Evidence for Changes in Microphysical Structure and Cloud Drafts Following AgI Seeding

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Abstract. A cloud physics aircraft was used in Texas during the period from 6 through 27 September 1998 to learn more about how silver iodide (AgI) seeding affects the microphysical structure and draft circulations within supercooled clouds. This was done in the context of the cold-cloud conceptual seeding model, which has been under development for many years. These investigations are part of a long-term master plan to provide a strong physical basis for glaciogenic seeding as practiced now both experimentally and operationally in both Texas and Thailand. An historical overview of past studies of relevance and an examination of the conceptual model are presented prior to discussion of the new results.

Twenty-one cloud physics units (14 Seeded and 7 Non-Seeded) were obtained during the 1998 studies. Composites of supercooled cloud liquid water, 2D-C concentrations and cloud drafts were constructed for the seeded and non-seeded cases relative to the center of the initial cloud pass for each case. Composite differences were then obtained as a function of the treatment decision. The composite differences at the time of the treatment pass just before release of the nucleant were small except for the region +5 to +10sec where the updraft for the S cases exceeded that of the NS cases. The S vs. NS differences were small in the period 60 to 180sec after the treatment pass within ± 10sec of the center of the pass composite. This suggests that the overall effect of the seeding was small within 3min of the initial seeding. By 181 to 420sec, however, the seeded clouds near the center of the composite had stronger updrafts with higher 2DC counts and less cloud water than the non-seeded clouds. These findings are in accordance with the conceptual model, which calls for invigorated updrafts during the transition from supercooled water to ice. This pattern persisted for the period 421 to 660sec and then decayed for passes > 660sec (11min) after the initial seeding. These results are supportive of the conceptual model that is guiding the Thai and Texas cold-cloud AgI experimentation, suggesting the main characteristic of seeded clouds is the existence and growth of ice particles in rising air that is being depleted of its cloud water by the growth of the ice.

1. INTRODUCTION

Over the past several years a partnership has developed between those in Texas who are conducting operational seeding for rain enhancement and those who are doing weather modification research in the state (Bomar et al., 1999). This continued in 1998 under the auspices of the Texas Natural Resource Conservation Commission (TNRCC) under the acronym TEXARC (Texas **Ex**periment in Augmenting **R**ainfall through **C**loud Seeding). The core effort in 1998 involved the use of a state-of-the-art cloud physics aircraft (a Piper Cheyenne turbo prop) in the period from 6 through 27 September 1998 to study the effects of seeding on Texas supercooled clouds. Weather Modification, Inc. in Fargo, North Dakota supplied the aircraft. Prior to its arrival in Texas it was being used in Mexico in a hygroscopic seeding experiment under the direction of the National Center for Atmospheric Research in Boulder, Colorado.

The initial motivation for the research was the testing of two silver iodide (AgI) flares that had been tested previously in the laboratory. The first flare was the TB1 formulation, which acts by contact nucleation and has been available to the weather modification community for many years. The second flare formulation was given the BF1 designation after its developer, Dr. William 'Bill' Finnegan, who is assisting Texas with its flare development on a pro bono basis. The BF1 flare acts by condensation freezing. These tests were part of a program to develop a seeding flare for Texas. The BF1 flare was found to outperform the TB1 flare in terms of the rapidity of induced glaciation and the total number of generated ice particles, although the measured differences in the clouds were small. This is consistent with the results of laboratory testing. Both flares produced similar changes in the clouds relative to those receiving no treatment. Woodley and Rosenfeld (1999) provide additional details about the flare tests. These are not the subject of this paper.

The second motivation for the tests was to learn more about how seeding affects the draft and microphysical structure of the clouds. This was done in the context of the cold-cloud conceptual seeding model, which has been under development for many years (Rosenfeld and Woodley, 1993). This is the focus of this paper.

2. CONTEXT OF THE TEXARC 1998 INVESTIGATIONS

2.1 Results of Experimentation

The TEXARC 1998 investigations were part of a program to provide a strong physical basis for glaciogenic seeding as practiced now both experimentally and operationally in Texas and Thailand. By providing the complete historical context for this research, the TEXARC 1998 studies can be better appreciated.

The randomized cold-cloud seeding experiments, which began over the Caribbean Sea (Simpson et al., 1967) and moved to Florida (Simpson and Woodley, 1971) and then to Texas (Rosenfeld and Woodley, 1993), continued in Thailand until scheduled program termination at the end of the 1998 season. The early experiments focused on the response of vigorous, individual, supercooled clouds to on-top seeding with silver iodide (AgI) free-fall rockets and flares. On average the seeded clouds grew 20% to 21% taller (Simpson et al., 1967; Simpson and Woodley, 1971) and produced > 100% more radar-estimated rainfall than comparable non-seeded clouds (Simpson and Woodley, 1971). All results are significant at better than the 5% level.

The next step involved area-wide experimentation, beginning in Florida over an area covering 1.3 x 10^4 km^2. The initial experiments were highly positive with indicated seeding-induced increases in rainfall of 49% and 23% for the "floating" and fixed target with statistical one-tailed P-values of 1% and 8%, respectively (Woodley et al., 1982). The results for the second phase of the area experimentation, while weakly positive, did not confirm the results of the initial exploratory area experiment (Woodley, et al., 1983).

