On the Documentation of Microphysical Signatures Following the Base-Seeding of Texas Convective Clouds Using Salt Micro-Powder

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1.0 INTRODUCTION

The goal of the weather modification research effort in Texas is to develop scientifically proven cloud seeding technologies for precipitation augmentation in the State. "Proven" is to be interpreted in terms of the "proof of concept" criteria set forth by Silverman (2001;2003) involving physical and statistical evidence for seeding effects. According to Silverman (2003), the statistical evidence for rain enhancement by cloud seeding is strongest for hygroscopic seeding. Even so, he argues that the physical evidence for effects of hygroscopic seeding is lacking in some areas, especially as it relates to the conceptual models that have guided randomized hygroscopic seeding experimentation. Indeed, these deficiencies are true generally for most cloud seeding activities.

Since the termination of randomized experimentation in Texas during the early 1990's, the overall weather modification in the state has focused on operational seeding for rain augmentation, because decision-makers feel that the collective statistical evidence from programs around the world warrants it on the benefit/cost basis. It has focused also on physical documentation of seeding effects in order to understand how seeding works and to make it more effective. The physical studies have been conducted under several program acronyms. The 2004 SPECTRA (**S**outhern **P**lains **E**xperiment in **C**loud Seeding of **T**hunderstorms for **R**ainfall **A**ugmentation Project was conducted throughout Texas, southeastern New Mexico and Oklahoma during August and September 2004. In recognition of the increasingly prominent role of aerosols in cloud seeding concepts, the SPECTRA plan called for measurements in microphysically continental and microphysically maritime clouds as quantified by extensive measurements of natural cloud condensation nuclei (CCN) and subsequent documentation of the cloud droplet spectra resulting from the ingested CCN aerosols.

SPECTRA also involved a collaborative effort among the participating organizations

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in an effort to document in-cloud seeding signatures for glaciogenic and hygroscopic base-seeding in the region. Although strong glaciogenic seeding signatures have been documented on several occasions in Texas clouds for "on-top" seeding of vigorous cloud towers using ejectable AgI flares, only limited physical documentation exists for glaciogenic and hygroscopic base seeding. The plan called for randomization of the manner of AgI seeding (i.e., flares or generators) and whether seeding would be done with common (NaCl) salt powder that has been milled to model-specified optimum sizes (3 to 5 microns diameter) using a world-patented process. The plan called also for the release of SF_6 gas to serve as a tracer during the seeding and simulated seeding and detected later in the cloud at several levels by a gas detector aboard the fully instrumented Texas cloud physics aircraft (see companion paper by Axisa et al., 2005) as an indicator of when and where it had intercepted the seeded plume. Comparisons were to be made of the habits and concentrations of the water and ice hydrometeors within the seeded plumes within the convective clouds using the array of particle measuring sensors on the aircraft.

Due to a number of administrative problems, SPECTRA got off to a late start and not all that was planned could be accomplished during the summer of 2004. The effort to develop a CCN climatology for Texas was completed as described by Axisa et al., (2005), but no randomized physical case studies were obtained. Only one "practice" case, involving deliberate hygroscopic seeding without the release and detection of the SF_6 tracer gas, was obtained. Ordinarily, that would have been the end of it, because the lack of a tracer gas would introduce some ambiguity as to whether the cloud physics aircraft had sampled air containing the salt nucleant even though GPS navigation could be used to mitigate this ambiguity. Despite this case deficiency, we decided to analyze this practice case anyway to see what could be learned. At the very least such an analysis might reveal design and/or procedural deficiencies that could be corrected before executing the first randomized case study, now planned for spring 2005. Upon completion of the analysis, however, it was obvious that the results were worthy of scientific exposition on their own, despite our initial misgivings. Those results are presented here following the appropriate background information.

2.0 BACKGROUND

There is renewed interest in hygroscopic seeding for rainfall enhancement, which is due in part to recent reported results for four randomized hygroscopic seeding experiments that were conducted in South Africa, (Mather et al, 1997), Thailand (Silverman and Sukarnjanaset, 2000), Mexico (Bruintjes et al., 2001, Fowler et al., 2001) and India (Murty et al., 2000). In his critical evaluation of these experiments Silverman (2003) concludes that all four experiments produced strong evidence for statistically-significant rain increases. On the other hand, he concludes that the physical evidence supporting the statistical results is presently rather weak, leading him to conclude that the four experiments "have not yet provided either the statistical or physical evidence required to establish that hygroscopic seeding of convective clouds to increase precipitation is scientifically proven." Especially disappointing was the finding that none of the four experiments was able to provide physical evidence linking the seeding intervention to the observed increases in precipitation from the clouds as postulated by the microphysical seeding hypothesis. In fact, dynamic effects had to be invoked to explain the apparent increases in precipitation.

The physical hypothesis for the four experiments assessed by Silverman (2003) was based on the "static-mode" seeding concept, or seeding for microphysical effects, whereby the hygroscopic particles would act to increase the efficiency of the rain formation processes by accelerating the condensation-coalescence-collision process in the cloud. The Thai and India experiments attempted to do this by introducing ultragiant nuclei ($\geq$ 10 microns diameter) to jump start the collision-coalescence processes. This is considered a "brute-force" seeding approach used widely in many parts of the world, because it requires that large aircraft carry tons of seeding agent. With this approach most feel that the salt grains are so large that they produce relatively few raindrops for the seeding mass. Even so, such seeding apparently has produced the desired result. The South African and Mexican experiments, on the other hand, made use of much smaller (0.5 microns mean diameter) CCN aerosols produced by burning flares to affect the condensation processes. This is done by broadening the initial cloud drop size spectrum to promote the competition effect whereby the larger nuclei are activated preferentially over the smaller ones.

