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Radar Results of the 1986 Exploratory Field Program Relating to the Design and Evaluation of PACE

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Abstract. The initial phase of the Precipitation Augmentation for Crops Experiment (PACE), directed at enhancing rainfall was conducted in Illinois during the summer of 1986. This first experiment resulted in a limited sample, (19 clouds and 3 experimental units), but one sufficient to provide information pertinent to the design and evaluation of future efforts.

In particular, it was determined that differences in meteorological conditions may mask any seeding signature present, requiring that the experimental units be stratified or normalized. It was found that for these clouds, the height of the echo at first detection and the age of the echo at treatment (AgI or placebo) have an important bearing on the expected growth of the echo. Additionally, the area and reflectivity of the echo at 6 km at the time of treatment seem to be related to the maximum size attained by the echo cores. That is, the larger the echo at treatment, the larger the echo can be expected to grow.

However, the growth of the echo core in terms of reflectivity, height and area appeared to slow as the echo cores matured. This suggests that explosive growth sometimes expected from cloud seeding may not be the rule in this area of the country and that a comparison of before and after treatment growth rates may not be a good evaluation tool. Rather, the post treatment growth, with the experimental units stratified by the age of the echo at treatment and by the height of formation may be more useful in discriminating seeding effects.

Radar derived predictor variables were examined to assess echo behavior based on the ambient weather conditions, and response variables were developed which may be useful in detecting potential seeding effects. Inferences were made with regard to stratification of the data, experimental unit definition, and cloud behavior. This work emphasized, as others have found, the need for predictor variables and a large sample.

1. INTRODUCTION

Small, actively growing cumulus clouds, isolated, clustered or adjacent to large storms have been the focus of cloud physics studies and weather modification research for many years. Much of the early research in the central United States centered on the naturally occurring microphysical processes potentially responsible for the onset of convective rainfall (e.g. Byers, et al., 1953; Koenig, 1963; Braham, 1964; Ackerman and Westcott, 1986). Evidence indicates that cloud droplet growth by condensation, followed by precipitation growth by coalescence is an important rain initiation mechanism in the Midwest. Glaciation often is observed concurrently or following the development of precipitation sized drops (Koenig, 1963; Braham, 1964).

More recently, a new effort has been initiated to determine whether and under what conditions summer precipitation in Illinois can be enhanced by cloud seeding as part of the Precipitation Augmentation for Crops Experiment (PACE). During July and August 1986, a field experiment was conducted in central Illinois as the first step in the exploratory phase of PACE. The experimental design involved randomized cloud seeding to test the dynamic seeding hypothesis, and the use of radar data, cloud microphysical aircraft data, and synoptic scale meteorological data as evaluation tools (Changnon, 1985; Changnon and Huff, 1987).

In the early stage of the 1986 radar reflectivity analysis, it was found that individual echo cores could be identified as the sampled clouds and that these cores could be tracked in height and time to when they first reached their maximum height, reflectivity, and >35 dBZ area. According to the dynamic seeding hypothesis, the seeding effects begin with the rapid release of latent heat, followed by enhanced vertical and horizontal cloud growth. It therefore should be easiest to detect effects in the behavior of the individual cores. Thus, the approach used here has been to study the growth characteristics of the individual treated cores employing interpolated reflectivity measurements, as in the Gagin, et. al. (1985), Kraus, et. al. (1987), and Rosenfeld and Woodley (1989) studies.

The objective of this investigation is to describe echo core growth properties in the context of the local environmental conditions in order to: 1) explore the usefulness of echo core characteristics at the time of first echo detection and at the time of treatment as possible predictors of convective conditions and 2) evaluate the use of echo core growth behavior following treatment as possible response variables. This paper also will examine the design of the experimental program and the analysis in light of the multicellular nature of the storms, the large degree of within day and between variability, and the requirement for a more rapid acquisition of sampling units.

2. DATA SOURCE AND METHODOLOGY

2.1 Field operations

The project operational center was located at the NSF/ISWS CHILL radar site in Savoy, Illinois (CMI). During the field program, 10-cm reflectivity data were collected at 512 range bins, each representing a 300 m deep (1^o wide) disk, out to 150 km. The radar was operated in a 360^o scan mode designed to top all echoes in the area, completing a volume of 10 to 16 elevation steps within 3 to 5 minutes.

The study area encompassed the region within 120 km of the radar. Seeding at the -10^oC level was accomplished by a Cessna 421C Golden Eagle III aircraft with 20 gram silver iodide or placebo pyrotechnic flares, in a manner similar to many operational projects in this area. These flares were released in-cloud, but near cloud top where liquid water concentrations were generally greater than 0.5 g m^{-3}, as measured by a Johnson-Williams hot wire meter and where updraft speeds were greater than about 2 m s^{-1}, as measured by a ball variometer. Aircraft positions were computed by both a Loran C and a VOR/DME system.

Randomization was based on an experimental unit that corresponded to a clearly definable rain producing synoptic weather system. Due to unusually dry weather conditions in August 1986, only three suitable daytime rain periods occurred during the program, one on August 6 and two on August 26. Treatment with silver iodide flares occurred during 2 of these fights and with placebo flares on a third flight. In all, 30 treatment passes were made through a total of 20 clouds.