By the late 1980's the randomized area experimentation had been moved to Texas where experiments over a floating experimental unit covering 1,963 km^2 were conducted on an intermittent basis through 1994. The experiments were terminated after the 1994 season due to a lack of funds. At program termination 38 randomized cases had been obtained. The average radar-estimated seed rainfall exceeded the average radar-estimated non-seed rainfall by 45% by 2.5 hrs after unit qualification. This result is not statistically significant (Woodley and Rosenfeld, 1996).

Analyses of the effect of seeding on the treated convective cells were conducted within the context of both the Florida and Texas area experiments. All treated convective cells within a particular experimental unit had the same treatment decision, because the randomization was done on a unit basis. Because of this lack of independence, the cells in a particular unit had to be viewed as a single data point, obtained by averaging the cell properties, for the purposes of statistical testing. Each data point was weighted according to the number of cells contributing to its average in relation to the overall cell sample. Further, the cells in a particular unit were not independent physically of one another. Thus, a cell seeded an hour after seeding commenced in the unit probably was affected in some way by the earlier treated cells.

The initial impetus for these cell analyses was the second Florida Area Cumulus Experiment (FACE-2), which failed to confirm the results of the first experiment (Woodley et al., 1983). The obvious question was whether any effect of treatment was evident in the cells, which received the actual AgI treatments. Gagin et al., (1986) did this analysis, finding seeded height and rainfall increases of 22% and 160%, respectively, for cells treated early in their lifetimes with $\geq$ 9 50-gm AgI flares with exploratory, one-tailed P-values of 2% and < 1%, respectively. There was no evidence of effects for the overall cell sample, suggesting the overall seeding effect was indeed weaker in the FACE-2 experiment.

Comparable cell analyses were completed in the context of the Texas area experiments with the finding for the overall sample that the seeded cells were 10% taller and produced 163% (i.e., SR = S/NS = 2.63) more rainfall than the non-seeded cells at P-values of 21% and 1%, respectively. The apparent seeding effects are larger for clouds having base temperatures $\geq$ 15°C, suggesting clouds with coalescence are more responsive than the overall sample.

These results from Woodley and Rosenfeld (1996) satisfied the requirement, expressed for all experiments in the series, that seeding effects must be evident first on the cell scale before one can hope to see seeding effects on an area basis. Considering it is the cells, which receive the treatment, this has seemed a reasonable requirement. How treated cells might communicate any effects to groups of cells and to the unit overall is addressed in the conceptual model.

The Thai randomized cold-cloud rain enhancement experiments were carried out during August 1991 and during portions of

April, May and June in 1993-1998 in the Bhumipol catchment area in northwestern Thailand. The experiments were conducted by the Bureau of Royal Rainmaking and Agricultural Aviation (BRRAA) of the Ministry of Agriculture and Cooperatives (MOAC) as part of its Applied Atmospheric Resources Research Program (AARRP).

The physical-statistical design of the Thai convective cloud-seeding area experiment was very similar to that employed in Texas. It was aimed at determining whether seeding with ejectable, free-fall, silver iodide flares near the tops (temperatures –6°C to –10°C) of vigorous supercooled convective clouds growing within a floating-target area would enhance the rainfall over that area (Silverman, et al., 1994).

Since cold-cloud seeding began in Thailand, 85 units (43 S and 42 NS) have been obtained. This includes 62 units for the *a priori* "demonstration" project and additional 23 units obtained during exploratory experimentation. During the course of the experimentation 1 to 10 20-gm flares normally were ejected on each pass of the seeder aircraft into or over the tops of suitable cloud towers when the decision was "Seed". When the treatment decision was "No Seed" the procedures remained the same and the flare ejections were simulated. The seeding duration averaged two hours and rain usually persisted in the unit for several hours after unit qualification. A full discussion of the design of the Thai cold-cloud experiment and its implementation is provided by Woodley et al. (1999a).

The Thai area seeding results are also positive (Woodley et al., 1999b). The *a priori* results show S/NS for the unit rain volumes of 1.48 at 300 min (5 hours) after qualification at a rerandomization P-value of 11%. Further, the exploratory analyses, making use of the entire sample, have S/NS single ratios of 1.56 and 1.90 at 300 and 600 min following unit qualification at one-tailed rerandomizaton P-values of 5% and 3%, respectively. One must hasten to add, however, that P-values for exploratory analyses do not carry nearly the weight of comparable P-values for the *a priori* analyses. Thus, the Thai cold-cloud area experiment is on the right track but it has not achieved statistical significance (Woodley et al., 1999b) for the *a priori* experiment.

As with the Florida and Texas experiments, cell analyses were done in the context of the Thai area experiments. The analysis of all treated Thai cells gave a ratio of S to NS rain volumes of 1.37 at a P-value of 7%. This apparent seeding effect on the total rain volumes is small relative to Texas where the comparable single ratio (SR) is 2.63 at a P-value of 1% (Woodley and Rosenfeld, 1996). This large disparity in apparent seeding effect between the two regions made no sense for a time, since the first author was of the view in real time that the apparent seeding responses were comparable in Texas and Thailand. Only after partitioning the Thailand data by a coalescence (SSI) index did the pieces of the puzzle seem to fall into place.

