (8 Seed and 7 No Seed) have been obtained to date, and they appear to be well-matched. Bias does not appear to have been a factor in the selection of these random cases and in the subsequent cloud treatments. Evaluation of these units and the convective cells contained within them is presented in Part II.

1.0 HISTORICAL BACKGROUND

Since the late 1960's, scientific and technical organizations in the Kingdom of Thailand have been involved with a series of experiments and operational programs to increase rainfall through cloud seeding. This effort has been under the direction of His Majesty King Bhumibol Adulyadej. A national program of weather modification under the direction of the Royal Rainmaking Research Development Institute (RRRDI) was formalized in 1975.

Since program inception, RRRDI leadership has attempted to improve the effectiveness of their program by taking advantage of the latest scientific findings. In recent years, His Majesty the King recognized the need for the development and implementation of a more comprehensive scientific approach to the design, operation, and evaluation of Thailand's weather modification program. Therefore, the Royal Thai Government (RTG) requested assistance of the U.S. Agency for International Development (USAID), which agreed to sponsor a visit by a team of experts to assess the RRRDI program and make suggestions for improvements. This assessment, which was conducted under the auspices of the U.S. Bureau of Reclamation at the request of USAID, was made by four scientists who visited Thailand from 7-26 September 1986. Their assessment and recommendations are contained in a report entitled "Weather Modification Assessment: Kingdom of Thailand" (Silverman et al., 1986).

The report recommended a comprehensive 5-year developmental program to improve the technical capabilities of the RRRDI through training, additional equipment and a demonstration cloud seeding project. These recommendations were accepted by USAID and a new, broadly-based program known as the Applied Atmospheric Resources Research Program (AARRP) was established.

Subsequent to the report by Silverman et al. (1986), a core training course was conducted in February and March 1988 to acquaint AARRP participants with the scientific principles, terminology and technology of weather modification as a water augmentation tool. Simultaneous with and following this training, a number of studies were conducted in preparation for the demonstration cloud seeding project. These are described in a report by Medina et al. (1989).

The basic concepts to be tested in Thailand, involving either warm-cloud seeding to increase the coalescence of liquid drops or cold-cloud seeding to produce dynamic effects and increased rainfall, were investigated using a number of cloud models. The model runs indicated that both seeding approaches have potential for increasing rainfall in Thailand and that perhaps 35 percent of the potential operational days might be suitable for seeding for dynamic effects.

Preliminary work on the design of the demonstration extended beyond the numerical studies of possible responses to seeding. After visiting potential experimental sites, officials of the RRRDI and Reclamation selected the Nám Mai Tun River area of western Thailand for the conduct of the demonstration project (Figure 1). The Field Operations Center was located first (1991) at the Bhumibol Dam site and later (1992) moved to Chiang Mai Airport, and a weather radar was installed in 1991 at a site about 9 kilometers southeast of Omkoi on a ridge (height 1,160 m) which provides a good view of the Nam Mai Tun River drainage.

Part I focuses on the design and execution of the Thai experiments and on the conceptual model that is guiding these investigations. Part II presents the initial results of this experimentation. This work was done 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.

2.0 SUMMARY OF RESULTS OF RELEVANCE TO THAILAND

The most systematic investigation of the potential of "dynamic seeding" for rainfall enhancement began in clouds over the Caribbean Sea in the mid-1960's (see Simpson et al., 1967) and continued in Florida in the series of experiments that came to be called the Florida Area Cumulus Experiment (FACE). Although the FACE program did not provide conclusive proof that seeding had increased the areal precipitation, the estimated rainfall increases ranged between 10 and 25% for the target area covering 1.3 x 10^4 km^2 and between 20% and 50% for groups of treated convective clouds within the target area (called the "floating target") (see Woodley et al., 1982; 1983).

The FACE program also provided strong evidence for substantial increases in rainfall from individual convective clouds and cells. The first experiment (in 1968 and 1970) indicated that the rainfall from individual clouds could be increased by over 100% (Simpson & Woodley, 1971). A major breakthrough in the second of the two experiments (in 1978-1980) was made with the development of a sophisticated method to identify, track and assess the properties of the treated clouds throughout their lifetimes. Use of this technique permitted a more comprehensive analysis of the effect of seeding on the individual convective cells. Again, the results indicate rain increases of over 100% (Gagin et al., 1986).