The use of hygroscopic flares has been hailed as the way of the future, because it apparently increases rainfall while bypassing the need for large aircraft to carry tons of seeding material. The recent model simulations by Yin et al. (2000) of hygroscopic seeding using a 2D, slab-symmetric, non-hydrostatic cloud model with explicit microphysics show there is good reason for this optimism. They agree with the hypothesis of Mather et al. (1997) that hygroscopic seeding with flares at cloud base, especially just above cloud base, could lead to a broadening of the cloud drop spectrum, an earlier formation of raindrops, graupel particles, and increased radar reflectivity at a lower altitude. The largest modeled positive seeding effects were noted in young microphysically "continental" convective clouds while small negative effects were noted in clouds with highly maritime microphysical structure. The largest particles produced by the flares, especially those with radii > 10 microns, account for the seeding effect. For particles of this size, however, it is not clear whether the competition effect is operative. Those flare particles < 1 micron diameter have a negative effect on the rain development. Thus, the large-particle tail of the flare particle size distribution accounts for the seeding effect.

The Yin model simulations indicate also that flare seeding will work best when the flares are burned just above cloud base, because the detrimental small particles do not produce cloud droplets. Further, the giant natural CCN hygroscopic particles in the ingested air do not suppress the formation of other cloud droplets, because they have already nucleated drops at cloud base. This allows the tail of the flare particle size distribution to operate at peak efficiency.

Additional simulations by Yin et al. (2001) show that hygroscopic seeding likely changes the raindrop size distribution of continental clouds and, therefore, the relationship between radar reflectivity Z and rain rate R, necessitating the use of different Z-R equations for the evaluation of seeded and non-seeded clouds. The use of the same Z-R equation to evaluate hygroscopic seeding of continental clouds is shown to overestimate the apparent effect of seeding. Even so, seeding effects of +30% to 40% are indicated still for the cases that were simulated. If these simulations represent reality, the radar estimates of seeding effects in the randomized, hygroscopic, flare, seeding experiments in South Africa and Mexico may have been overestimated.

Despite this important uncertainty, the results of the randomized experiments and these subsequent model simulations warrant the continued use of flares for hygroscopic seeding. Even so, current flare technology is limited by two major factors. First, the particle sizes produced by the flares are typically smaller (< 1 micron diameter), than is optimal according to the models and second, the mass of the active material used in seeding is generally smaller than is needed, according to the hypothesis of hygroscopic seeding for microphysical effects. If more flares are needed, this is going to increase the cost.

There are several options available to address the shortcomings of hygroscopic flare seeding. The most obvious is to fine-tune the flares to produce fewer small particles and more of optimum size which models suggest should be > 1 micron diameter. Such an effort is currently underway at the National Center for Atmospheric Research. A second approach is to identify an alternative to flares that produces more CCN particles in the optimum range. This is the approach selected by the first two authors, who have identified a patented means of processing common salt (NaCl) to virtually any desired size as verified after production by analysis with an electron microscope (Fig. 1). They have been involved also with their own extensive modeling effort to determine the optimum sizes of the salt nucleant (Segal et al., 2004). The search for the optimum particle sizes was conducted in the context of the hygroscopic seeding hypothesis, involving the competition effect, because the identified optimal sizes fell short of the “brute-force” ultra-giant threshold of 10 microns diameter.

Having identified a method to produce CCN particles of optimum sizes, two metric tons of salt powders were produced for SPECTRA. A desiccant was added to the salt powder during its production to prevent its clumping. Based on the model simulations of Cooper et al. (1997) the goal at the outset of the development effort was to process salt particles down to 1 micron diameter. This was done successfully (Fig. 1). When the model simulations of Segal et al. (2004) indicated that 3 to 5 microns diameter would be a better size range, particles of this size were produced for SPECTRA using the patented process. A portion of this latest batch of processed salt was dispersed from an agricultural sprayer/duster aircraft (Fig.2) during the practice seeding.

Fig.1 Photograph of processed salt particles viewed with an electron microscope. A size reference is provided in the picture.

3.0 RESEARCH TOOLS

3.1 Radar

A useful tool during SPECTRA was the Texas regional mosaic IRaDS (Integrated Radar Data Services) WSR-88D Level II data. These National Weather Service (NWS) WSR-88D sites cover the Texas weather modification programs’ target areas. NEXRAD data is run through Thunderstorm

Identification, Tracking, Analysis, and Nowcasting (TITAN) as a graphic user interface, enabling the radar meteorologist to examine the three-dimensional structure of echoing clouds in real time. Individual echoes and groups of echoes can be tracked and their development and motion projected in time. Airborne Data Acquisition and Telemetry System onboard the research aircraft allows the radar meteorologist at each seeding target to track the SOAR research aircraft on TITAN and vector the aircraft to regions of enhanced convection within the Ultra High Frequency (UHF) range of the telemetry system. During the field measurement program (phase 1), the SOAR research aircraft was mostly deployed in targets of existing weather modification programs in Texas. This allowed the crew on the research aircraft to communicate with the project meteorologist at each weather modification site in Texas to obtain supplemental radar information to that available onboard the research aircraft. The aircraft flight tracks can also be used to associate the cloud physics in situ data with the cloud radar echoes.