Upon looking at the single ratios (SR's) for the cell rain volumes in three SSI categories (Category 1 = little if any in-cloud coalescence, Category 2 = light to moderate in-cloud coalescence and Category 3 = heavy in-cloud coalescence), it became apparent that the effect of seeding on Thai convective cells was confined to categories 1 and 2 and averaged +73% (Woodley et al., 1999c) at P values of 11% and 4%, respectively. The rain increment for Category 3 clouds averaged –34% for rain volumes. Although this suggests a negative effect of seeding, the result is not statistically significant.

Thus the apparent effect of seeding on convective cells in Thailand exists only for Category 1 and 2 clouds, which conform best to the conceptual model. Category 3 clouds, which are unsuitable for seeding from the perspective of the conceptual model because of their heavy loads of raindrops and early natural glaciation (Rosenfeld et al., 1999a,b), may have been affected negatively by seeding. It is obvious, therefore, the overall positive seeding effect in Thailand is diminished by including clouds with vigorous coalescence activity. Such clouds do not exist normally in West Texas.

2.2 The Conceptual Model

The conceptual model guiding this series of experiments has evolved with time as new observations and new insights have become available. The initial conceptual model of the late 1960's and 1970's focused primarily on the hypothesized dynamic invigoration of the cloud as a consequence of the released latent heats during seeding-induced glaciation. It was argued that as a consequence of this invigoration, the cloud would grow taller and broader, last longer and produce more rainfall. The details of the microphysical processes were not addressed other than to require that the seeding produce more ice, as verified by Sax et al. (1979). It was even conceded that the seeding might render the seeded clouds less precipitation efficient than unseeded clouds but that the great increase in cloud size and duration would more than compensate for the momentary microphysical inefficiencies. This conceptual model became known as the dynamic seeding conceptual model (Simpson and Woodley, 1971). During this evolutionary process, Simpson (1980) argued persuasively for downdrafts as the mechanism whereby a seeded cell might communicate to the larger scales by generating new clouds in the convergent regions between storm outflows and the ambient flow.

Early in the Texas experimentation the second author argued that the seeding-induced increases in precipitation from cells were larger than could be explained simply by the increase in cell height, as estimated from echo height vs. rain volume relationships. He argued that the seeded clouds must actually be more precipitation-efficient, if the rainfall results were to be explained. The finding that seeded clouds of a given echo height produce more rainfall than non-seeded clouds of the same echo height (Rosenfeld and Woodley, 1993) supported his argument. Further, the argument for more microphysically efficient seeded clouds dovetailed nicely with Simpson's arguments regarding downdrafts, because more efficient clouds would produce more rainfall and stronger downdrafts. These interactions culminated in the revised cold-cloud seeding conceptual model, which places more emphasis on the interactions between cloud dynamics and microphysics (Rosenfeld and Woodley, 1993).

Thus, the Texas and Thai experiments were conducted in the context of a conceptual model, which involves a hypothesized series of events beginning initially on the scale of individual treated clouds or cells and cascading ultimately to the scale of the experimental unit, covering 1964 km^2, in which these cells reside. This seeding is hypothesized to produce rapid glaciation of the supercooled cloud liquid water content (SLWC) in the updraft by freezing preferentially the largest drops so they can rime the rest of the cloud water into graupel. This seeding-induced graupel is postulated to grow much faster than raindrops of the same mass so that a larger fraction of the cloud water is converted into precipitation before being lost to other processes. Ice multiplication is not viewed as a significant factor until most of the cloud water has been converted into precipitation. This faster conversion of cloud water into ice precipitation enhances the release of latent heat, increases cloud buoyancy, invigorates the updraft, and acts to spur additional cloud growth and/or support the growing ice hydrometeors produced by the seeding (Rosenfeld and Woodley, 1993). These processes result in increased precipitation and stronger downdrafts from the seeded cloud and increased rainfall through downdraft interactions from groups of seeded and non-seeded clouds. "Secondary seeding," whereby non-seeded clouds ingest ice crystals produced by earlier seedings, is thought also to play a major role in the precipitation enhancements (see Woodley and Rosenfeld, 2000). The net effect is increased rainfall over the floating target area (Rosenfeld and Woodley, 1993).

2.3 Evidence Supporting the Conceptual Model

Beginning with the first steps of the conceptual model, vigorous supercooled clouds rich in cloud water are required for glaciogenic seeding to work. Cloud water provides the fuel for the growing graupel particles and it provides a major energy source for the cloud when it is accreted and frozen onto the graupel particles.