2.2 Data analysis

Volumes covering the history of the treated clouds were interpolated using a bilinear interpolation scheme (8 closest radar bins to a particular grid location) onto 121 km x 61 km x 15 km Cartesian grids, with 1 km resolution in each direction. The approximate location of the aircraft penetrations were plotted on the reflectivity fields.

For purposes of comparison, a minimum reflectivity of 15 dBZ was imposed on the data used in this analysis. The areal coverage and reflectivity history of the specific echo cores associated with 19 of the treated clouds were manually tracked in time and height. Eighteen of the 19 cores were joined at some point in their life with an adjacent core at some reflectivity level, half within their first five minutes and the remainder within 20 minutes. In these cases, a boundary indicated by a minimum in reflectivity values was delineated in order to sum the area of the echo core at each given height. The history of each echo core was ended not when it became joined with another but when it could no longer be distinguished with any certainty. In most cases this occurred after the core had reached its maximum height, area, and reflectivity. In the following discussion, the echo cores are referred to simply as echoes.

The maximum reflectivity and the area of the echo at each height were recorded. For each given radar volume, the peak value of reflectivity and the peak area at any height within the echo were used to provide a general indication of the echo size and strength at that time. The peak echo core area was computed for coverage by reflectivities of >15 and >35 dBZ. The echo top height associated with each treated cloud also was recorded for each given time. The height of the peak reflectivity at the time of initial detection and at the treatment time was noted, to help visualize the structure of the echo. In addition, the value of the peak reflectivity and echo area at the 6 km level were considered to provide an indication of the cloud conditions found near the treatment level (about 5.5 km).

The peak values at the time of first detection (for reflectivities > 15 dBZ) at the treatment time, and at the time the maximum value of a particular parameter was reached (see Appendix), were used in calculating the growth rates of the individual echoes. Because the radar volumes spanned 3 to 5 minutes, the time of first detection and the time of maximum value are approximations and could have been underestimated by as much as 5 min. Thus, the rates calculated are only estimates. The mid-time of the radar volume to the nearest half minute was used as the observation time, and the aircraft pass time was taken as the nearest half minute to the mid-time of the aircraft pass.

3. DESCRIPTION OF THE EXPERIMENTAL UNITS

The environmental conditions under which convection took place were similar in several respects. In particular, the three convective periods were characterized by relatively warm cloud base temperatures (16 - 20°C) and ample moisture in the lowest part of the troposphere, (surface mixing ratios of 14-16 g/kg). However, as will be noted, other conditions prevailed which influenced the growth behavior of the individual cores.

3.1 Afternoon of August 6, 1986

The first experimental flight occurred between 1556 - 1746 cdt and was centered on a narrow line of thunderstorms located 65 km to the southwest of CMI. The afternoon convection was associated with a gradually strengthening trough extending from a surface low to the north which was moving into the area. By 1800 CDT, the trough was analyzed at the surface as a cold front stretching from Chicago southward through east-central Illinois and then southwestward through St. Louis. Treatment began at 1631 cdt and was terminated abruptly at 1703, after a weak tornado was sighted within the study area. While scattered high-based clouds had been observed in the area since late morning, only after 1500 CDT did this convection become suitable for treatment (grow to the -10°C level). The 1514 sounding launched from the radar site (CMI) was conditionally unstable below the lifted condensation level (LCL), and neutral with respect to the saturated adiabat above 880 mb. A prominent feature of this sounding was a very rapid drying above 600 mb (4.4 km msl).

The LCL and the convective condensation level (CCL) were nearly identical (16°C at 1.1 km), suggesting that surface heating was sufficient to initiate convection. Also, the target surface convergence during the afternoon (10^{-4} s^{-1}, as determined from analysis of the NWS first-order stations) was favorable for enhancement of the convection moving into the study area from the west. The vertical shear of the wind (surface to 500 mb) on this afternoon and on the afternoon of 26 August was fairly weak (15-20 m/s).

Visual observations from the project aircraft indicated cloud base at 0.8 km. Echoes formed at or below the freezing level, 4.4 km msl (minimum reflectivity of about 10 dBZ). The time-height history of cloud 3 presented in Fig. 1 illustrates the tendency of the echo cores to form low and then slowly grow in height. The treated system had been active for some hours, but cloud tops had not reached the flight level. Eight treatment passes were made through 5 clouds concentrated within this single line of storms. New growth was occurring on the WSW end of this small line. In examining Fig. 2, it is apparent that substantial echo was present below the flight level at the time of treatment, even though the aircraft treated the cloud as it rose through the -10° level. The nearest area of convection reaching 6 km during this period was 100 km to the NE.

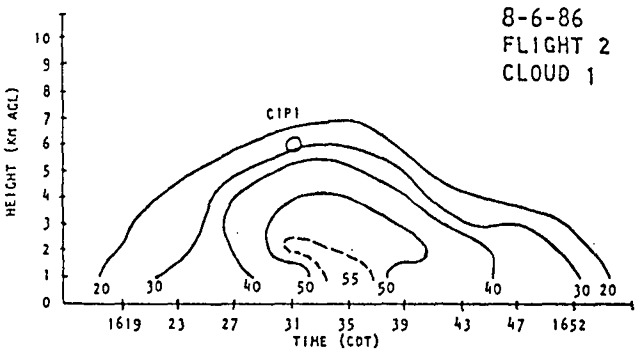

Figure 1. Time-height history of the peak reflectivity found in echo core 1 on August 6, 1986. The treatment pass is denoted by a circle at 6 km.