Fig. 2 Photograph of the SOAR salt seeder dispensing processed salt.

3.2 The Cloud Physics Aircraft

The SOAR research aircraft is a Piper PA 31T Cheyenne II. Since the aircraft is a cloud penetrating aircraft, it is certified for flight into known icing conditions. The Cheyenne has research airspeeds of 85 ms^{-1} to 95 ms^{-1} and when performing climbing penetrations, the research ceiling is 25000 feet. The research aircraft has the capability of measuring the size distribution of aerosols ranging from 0.1 µm to 3 µm and hydrometeors from 2 µm to 1.55 mm in diameter. According to Axisa et al. (2005) the instrumentation on the SOAR research aircraft during SPECTRA consisted of the Particle Measuring Systems' (PMS) Passive Cavity Aerosol Spectrometer Probe (PCASP SPP-200), the Droplet Measurement Technologies (DMT) Cloud Droplet Probe (CDP) and the DMT Cloud Imaging Probe (CIP). This range gives the scientists a spectrum of measurements in the temporarily suspended aerosol range and in the cloud hydrometeor range. In addition, inferences on the cloud composition and the particles that act as CCN can be achieved by DMT's airborne CCN counter operating at a supersaturation as low as 0.1%. The SOAR research aircraft was also equipped with Texas A&M University's aircraft-based high flow rate Differential Mobility Analyzer (DMA)/Tandem Differential Mobility Analyzer (TDMA) for sequential measurement of the hygroscopic growth of particles and measurements of the aerosol concentrations as a function of size to determine the critical supersaturation spectrum of aerosols.

4.0 THE CASE DAY

4.1 Weather

The day selected for the practice hygroscopic seeding test case was September 4, 2004. It was declared "practice" primarily because the system for the release and later detection of the SF_6 gas, which was needed for unambiguous identification of the seeded region, was not in place. The morning was overcast with low stratus and stratocumulus clouds that "burned off" by late morning and a cumulus field had developed by early afternoon. The clouds were taller and more numerous to the west in New Mexico. Those clouds developing over the mountains were weak cumulonimbus clouds. Those elsewhere were appeared to be capped at about 5 km. This made sense since the morning Midland, Texas, sounding showed a temperature inversion at the -7°C isotherm level or about 17,000 ft. This readily explains the capped clouds and the accumulation of cloud debris at this level.

The clouds capping at around the -7°C level were good candidates for the testing of hygroscopic seeding because there was no natural rain coming down through the clouds from above. This would make any claims that rain from these clouds was due to the hygroscopic seeding more credible.

5.0 FLIGHT OPERATIONS

By late afternoon the clouds had developed depths that warranted a general scramble of the project aircraft, including the cloud physics aircraft (S1) carrying its pilot, Rosenfeld and Axisa, the duster seeder aircraft (S3) with its pilot (Fig. 2) and a Piper Comanche, single-engine, chase aircraft (S2), carrying the pilot, Woodley and a videographer, for flight with the seeder at cloud base. All aircraft were airborne just after 2306 Z in the following order: cloud physics aircraft, duster/hygroscopic seeder and the chase aircraft. The cloud physics aircraft flew to the northwest into New Mexico where the satellite imagery and visual sightings from the ground indicated that the most suitable clouds were located. By 2310 Z cloud base had been noted at 8,800 ft at a temperature of 14°C. The ascent continued to 18,000 ft as attention was focused on a fairly hard cloud group estimated to have a visual top of 22,000 ft. (Fig. 3) and was overshooting the inversion level as the aircraft approached for penetrations. The complete record of all cloud passes is given in Table 1, which has the times and heights of the individual cloud passes, the concentration per cm^3 of drops > 100 microns diameter and the largest observed particle. The colored lettering and numbering in Table 1 corresponds to the colored letters and numbers on the maps shown in the experiment layout in Fig. 5, which contains the S1 and S3 flight tracks, the positions of initial salt releases, the locations of the S1 monitoring passes and the radar depiction.

Fig. 3: Photograph taken from the cloud physics aircraft as it approached the cloud.

Fig. 4 Picture from the cloud physics aircraft just before cloud-pass A at 2328 Z

The first cloud pass (pass A) in the first cloud (Control cloud #1) came at 2328 Z about 500 ft below the 19,000 ft cloud top. Note that the cloud towers were fairly uniform in height but still hard in appearance (Fig. 4). Four more cloud passes