Thai clouds contain copious amounts of cloud water, which is persistent in the absence of seeding. Sukarnjanaset et al. (1998) documented 294 aircraft passes into Thai clouds and found high cloud water contents, some with up to 3 gm/m^3 at temperatures of –30°C. This is true in vigorous clouds without much coalescence (Category 1) and to a slightly lesser extent in clouds with some coalescence and raindrops (Category 2). In clouds with heavy coalescence (Category 3), however, the cloud water contents are much lower because of their early natural production of graupel particles at warm temperatures, which consume the cloud water (Rosenfeld et al., 1999b). This likely explains the lack of seeding effect on the cell scale in Category 3 clouds. Otherwise, the seeding window of opportunity is wide open in Thai clouds, thus satisfying the requirements of the conceptual model. The seeding window is also wide open in Texas where the two authors recently measured large quantities (> 1.5 gm/m^3) of SLWC to nearly –38°C (Rosenfeld and Woodley, 2000).

Sudhikoses et al. (1998) documented the rate of decay of the cloud water in the temperature range –8°C to –12°C and found that it takes 10 to 12 minutes for the maximum cloud water in unseeded continental clouds to decrease to 50% of their initial maximum values. In clouds with coalescence and raindrops it takes about 5 to 6 minutes for their cloud water to drop to 50% of their initial maximum values. Of most importance, these decay times are cut in half in seeded clouds. This agrees with the conceptual model, although it can not be proved in the conventional (statistical) sense that the more rapid decay of the cloud water is due to its accretion by the growing graupel particles, which originated as drops, frozen preferentially by the seeding. The few cases analyzed to date suggest this is what is happening in seeded clouds but it can not be proven that this is true generally.

Every case study obtained to date, regardless of whether it was obtained in Thailand or Texas, shows that AgI seeding increases the ice content of the cloud relative to comparable non-seeded clouds. If the cloud has no coalescence and is short-lived, the ice takes the form of numerous small graupel particles, which do not grow much, before the cloud dissipates. If the cloud has coalescence and raindrops, the seeding results in the rapid freezing of the raindrops and their growth as larger graupel.

The relationship between seeding-induced microphysical changes and the cloud drafts are an important component of the seeding conceptual model. These had not been addressed in a systematic way prior to the TEXARC 1998 investigations. The new results, provided in Section 3.0, are the focus of this paper.

The vertical growth of the top heights of the seeded clouds relative to the non-seeded clouds is a puzzle. Clouds seeded in Texas and Thailand apparently show about 50% less vertical growth (< 10% overall) than the growth documented for clouds over the Caribbean and Florida (about 20%). Only in Category 2 Thai clouds, which are most suitable from the perspective of the conceptual model, is the vertical growth appreciable (11%). Also, in Texas clouds having base temperatures ≥ 15°C the growth following seeding is 29% greater than the non-seeded clouds. Such clouds are also more suitable from the perspective of the conceptual model.

The lack of cloud growth in the overall Thai and Texas sample relative to the Caribbean and Florida samples, despite comparability in rainfall results, has several possible explanations. During the Caribbean and Florida single cloud experimentation the cloud tops were measured by flying a B-57 jet aircraft just above the cloud top, even if the cloud was a tall cumulonimbus. In the Texas and Thai experimentation the estimates of cloud top have been made using 5-cm and 10-cm radar, respectively, at a reflectivity threshold of 12 dBZ. Thus, the frame of reference for estimating the growth of the cloud following seeding was the visual physical cloud top in the Caribbean and Florida single cloud experiments whereas it was echo top at 12 dBZ in Texas and Thailand. During their years of field experience, the authors have noted that echo tops are always ≤ the actual cloud in the absence of radar sidelobe errors. Thus, the physical cloud tops in Texas and Thailand have been underestimated relative to the Caribbean and Florida clouds.

This is not a problem for the estimate of the effect of seeding on cloud growth, however, as long as the radar "sees" seeded and non-seeded clouds the same way. This is not likely the case. As shown by Woodley and Rosenfeld (1999c), seeding apparently makes Category 1 and 2 clouds more like Category 3 clouds, which are characterized by early glaciation and fallout of precipitation-sized particles. It is known experientially that radar underestimates the echo tops of clouds with heavy coalescence relative to more continental clouds, which have a different microphysical structure. Thus, if seeded clouds are more like Category 3 clouds than the non-seeded clouds, it follows the radar is going to underestimate their tops at 12 dBZ more than non-seeded clouds. The seeded clouds may actually be physically taller than the non-seeded clouds but that cannot be known through the radar measurements. The measurement of cloud tops using aircraft and/or infrared satellite imagery is necessary to resolve this uncertainty. Plans are being made to make these measurements.

This is not a trivial matter. Until it is resolved, one might conclude that something fundamentally changed when the cold-cloud experiments were moved out of Florida and that, based on current measurements, the link in the conceptual model calling for increased growth of the clouds following seeding should be removed. Even with this matter currently unresolved, it should be noted that the seeding effect on echo height averages +11% for Category 2 Thai clouds and +29% for warm-based Texas clouds, which are most suitable for glaciogenic seeding intervention according to the conceptual model. Thus, the results for a large subset of the current data in Texas and Thailand call for retention of this link in the conceptual chain.

