CLOUD MICROPOHYSICAL OBSERVATIONS OF RELEVANCE TO THE TEXAS COLD-CLOUD CONCEPTUAL SEEDING MODEL

Daniel Rosenfeld
Hebrew University of Jerusalem
Jerusalem, Israel

and

William L. Woodley
Woodley Weather Consultants
Littleton, Colorado 80127

Abstract. Three pairs of seeded and non-seeded supercooled convective clouds, obtained in west Texas during August 1995, are studied because of their relevance to the cold-cloud conceptual seeding model that is guiding randomized seeding experimentation in this region. In comparing seeded and non-seeded clouds without supercooled rain drops on the initial pass, seeding appeared to result in: 1) graupel growth that was too slow to convert cloud water into precipitable size particles during the lifetime of the updraft, except for the most vigorous and vertically developed clouds, 2) a glaciation rate that was too slow for enhancement of the updraft and 3) glaciation during the collapse of the cloud, which accelerated its dissipation, leaving holes in the cloud field. In contrast, in clouds with supercooled rain drops on the initial pass, seeding appeared to result in: 1) fast freezing of the supercooled rain drops and their continued growth as graupel, 2) enhanced growth of the graupel as compared to supercooled rain drops in accordance with theoretical considerations and 3) rapid glaciation within the updraft, which increased cloud buoyancy and invigorated the updraft, providing a mechanism for the support of the growing graupel particles. Considering the small sample, these results are tentative. This research effort is continuing.

1. INTRODUCTION

The testing of cold-cloud seeding concepts for the enhancement of rainfall has been conducted in west Texas on an intermittent, as-funds-permitted basis since the summer of 1986. Attention was focused initially on evidence for seeding effects on convective cells, which are the treatment units for the experiments. The results of this effort through 1990, indicating seeding-induced rainfall increases on the cell and experimental unit scale have been presented by Rosenfeld and Woodley (1993).

The Texas rainfall results have provided physical insights that are now manifest in the revised dynamic-seeding conceptual model that is guiding the Texas experimentation (Rosenfeld and Woodley, 1993). These results have helped identify the physical processes that are likely operative in west Texas clouds and they have underscored the importance of continuing this experimentation. The current effort has the acronym TEXARC (Texas Exercise in Augmenting Rainfall through Cloud-Seeding).

The focus of the TEXARC 1994 and 1995 research was on the first few steps in the revised dynamic seeding conceptual model that involve seeding-induced glaciation of clouds containing rain drops followed by the formation and growth of graupel particles that are sustained aloft by the invigorated seeded updraft. The conceptual model applies to the ideal situation when seeding is thought to induce the growth of large precipitating clouds that are not able to develop under the natural forcing. In the real world there may be a hierarchy of clouds on any given day, some that will respond to seeding and others that are able to grow to massive stature without seeding intervention. The complete conceptual model as put forth by Rosenfeld and Woodley (1993) is presented below:

A) NONSEEDED STAGES (When the clouds are not able to reach massive stature without seeding intervention.)

(i) Cumulus Growth Stage

The freezing of supercooled raindrops plays a major role in the revised dynamic seeding conceptual model. Therefore, a suitable cloud is one that has a warm base and a vigorous updraft that is strong enough to carry the raindrops that are formed in the updraft above the 0°C isotherm level. Such a cloud has a vast reservoir of latent heat that is available to be tapped by natural processes or by seeding.

(ii) Supercooled Rain Stage

At this stage a significant amount of supercooled cloud and rainwater exists between the 0°C and the -10°C levels, which is a potential energy source for future cloud growth.

A cloud with active warm rain processes but a weak updraft will lose most of the water from its upper regions in the form of rain before growing into the supercooled region. Therefore, only a small amount of water remains in the supercooled region for the conversion to ice. Such a cloud has limited seeding potential.

(iii) The Cloud-Top Rainout Stage

If the updraft is not strong enough to sustain the rain in the supercooled region until it freezes naturally; most of it will fall back toward the warmer parts of the cloud without freezing. The supercooled water that remains will ultimately glaciate. The falling rain will load the updraft and eventually suppress it, cutting off the supply of moisture and heat to the upper regions of the cloud, thus terminating its vertical growth. This is a common occurrence in warm rain showers from cumulus clouds.

(iv) The Downdraft Stage

At this stage, the rain and its associated downdraft reach the surface, resulting in a short-lived rain shower and gust front.

(v) The Dissipation Stage

The rain shower, downdraft, and convergence near the gust front weaken during this stage, lending no support for the continued growth of secondary clouds, which may have been triggered by the downdraft and gust front.

B) SEEDED STAGES

(i) Cumulus Growth and Supercooled Rain

These stages are the same for the seeded sequence as they are for natural processes.

(ii) The Glaciation Stage

The freezing of the supercooled rain and cloud water near the cloud top at this stage may occur either naturally or be induced artificially by glaciogenic seeding. This conceptual model is equally valid for both cases.

The required artificial glaciation is accomplished at this stage through intensive, on-top seeding of the updraft region of a vigorous supercooled cloud tower using a glaciogenic agent (e.g., AgI). The seeding rapidly converts most of the supercooled water to ice during the cloud's growth phase. The initial effect is the formation of numerous small ice crystals and frozen raindrops.

This rapid conversion of water to ice releases fusion heat — faster and greater for the freezing of raindrops -- which acts to increase tower buoyancy and updraft and, potentially, its top height. (The magnitude of the added buoyancy is modified by the depositional heating or cooling that may occur during the adjustment to ice saturation; see Orville and Hubbard, 1973.) Entrainment is likely enhanced in conjunction with the invigorated cloud circulation.

The frozen water drops continue to grow as graupel as they accrete any remaining supercooled liquid water in the seeded volume and/or when they fall into regions of high supercooled liquid water content. These graupel particles will grow faster and stay aloft longer because their growth rate per unit mass is larger and their terminal fall velocity is smaller than water drops of comparable mass (Pinsky et al., 1997). This will cause the tower to retain more precipitation mass in its upper portions. Some or all of the increased cloud buoyancy from seeding will be needed to overcome the increased precipitation load.

If the buoyancy cannot compensate for the increased loading, however, the cloud will be destroyed by the downdraft that contains the ice mass. The downdraft will be augmented further by cooling from the melting of the ice hydrometeors just below the freezing level.

The retention of the precipitation mass in the cloud's upper portions delays the formation of the precipitation-induced downdraft and the resultant disruption of the updraft circulation beneath the precipitation mass. This delay allows more time for the updraft to feed additional moisture into the growing cloud.