Table 1: Research Flight: 4 September 2004; 23:06 to 01:23 Z

	Time Z	Height Feet, m	Drizzle D >100 μm m^{-3}	Largest Drop μm	Comment
	2310	8800			Cloud base
	Control cloud #1				Actually the seeded cloud BEFORE seeding
A	2330	19000, 6210	12	1100 (ice?)	500' below cloud top; no raindrops
B	2332	6120	0		
C	2333	19000, 5910	0		500' below cloud top; no raindrops
D	2336	18000, 5400	0		400 fpm; no raindrops
E	2339	16000, 5000	1	250	1000 fpm; no raindrops
F	2343	15000, 5150	0		1400 fpm, no raindrops
G	2346	15000, 5200	0		1000 fpm, no raindrops
H	2351	4750	0		Penetrations chasing the seeder
I	2354	4200	0		Penetrations chasing the seeder
J	2356	3900	0		Penetrations chasing the seeder
K	2358	3950	17	400	Penetrations chasing the seeder
	Seeded cloud				
1	2359	14000, 3920	0		Over the seeder, within the deck
2	0002	16000, 4470	25	350	Just at the top of the deck. Seeded cloud overshoots
3	0003	4700	101	1375	
4	0004	4900	2	775	
5	0005	5100	16	850	
6	0006	5200	51	1250	
7	0008	16000, 5200	259	1450	Short bursts of rain, 1 cm on windshield
8	0010	16000, 5200	312	1475	500 fpm; small raindrops
9	0014	16000, 5200	164	1475	Rain about 7 mm on the windshield
10	0016	17000, 5500	521	1200	No rain
11	0019	16500, 5350	437	1225	Small rain, cloud tops at 17 kft
12	0021	16500, 5350	296	1325	Few raindrops
13	0024	16500, 5350	189	1325	No rain
	Control cloud #2				~ 5 miles NW of seeded cloud, similar cloud top.
a	0027	16500, 5330	0		Across shear. Top at 17000, No rain.
b	0029	16700, 5350	0		Along shear. No rain.
c	0032	5360	2	100	
d	0035	13000, 4250	0		
e	0037	12100			
f	0039	11600, 3700	0		300' above base; 300 fpm; +3.6C
	0042	11600			300' above base; 300 fpm; +3.6C
	0044	11400, 3500	0		Cloud base

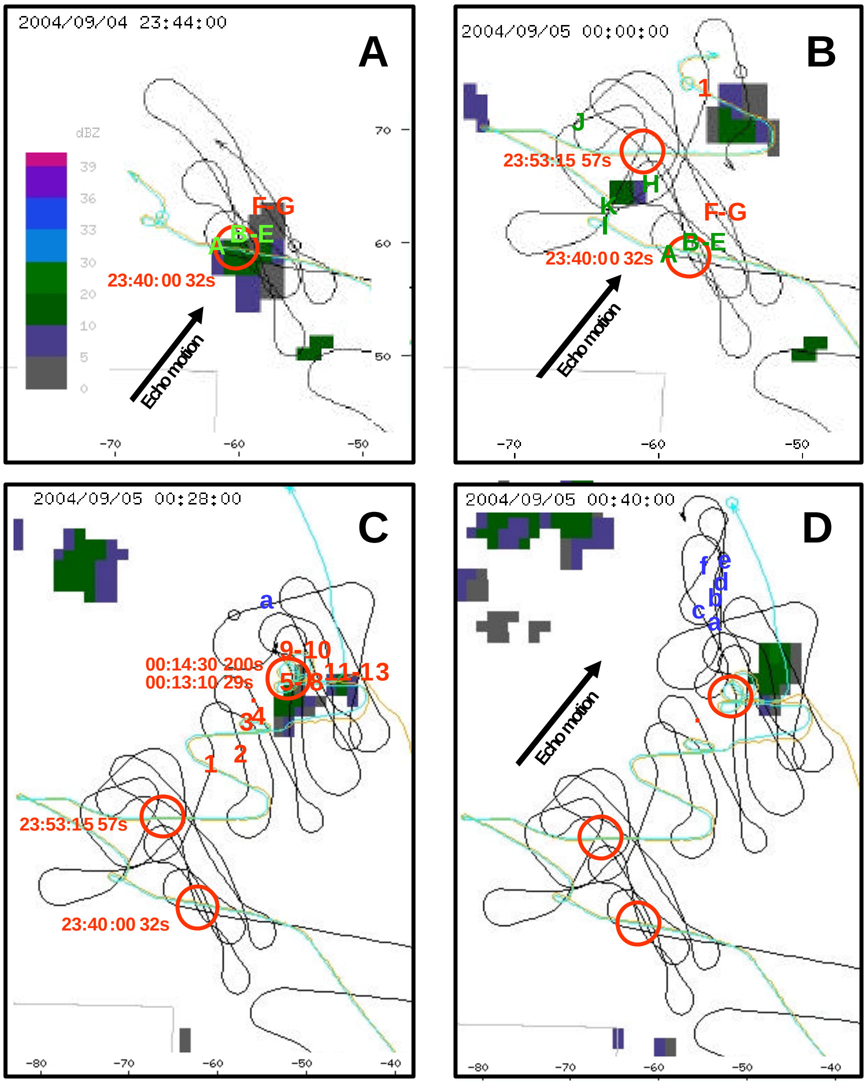


Fig. 5: Layout of the control and seeded cloud passes for the salt powder seeding experiment. Each panel shows the accumulated activity until the time shown in the upper left corner. The intensity of the radar echoes at the panel time is shown according to the scale at the upper left. The distance to the west and north of the project headquarters [km] at Plains, Texas is shown at the bottom of the panels. The seeder aircraft trajectory is the green line. Seeding coordinates are marked by the red circles with the text showing the seeding start time [GMT] and its duration in seconds. The black line marks the trajectory of the cloud physics aircraft. The monitoring passes in control cloud 1 are marked by the orange and green capital letters listed in Table 1; the passes in the seeded cloud are marked by red digits; the passes in the control cloud 2 are marked by small blue letters. The marking of the passes is numbered identically in the pass table (Table 1).

were made through the cloud towers in this cloud mass prior to initial seeding at 2340Z.