From the authors' perspective, the key element here is not so much the physical growth of the cloud but the invigoration of the in-cloud circulations. This is paramount for rainfall enhancement because it is in the updraft regions that the particles are grown to precipitation size. It is questionable whether the upper portions of large clouds play a major role in the generation and augmentation of the rainfall. It may be that the growth of cloud top is merely a manifestation of the invigoration of the updraft. This important link in the conceptual chain is addressed in Section 3.0.

The evidence for the most suitable Category 2 clouds indicates that seeding increases rainfall from clouds by increasing their size (top height and area), volumetric rain rate, and duration. In addition, the echo clusters containing the seeded cells have twice as many cells as the echo clusters containing the non-seeded cells (Woodley et al., 1999c). All of this is in good agreement with the conceptual model.

Anyone who has studied convective clouds is aware of the role of downdrafts in generating new clouds in the convergent regions between the out-flowing downdraft air and the ambient flow. Simpson (1980) emphasized its importance for the cold-cloud seeding experiments. It has been found that the seeded cells are more clustered with other cells than the non-seeded cells, especially for the tallest clouds. This is either a natural bias favoring the seeded cells or it is an effect of seeding. If the downdrafts were enhanced following seeding, as required by the conceptual model, it would result in the generation of more cells. Thus, cells seeded later in the unit history would themselves be associated with more cells because of the seeding that preceded them. One might argue, therefore, the increased clustering of the seeded cells is an indirect manifestation of the role downdrafts play in communicating effects of seeding on the cell scale to the unit area. Such communication is pivotal to the conceptual model.

Secondary effects of seeding cover a range of potential effects. In the context of the Thai cold-cloud experiment, it includes the propagation of downdrafts through the unit with time, beginning with downdrafts from the directly treated cells. Secondary effects of seeding also might include the ingestion of ice crystals produced by earlier seedings ("secondary seeding"). This is addressed in the companion to this paper (Woodley and Rosenfeld, 2000).

In view of our burgeoning knowledge of the physical processes operative in seeded clouds to enhance precipitation, the old argument whether a particular conceptual model is "static" or "dynamic" is outdated. With regard to the Thai and Texas cold-cloud experiments, it appears that the effects of seeding begin with alteration of the cloud microphysical processes (i.e., preferential freezing of the raindrops and their growth as large graupel, the proliferation of graupel generally, the consumption of the cloud water, etc.) and these alterations cause changes in the cloud dynamics (increased buoyancy and invigoration of the updraft, increased cloud growth, increased cloud duration, increased precipitation loading of the updraft, enhanced downdrafts, increased convergence on the periphery of the seeded cells, more clustering of the cells, etc.). Without the microphysical changes the cloud dynamics would not be affected. Without the dynamical changes, the rain enhancements would be small to non-existent.

Even the processes operative to communicate the effect of seeding on the cell scale to the overall unit are both microphysical and dynamic. Downdrafts appear to play a major role in this communication. Downdrafts are dynamic processes, but they had their origin through alteration of cloud microphysics. Secondary seeding, which has not had much emphasis to date, is another way the effect of seeding on the cell scale may be communicated to the unit area. It begins microphysically but then must feed into the cloud dynamics in much the same way direct seeding does (see Woodley and Rosenfeld, 2000).

Thus, the argument "static" or "dynamic" should be retired from serious discourse on the effects of cloud seeding. It is not an "either-or" proposition. Both static (microphysical) and dynamic processes are integral parts of the conceptual model guiding the Thai and Texas experimentation and to the reality of rain enhancement.

3. THE TEXARC 1998 FINDINGS

The relationships between seeding-induced microphysical changes and the cloud drafts are at the core of the seeding conceptual model. It is important to know whether the seeding- induced glaciation acts to invigorate the in-cloud circulations through the release of latent heat, thereby providing an environment in which the ice particles can grow to precipitation size. This had not been addressed in a systematic way prior to the TEXARC 1998 investigations. The design and results of these studies and their implications are addressed in the sections that follow.

3.1 Design

The cloud physics aircraft was equipped with reverse-flow temperature and dew point probes to make atmospheric soundings close in time and space to the intended cloud studies. It had a Ball variometer for the inference of cloud drafts. The variometer does not, however, give an absolute measure of in-cloud vertical motions and is strongly influenced by the actions of the pilot. Care must be taken to maintain constant attitude during cloud penetration. This allows relative comparisons among the clouds. The PMS probes on the Texas cloud physics aircraft were used to measure droplet and particle sizes in the range from 3 to 800 microns. The FSSP probe was used to document the development of the cloud droplet spectrum with height, beginning at and about 100 m above cloud base. The 2D-C probe was used to document the habit, concentrations and sizes of the cloud hydrometeors before and after cloud treatment as the aircraft flew perpendicular to the seeding curtain. The aircraft was equipped also to measure total aerosols and CCN using PCASP and CCN instrumentation, respectively.

The aircraft seeding system, consisting of a flare rack and ejectable AgI flares, was used for the seeding component of the investigations. The forward-looking video camera was used for the documentation of each mission immediately after each flight and for subsequent analyses. The GPS navigation system was crucial to specifying where the seeding took place. Finally, a functional aircraft data system that allowed for the recording of the measured parameters and for the transfer of the data to an Exabyte tape for subsequent copying and use was essential to a successful mission.