These results for tropical clouds in Florida provided the impetus for continuation of dynamic seeding research in Texas. The Texas research to date indicates that dynamic seeding has enhanced the rainfall from individual cells by over 100%, thereby replicating many of the Florida results. In addition, rain increases of 25-30% are indicated for the experimental unit (i.e., the small mesoscale convective cluster) that covers

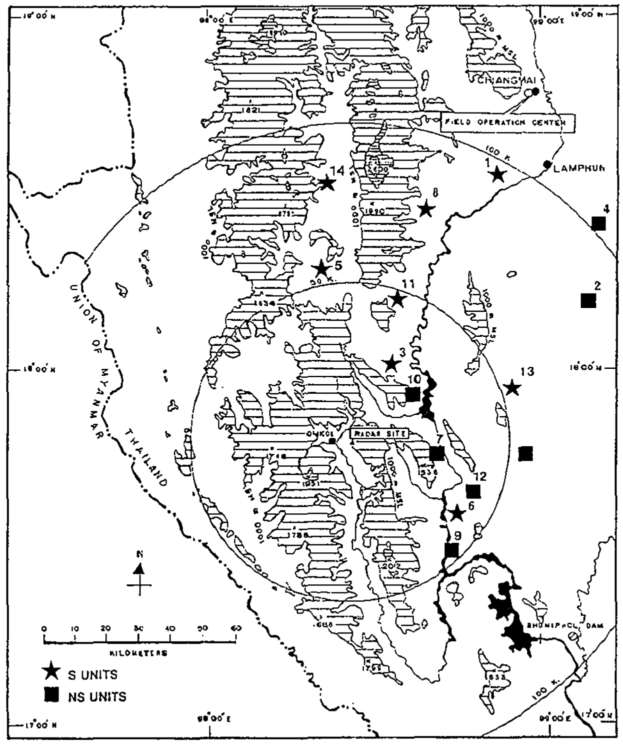

Fig. 1. Map of the project area. The range rings (in km) are relative to the AARRP radar. The locations of each experimental unit are plotted on the map as either solid squares (NS cases) or stars (S cases). The numbers identify the units in the order that they were qualified, beginning in 1991. See Table 3 for listing.

nearly 2,000 km^2 (Rosenfeld and Woodley, 1989, 1993). This effort is continuing.

In summary, the scientific evidence from cloud seeding research programs in Florida and Texas that have employed dynamic seeding techniques indicates that rainfall can be increased from convective clouds by over 100% on the scale of individual cells, by 25 to 50% percent on the scale of groups of convective clouds and by 10% to 25% over targets up to 13,000 km^2 in size. The strength of the evidence for enhanced rainfall decreases, therefore, as the scale of the rainfall increases. The evidence is strongest for individual cells where the seeding signal is largest and weakest for large target areas where the seeding signal is small.

3.0 THE DYNAMIC SEEDING CONCEPTUAL MODEL

The revised dynamic seeding conceptual model has been discussed recently by Rosenfeld and Woodley (1993). The main departure of the new dynamic seeding model from the "classical" model of the past (Woodley, et al., 1982) is the realization that dynamic seeding can also produce a substantial increase in convective rainfall without a large increase in the maximum height of the seeded entity.

The steps in the new conceptual chain are supported by new and old scientific findings from a number of research projects. These findings have been combined with the new results to synthesize a revised conceptual model for dynamic seeding, that in no way contradicts the precepts of the old, but merely builds and expands on them in places where physical insight was lacking.

In building on the conceptual models that guided the Florida and Texas experimentation, it is suggested that seeding for dynamic effects operates to produce more rain from individual cells and groups of cells through the following steps that are listed in Table 1:

Table 1

CONCEPTUAL MODEL FOR DYNAMIC CLOUD SEEDING
(Revised as of July 1992)

Lifecycle Stages of Suitable Unseeded Clouds

1. Cumulus Growth Stage
Warm-based growing cumulus cloud with vigorous updraft and active warm-rain processes.

2. Supercooled Rain Stage
Active updraft thrusts large amounts of supercooled rain and cloud water from the 0°C level toward the -10°C level. This is the seeding time window.

3. Cloud Rainout Stage
Increased drop sizes and precipitation loading causes most of the supercooled rain to fall back into the warm portions of the cloud without freezing; that which remains glaciates. The falling rain suppresses the lower portions of the updraft, thus terminating the growth of the cloud.

4. The Downdraft Stage
The rain and associated downdraft reach the surface, resulting in a short-lived rain shower and gust front.

5. The Dissipation Stage
The cloud dies.

The above sequence of stages is an idealization. Dissipation may follow the glaciation stage of seeded clouds or any subsequent stage, if the required conditions are not present.

Lifecycle Stages of Clouds Following Seeding

Cloud-top seeding to produce a vertical curtain of ice nuclei is done at the **Supercooled Rain Stage**, such that the nucleant is dispersed in the supercooled volume as it ascends through the -10°C level.

3. Glaciation Stage
The raindrops freeze and continue their growth as graupel particles with increased growth rates and reduced fall velocities. All or a portion of the released latent heat supports the increased precipitation loading. Leftover buoyancy induces added vertical cloud growth. This prolongs the updraft at lower levels, which carries additional water into the supercooled region to increase precipitation mass.