3.2 Morning of August 26, 1986

The treatment flight for this experimental unit was from 0846 - 1202 CDT. This system was composed of thunderstorms forming in the warm air mass about 250 km ahead of a strong, slowly moving cold front. The 0700 CDT, Salem sounding (SLO, 160 km to the SSW of CMI) showed conditionally unstable conditions above a shallow surface inversion to 500 mb, with a deep moist layer from the surface to 450 mb (6.5 km msl). Visual reports from the aircraft indicated a variable cloud base, with multiple layers of clouds. The cloud-base temperature and height were estimated as 18-19°C, at about 1-1.5 km msl. Surface heating was inhibited by a cirrus overcast and an analysis of surface winds indicated only weak convergence in the area. The vertical shear from the surface to 500 mb was weak (8 m/s).

The area of convection that was treated had originated in southern Iowa near midnight and moved southeastward into the study area by morning. By 1145 CDT, the clouds were moving out of the study area and rapidly diminishing in intensity. Little convective activity occurred in the area from 1200 until 1500, when convection more directly associated with the cold front began to move into the area.

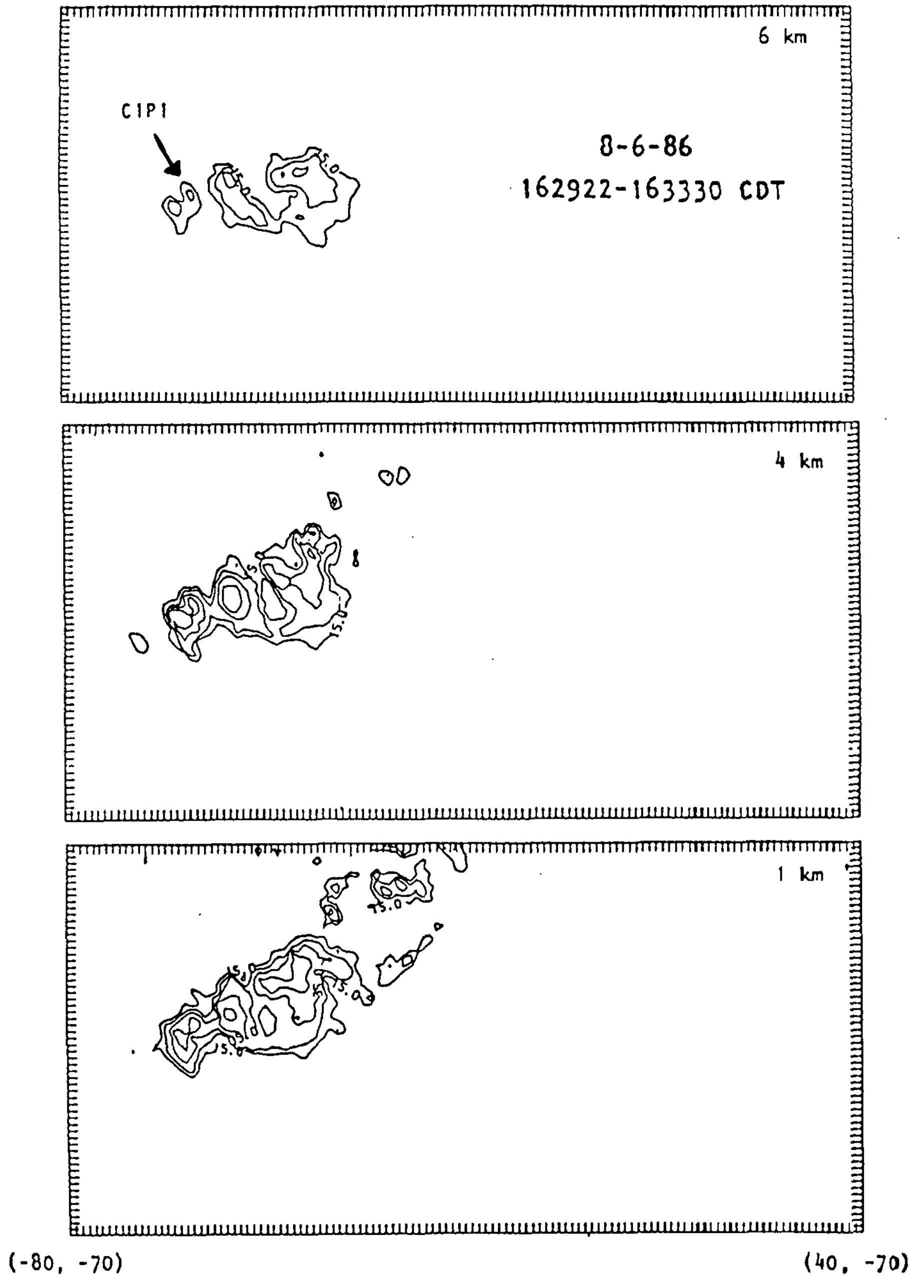

Figure 2. 1, 4, 6 km CAPPIs near the time of cloud 1 pass 1 on August 6, 1986. Reflectivity is contoured in 10 dBZ intervals, beginning at 15 dBZ. Distance from the radar is noted in parentheses. The echo core associated with the treated cloud is indicated by an arrow at 6 km.