On each day of flight for the cold-cloud investigations the cloud physics aircraft was loaded with two types of flares (TB-1 and BF-1). The flight crew was supplied with the lettered treatment decisions corresponding to TB-1, or BF-1 or No Seeding and told where flares corresponding to the lettered decisions could be found. It was critical to complete this randomized 3-way sequence at least once on all days. Whenever a No Seed decision was drawn seeding was simulated from a position in one of the racks without flares.

When a cloud physics unit was selected, the rack position corresponding to the randomized treatment decision was selected. The initial cloud penetration was the treatment pass. The "pointer" system was activated to mark the position of the first flare ejection or simulated flare ejection. Subsequent passes at the same altitude as the treatment pass were to be made in three minutes or less. Passes for a specific cloud were terminated when the cloud had dissipated as evidenced by its collapse below the aircraft and/or its visual appearance and/or the lack of cloud water and updraft on the previous pass. For all passes the aircraft was navigated back to the position of initial treatment using the "pointer" system on the aircraft.

In cases when the treated cloud dropped below the flight level of the cloud physics aircraft within 5 minutes of the initial pass, a second cloud was selected and treated in the same way as its immediate predecessor. This was done to ensure a good sample size for each treatment on a given day.

3.2 Results

During TEXARC 1998 there were 15 flights on 13 days with the expenditure of 33.87 flight hours by the Cheyenne cloud physics aircraft. There were 5 flights on 5 days with the qualification of 21 cloud physics units (7 TB1, 7 BF1 and 7 NS). On three occasions a cloud died immediately after its selection, requiring in each instance another cloud be selected to replace it. A synopsis of each flight day for the qualification of cloud physics units is provided by Woodley and Rosenfeld (1999).

Composites of the key microphysical parameters as a function of time relative to the center of the pass were derived for the S (two treatments) and NS clouds. Differences between the average properties were calculated. The interest here is on (TB1+BF1) – NS. The comparisons among flare types are addressed by Woodley and Rosenfeld (1999). As stated earlier, the AgI flares were observed to produce comparable effects in the clouds.

The derivation of the composite plots involved several steps. First, a pass template was constructed using the center point and the entry and exit points for the first pass of each randomized case. Second, 10sec were added to the template both before entry and after exit of the aircraft from the cloud. Third, this pass template was used to identify the treated region on all subsequent passes for the case. This was done by centering the template on subsequent passes at the point closest to the navigation point set initially for the case. If the closest approach was > 2 km from the original point, the pass was not used. Fourth, the passes for a particular case were composited in several time intervals.

The composites in intervals 0 to 59sec, 60 to 180sec, 181 to 420sec, 421 to 660sec and > 660sec for (TB1+BF1) – NS are given in Figures 1 to 5. The measurements on the first pass are unaffected by the treatment since the observations were made forward of the racks from which the flares were ejected. With the aircraft flying at about 100 m/sec a distance of about 2km is represented in the plots. This is the region where most of the AgI (TB1 + BF1) and simulated AgI seeding was concentrated. Fourteen S cases and 7 NS cases make up the composites. Within each panel are composite difference plots ± 10sec from the center point of the pass of the supercooled cloud liquid water content, the 2DC counts and the cloud drafts.

The initial differences are small except for the region +5 to +10sec where the updraft for the S cases exceeds that of the NS cases. This pattern had not changed much for the period 60 to 180 sec, although the draft differences were smaller than for the first pass. This suggests that any effect of the seeding was small within 3min of the initial seeding. By 181 to 420sec, however, stronger LWC, 2DC and draft differences had emerged within ± 5sec of the pass center. The LWC for the S cases was less and the 2DC counts and updrafts were greater than the NS cases. It can be seen, therefore, that seeded clouds had stronger updrafts with higher 2D-C shadow/or counts and less cloud water than the non-seeded clouds. This pattern persisted for the period 421 to 660sec and then decayed for passes > 660sec (11min) after the initial seeding. Despite the small sample and enormous cloud-to-cloud variability, these results are strongly supportive of the conceptual model that is guiding the Thai and Texas cold-cloud AgI experimentation, suggesting the main characteristic of seeded clouds is the existence of ice particles in rising air.

Although SSI measurements were not made in these Texas clouds, the 2D-C and video data suggest they were Category 1 and possibly Category 2 type clouds having some coalescence. The first author was flight director on these flights and noted in his scientific log that none of the clouds studied were Category 3 type clouds.