4. Unloading Stage
The increased precipitation mass eventually descends. The unloaded cloud top, which still contains some of the released latent heat, renews its vertical growth, producing additional ice precipitation. In many cases, this cloud tower reaches cumulonimbus stature. The unloaded precipitation initiates a downdraft at the lower levels.

5. Downdraft and Merger Stage
The enhanced precipitation and downdraft reaches the surface, resulting in increased outflow, increased convergence at the gust front, new cloud growth and merger.

6. Mature Cumulonimbus Stage
Growth continues in the convergent regions, leading to an expansion of the cloud system and the formation of a mature cumulonimbus system.

7. Convective Complex Stage
Application of seeding to several suitable towers results in additional cloud growth and merger, leading potentially to a small mesoscale convective system and greater overall rainfall.

This is an idealized sequence of events. Dissipation may follow the glaciation stage or at any subsequent stage, if the required conditions are not present.

It is important to note that the above model applies to convective clouds in which the coalescence process is active to produce rain drops in the supercooled region. It is the freezing of these raindrops that produces the bulk of the fusion heat release (see Lamb et al., 1981). A useful guideline for distinguishing between clouds that are likely to produce supercooled rain and those that will not, involving parcel buoyancy at 500 mb and cloud-base temperature, is provided by Mather et al. (1986).

This conceptual model applies optimally to clouds having mean updrafts strong enough to carry the rainwater to temperatures where it can be nucleated artificially but not having updrafts strong enough to carry the rainwater to heights where the temperature is cold enough for complete natural freezing. The updraft velocities should be at least comparable to the terminal fall velocity of the raindrops at that level (i.e., about 10 m/sec). Assuming that the rate of ascent of cloud top is half the peak updraft velocity, a minimum of 5 m/sec vertical growth rate is required for the cloud top, while growing through the 0 to -10C levels. This means that a suitable cloud must cover the 1600 m vertical distance that normally exists between the 0°C and -10°C levels in at most 5 minutes.

To be effective, several seeding flares should be ejected into the updraft region to ensure that the freezing will be completed before the updraft begins to wane. Although one flare contains a sufficient number of ice nuclei to seed a typical updraft, there may not be enough time to disperse this material within the updraft during the short time (< 5 min) that the supercooled rainwater exists at the seeding level.

The consequences of seeding too late in the life cycle of a cloud is usually accelerated dissipation. This occurs when a mass of supercooled rainwater is glaciated artificially without an attendant updraft. The released heat, which is not sufficient to re-generate a significant updraft, remains aloft while the frozen precipitation continues downward. When this frozen precipitation eventually melts and cools the cloud, it destroys the updraft and/or enhances the downdraft, resulting in the destruction of the cloud.

It must be emphasized that artificial seeding merely imitates a natural process, which is often the mechanism that transforms cumulus convection to cumulonimbus convection. Seeding is most effective, however, when this transformation is unable to proceed naturally. It is crucial, therefore, that seeding tests be conducted during these marginal conditions and not when deep, vigorous, natural cumulonimbi are prevalent.

This rather complex conceptual model is backed by observations that taller convective cells precipitate more. Observations of natural convective rain clouds in Florida (Gagin et al., 1985) and in Texas (*Rosenfeld and Woodley, 1989*) indicate that an increase of cell top height by 20% nearly doubles its rain production. If a seeding-induced enlarged cloud behaves as a natural cloud reaching the same top height, the rainfall from the treated cloud will be increased accordingly. This was nearly the case in two Florida studies (Simpson and Woodley, 1971; Gagin et al., 1986), where 20% increases in mean cell height explained about 70% of the factor of 2.60 seeding effect on the rainfall.

This has not been the case in Texas, however, where it now appears that more than a doubling of the rainfall has been associated with only about a 7% increase in mean maximum cell height. This finding in conjunction with the evidence that seeded clouds in Texas produce more rainfall than unseeded clouds of the same height suggest that additional physical processes are at work in enhancing the rainfall by seeding. These have been addressed in the new model.

The revised conceptual model is different from the original model in several important respects. It was assumed implicitly in the early model that the AgI treatment would produce high concentrations of very small ice crystals and, in effect, "overseed" (i.e., too many nuclei for the available water supply) portions of the treated volume, resulting in less efficient precipitation processes. This possible outcome was viewed "as a small price to pay" in exchange for the release of fusion heat that would lead eventually to a larger, longer-lasting cloud in which natural precipitation processes would dominate.