Note that a weak echo formed (Fig. 5) at the intersections of all the passes through Cloud 1, which was the largest and most vigorous of the three studied. Even so, the cloud did not have many large drizzle drops and it had very little ice.

Table 2

Case Seed Times (GMT)

Begin	End	Duration (sec)
23:40:00	23:40:32	32
23:53:15	23:54:12	57
00:13:10	00:13:39	29
00:14:30	00:17:50	200

While S1 was making its 5 profile passes of Cloud 1, S3, followed by S2, made its initial salt release at 2340GMT along the northwest edge of the weak echo, lasting 32sec. Table 2 provides the times of the initial salt releases at the places shown in Fig. 5. S1 then made several more profiles passes F and G over the area, but less than 6 minutes after the initial salt release. S3 made another salt release at 23:53GMT lasting 57 sec. S1 again made profile passes H-K on the periphery of the seeded region. All were made less than 5 minutes after the salt release at 2353GMT. These are recorded as passes in non-seeded cloud because they are not in the region of seeding and not enough time had elapsed to carry the nucleant to the level of the aircraft in any case. The next recorded seeding interval came at 0013GMT lasting 32sec, although there is some question as to what took place 9 minutes earlier when the seeder flew a left orbit at the position shown by the dotted red circle. An unrecorded salt release may have taken place here as well. The seeded passes are those that could be affected from the seeding at 2553GMT and onward. Note that the cloud physics aircraft made two passes through this dotted circle (passes 3 and 4) finding some evidence for larger drops (Table 1). S1 followed shortly. The last salt release came at 0014Z and lasted just over 3min and was only a short distance from the salt release at 0013Z. This is the heavily seeded region and S1 made 9 monitoring passes through cloud towers in this area within 11 minutes of the seeding at 0013Z. Note that the concentrations of drizzle drops having sizes > 100 microns and the size of the maximum drop size for each pass are quite elevated for these 9 monitoring passes. At this point S3 and S2 returned to base due to low fuel. S1 then located a new target about 10 km to the NW of the seeded cloud to use as a control and profiled it on 6 passes, encountering no drizzle drops and no large particles. Afterwards, all aircraft and personnel returned to base for debriefing.

The total known seed time for this case had been 408 sec or 6.8 min. This gives an estimated cumulative salt expenditure of 20.4 kg, which is based on an estimated seeding rate of 3 kg/min. This is a higher seeding rate than the 0.5 kg/min that has been typical with flare seeding cases to date. The two control clouds had been monitored on 13 total passes and 13 monitoring penetrations had been made in the seeded cloud mass.

6.0 CLOUD-PASS DOCUMENTATION

Because the intent of the hygroscopic salt seeding in Texas is to alter the cloud-droplet spectrum, leading to larger drop sizes, enhanced coalescence and more rainfall, the primary instrumentation for the cloud-pass documentation are the cloud droplet (CDP) and cloud imaging probes (CIP) covering a total size range from a few microns to 1,500 microns or 1.5 mm. This documentation is presented for individual cloud passes and for composites of all passes.

During the analysis the decision as to which clouds were seeded and which were not seeded was based primarily on GPS navigation and TITAN on the radar as shown above. This is the best that could be done for this case without SF_6 tracer gas, released along with the salt powder from the seeder aircraft and detected subsequently by sensors on the monitoring cloud physics aircraft. Whether particular cloud towers were seeded or not seeded cannot be known for sure except for those clouds sampled before any seeding began. Thus, although the evidence to be presented for a hygroscopic seeding signature is strong, this cannot be claimed definitively. To do so would contradict the claims of the first two authors who have long argued for the use of tracer gases for the unambiguous documentation of seeding signatures.

The presentation by pass for the two control clouds and for the seeded cloud is given in Figs. 6a-and 6b. The left side of each two-panel figure for each cloud gives the drop size distribution for all of the aircraft passes from the CDP instrument in the form of drop sizes vs. relative droplet concentrations. Each line plot in the panel corresponds to one pass at the altitude shown. The right side of the figure gives the same information for observations by the CIP instrument.

Upon examining the plots in their entirety, the drop size plots from the CDP instrument (maximum sizes of 60 microns diameter) show an increase in drop sizes with altitude regardless of seeding treatment. Although there may be subtle differences as a function of treatment, such differences are not obvious upon this cursory examination. On the other hand the plots for observations by the CIP (maximum sizes of 1.5 mm diameter) are very different. The plots for the seeded cloud clearly show much larger drops than the comparable pass plots for the two control clouds. If due to seeding, differences of such magnitude are not likely due to the competition effect, but more likely due to the effect of the introduced giant nuclei. Although these findings are consistent with our expectations, it cannot be claimed that this is proof of the microphysical efficacy of the salt powder without positive SF_6 identification of the seeded volumes.

These indications are supported by compositing the observations for all clouds by both the CDP and the CIP instruments in terms of the effective drop diameter (Deff) as shown in Fig. 7. The droplet results in terms of Deff are presented as a function of pass altitude. Each plotted point for the CIP instrument gives 1 sec of data for volumes in which the drop concentrations were > 100 m^{-3}. This requirement was invoked in order to have some confidence in the droplet results. Regardless of the presentation, the differences between the CIP-measured larger droplet sizes for the seed and control clouds are dramatic.