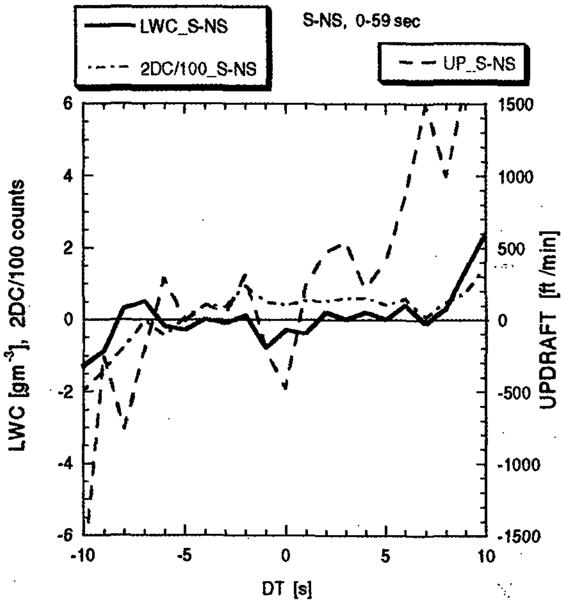

Figure 1. Plots of (TB1 + BF1) – NS for SLWC, 2D-C counts and cloud drafts in seconds relative to the center of the pass where AgI or simulated AgI flares were ejected on the first cloud pass. The time period is 0 to 59 sec.

In both Texas and Thailand the existence of high concentrations of ice particles in rising air is not typical for unseeded Category 1 and Category 2 clouds. Ice usually forms after the updraft has decayed.

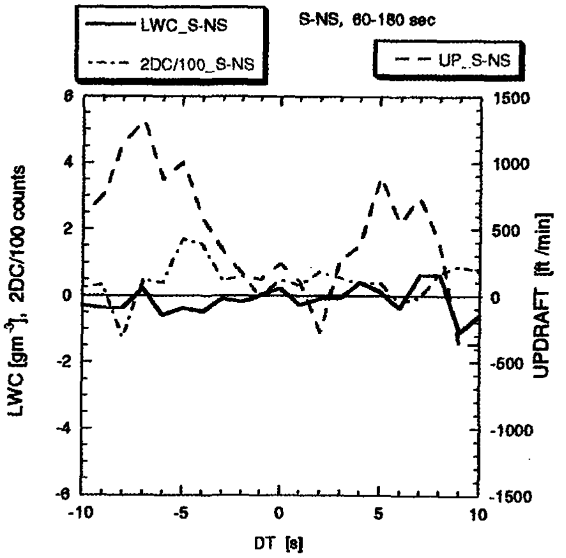

Figure 2. Same as Figure 1, but for time period of 60 to 180 sec.

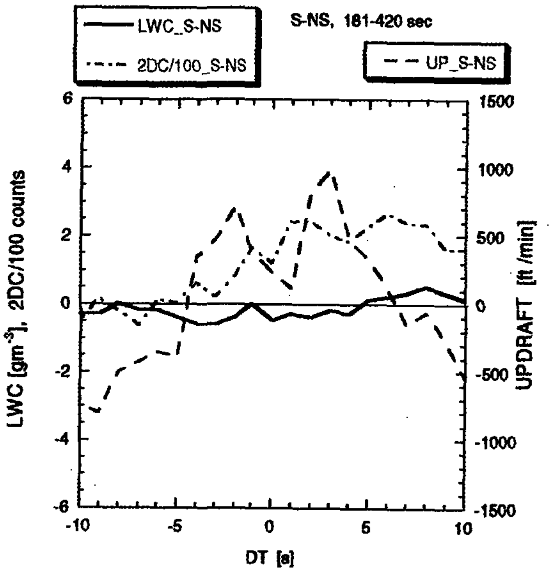

Figure 3. Same as Figure 1, but for time period of 181 to 420 sec.

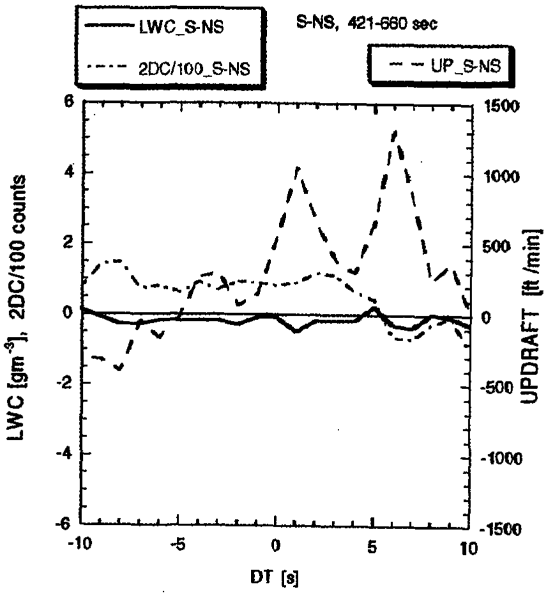

Figure 4. Same as Figure 1, but for time period of 421 to 660 sec.

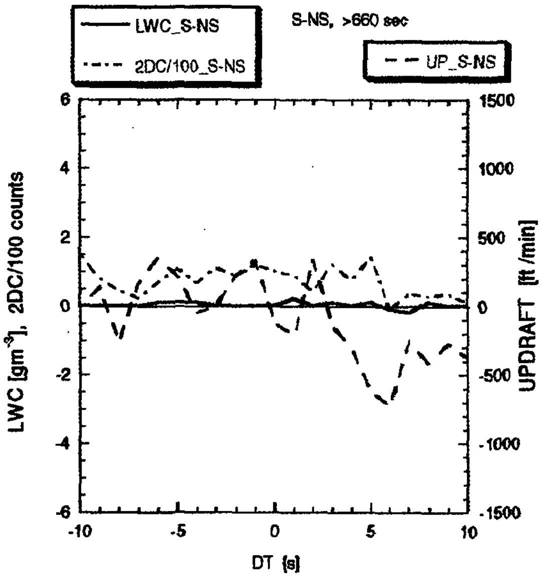

Figure 5. Same as Figure 1, but for time period > 660 sec.