More recent thinking, however, suggests that this "over-seeding" concept may not be valid in vigorous warm-based clouds (Rokicki and Young, 1978). A large amount of supercooled water normally exists at the seeding level in such clouds. Although seeding produces an obvious glaciation signature (Sax et al., 1979), it is rare to encounter an extensive overseeded region. The normal circumstance in cloud immediately following seeding is a mix of cloud water, seeding-induced ice crystals and raindrops, a situation that should be conducive to the formation of graupel through the aerodynamic capture of the ice crystals by the raindrops which then freeze (Lamb et al., 1981). Under such circumstances, much of the cloud's water mass may be intercepted before it can be evacuated in the anvil.

Once the enhanced graupel mass exists, Johnson (1987) indicates that the graupel will fall slower and grow faster than water drops of comparable mass. This means that the seeding-induced graupel will reside in the cloud tower longer and achieve greater size than a population of water drops within a similar unseeded cloud.

This effect is consistent with the increased reflectivity aloft after seeding, accompanied by some decrease of reflectivities at lower levels. This area of larger reflectivity reaches cloud base as additional rainfall about 40 minutes after initial seeding. Bruintjes et al. (1992) have also noted increases in the reflectivities aloft after seeding clouds in South Africa, which he attributes to the same effect of conversion from rain to graupel, as suggested by Johnson (1987).

The increased precipitation loading in the seeded tower will require greater cloud buoyancy and a stronger updraft to keep it aloft. It is possible, therefore, that some of the increased buoyancy in Texas clouds is expended in carrying the larger precipitation load, leaving little buoyancy left over for the production of higher cloud tops. In Florida, however, the fusion heat releases should be higher because of higher rainwater contents. This may allow seeded Florida clouds to carry the increased precipitation load and still have enough buoyancy left for additional vertical cloud growth. Only with numerical cloud modeling with explicit microphysics will it be known for sure.

The retention of the increased ice mass high in the cloud is an important new aspect of the dynamic seeding conceptual model. It may help explain how an effect of seeding is communicated immediately to the rest of the cloud. If the precipitation mass can be held aloft as a result of the seeding, the downdraft is delayed. This provides additional time for the growth of the cloud tower. Only until this precipitation mass begins to move downward is the updraft in jeopardy. Under conditions of vertical wind shear, the precipitation may fall adjacent to the parent updraft and not disrupt it. In addition, the decreased precipitation loading in the cloud tower that formerly contained the water mass may allow it to renew its growth to greater heights, possibly reaching cumulonimbus stature. This second surge of growth is a common phenomenon in natural clouds, especially in the tropics where warm-rain processes are most active. Seeding may also produce this second surge of growth in clouds that could not have done so naturally.

There is no doubt that downdrafts are vitally important to the development of a cloud system. This is why the dynamic seeding conceptual model incorporates the ideas of Simpson (1980), regarding the role of the downdraft following seeding. It is doubtful, however, that the downdraft can explain the explosive initial growth of the seeded tower that sometimes occurs following seeding, since this growth often occurs prior to or simultaneous with the rain reaching the ground.

Evidence in support of the portion of the conceptual model dealing with increased cloud growth, greater cloud duration, more mergers and additional rainfall has been presented earlier by Rosenfeld and Woodley, 1989; 1993). The observational evidence to date clearly supports these links in the conceptual chain.

4.0 DESIGN OF THE THAI COLD-CLOUD EXPERIMENTS

4.1 Aircraft and Radar Systems

An Aero Commander 690B turbo-prop aircraft was provided to the RRRDI and its AARRP effort under lease from Thai Flying Service. This turbo-prop aircraft was equipped with an airborne data acquisition and seeding system and served as the cloud physics platform and seeder for the program. In addition to standard avionics and flight instrumentation, the Aero Commander was equipped with the following instrumentation: a Johnson-Williams-type liquid water content meter manufactured by Cloud Technology, Inc., a thermo-electric dew point hygrometer, a reverse flow thermometer, a Ball variometer and a satellite-based (GPS) navigation system that permits location of the aircraft to within 100 m. A forward-looking nose video camera was mounted in the cockpit and provided a continuous view of cloud conditions during flight through the extreme right side of the windshield.

The liquid water hot wire and the Ball variometer were configured to measure water contents and draft speeds up to 6.0 gm/m^3 and 2,000 ft/min, respectively. No Thai cloud had water contents approaching 6.0 gm/m^3, so this threshold was never exceeded. Many Thai clouds did, however, have drafts exceeding 2,000 ft/min, particularly during pre-monsoon conditions, so the measured maxima and the calculated mean maxima are underestimates of the true values.

The main operational and research radar for the AARRP effort is an Enterprise Electronics Corporation (EEC) Model DWSR-88S S-band (10-cm) Doppler Weather Surveillance Radar with a 1.2° conical beam. The AARRP radar is situated on a hill 9 km southeast of Omkoi (17° 47'54"N; 98° 25'57"E) at an elevation of 1,160 m. The surrounding terrain is below

1° elevation except between 225° and 275° azimuth, where one hill top extends up to 2.3° elevation. During the program the radar was operated 24 h per day in either the surveillance or volume-scan modes. The characteristics of this radar are provided in Table 2.