The portion in each panel plot giving the CDP data indicate only small differences, suggesting that the competition effect was not strongly operative during seeding for this case. A closer look at the data presented in a different form, however, suggests that the competition effect was weakly operative in addition to the effect of the giant nuclei. Beginning with a plot of Deff for the two control clouds and for the seeded cloud as a function of liquid water content, which was derived by integration of the CDP data, for cloud passes at altitudes between 5,000 to 5,600 m (Fig. 8), one can see that the seeded cloud had larger CDP effective diameters for a given water content than the two control clouds. This is true especially for water contents > 1g m^{-3}. This suggests a weak competition effect was operative in the seeded cloud. This impression is supported

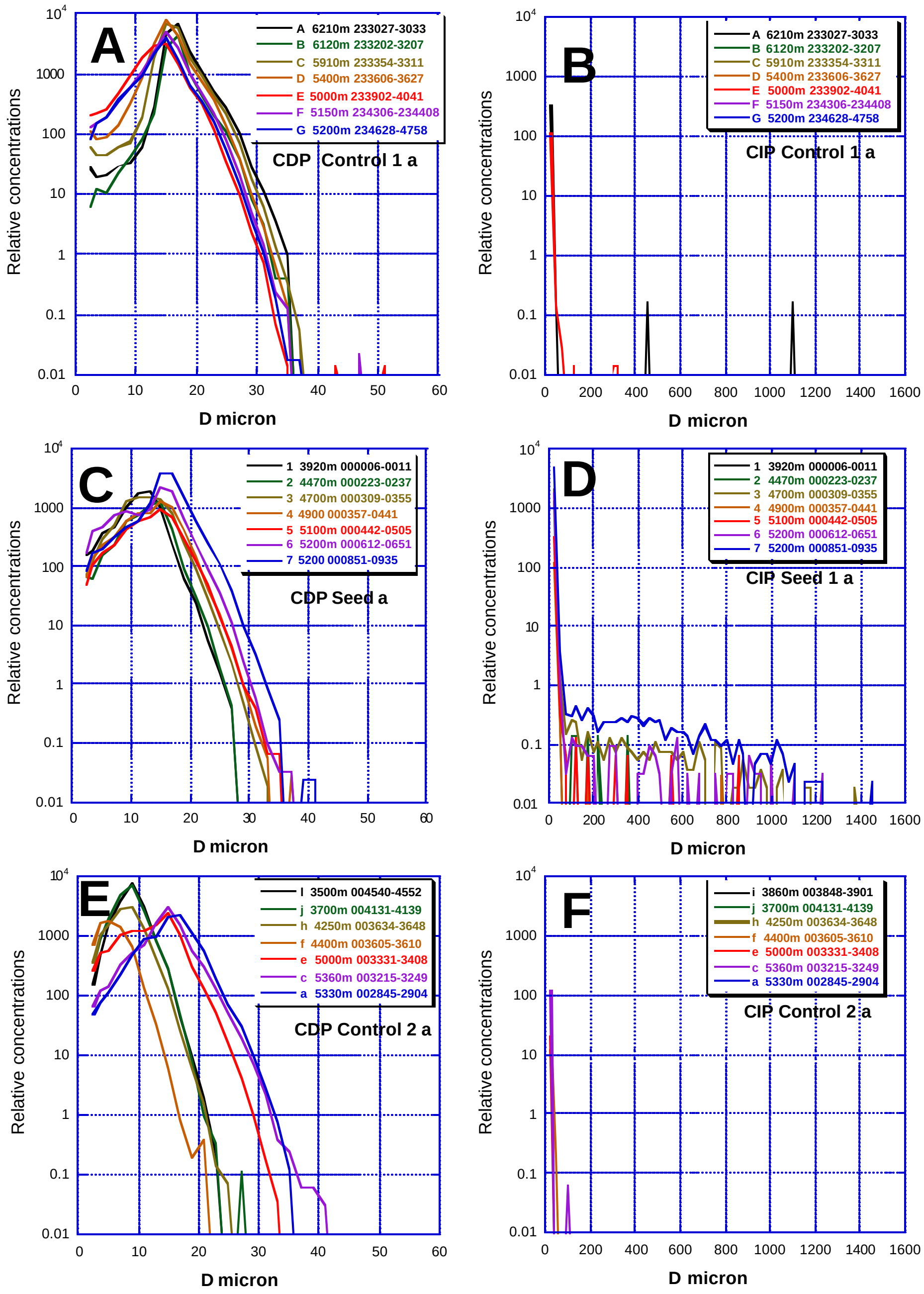


Fig. 6: Plots of the droplet sizes and concentrations, sorted by treatment, for the cloud passes shown in the figure legends, giving the height of the cloud passes and their beginning and ending times. The left and right panels give the DSD as derived from the CDP and CIP instruments, respectively.