(iii) The Unloading Stage

The greater precipitation mass in the upper portion of the tower eventually moves downward along with the evaporatively cooled air that was entrained from the drier environment during the tower's growth phase. When the precipitation descends through the updraft, it suppresses it. If the invigorated pulse of convection has had increased residence time in regions of light to moderate wind shear, however, the precipitation-induced downdraft may develop adjacent to the updraft, forming an enhanced updraft-downdraft couplet. This unloading of the updraft may allow the cloud a second surge of growth to cumulonimbus stature.

When the ice mass reaches the melting level, some of the heat released in the updraft during the glaciation process is reclaimed as cooling in the downdraft. This downrush of precipitation and cooled air enhances the downdraft and the resulting outflow beneath the tower.

(iv) The Downdraft and Merger Stage

The precipitation beneath the cloud tower is enhanced when the increased water mass reaches the surface. In addition, the enhancement of the downdraft increases the convergence at its gust front.

(v) The Mature Cumulonimbus Stage

The enhanced convergence acts to stimulate more neighboring cloud growth, some of which will also produce precipitation, leading to an expansion of the cloud system and its conversion to a fully developed cumulonimbus system.

When this process is applied to one or more suitable towers residing within a convective cell as viewed by radar, greater cell area, duration, and rainfall are the result. Increased echo-top height is a likely but not a necessary outcome of the seeding, depending on how much of the seeding-induced buoyancy is needed to overcome the increased precipitation loading.

(vi) The Convective Complex Stage

When seeding is applied to towers within several neighboring cells, increased cell merging and growth will result, producing a small mesoscale convective system and greater overall rainfall.

- End of Conceptual Model -

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 must be emphasized 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 updrafts strong enough to carry the rain water 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 efficient 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/s). Assuming that the rate of ascent of cloud top is half the peak updraft velocity, a minimum of 5 m/s vertical growth rate is required for the cloud top, while growing through the 0°C to -10°C levels. This means that a suitable cloud must grow through the 1600-m vertical distance that normally exists between 0°C and -10°C levels in at most 5 min.

To be effective, several seeding flares should be ejected into the updraft region to ensure that the freezing of the supercooled rain drops and subsequent collection of the cloud water by rimming will be well advanced before the updraft weakens. Although one flare contains a sufficient number of ice nuclei to seed a typical updraft, there may not be enough time for this material to disperse within the updraft during the short time that the supercooled rainwater exists at the seeding level.

The consequence 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 regenerate a significant updraft, remains aloft while the frozen precipitation continues downward. When this frozen precipitation eventually melts, it cools the cloud and destroys the updraft and/or enhances the downdraft, killing the cloud.

Analysis and interpretation of TEXARC cloud microphysical data of relevance to the conceptual model are the focus of this paper. It is recognized at the outset that because of the small sample and the tremendous natural variability, one cannot be certain that the microphysical differences between seeded and non-seeded clouds are due to seeding.

2. INSTRUMENTATION

Aircraft and radar have been used in the physical studies of west Texas clouds. The cloud physics aircraft were the T-28 of the South Dakota School of Mines and Technology in 1994 and the Piper Cheyenne of Weather Modification, Inc. in 1995. Temperature (Reverse-Flow and/or Rosemount), dew point, cloud drafts, cloud water using either the Johnson-Williams hot wire (on the T-28) or the King hot wire (on the Cheyenne), GPS position, and particle sizes (PMS FSSP and 2D-C) were measured. Seeding was accomplished from a Cessna 340 in 1994 and from the Piper Cheyenne in 1995. The C-band Skywater radar system, which was situated 10 miles east-northeast of project headquarters, provided the radar observations for the effort.

The research plan was to document the physical processes in vigorous supercooled cloud towers before and after randomized treatment. In 1994, the T-28 cloud physics aircraft made a pass through the subject tower immediately prior to its treatment from the Cessna 340 and made repetitive passes through the tower afterwards. In 1995, the Cheyenne made measurements during the treatment run and thereafter.

The King cloud water instrument, which senses liquid drops up to 100 microns diameter, was used as the standard for the measurement of cloud water. This instrument was functional on most days in 1995, providing SLWC measurements for droplet sizes up to 100 microns diameter. The Johnson-Williams hot wire, which senses drops up to about 50 microns diameter, operated intermittently on the T-28 in 1994. Rather than "mix and match" data sets from the two years, we decided to focus exclusively on the TEXARC 1995 data for this study.

In 1995, the draft estimates were provided in 1-sec intervals by the Ball variometer instrument. This method provides a crude approximation of the draft speeds as long as the pilot flies the aircraft at a constant attitude.

Although the PMS 2D-C probe is designed to measure cloud particles up to 800 microns diameter, larger particles were detected and sized with this instrument by laboriously fitting circles of various diameters to the portions of the larger particles that appeared within the field of view of the 2D-C probe. When a fit was obtained, the drop or particle size was duly recorded and attention was focused on the next large particle.

3. EXPERIMENTAL PROCEDURES

During TEXARC 1995, flights of the Piper Cheyenne were conducted on all days on which suitable clouds were expected. Flight-level temperatures ranged typically between -6°C and -10°C. Once an initial suitable cloud was found, the treatment decision was determined just before cloud entry by the flip of a coin either at the radar site, if the cloud was within radio range of the radar, or aboard the aircraft. The treatment decision was carried out during the first pass, ejection or simulated ejection of 20-gm AgI flares at about 1 sec intervals while the aircraft was in updraft and high SLWC. In some instances a second treatment pass was made approximately orthogonal to the first pass. The treatment decision for the second suitable cloud of the day was the opposite of the first. Although this introduced the possibility of bias in cloud selection, this was done to ensure that at least one seeded and one non-seeded cloud would be obtained on each day. On a few days more than two clouds received treatment. The treatment decision of the first cloud of the next pair was determined randomly. Fifteen clouds received simulated treatment and 19 clouds received AgI treatment during TEXARC 1995.

In monitoring the clouds subsequent to treatment we attempted to return to the initial treatment positions using the aircraft pointer system to account for the drift of the cloud with time. Unfortunately the gyro input to the pointer was inoperable, making it unreliable. In most cases the return to the cloud was done visually, independent of the pointer system. Because of this ambiguity, the best relatively isolated clouds were selected for case study.

4. SELECTED CASE STUDIES

Three case studies are presented on three days. A cloud pair, one unseeded and the other seeded, makeup each case study. Each addresses a particular class of cloud conditions: moderately-vigorous cold-based clouds, vigorous cold-based clouds and warm-based clouds, where a cold-based cloud is defined as one have a cloud base temperature $\leq$ 15°C. Within each class, general impressions are presented first based on the entire sample of clouds for that class. This is followed by the specific cloud pair, which illustrates the points being made. The unseeded cloud conditions are presented first, followed by the presentation for the seeded cloud. All pass times, rounded to the nearest minute, are relative to the time of the initial pass through the cloud.