Table 2

Characteristics of Thailand's DWS-88S Doppler Weather Radar*

Frequency	2.7-2.9 GHz
Wavelength	10.8 cm (S-band)
Peak Trans. Power	500 kW
Pulse Dur. (width)	2.0 μs for intensity mode (reflectivity) 0.8 μs for velocity mode
Pulse Rep. Freq.	250 pulses/sec for intensity mode Dual 600 to 1000 pulses/sec for velocity mode
MDS	-106 dBm
Antenna diameter	6.1 m (beamwidth approximately 1.2°

* Manufactured by Enterprise Electronics Corporation

4.2 Experimental Layout

The Thai experiments were carried out in accordance with the Design Document and AARRP Operations Plans by Woodley et al. (1991). This was an exploratory experiment and the design changed slightly from 1991 to 1993 as is characteristic of exploratory efforts. The treatment decisions were randomized on a unit-by-unit basis and all suitable convective cells within the unit received the same treatment -- silver iodide (AgI) in the case of a seed (S) decision or simulated AgI in the case of a no seed (NS) decision.

The selection of the experimental unit was based upon the following requirements:

1. The qualification cloud must have a maximum (1-sec values) liquid water content $\geq$ 1.0 g m^{-3} and a maximum (1-sec value) updraft $\geq$ 1,000 ft min^{-1} (i.e., $\geq$ 5 ms^{-1}), as determined from real-time readouts aboard the aircraft.

2. The experimental unit consists of the small multiple-cell convective system located within a radius of 25 km and centered at the location of the convective cell that qualified the unit for the first treatment.

3. All cells within the experimental unit at the time of initial treatment had to have echo tops $\leq$ 10 km AGL.

4. At least some of the subject cells had to have top temperatures of -10°C or colder.

5. At the time of selection, the center of the experimental unit had to be at least 40 km from cumulonimbus clouds, displaying radar reflectivities of 50 dBz or greater in the vicinity.

During the experimentation on a particular experimental unit, the following requirements applied:

1. The center of the experimental unit is to be positioned at the location of the qualification pass of the aircraft. This position is to be advected with time with the mean direction and speed neighboring convective cells.

2. All untreated cells contained entirely within the 25-km circle become potential seeding targets and, by definition, become a part of the experimental unit.

In the Thai design, therefore, the treatment units are the convective cells, which contained cloud towers that met the liquid water and updraft requirements. It is the cell that receives the treatment, and any effect of seeding should manifest itself first on this scale before it is seen in the experimental unit that contains the cells.

Prior to commencement of the 1993 experiments, it was decided to allow for relaxation of the stringent requirements for qualification of an experiment. Specifically, the 1.0 gm/m^3 requirement was relaxed to 0.5 gm/m^3 and the requirement that no cell within the unit shall have an echo top exceeding 10 km was eliminated, as was the 40 km separation distance between the center of the prospective unit and nearby 50 dBz cores. This was done in the hope of qualifying more units with the intention of stratifying them later during the analysis phase.

During the actual experimentation, however, the flight scientists "attempted to play by the old rules." As best can be determined, all units were qualified by the old protocol with no loss in unit qualifications as a consequence of adhering to the old qualification rules.

The randomized seeding instructions for the single-cell experiment were prepared by the Bureau of Reclamation in Denver, Colorado, USA. In 1991, the blocking of the randomization was based on the time that the first cumulonimbus echo in Thailand, having a top exceeding 10 km, formed within 159 km of the radar. There were three blocks:

Block 1 - Used on days when the first

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Cb echo forms in the study area prior to 1300 LST.

Block 2 - Used on days when the first Cb echo forms in the study area after 1300 but before request for a treatment decision.

Block 3 - Used on days when no Cb echo has formed in the study area prior to request for a treatment decision.

This blocking scheme was developed to account for the fact that the weather is different on days with early deep convection from days on which deep convection is delayed until late in the day.

By 1993, however, the view prevailed that the blocked randomization was too complex for the initial Thai experiments. A new set of randomized instructions without blocking was prepared and used in the 1993 experiments. Thus, only one experimental unit was qualified with the blocked scheme and 14 were qualified with the simple randomization.