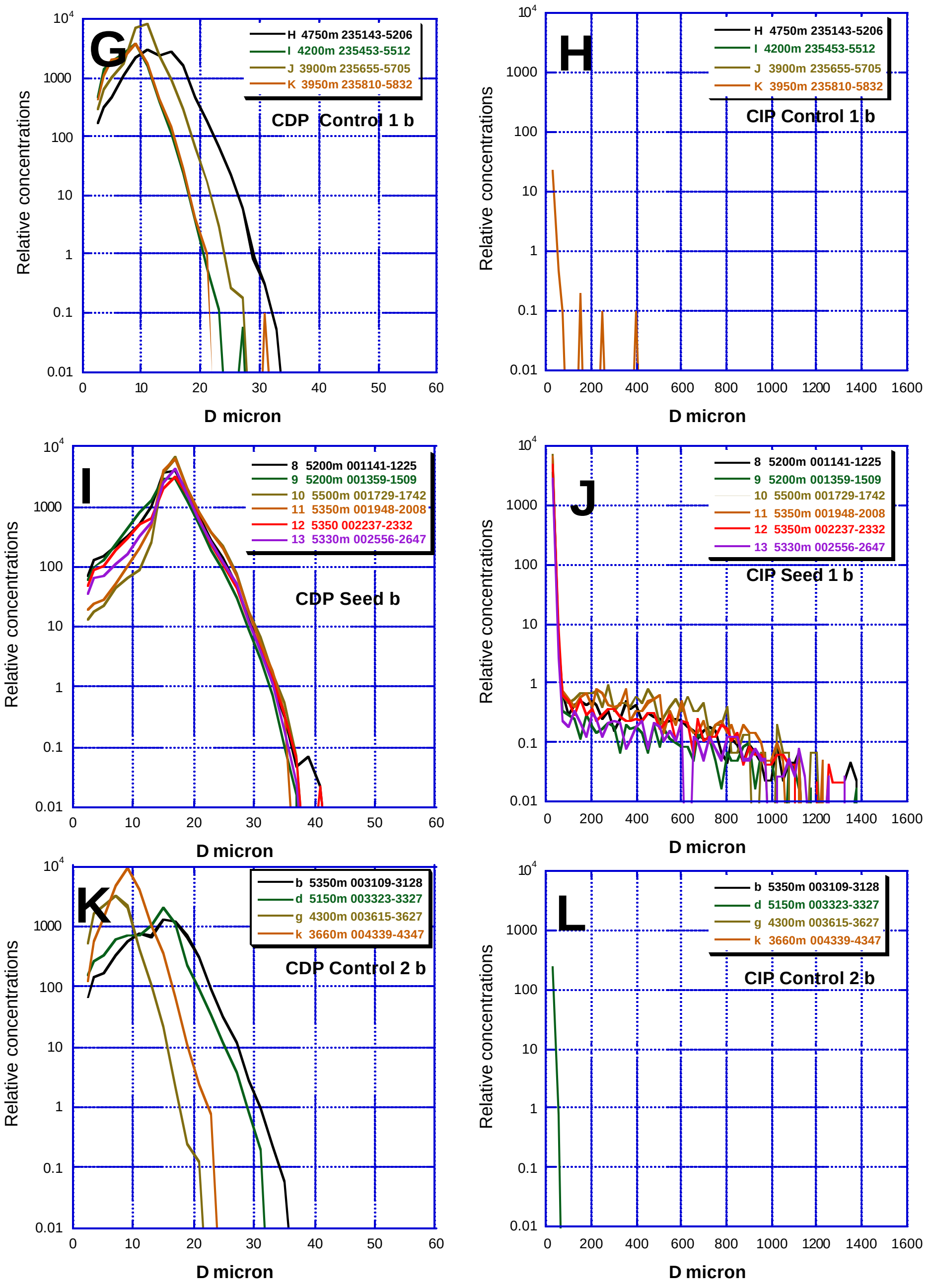


Fig. 6b: Same as for Fig. 6a (above), but for additional cloud passes.

Fig. 7. Effective drop diameter from observations made by the CDP and CIP instruments on the cloud physics aircraft after partitioning by treatment. The black points correspond to the seeded cloud. All other points are for the two control clouds.