Ten treatment passes were made in a total of 8 clouds between 0958 and 1131 CDT, in a region 60 to 75 km to the SW and SE of the radar. Echoes (10 dBZ) first formed at or above the freezing level (4.4 km msl). An example of the tendency for these echoes to form aloft and then appear to grow downward is presented in the Fig. 3, time-height history. In five instances, treatment occurred in echoes (15 dBZ minimum reflectivity) separated from all other echoes by at least 3 km, and in the other three cases new growth was immediately adjacent to an existing echo. An illustration of the echo field is presented in Fig. 4.

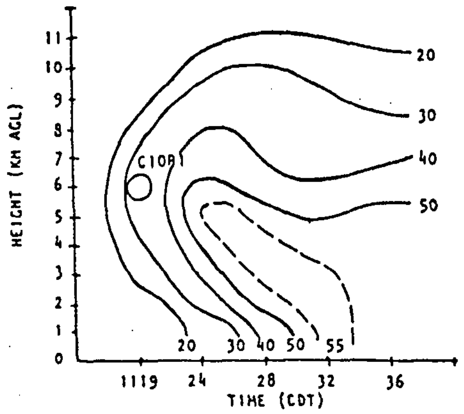

Figure 3. Time-height history of the peak reflectivity found in echo core 10 on August 26, 1986, flight 1. The treatment pass is denoted by a circle at 6 km.

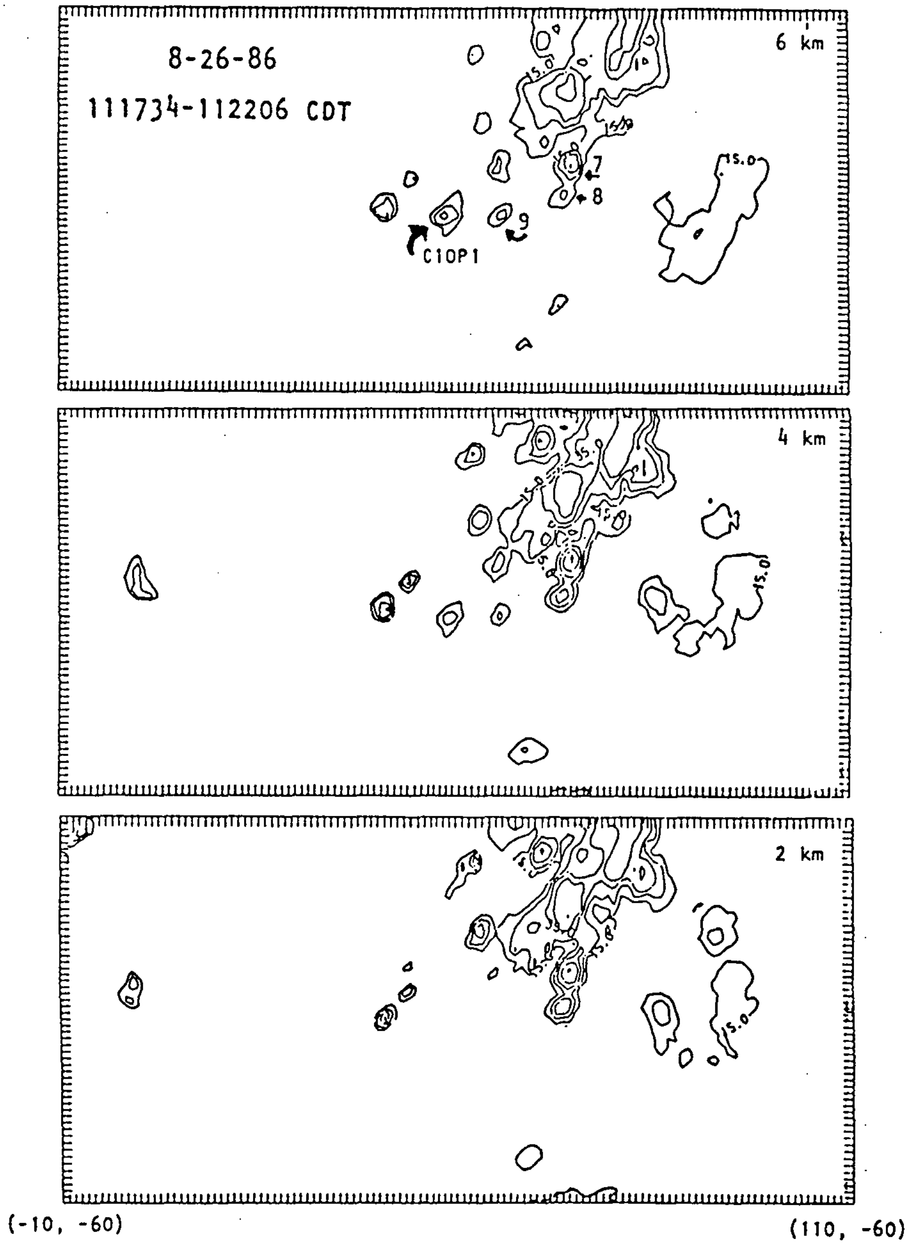

Figure 4. CAPPIs at 2, 4, and 6 km near the time of cloud 10 pass 1 on August 26, 1986, flight 1; as in Fig. 3.