The AgI nucleant that was used in this experiment was the EJ-20-E-20 type FA6 formulation manufactured by Atmospherics Inc., in Fresno, California, USA. This flare is complexed with chlorinated hydrophilic material that allows it to nucleate at a faster rate (i.e., 90% activation in the first 3 min) than the modified TB-1 formulation (i.e., 10% activation in the first 3 min) that has been used in Texas. According to tests at the Cloud Simulation and Aerosol Laboratory at Colorado State University, the EJ-20/FA6 and the modified TB-1 flares produce about 3 x 10^{14} and 8 x 10^{14} ice crystals per gram of silver iodide, respectively, at -10°C. Both flares yield about 10^{13} ice crystals per gram of silver iodide at -7°C (Figure 2).

The flares were ejected at the seeding flight altitude (normally 21,500 ft) from the project Aero Commander 6903 turbo-prop aircraft. When ejected at seeding altitude, each flare normally burns for at least 50 sec and falls more than 1.5 km in still air. The actual fall distances were likely less because the flares normally were dropped into vigorous updrafts. The seeder aircraft carries 200 20-gm flares on each flight.

5.0 EXPERIMENTAL PROCEDURES

During the randomized experimentation, suitable supercooled convective cloud towers within the convective cells received either simulated AgI treatment or actual AgI treatment near their tops (typical tops heights of 6.0 to 7.0 km and top temperatures -7°C to -9°C). Between 1 and 10 flares normally were ejected during a seeding pass. The flare ejection button was pressed approximately every second while the cloud liquid water

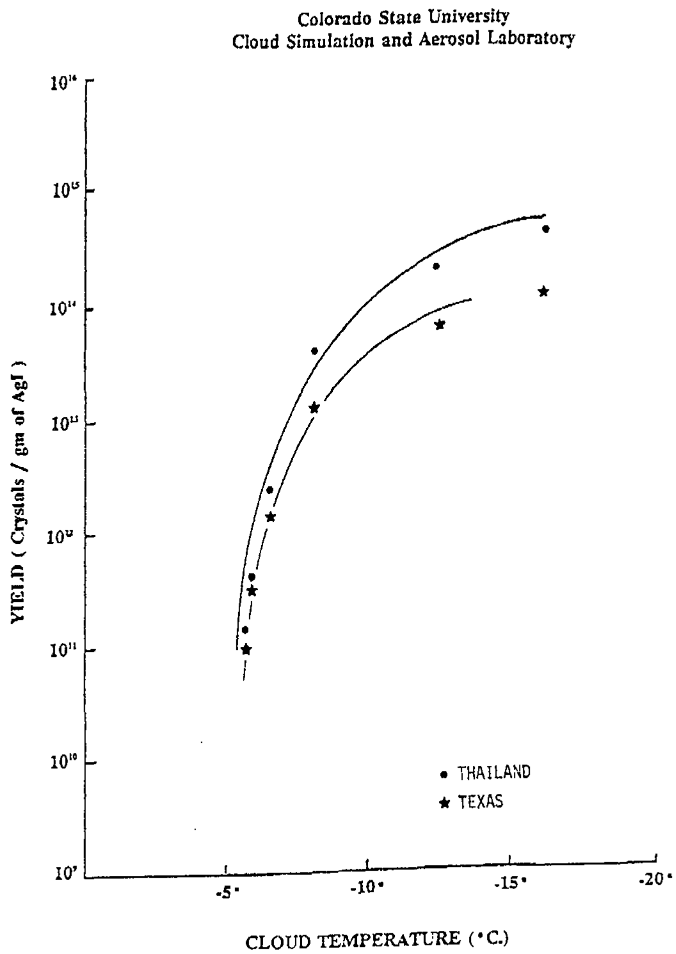

Fig. 2. The yield in ice crystals per gram of silver iodide as a function of temperature for two pyrotechnic formulations produced by AI, Inc. of Fresno, CA. The top curve corresponds to the EJ-20/FA6 flare that is used in Thailand and the bottom curve corresponds to the modified TB-1 flare that is used in Texas. The tests were performed in the Cloud Simulation and Aerosol Laboratory at Colorado State University in Ft. Collins, CO.

reading was greater than 0.5 g/m^3 and the aircraft was in updraft (the 1.0 gm/m^3 and 5 m/sec requirement applied only to the initial qualification pass). In some cases, seeding or simulated seeding was done 1,000 ft or less over the top of an especially vigorous hard tower, when previous cloud passes on a particular day had established the suitability of the subject clouds. In the simulated seeding passes no flares were actually ejected when the button was pressed, but the event was still recorded in the aircraft data system by activating an event switch.

The treatment decision for each experimental unit was revealed after the qualification pass. This was done to maximize the learning experience of the Thai scientists and to avoid the extra costs that would have been incurred through the use of placebo flares. This decision is not without its risks, however, since knowledge of the treatment decision could result in inadvertent bias either in the conduct of a given experiment and/or in the selection of the next experimental unit. This potential problem is discussed in more detail in the next section.