4.1 Moderate Cold-Based (i.e., CBT < 15°C) Clouds

General Impressions

Seeding cold-based clouds with little or no supercooled rain (i.e., < 500 microns diameter) appeared to cause very slow glaciation, which was manifested as many small equi-dimensional graupel that grew slowly without much of an impact on the cloud water within the first 5 minutes. The graupel diameters typically did not exceed 2 mm before the collapse of the cloud top. Most of the seeded clouds without supercooled rain that have been studied to date started to collapse before significant glaciation occurred. In many clouds glaciation progressed during their collapse, and was associated with accelerated dissipation, leaving holes in the cloud field. Even in the rare cases that the cloud did not collapse by 6 to 10 minutes no large graupel formed, probably due to the competition among hydrometeors or fallout from cloud top.

Example: Cloud Pair on August 22, 1995

Cloud-base temperatures were +12°C and cloud tops around -10°C on August 22, 1996. The clouds were moderately vigorous but of rather short duration.

The Unseeded Cloud

Although it had the strongest updraft of the day of about 15 m/sec and an initial King Supercooled Liquid Water Content (KSLWC) of 2.1 gm/m^3, the unseeded component of the cloud pair did not fare very well. It received 7 simulated flares on the first pass but collapsed quickly thereafter, descending below the seeding level by 6 minutes after the initial simulated seeding.

A summary of the cloud properties on these five passes is provided in Figure 1. The top panel gives the maximum updraft and downdraft on each pass and the bottom panel gives the maximum KSLWC (gm/m^3), the maximum 2D-C particle diameter (mm) and the maximum 2D-C shadow/or counts (#/L divided by 100).

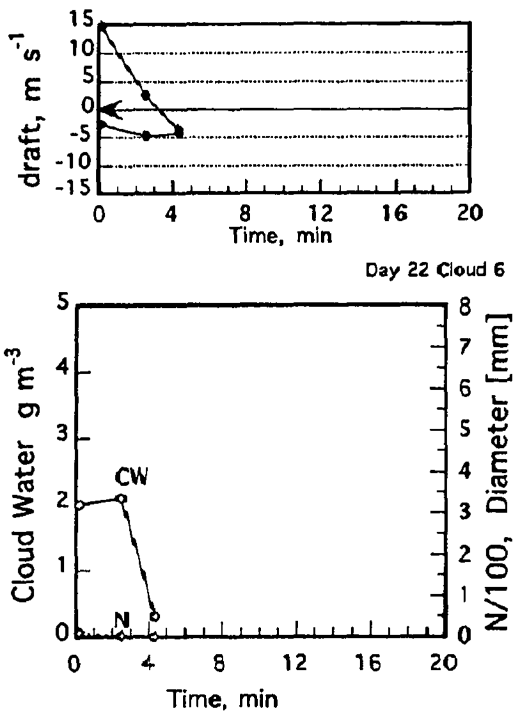

Figure 1. The evolution of cloud properties at the seeding level for the unseeded cloud on August 22, 1995. See text for details.

The Seeded Cloud

The seeded cloud of the pair was selected as a random cloud physics unit and the treatment decision (Seed) was determined by a flip of the coin at the radar site just before the aircraft entered the cloud. A total of 14 20-gm AgI flares were ejected into the cloud on three seeding passes at a temperature of about -7°C. Two additional monitoring passes followed.

The maximum cloud updraft was ≥ 5 m/sec through the first four passes encompassing about 8 minutes (Figure 2). Numerous small graupel particles developed slowly in the cloud, reaching a maximum diameter of 2 mm, without depleting much of the KSLWC, which still exceeded 1.0 gm/m^3 by nearly 15 minutes after the initial seeding. Considering the longevity of the supercooled water, "overseeding" was not a problem for this cloud. The maximum 2D-C counts ranged between 100 and 120 counts/L and decreased thereafter. By 18 minutes after seeding the cloud and its seeding-induced ice particles had collapsed below the aircraft, leaving a crater in the cloud field. This "cratering" was typical to the behavior of the other seeded clouds in this class.

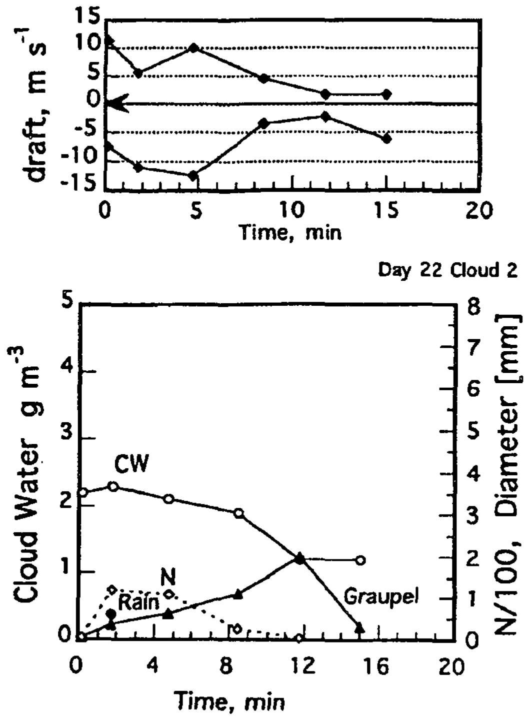

Figure 2. The evolution of cloud properties at the seeding level for the seeded cloud on August 22, 1995.

4.2 Vigorous Cold-Based Clouds (i.e., CBT < 15°C)

General Impressions

In clouds without supercooled rain drops but with vigorous updrafts that carried the cloud to 1 km or more above the aircraft, larger graupel was observed in addition to the graupel observed in the moderately vigorous clouds. In such taller, colder and longer-lasting clouds precipitation is more likely and seeding might act to enhance the process.

Example: Cloud Pair on August 25, 1995

Two clouds, having base temperatures of about 11°C, were selected for treatment on this day. Neither cloud had rain drops during the initial pass. Ice developed more rapidly, reached larger concentrations and larger sizes in the AgI-seeded cloud than in the non-seeded cloud. The differences began to show on the third pass about 4 minutes after the initial aircraft pass. The cloud water decayed more rapidly in the seeded cloud. Maximum particle sizes in the seeded cloud were 2 to 4 mm diameter while those in the non-seeded cloud were 1 to 2 mm diameter. The updraft had ceased in the non-seed cloud by 10 minutes after simulated treatment and by 14 minutes in the seeded cloud.