3.3 Afternoon of August 26, 1986

The treatment flight within the third experimental unit was from 1507 - 1900 CDT, in an area of thunderstorms forming just ahead of a strong cold front. Frontal passage at CMI occurred at approximately 1800 CDT. The 1417 CMI sounding indicated unstable conditions below the LCL, conditional instability to 700 mb, and neutral stability above to at least 500 mb. As in the morning moisture was available through a deep layer to 450 mb (6.5 km msl). The morning and mid afternoon soundings on August 26 both were more unstable than the August 6 CMI sounding. Cloud base temperatures estimated from the LCL and CCL were 20 and 16 C, respectively, at heights of 1.5-2.0 km msl. Visual observations from the aircraft indicated a cloud base of 2 km msl. Surface convergence greater than -2 x 10^{-5} s^{-1} was present in the east-central Illinois area during much of the afternoon.

Treatment of 7 clouds occurred between 1558 and 1828 CDT, although only 6 clouds were analyzed due to a problem in determining the aircraft position for that cloud. The echoes appeared to straddle the freezing level (4.7 km msl) at formation, as exemplified in the Fig. 5 time-height history. These clouds were generally a part of a broad line, associated with the cold front (Fig. 6).

4. RESULTS ON RADAR ECHO BEHAVIOR RELATING TO METEOROLOGICAL CONDITIONS

An important early finding of this study was that an echo was typically present in the target clouds before or at the time of treatment. It follows that in order to separate out treatment effects from that of the local environment in which the cloud develops, echo characteristics of the clouds when they first are observed and at the time of treatment are important control parameters. The character of the echoes at first detection may aide in predicting the intensity of the convection, as in the results of Towery and Changnon (1970), Changnon (1976, 1978), Braham (1981), and Westcott (1989). These studies indicated that echoes which grow within or become part of a more organized system tend to form at a higher altitude than those that are more isolated. Other work (Ochs and Semonin, 1979; Johnson, 1982; and Smith et. al., 1986) has indicated that the height of the first echo can be related to the thermodynamic structure of the environment and possibly to the strength of the updraft of the individual cores.

In a population study of radar echoes cores taken from two days during PACE86, Westcott (1989) also found that the variability of first echo heights was as large within a day as between days. This variability may result from both the individual cloud characteristics as well as from the radar volume sampling period (~4 min.). Here, in order to compensate for the large variability and the small number of echo cores, the cores were grouped on an experimental unit basis to more easily delineate trends caused by meteorological factors relevant to a given day.

4.1 Echo characteristics at first detection

Distinct differences in the average heights of the first echo are clearly observed for the 3 units (Table 1). The echoes on the morning August 26 (unit 2) formed at levels at or above the $0^{\circ}C$ isotherm, and the echoes in units 1 and 3 formed at or below the freezing level. However, there were only small differences in the reflectivity and area of the echoes at the time of their first detection, with the first echoes from August 26, in the

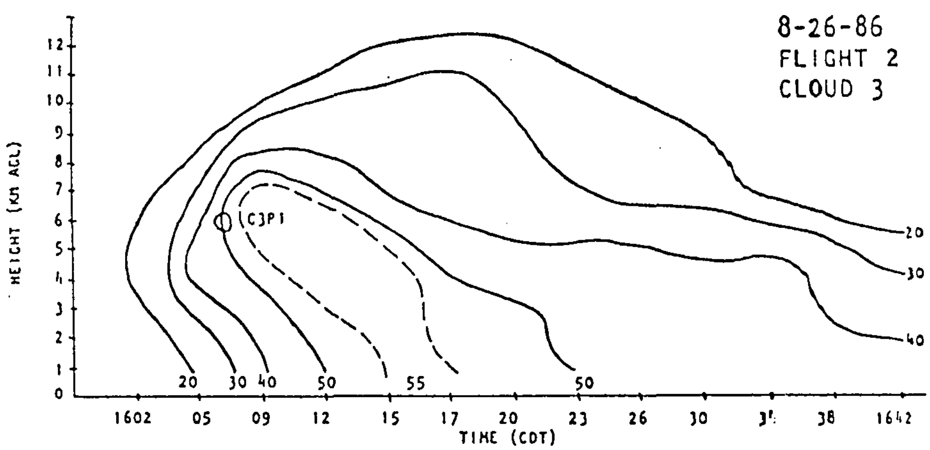

Figure 5. Time-height history of the peak reflectivity found in echo core 3 on August 26, 1986, flight 2. The treatment pass is denoted by a circle at 6 km.