Once the decision on a particular unit had been made, it was irrevocable, and could not be changed, nor could the unit be eliminated from the sample. Only failure of the radar can result in elimination of a unit from the sample. Without the radar, no rainfall data will be available to evaluate the unit.

During the operations the pilots and flight scientists attempted to make certain that all seeding or simulated seeding passes took place within the confines of the experimental unit (i.e., within 25 km of the qualification point). The "cloud pointer" on the aircraft was used to mark the position of the qualification pass, and this pointer was used to keep the aircraft within the unit. As the unit moved, however, the flight scientist sought a new center position from the radar operator, who was plotting the unit on the radar display and moving it along with the motion evident in the radar echoes nearby. This position was then used to update the pointer aboard the aircraft.

Regardless of the treatment decision, the flight patterns were essentially the same. The object was to recognize what nature was trying to do with a particular cloud or cloud group and then seeding to enhance the natural tendencies. This usually required multiple passes through suitable young towers growing on the upshear flanks of the parent cloud, and the ejection or simulated ejection of about 1 AgI flare per sec while in suitable conditions.

Doing the seeding within young vigorous clouds, as they moved through the treatment level, required teamwork between the flight scientist and the pilots. Care was taken not to fly into mature large clouds that could have beat up the aircraft and were not suitable for seeding in any case. This generally meant that young upshear towers were worked at angles to the shear vector, so that the large cloud, which was normally downshear, was not penetrated. The echo cores could be located on the aircraft radar. Most cloud towers more than 5,000 ft above the aircraft already had echo cores and were unsuitable. Flight patterns requiring a 90° left turn and then a 270° degree right turn (or vice versa) frequently were helpful, as were race-track patterns that permitted visual monitoring of the cloud on one of the legs of the racetrack and repenetration of suitable towers and seeding on the other. Sometimes no set patterns were possible because of intervening cloud clutter, and the aircraft was flown in whatever way necessary to get the job done.

A good unit was one that had a treatment duration of at least 1 hour following qualification and had 20 to 30 treatment passes, which resulted in the ejection or simulated ejection of 100 or more AgI flares. This could not always be controlled, however, and one was left to make the best of a particular situation.

Seeding continued in the unit as long as there were suitable towers, regardless of the treatment decision. There was no set limit to the duration of seeding and to the amount of nucleant that was expended in each experimental unit. As long as cloud conditions were suitable, treatment continued. In a few cases treatment was terminated, when the aircraft ran out of fuel and/or the experimental unit moved beyond 159 km quantitative range from the radar.

6.0 OPERATIONAL SUMMARY

One experimental unit was qualified in 1991 and 14 experimental units were qualified in 1993 for a total of 8 Seed and 7 No Seed units. Information for these cases is provided in Table 3, and a plot of their locations is provided in Figure 1. Further details are provided by Woodley and Rosenfeld (1993).

Although the Operations Plan allowed for relaxation of the qualification criteria that had been observed in 1991, it did not prove necessary. Only on April 21 was a unit qualified with a SLWC < 1.0 gm/m^3. The qualification value was 0.74 gm/m^3, but there is some uncertainty concerning the accuracy of this measurement, because the heater on the hot wire probe failed entirely three passes after the qualification pass. It is possible also that one cloud in the experimental unit of 9 May 1993 may have exceeded 10 km on its southern boundary for about 5 minutes around the time of the qualification pass.

Potential bias in the conduct and evaluation of a cloud seeding experiment should be evaluated wherever possible. It is important, therefore, to determine whether bias may have played some role in the Thai cold-cloud seeding experiments. At this point there is no evidence that deliberate or unintended bias has been a factor in the selection of the random cases, at least for the qualification pass, as can be seen in Table 4 for which maximum SLWC and updraft have been listed.

Table 3

SUMMARY OF RANDOMIZED CASES

DATE	CLOUD BASE TEMP (°C)	TIME OF QUALIF PASS (LST)	POSITION OF QUALIF PASS (LAT; LONG)	TREATMENT DECISION (S OR NS)	# OF FLARES FIRED	# OF TREATED TOWERS	TIME OF 1ST TREATMENT (LST)	TIME OF LAST TREATMENT (LST)	TREATMENT DURATION (MINUTES)
8/7/91	22	15:34	18 34.8;98 51.6	S	29(29)	13	15:40	17:11	92
4/15/93	18	14:53	17 59.8;99 16.7	NS	45(0)	9	15:04	15:46	42
4/18	11	15:41	17 55.7;98 36.7	S	57(57)	12	15:45	16:33	48
4/20	15	15:19	18 13.6;99 17.3	NS	79(0)	13	15:30	16:36	66
4/21	15	13:59	18 16.8;98 21.0	S	112(112)	18	14:04	16:10	126
4/22	18	15:40	17 34.2;98 44.3	S	70(70)	13	15:47	17:11	84
4/23	18	14:20	17 45.0;98 41.0	NS	91(0)	17	14:27	16:19	112
4/25	16	14:45	18 27.4;98 36.2	S	118(118)	25	14:56	17:32	160
4/29	19	15:18	17 28.6;98 41.5	NS	96(0)	17	14:26	15:50	84
5/4	22	15:17	17 52.0;98 40.2	NS	57(0)	17	14:30	17:11	101
5/7	21	13:52	18 09.9;98 34.0	S	77(77)	18	14:02	15:46	104
5/8	15	14:50	17 38.3;98 44.7	NS	89(0)	18	14:59	17:20	141
5/9	18	14:26	17 50.6;98 56.8	S	156(156)	29	14:34	17:26	172
5/27	22	14:36	18 30.8;98 18.8	S	124(124)	25	14:47	17:15	148
6/4	21	15:08	17 41.7;98 57.4	NS	124(0)	22	15:13	17:42	129