The Unseeded Cloud

The unseeded cloud of the pair was rising through 20,000 ft when it was penetrated for the first time. Ten flares were simulated on this pass which lasted 11 sec. The cloud had several nice clouds growing immediately adjacent to it on its left and right. It had no 2D-C particles, an updraft of 11.5 m/sec and a max KSLWC of 3.2 gm/m^3 (Figure 3).

The cloud pass 2 minutes later had a few very small graupel particles, a max updraft of 4 m/sec and a max KSLWC of 3.7 gm/m^3. The max 2D-C shadow/or counts were 121 particles/L (Figure 3).

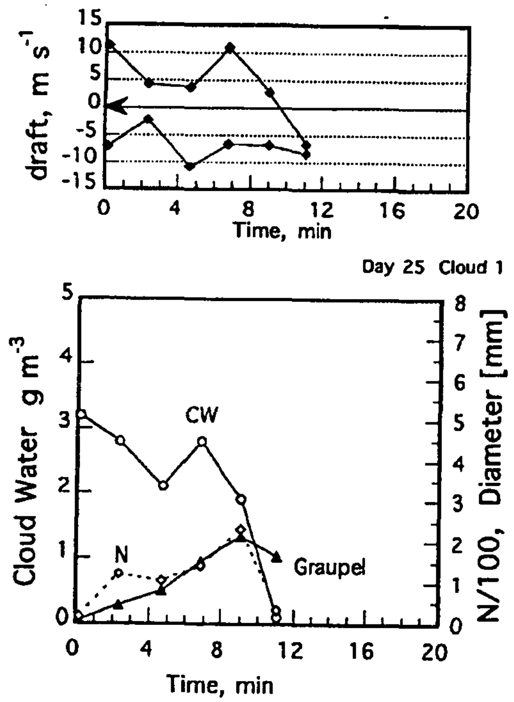

Figure 3. The evolution of cloud properties at the seeding level for the unseeded cloud on August 25, 1995.

The cloud had weakened slightly by 5 minutes after simulated treatment. The updraft was 5 m/sec and the maximum KSLWC of 2.0 gm/m^3 was in the downdraft. The maximum shadow/or counts were 112/L and the particles were small graupels up to 0.3 mm.

The pass 7 minutes after simulated seeding had an updraft of 10 m/sec and a few graupel particles up to 1.5 mm diameter. The maximum KSLWC had risen to about 2.8 gm/m^3. These observations were likely made through a new cloud element on the side of the original tower. Maximum 2D-C counts were 139 particles/L.

The cloud pass at 9 minutes after simulated seeding showed a peak of 2D-C counts in the downdraft up to 231/L. The particles were graupels up to 2 mm diameter. The MAX KSLWC of about 1.9 gm/m^3 was in the downdraft regions; the updraft had diminished to 2.5 m/sec.

The remnants of the cloud were penetrated 11 minutes after the initial treatment. It had no KSLWC and was only downdraft. The particles were small graupels 1 to 2 mm diameter.

The Seeded Cloud

The seeded cloud was about the same size but more isolated than the non-seeded cloud. Nevertheless, it was vigorous during first aircraft penetration when 7 AgI flares were ejected. It had an updraft of 13 m/sec, KSLWC of 3.2 gm/m^3 and had 27 shadow/or counts, produced solely by water "streakers" (Figure 4). The initial pass lasted for 13 sec.

The second pass was made 3 minutes later. The cloud had updraft on its north side of 9 m/sec and very small 2D-C particles in the updraft. The south side of the cloud had downdraft and a decrease in the KSLWC from about 3.1 gm/m^3 on entry to about 2.0 gm/m^3 before exit.

The cloud was growing strongly, draped in pileus, on the third pass 5 minutes after seeding. The tower showed an updraft of about 5 m/sec and a max KSLWC of 3.0 gm/m^3 and no obvious seeding signature, although the maximum 2D-C shadow/or counts were about 146 particles/L. The KSLWC decreased in the downdraft and then increased again in another smaller updraft. A few dendritic ice crystals were noted in the secondary updraft region, indicating that they had somehow come from above. Our clear-air flight temperature was about -8°C and dendritic crystals do not normally originate at such a warm temperature.

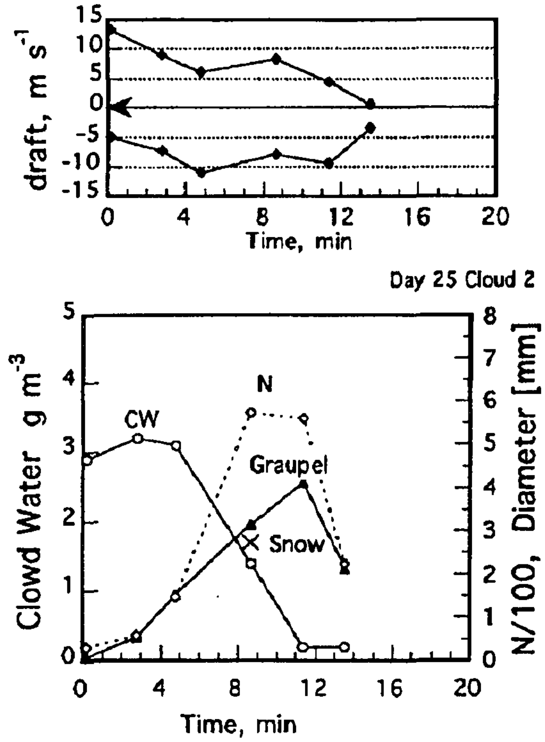

Figure 4. The evolution of cloud properties at the seeding level for the seeded cloud on August 25, 1995.

The fourth pass into the cloud, 8 minutes after its seeding, showed an apparent seeding signature. Max 2D-C counts were 572/L in a general downdraft of 5 m/sec with peaks to 7.5 m/sec. The KSLWC had decreased dramatically and there were many small graupels plus a few larger ones up to 4 mm diameter plus rimmed dendrites and aggregates. The larger particles likely developed as it grew up to 2 km above the aircraft before collapsing.

The fifth pass came 11 minutes after seeding. The entry point still had updraft, particle concentrations were still about 533/L, the cloud water was totally depleted and there were a few large graupels up to 5 mm diameter. Most of the cloud still had weak updraft in the icy regions. A few dendritic particles were seen in the downdraft region.