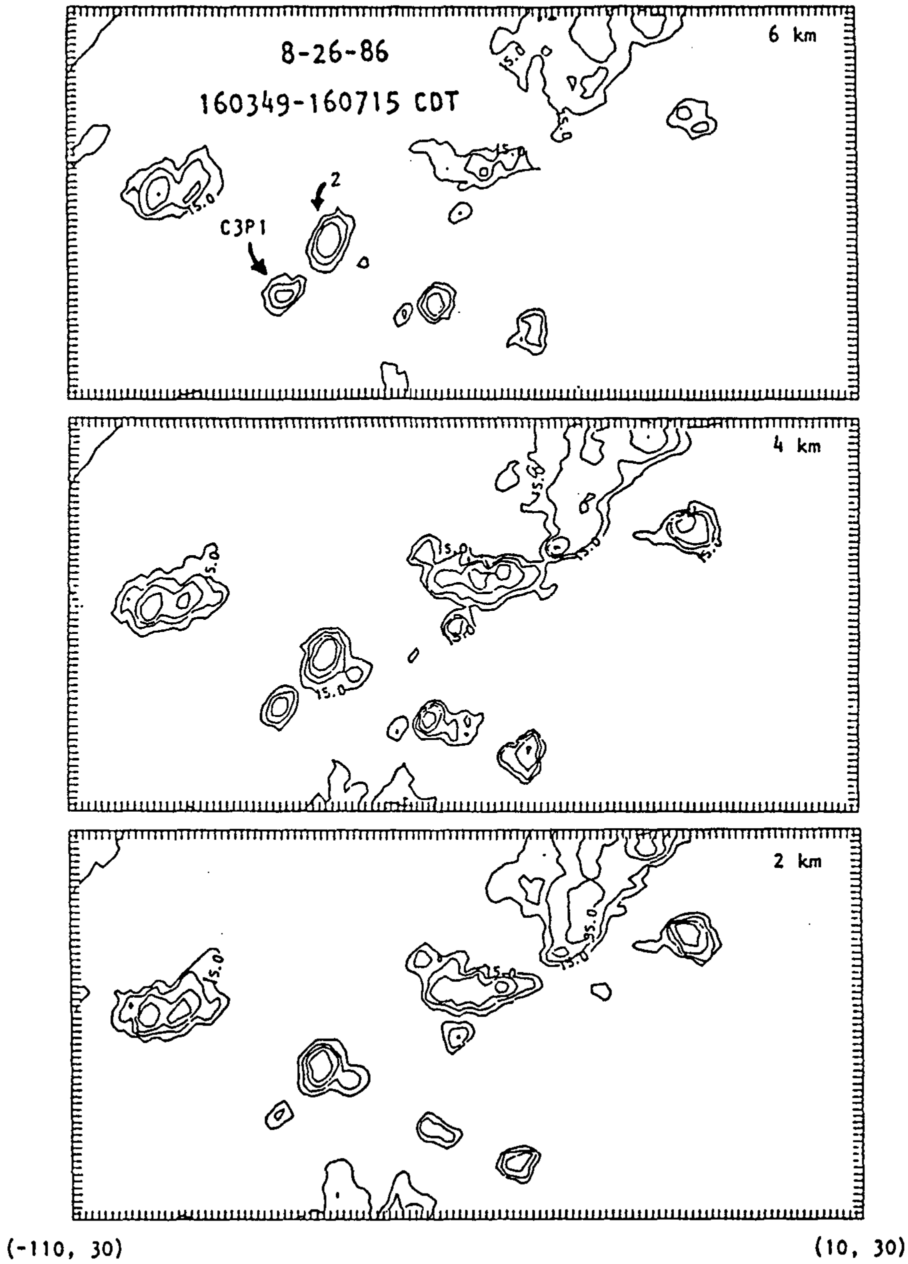

Figure 6. CAPPIs at 2, 4, and 6 km near the time of cloud 3 pass 1 on August 26, 1986, flight 2; as in Fig. 3.

mean, taller, and slightly larger and stronger than those from August 6.

4.2 Echo characteristics at first treatment

Echo characteristics at the time of treatment not only could be important in evaluating echo behavior resulting from environmental conditions, this information in the context of that taken at first detection will indicate the stage of development in which treatment first occurred.

Between day differences in the mean reflectivity and area of the sample echoes (Table 2) were larger at the time of treatment than at first detection. In general, the units with wider echo cores had larger mean reflectivities. The height of the echoes at this time, however, did not appear to be related to either their area or reflectivity. Rather, the trend might be explained by a combination of both the height of formation of the echo and by the age of the echo at first treatment.

Table 1. Sample mean (X), standard deviation (SD) and sample size (N) for echo parameters at time of first detection.

Date	Unit No.		Refl. (dBZ)	Ht. of Peak Refl. (km)	Echo Top (km)	Area dBZ > 15 (km^2)	Ht. of 0°C Isotherm (km agl)
8-06-86 PM	1	X	19.8	2.3	4.0	5.0	4.2
		SD	4.6	1.0	0.8	2.2	
		N	4	4	4	4	
8-26-86 AM	2	X	23.9	5.2	6.0	6.1	4.2
		SD	8.2	0.8	1.1	7.5	
		N	8	8	8	8	
8-26-86 PM	3	X	26.0	3.8	5.3	5.8	4.6
		SD	4.6	0.7	1.2	3.4	
		N	6	6	6	6	

Table 2. Sample mean (X), standard deviation (SD), and sample size (N) of the time from first detection to treatment, and for parameters at the time of first treatment.

Unit No.		Time to First Treatment (min)	Refl. (dBZ)	Ht. of Peak Refl. (km)	Echo Top (km)	Area dBZ > 15 (km^2)
1	X	17	50.1	2.3	7.0	41.2
	SD	4	9.1	0.8	0.7	10.2
	N	4	5	5	5	5
2	X	4	35.3	5.2	7.3	13.6
	SD	3	12.9	0.9	1.1	7.7
	N	8	8	8	8	8
3	X	9	48.0	4.0	7.9	30.4
	SD	3	3.8	0.8	1.0	10.0
	N	6	6	6	5	6

On August 6 (Unit 1), some 12 to 20 minutes elapsed between first detection and the first treatment pass for the 4 echoes included in this sample. Treatment for all five clouds occurred above an area of previously existing echo. These echoes again formed at or below the freezing level, and then appeared to grow upward. During Unit 2, the echoes formed at a higher level and were treated earlier in their histories (0 to 9 minutes), and thus were generally smaller in area and reflectivity. The echoes during Unit 3, were treated some 5-15 minutes after first detection. The average area of the echo cores (for reflectivities >15 dBZ) during this unit was intermediate between those of Unit 1 and 2.