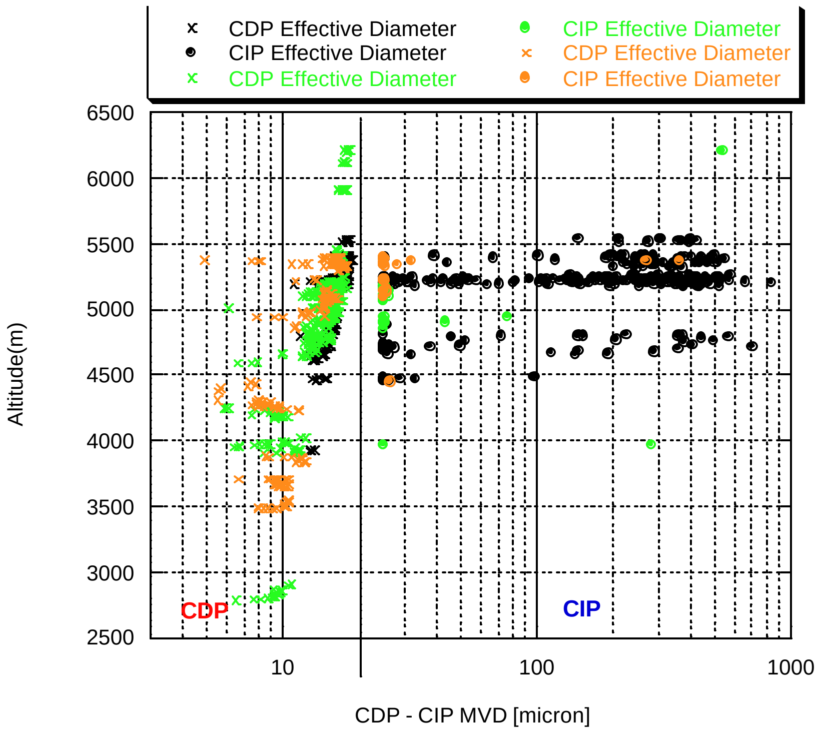
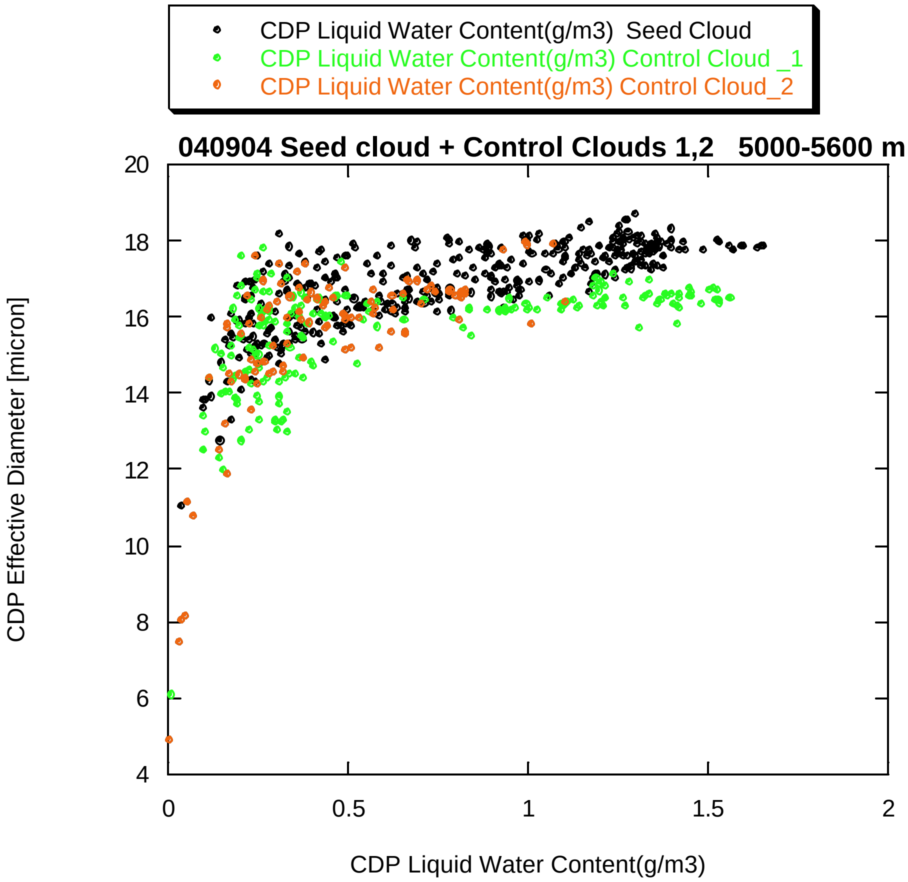


Fig. 8. Scatter plot of droplet sizes from the CDP instrument for the seed and control clouds presented in terms of the effective diameter (ED) as a function of cloud liquid water content.



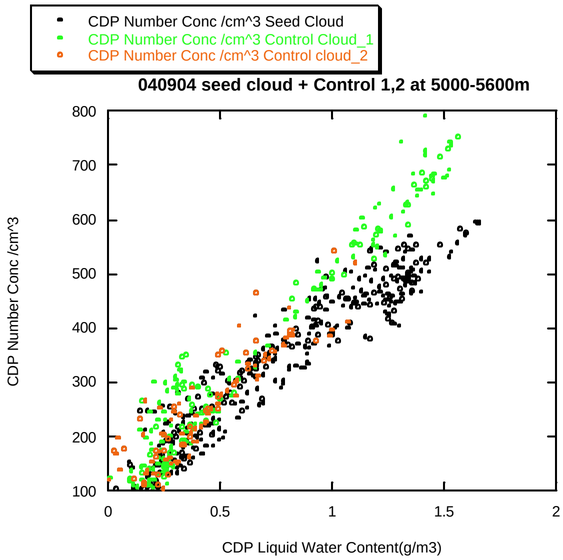


Fig. 9. Scatter plot of droplet concentrations for the seed and control clouds as a function of the CDP-derived cloud liquid water content.

upon examination of a plot of CDP number concentration versus the CDP liquid water contents for cloud passes in the same height range (Fig. 9). In this plot note that for a given CDP cloud water content the number concentrations are greater for the control clouds, again especially for water contents > 1 g m^{-3}. This makes sense. It stands to reason that, if seeding results in larger drops, it will mean fewer drops at given water contents.

7.0 CONCLUSIONS

Although administrative problems did not permit the microphysical case studies to be conducted with randomized treatment and SF_6 gas release and detection in SPECTRA as planned, the conduct of the "practice" deliberate hygroscopic seeding test case and its analysis has produced what appears to be a strong microphysical seeding signature. If seeding did indeed change the microphysical structure of the seeded cloud as documented, it appears to have done so primarily through the effect of the giant salt nuclei and secondarily through a weak competition effect. Rather than arguing these points, time would be better spent in conducting the cloud microphysical experiments as they were designed with the gas tracers.

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