In unseeded Category 3 clouds, however, large graupel concentrations in updraft regions are typical. It appears that seeding makes Category 1 and Category 2 clouds more microphysically like Category 3 clouds. This is the conclusion reached earlier by Woodley et al. (1999c).

These analyses strengthen the physical basis for both the Texas and Thai experiments. Seeding appears to result in the production of graupel ice in invigorated updraft regions with a concomitant decrease in the cloud water as required by the conceptual model. This is consistent with the model simulations of Orville and Chen (1982), which show an increase in vertical velocity, increases in snow and hail mixing ratios and decreases in cloud water in the seeded cloud compared to the unseeded cloud 8 minutes after seeding. This consistency gives greater impetus for the use of AgI seeding for rain enhancement.

4.0 CONCLUSIONS

Seeding appears to result in the production of graupel ice in invigorated updraft regions with a concomitant decrease in the cloud water as required by the conceptual model. This gives greater impetus for the use of AgI seeding for rain enhancement. Although these results are encouraging, the sample of cloud physics cases is still too small to justify a claim that the effect of AgI seeding on in-cloud structure and circulations has been demonstrated. Additional cases should be qualified and analyzed to strengthen further the physical basis for the cloud seeding experiments. Overall, however, an encouraging and physically consistent picture is emerging in the documentation of the effects of seeding on Texas and Thai clouds.

5.0 ACKNOWLEDGEMENTS

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Current Status and Future Direction of the Oklahoma Weather Modification Program

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Abstract. The primary focus of the Oklahoma Weather Modification Program is to suppress hail and augment rainfall. Initiated in the fall of 1996, the demonstration program is patterned after similar successful efforts underway in Kansas, North Dakota, Texas and Alberta, Canada. In 1997 and 1998, the statewide program incorporated an independent evaluation to measure results, although no randomized cloud seeding operations were conducted. Results of the evaluation are promising. Prompted, in part, by the need for additional resources to implement the program at the desired capacity, the State Legislature passed legislation in 1999 to create a cooperative, long-term funding mechanism between the state and Oklahoma's insurance industry. Potential interstate cooperation with weather modification efforts in Texas and Kansas bode well for the continuation and future growth of the program.

1. INTRODUCTION

Passage of Senate Bill No. 101 (Oklahoma Weather Modification Act, Section 1801.2 of Title 82) by the Oklahoma State Legislature in May 1999, may be interpreted as the turning point of the Oklahoma Weather Modification Program (OWMP). Initiated on August 20, 1996 and administered by the Oklahoma Water Resources Board (OWRB), the program has evolved into an operational effort fueled by a cooperative state/private insurance funding mechanism. Since inception, the program has utilized two C-band (5 cm wavelength) project radars strategically placed at municipal airports in Oklahoma City and Woodward with three Cessna 340 project aircraft (Vance and Mathis, 1997). In addition, the recent employment of the Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) software package allows more accurate examination for hail suppression efforts. The contractor dispenses the seeding agent, Silver-iodide (AgI), by three sources: droppable flares, end-burning flares, or wing mounted AgI acetone generators (burners).

Weather Modification, Inc. (WMI), of Fargo, North Dakota, has been contracted to conduct both hail suppression and rainfall augmentation operations during four separate periods of operation, generally conducted from March through October each year with a winter recess period. The continued partnership with a single contractor facilitates continuity from one operational period to the next. In addition, an independent evaluation of the OWMP has been performed by the Environmental Verification and Analysis Center (EVAC) of the Oklahoma Climatological Survey (OCS) on the effectiveness of seeding operations (Greene, *et al.*, 1997, 1998).

Several periods of mild to severe drought in Oklahoma, which have prevailed throughout much of the 1990s, have renewed interest in weather modification, primarily due to the enormous financial impacts that drought typically inflicts on the Oklahoma economy (Vance and Mathis, 1997). During the past year, however, there has been growing interest in the prospects of hail suppression and related potential savings to the state's crops and property. Oklahoma crop losses due to hail average approximately $2.5 million per year in loss claims alone -- not including property/casualty claims (Fisher, pers. comm.) In Alberta, Canada, where hail suppression operations have been conducted for several years and funded through the province's insurance industry, annual hail damages range from $16 to $340 million.

To direct the current activities of the OWMP, SB 101 created the Oklahoma Weather Modification Advisory Board (OWMAB). The OWMAB consists of (or the designees of) the Executive Director of the Oklahoma Water Resources Board, the Commissioner of Agriculture, the Executive Director of the Oklahoma Department of Tourism and Recreation, the Insurance Commissioner, one member familiar with the insurance industry appointed by the Governor, two members appointed by the President Pro Tempore of the