Note: In the "# of Flares Fired" column, the first number for the Seed cases is the number of flares attempted and the second number in parentheses is the number of flares actually fired. For the Seed cases all of the flares did fire --- a remarkable performance for the seeding system. For the No Seed cases, the first number refers to the number of times that a toggle switch was activated to simulate seeding. Each activation was recorded by the data system. The second number in parentheses is zero (0), because no actual seeding was done and no flares left the rack.

Table 4

LISTING OF SLWC AND UPDRAFT VALUES
FOR THE QUALIFICATION PASSES

Seed Cases			No Seed Cases		
Date	Max SLWC (gm/m^3)	Max Updraft (ft/min)	Date	Max SLWC (gm/m^3)	Max Updraft (ft/min)
8/7/91	3.57	1300			
4/18	3.05	1100	4/15	1.89	2000+
4/21	0.74	1900	4/20	1.36	2000+
4/22	1.43	2000+	4/23	1.43	1400
4/25	1.47	2000+	4/29	1.61	2000+
5/7	1.17	2000+	5/4	1.07	2000+
5/9	1.20	1900	5/8	3.53	2000+
5/27	1.22	1600	6/4	1.45	1300
Avg.	1.73	1725	Avg.	1.77	1866

Table 5

LISTING OF THE ECHO DURATIONS WITHIN
THE EXPERIMENTAL UNITS
AFTER THE QUALIFICATION PASS

Seed Cases			No Seed Cases		
Time of No Echo	Qual. Time	Dur. (min)	Time of No Echo	Qual Time	Dur. (min)
2130	1534	356			
1715	1453	97	1650	1453	117
1900	1359	301	1710	1519	111
1955	1540	255	1750	1420	220
1715	1445	150	1901	1518	223
1820	1352	268	1740	1517	143
2031	1426	249	1715	1450	145
1728	1447	199	2155	1508	407
Means:		234			195

A second concern is whether the conduct of the experiment might have been biased after the treatment decision had been revealed. This possibility is more difficult to investigate, because the effect of seeding itself may be a confounding factor. For example, the mean number of AgI flares expended and simulated in S and NS units were 93 and 83, respectively. The corresponding mean treatment durations (i.e., time of last treatment minus time of first treatment) were 117 min and 96 min, respectively. Are these flare expenditure and treatment duration differences indicative of a bias in the conduct of the experiment, or do they indicate that the AgI-treated clouds last longer and provide more seeding opportunities?

Listed in Table 5 are the durations of echoes within each experimental unit after the qualification pass, obtained from the set of radar analyses to be discussed in Part II. Note that the 8 S units lasted 39 minutes longer on radar than the NS units. When the longest duration unit is eliminated from both the S and NS samples as a sensitivity test, the S vs NS disparity increases to 56 minutes. This indicates that the S systems lived longer and, thereby, provided more seeding opportunities. Although this result could have occurred by chance, it is consistent with an effect of seeding.

Looking further at the question of bias, the mean number of treatment passes per day are 19 and 16 for the S and NS cases, respectively. This is consistent, of course, with the longer treatment durations for the S cases. Some might still view it as an indication of bias. It is interesting, however, that the treatment rate (i.e., # of AgI or simulated AgI flares per pass) is virtually identical for the two treatment categories --- 4.9 flares per pass for the S cases and 5.2 flares per pass for the NS cases.

7.0 SUMMARY AND CONCLUSIONS

The Thai cold-cloud experiments have gone very well to date. The clouds are highly suitable microphysically for glaciogenic seeding intervention and they appear to be responsive to seeding as is described in Part II. The experimental design has been implemented without problem. Its great similarity to that for the Texas experiments (Rosenfeld and Woodley, 1993) will make it possible to compare the results for both regions. This is illustrated in Part II. Such an interactive process should enhance the learning experience for the scientists involved in both projects.

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