However, the peak reflectivity values at treatment time of the two afternoon Units (1 and 3) were similar, even though those of Unit 3 were somewhat younger. This in combination with the observation that the echoes at treatment during Unit 3 were taller may suggest that the Unit 3 convective environment might have been more favorable for large clouds.

4.3 Echo characteristics at 6 km at first treatment

One might expect that echo characteristics near the treatment level at time of treatment would provide an indication of the suitability of the individual clouds for treatment, if these clouds contained liquid water at -10 C in the form of supercooled drizzle. This is generally the case in Illinois (Czys, 1988). Reflectivity and area provide information relating to the mean drop size and the areal extent of the cloud containing precipitation sized drops, and thus have important bearing on the effectiveness of cloud seeding. For example, the wider clouds may be less affected by entrainment.

Individual echo heights at first treatment, ranged from 6 - 9 km with the shortest echoes found during unit 1 (August 6) and the tallest echoes occurred during unit 3 (Table 2). Likewise, the smallest areas and reflectivities at 6 km were observed for unit 1 and the largest for unit 3 (Table 3). It appears that the mean area (and the aircraft derived pass length), the reflectivity at 6 km, and the height of the echo at treatment might be related. If it is borne out that the larger, more reflective clouds at 6 km at the time of treatment, grow larger than the smaller ones, the conditions at first treatment might be useful in predicting expected natural cloud growth.

5.0 RESPONSE VARIABLES FOR EVALUATION OF DYNAMIC CLOUD SEEDING

Cloud seeding studies which have taken a "single cloud" approach have looked at the maximum height of the treated echo or cloud as a responses variable (e.g. Simpson, et. al., 1967; Simpson and Woodley, 1970; Gagin, et. al., 1985; Dixon and Mather, 1986; Kraus et. al., 1987; Morrison et. al., 1986; Dennis, et. al., 1975; Rosenfeld and Woodley, 1989). Results from the first six studies suggest that seeded clouds grow taller than non-seeded clouds. Results from the later two studies suggest little or no difference in maximum height of seeded and control echo cores for their particular regions of the country.

Other echo parameters that have been examined include: whether or not a cloud produced a radar echo, the maximum horizontal area and the maximum reflectivity attained by the echo, the duration of the echo, and the radar-estimated rainfall output at the base of the storm. For comparison, many of these parameters have been examined here with the exception of the radar-derived rainfall. No attempt was made to relate the initial echo behavior to rainfall production on a core basis, because all but one of the Illinois echo cores were found to become part of a multicellular echo mass which continued to produce rain long after the individual cores had become indistinguishable. Finally, because so many of the clouds had radar echoes at the time of treatment, the before and after treatment growth rates of echo core area, height and reflectivity were examined, in addition to those more standard parameters.

5.1 Maximum values of area, height and reflectivity

A number of differences were observed between experimental units for the maximum values attained by the echo cores of reflectivity, height and area (Table 4). First, while the mean values of the maximum reflectivity are similar for the 3 units, the maximum areal coverage of the echoes are much smaller for the morning unit 2. This difference in area might be expected as the convection during this experimental unit was apparently not tied to the surface forcing and was generally diminishing in areal coverage.

A second difference lies in the maximum height of the echoes during the two afternoon units, and the difference in the distribution of values. The average echo top height for the August 6 unit was some 2.4 km lower than for August 26, yet the average of their maximum areas were comparable. The echo tops for unit 1 also had a bimodal distribution even though the echoes were from the same line of thunderstorms, and were treated within a half-hour of each other. Additionally, the variance of the maximum reflectivity and of areal extent (>35 dBZ) were larger during unit 1 than on the afternoon of August 26 (Unit 3) when the treatment passes spanned 2.5 hrs.

Table 3. Sample mean (X), standard deviation (SD), and sample size (N) of the interpolated time from first - 15 dBZ detection at 6 km to treatment and for reflectivity, area and echo diameter at 6 km at the time of first treatment, and the corresponding aircraft pass length.

Unit No.		Time to First Treatment (min)	Refl. (dBZ)	Area dBZ > 15 (km^2)	Echo Diam. dBZ > 15 (km)	Pass Length (km)
1	X	7.5	26.8	9.1	3.0	2.4
	SD	4.4	12.3	8.1		1.1
	N	4	5	5	5	5
2	X	4.6	31.6	11.7	3.4	4.2
	SD	3.3	11.3	7.6		1.3
	N	8	8	8	8	8
3	X	7.3	40.0	18.6	4.3	4.6
	SD	2.3	7.3	9.4		0.7
	N	6	6	6	6	6

Table 4. Sample mean (X), standard deviation(SD) and sample size (N) for maximum values of treated echoes by experimental unit.