The sixth pass at 13 minutes after seeding was through the debris of the cloud, which now was mostly downdraft. The particle maximum 2D-C counts had dropped to 223/L and the particles were small graupels, generally < 2 mm diameter, and aggregates. No KSLWC remained.

The seeded cloud had shown an apparent temporary response to seeding. By 5 minutes after its seeding, the cloud was growing hard with pileus draped on it. This coincided with the rapid development of ice particles and the depletion of the cloud water. With the exception of a few large graupels between 4 and 5 mm diameter, most of the ice was in particles < 1 mm. This sequence of events differed from its non-seeded predecessor. The entire cloud mass was looking glaciated and it had turned totally to ice by 11 minutes after initial treatment.

4.3 Warm Based Clouds (i.e., CBT > 16°C)

General Impressions

Clouds with bases warmer than 15°C often produced supercooled rain drops at the -10°C level, especially when the new tower was observed to grow through the debris of cloud towers that had preceded it. This decayed cloud matter appeared to provide rain drop embryos for the production of rain drops by the new tower. This possibility is addressed in more detail in Section 5.0.

Many of the natural clouds with supercooled rain collapsed either without freezing of the rain drops or with freezing of the supercooled rain drops primarily in the downdrafts. In contrast, seeding such clouds froze the rain drops in the updraft in two to three minutes. Examination of the 2D-C images revealed that by 5 to 6 minutes after seeding most of the frozen rain drops had become heavily rimmed into 5 to 8 mm graupel while depleting the cloud water. This was associated with invigoration of the updraft that by this time would normally turn into downdraft in unseeded clouds. Shortly thereafter, the seeded cloud had totally glaciated with a mixture of small and large ice. The updraft continued, however, with virtually no cloud water at the -8°C to -10°C level. Although there is no proof that seeding was causal, this sequence of events is consistent with the initial stages of the conceptual model presented in the introductory section.

Example: Cloud Pair on August 31, 1995

The Unseeded Cloud

The unseeded cloud of the pair was obtained to the north of San Angelo, but out of range of the project radar. It looked quite hard on the approach and it had high KSLWC for nearly 10 minutes after the initial simulated seeding pass on which the ejection of 4 flares was simulated. A few rain drops were noted in the cloud on passes 2, 3 and 4 and these drops had begun to freeze on passes 3 and 4. The maximum ice particle concentrations were much less than in the seeded cloud. The first pass into the cloud measured a maximum updraft of 2.5 m/sec. It was relatively weak initially but persisted and increased with time. The cloud had a few isolated drops of about 0.3 mm diameter and 2D-C counts of 18/L (Figure 5).

The next pass 2 minutes after simulated had SLWC of 2.9 gm/m^3, and a few rain drops with maximum diameters of 1.5 mm; most were not yet frozen. The maximum 2D-C counts had increased to 57/L. The updraft had increased slightly to 3 m/sec (Figure 5).

The third pass into the subject cloud 5 minutes after simulated seeding showed an increased KSLWC of 3.6 gm/m^3 within a downdraft of 10 m/sec. The maximum updraft had increased to 5 m/sec as a new bubble grew up through and adjacent to the original tower. 2D-C particle concentrations, consisting of graupel and rain drops were 115/L with maximum sizes ranging between 1 and 2 mm (Figure 5).

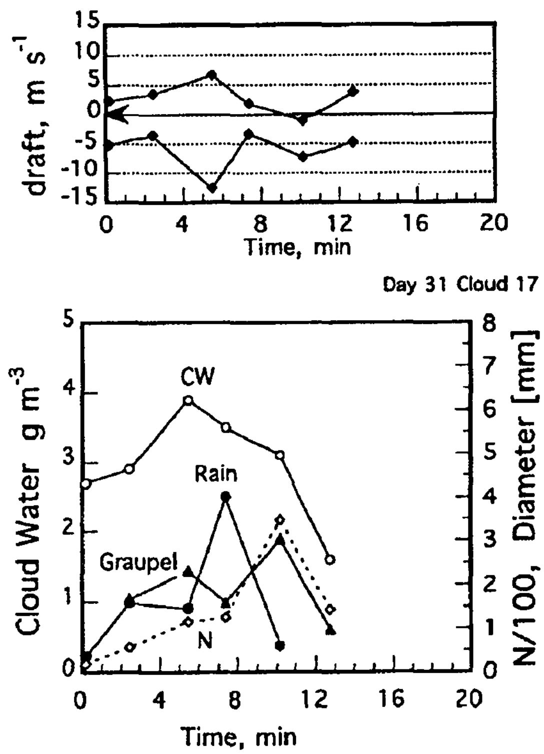

Figure 5. The evolution of cloud properties at the seeding level for the unseeded cloud on August 31, 1995.

Pass four 7 minutes after simulated seeding still showed a dominating downdraft, a KSLWC of 3.4 gm/m^3 and the persistence of the supercooled rain drops whose maximum sizes had increased to 4 mm diameter. The few graupel particles were smaller at 1.5 mm diameter. Maximum 2D-C counts were 132/L.

The cloud consisted of mostly small graupel and a few water drops on the fifth pass 10 minutes after simulated seeding. The cloud was dominated by downdraft as it collapsed while the larger hydrometeors were freezing. The KSLWC still had a value of 3.0 gm/m^3, which was remarkable considering that 10 minutes had elapsed since the initial simulated treatment pass. Maximum particle concentrations had increased to 347/L, consisting of a few rain drops and more and larger graupel having maximum diameters of 3 mm.

The last pass into the cloud took place 13 minutes after the initial seeding. By now the dissipating cloud consisted of mostly junk ice of various kinds and shapes. The aircraft had to descend slightly to penetrate the cloud on this pass. The maximum KSLWC was 1.5 gm/m^3.

The Seeded Cloud

The seeded cloud of the pair, identified as cloud 9 for the day, was seeded near its top with 14 AgI flares at 1719 CDT. It was to the east and well out of range of the project radar. It had a KSLWC of 4.1 gm/m^3, high 2D-C counts > 500/L, including drops up to 5 mm diameter, and an updraft of 5.5 m/sec. There were no signs of glaciation except upon exit where some graupel was noted in a downdraft of 7.5 m/sec. After its seeding, its development into a small glaciated cumulonimbus was monitored on 7 passes. The maximum updraft averaged 8 m/sec in the 8 minutes after initial treatment (Figure 6).

By 2 minutes after seeding there were signs of an apparent seeding signature in the form of many small ice crystals in concentrations up to 755/L. The small crystals existed with large graupels up to 4.5 mm diameter and large frozen drops up to 7 mm diameter. The updraft had increased to 7 m/sec and the KSLWC had decreased to 3.4 gm/m^3. Pockets of the cloud were still not glaciated but some of the large drops had been frozen and were starting to rime (Figure 6).

The third pass into the seeded cloud 6 minutes after seeding showed equi-dimensional graupels < 1 mm diameter along with huge graupel particles approaching 8 mm diameter. The peak updraft had increased further to 9.5 m/sec and the peak KSLWC had dropped 50% to 1.7 gm/m^3 in 4 minutes. This cloud water apparently was being scavenged by the accretional growth of the ice particles which had concentrations of 490 counts/L (Figure 6).

The fourth pass came 8 minutes after seeding. It showed diminished KSLWC of 0.8 gm/m^3, an updraft of 10.5 m/sec, some rimmed particles, some aggregates and maximum 2D-C counts of 687/L. Most of the ice particles, which had decreased somewhat in size to 5 mm diameter, existed in updraft. Snow made its first appearance in the cloud (Figure 6).

The fifth pass 11 minutes after seeding was estimated to have come no closer than 4 km to any of the seeding positions on the first pass and may, therefore, have been out of the area of effect of the seeding. It showed an updraft of 6.5 m/sec, maximum ice particle concentrations of about 505 counts/L and an increase of KSLWC to 1.0 gm/m^3. This jump in KSLWC suggests that the pass may indeed have been outside the area of effect of the AgI flares. For this reason pass 5 measurements are not plotted in Figure 6.

Pass six 13 minutes after seeding, which was within 1 km of the extrapolated position of previous seed positions, showed higher ice particle concentrations of 843 counts/L, maximum graupel sizes of 4 mm, snow clumps approaching 6.5 mm diameter and a weakened maximum updraft of 3.5 m/sec. The KSLWC had decreased to nearly 0 (Figure 6).

Pass seven 17 minutes after seeding showed a maximum ice particle concentration of 732/L. Although a few of the particles had maximum diameters of 4 mm, most of the particles were quite small, and some of them were columns. A new updraft region with a maximum of nearly 10 m/sec was penetrated just before exit of the overall cloud mass. Some snow masses with diameters of 7 mm were encountered in downdraft just before cloud exit. No KSLWC remained along the track of the aircraft even in the new vigorous updraft region.

The last pass in the cloud came 20 minutes after seeding. The particles observed in the cloud were snow, unrimmed graupels, columns and an assortment of other particles usually found in anvil debris. The updraft still existed but it had diminished to 4 m/sec.

Although there is no proof that this sequence of events was due to the seeding, it illustrates nevertheless what is expected of a seeded cloud. The existence of rain

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drops on the initial pass likely was crucial to the rapid glaciation and the decay of the KSLWC as the rain drops froze, rimmed and grew to large sizes in the invigorated updraft, which persisted in the seeded region for over 20 minutes.

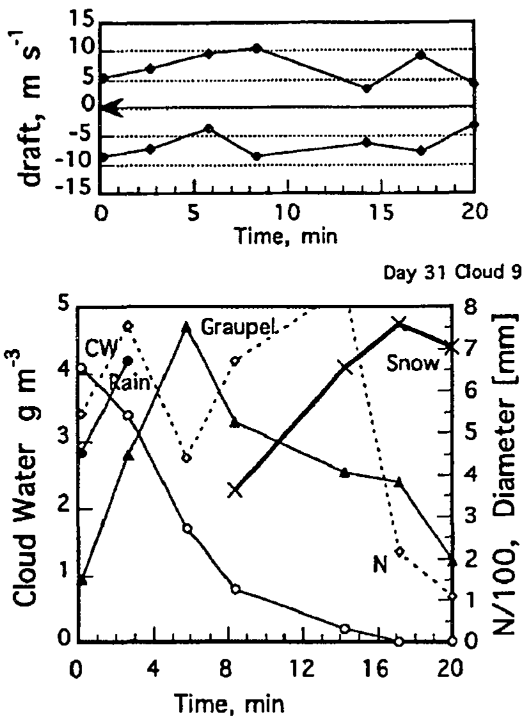


Figure 6. The evolution of cloud properties at the seeding level for the seeded cloud (Cloud 9) on August 31, 1995.

5. INTRA-DAY CLOUD MICROPHYSICAL VARIABILITY

The variability of natural atmospheric processes greatly complicates any attempt to document artificially-induced alterations of these processes. Only when these changes fall outside the envelope of natural variability can one be confident that an alteration is due unequivocally to seeding.

A major factor in cloud microphysical variability is the interactions of a given cloud with its neighbors. Clouds growing in isolation are usually much different from those growing in a clustered environment, especially from those clouds growing through old cloud matter and ingesting material from the dead clouds. The cloud photographs in Figure 7 readily illustrate this process on August 31, 1995.

The first photograph (Figure 7a), taken from the aircraft video nose camera at 15:59:58 CDT looking southeast, shows a cloud mass with a prominent bubble emerging through it in the background and two other minor bubbles closer to the camera on the right. The rest of the cloud mass, which extends well below the aircraft, appears to be inactive older cloud. A closer look at this same area at 16:01:10 CDT is provided in Figure 7b.

This general cloud mass persisted for some time, repeatedly generating cloud towers that grew and died, ultimately sinking into the inactive cloud mass. Other examples of new cloud towers coming through the cloud debris are shown in Figure 7c at 16:15:00 CDT and later still at 16:35:16 CDT in Figure 7d.

Many of the clouds studied on this day, including the seeded cloud (Cloud 9) addressed in Figure 6 grew through this dead cloud matter. Cloud 7 on this day did not. Considering that clouds 7 and 9 were separated in space by only 30 km and in time by only 22 minutes, it is interesting to take a more detailed look at their microphysical evolution.

Cloud 7 was growing nicely all by itself when it was qualified and seeded with 6 flares. It contained only cloud water on this pass. Another seeding pass at a right angle to the first was made with the ejection of an additional 5 flares. This was followed by three monitoring passes into the cloud. It grew vigorously for a time following seeding, glaciated and then died.

A pass-by-pass examination of Cloud 7 is provided in Figure 8 for comparison with the plots in Figure 6 for cloud 9. Cloud 7 had 3.4 gm/m^3 on the first pass and small 2D-C counts, which were due to water streakers off the probe. The updraft was 5 m/sec. The second seeding pass came 55 sec later. The cloud had 4.1 gm/m^3 on this pass, a maximum updraft of 5 m/sec and maximum 2D-C counts of 157/L. Only small drizzle was evident in the 2D-C images.

By the third pass at 1700 CDT (3 min 26 sec after treatment), the KSLWC had dropped to 3.0 gm/m^3, the maximum updraft remained at 5 m/sec and an apparent seeding signature, consisting of many very small graupels, could be seen. Most of the cloud was still water and this suggests that the release of latent heat was slow even though a seeding signature appeared to be present in the cloud (Figure 8). By contrast cloud 9 had much higher 2D-C counts, consisting of graupel

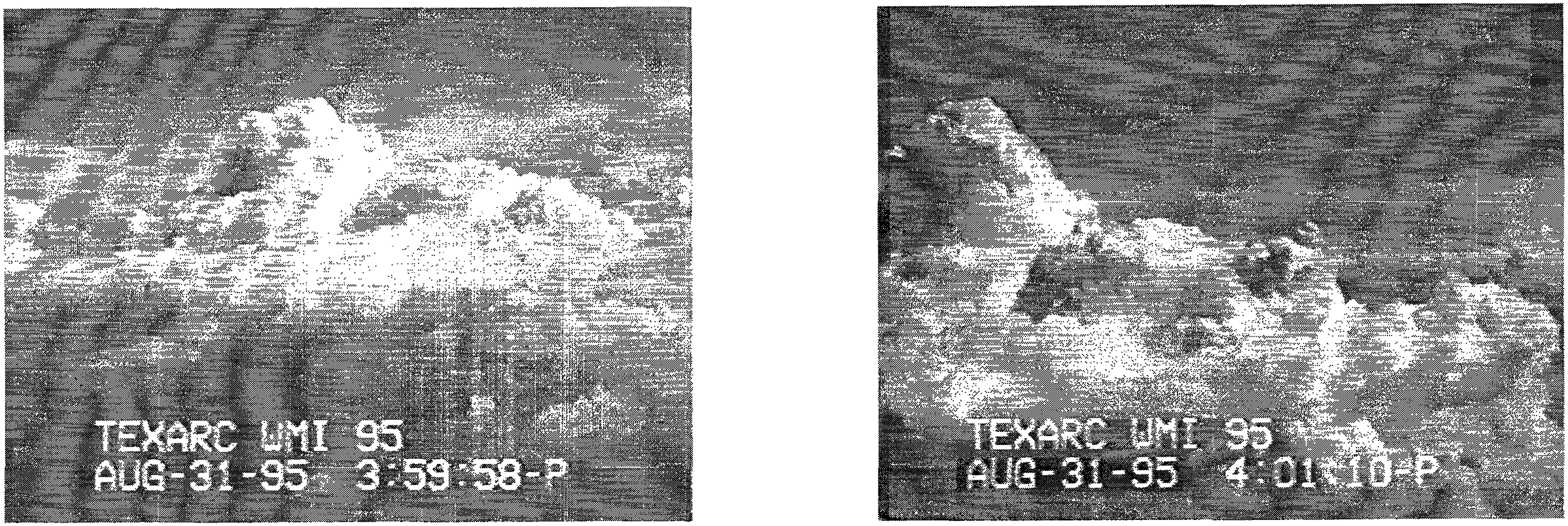
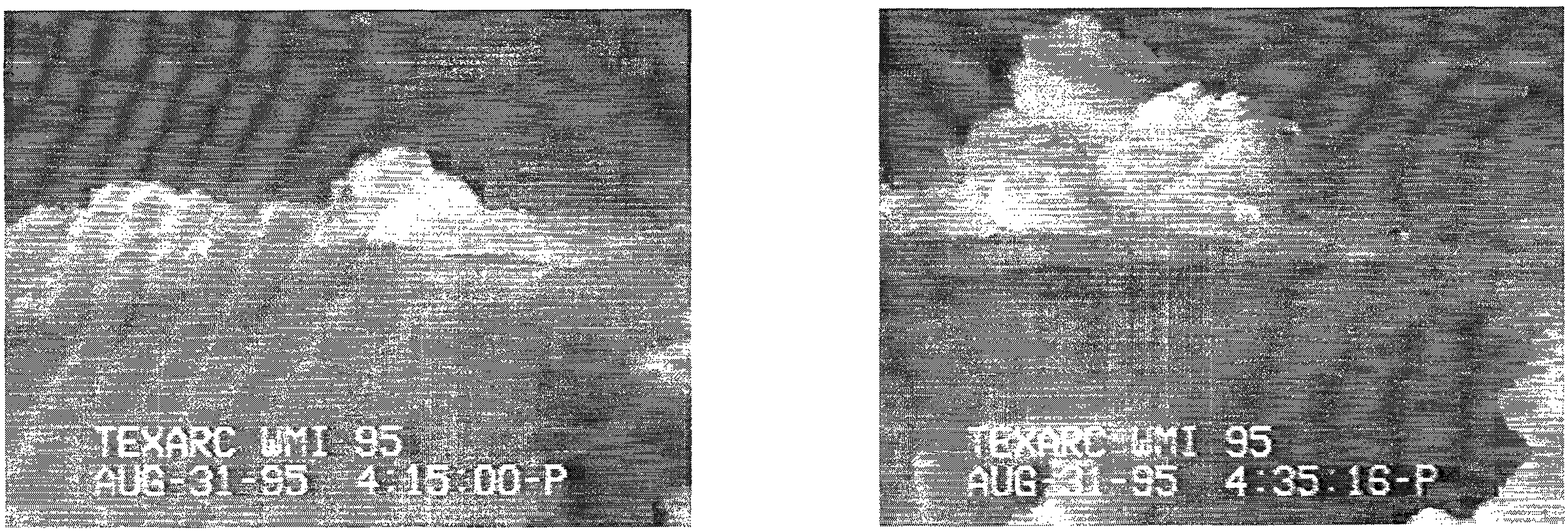


Figure 7. Photographs of convective cloud towers growing through cloud debris on August 31, 1995. The photographs were taken during TEXARC 1995 by the forward-looking video camera on the Cheyenne seeder/cloud physics aircraft flying at 6 km.



particles up to 4.5 mm diameter, and a stronger updraft at a comparable time after initial seeding (Figure 6).

The apparent seeding signature in cloud 7 was stronger by the fourth pass at 170236 CDT (5 minutes after initial seeding) with maximum 2D-C counts of 873 counts/L, but the particles existed in downdraft and cloud water up to 3.0 gm/m^3. The maximum updraft had waned to 2.0 m/sec (Figure 8). In contrast, by 5 minutes after the treatment of cloud 9 the graupel particles were still increasing in size up to 8 mm diameter and the maximum updraft had increased to 10 m/sec (Figure 6).

The differences between cloud 7 and cloud 9 were even more pronounced nearly 8 minutes after their initial seedings. Cloud 7 was mostly ice, including dendrites and frozen unrimmed drops, the updraft had disappeared and there was no KSLWC, except in a new tower that was penetrated before getting into the seeded region (Figure 8). By 8 minutes after initial seeding of cloud 9, however, the KSLWC had decreased to < 25% of its initial maximum value, the maximum updraft was 10.5 m/sec and the maximum particles sizes were around 5 mm (Figure 6).

Cloud 7 and cloud 9 were clearly very different. Although both were seeded at their time of maximum vigor, their apparent responses to this seeding were dissimilar. The reason may lie in their initial conditions. Unlike cloud 9, cloud 7 had no rain drops on the first treatment pass. Even on the second pass on which an additional 5 flares were expended only a few small drizzle drops were noted. Cloud 9, on the other hand, had large rain drops on the first pass which appear to have been frozen following the seeding. This likely set into motion a chain of events in accordance with the conceptual model whereby the seeding-induced ice particles grew in the invigorated updraft by accreting the cloud water.

Cloud 7 did not contain rain drops because it appears to have grown rapidly from below as an isolated cloud, leaving too little time for rain formation. In addition, unlike cloud 9, it did not ingest precipitation embryos from old cloud matter. Other than perhaps the large concentrations of ice particles (maximum of 873/L) noted during pass 4, cloud 7 did not respond to seeding in the way required by the conceptual model. Even here, the large concentrations of ice particles existed in downdraft and not updraft. The lack of rain drops on the first pass, which is required by the conceptual model, may explain this discrepancy.

The large inter-cloud microphysical variability on August 31, 1995 makes it obvious that this variability must be taken into account in searching for a seeding signature. This is best done by using the conditions on the initial pass as a means of matching clouds of similar characteristics. Those clouds that existed in a clustered environment and ingested embryos from decayed clouds contained large rain drops on the initial pass. Ice formed faster and the KSLWC decayed more rapidly in these clouds. AgI seeding appeared to hasten these processes producing large concentrations of ice particles in rising air. Comparable concentrations of ice were noted in the unseeded cloud, but the ice particles were generally in downdrafts.

Clouds that were relatively isolated during their growth phases retained their KSLWC longer than clustered clouds. Rain drops were rare during the initial cloud passes and increased only slightly late. Although ice formation was rather slow in isolated clouds, it was faster in the seeded clouds. There is no evidence to suggest, however, that this resulted in more rainfall.

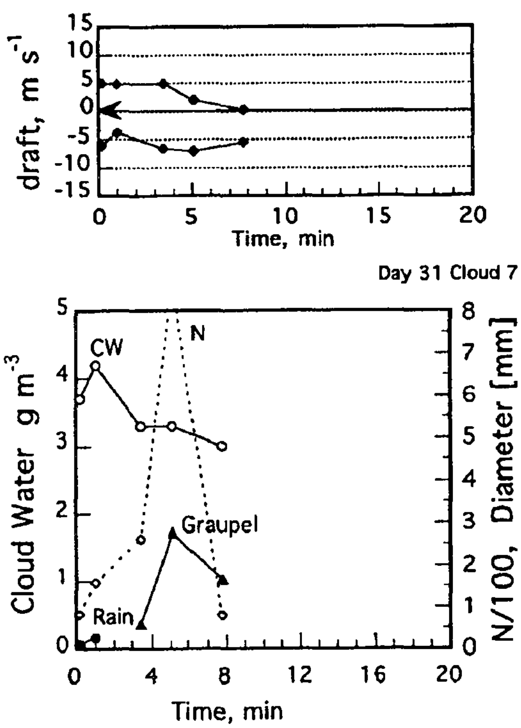


Figure 8. The evolution of cloud properties at the seeding level for seeded cloud 7 on August 31, 1995.

6. SUMMARY AND CONCLUSIONS

The detailed microphysical investigations in the context of TEXARC have led us to the conclusions listed below. We note in passing that several of them are not original to us.

For Unseeded Clouds

a. The probability that a cloud will contain supercooled rain drops increases as the cloud-base temperature increases.

b. For a given cloud-base temperature, the probability that a cloud will contain supercooled rain drops increases if it has had the opportunity to grow through decayed cloud matter and ingest precipitation embryos.

c. The supercooled cloud water typically decreases rather slowly, reaching perhaps 50% of its initial maximum value in 5 to 10 minutes. The limited data suggest that the decay times are faster in clouds that contain supercooled rain drops and graupel which scavenge the cloud water.

d. The initial conditions in a cloud and the duration of its sustaining updraft determines when and how a cloud will produce precipitation.

In Seeded Clouds

a. The seeding of clouds without supercooled rain drops leads to:

1) Slow growth of graupel at a rate that is too slow to convert cloud water into precipitable size particles (several mm) during the lifetime of the updraft, except for the most vigorous and vertically developed clouds.

2) A glaciation rate that is too slow for the production of a significant positive dynamic response.

3) Glaciation during the collapse of the cloud, which accelerates its dissipation, leaving holes in the cloud field.

b. The seeding of clouds with supercooled rain drops apparently leads to:

1) Fast freezing of the supercooled rain drops and its continued growth as graupel.

2) Enhanced growth rate of the graupel as compared to supercooled rain drops in accordance with the theoretical calculations of Pinsky et al., (1997).

3) Fast seeding-induced glaciation within the active updraft, which increases cloud buoyancy and further invigorates the updraft at a time when it is needed to support the growth of the large precipitation particles.

4) More rapid removal of the cloud water as compared to clouds without seeding due presumably to its accretion on the seeding-induced graupel particles.

These results suggest the importance of when and where the various microphysical processes take place within the cloud and when and where the seeding takes place that is intended to alter these processes. Both the Rosenfeld/Woodley conceptual model and these results suggest that, when seeding for rain enhancement, it is crucial to produce glaciation artificially within the vigorous supercooled updraft region of the cloud. It is in this region that large artificially-nucleated precipitation-sized particles can be grown most efficiently. Accomplishing this through seeding requires great care in the placement of the nucleant either in the updraft directly near cloud top or in the strong inflow region at cloud base in well-developed convective systems.

All of the microphysical results to date are consistent with the dynamic seeding conceptual model that is guiding the TEXARC experimentation. More cases are necessary to discern the microphysical effect of seeding on west Texas clouds, especially in clouds that contain supercooled rain drops. Compositing the cloud characteristics as a function of the conditions on the initial pass and as a function of treatment (AgI seeding or simulated AgI seeding) likely will be helpful to this discernment. This work is currently underway.

7. ACKNOWLEDGEMENTS

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