Unit No.		Max Refl. (dBZ)	Max Echo Top (km)	Max Area dBZ ≥ 15 (km^2)	Max Area dBZ ≥ 35 (km^2)
1	X	52.8	8.8	65.0	27.2
	SD	7.7	2.5	21.7	18.5
	N	5	5	5	5
2	X	53.5	9.0	41.7	14.8
	SD	8.6	2.1	19.1	9.0
	N	8	*7	8	8
3	X	55.5	11.2	64.7	28.7
	SD	2.0	2.1	19.0	10.7
	N	6	*5	6	6

*The sample size for maximum echo top height was smaller than for the other parameters for units 2 and 3 because one of the treated echoes during each of these units was so close to the radar (within 30 km) that it could not be topped.

These observations may be explained by the very dry air above 4.5 km on August 6. They suggest that on this day only the largest, most vigorous clouds could survive in an unfavorable environment. On the afternoon of August 26, the echo core area, reflectivity and height values were more uniform and larger than during the other 2 units. This may be due to the strength of the forcing, i.e., the presence of the strong cold front, and the presence of adequate moisture to 450 mb on the afternoon of August 26.

The taller echoes in Unit 3 may be explained and predicted by the area of the echo at 6 km at treatment as well as the echo top at treatment time which were largest for the unit 3 echo cores. Also, in examining the individual echoes, for each given experimental unit, the larger the echo core at the time of treatment, the larger the maximum area reached (Appendix). Both modeling results and observations suggest that for either seeded or control clouds, the larger the cloud at treatment, the larger the cloud will grow (Simpson, 1967; Simpson et. al., 1969; Dennis, et. al, 1975; Ackerman and Sun, 1985). This may be related to the larger updraft core being protected from entrainment in the larger clouds, as well as an indication of a more vigorous cloud.

A pattern of reaching maximum values of reflectivity and echo top height first, followed by maximum values of area were found for each of the three units (Table 5). This is in agreement with observations by Simpson (1980). This suggests that for this sample, the growth rate of maximum reflectivities or of the larger drops may be more closely correlated with factors relating to the vertical extent of the echo (such as the vertical updraft strength and the efficiency of the precipitation forming processes and the availability of water) rather than with factors relating to horizontal expansion (interaction with adjacent cores, overall storm circulation). However, large reflectivities can be reached even with shorter echoes with sufficient time and supercooled water as in the case of Unit 1; or with smaller echoes if the atmosphere is sufficiently unstable with adequate moisture available aloft as in the case of Unit 2.

5.2 Growth before and after treatment

A seeding effect might be evidenced by a difference in echo reflectivity and a larger increase in area following treatment for the seeded echoes than for non-seeded echoes. Reflectivity might increase if larger amounts of water were processed by the cloud because of an invigoration caused by seeding, or it might decrease if the larger drops grew rapidly after being frozen and began to descend leaving the smaller frozen drops behind.

Here, the change in reflectivity and the areal growth subsequent to treatment appeared to be a function of the age of the echo and the height of the initial echo formation. This was demonstrated by the echoes sampled during the morning unit on August 26 which increased in reflectivity after treatment more than those of the other two units because the Unit 2 treatment occurred at an earlier time in the echo core developmental history. The maximum reflectivities reached during all three units were similar (Table 4). The percent change in reflectivity and area after treatment was greatest for the younger echoes found in Unit 2 and least for the oldest echoes found in Unit 1 (Table 6).

5.3 Pre- and post treatment growth rates

Post treatment growth rates were based on differences in echo characteristics between the time of first treatment and the time of the maximum value of the particular echo parameter, and pre-treatment rates from the time of first detection to the time of treatment (Table 7). Growth rates for all echoes except for one during Unit 3 were positive, indicating that actively growing cumulus were selected for treatment. However, in many cases, even for the morning unit when the echoes were generally treated earlier in their history, the post treatment growth rates were smaller than the pre-treatment rates. The average values of the pre- and post treatment rates reflect this to some extent. Omitting the two echoes which were first observed at the treatment time, 75 percent of the echoes had smaller post treatment rates for reflectivity, echo top heights and echo areas > 15 dBZ (Table 7). It appears that on these days, the echoes generally grew more rapidly early in their growth period, and as they matured their growth slowed.

Lastly, only for the area > 35 dBZ for all units, and for the area > 15 for Unit 1, were the average post treatment growth rates larger than the average pre-treatment rates (Table 7). Fifty percent had larger post treatment growth rates for echo areas > 35 dBZ. This may in part reflect the longer time to reach the maximum areal coverage observed in Table 2.

Table 5. Sample mean (X), standard deviation (SD) and sample size (N) for growth rates from the time of first echo detection to the maximum value. Time from first detection to maximum value (min).

Unit No.		Rate of Increase to Maximum: Refl. (dBZ/min)	Echo Top (m/s)	Area dBZ >15 (km^2/min)	Area dBZ >35 (km^2/min)	Time Elapsed to Maximum: Refl. (dbz/min)	Echo Top (m/s)	Area dBZ >15 (km2/min)	Area dBZ >35 (km2/min)
1	X	1.7	3.6	2.4	1.0	19	19	22	23
	SD	.9	1.5	.5	.7	5	7	5	5
	N	4	4	4	4	4	4	4	4
2	X	2.5	4.6	1.6	1.0	13	11	23	17
	SD	.9	1.5	.9	.8	4	5	7	3
	N	8	7	8	8	8	7	8	8
3	X	2.5	5.0	2.1	1.5	14	20	30	23
	SD	1.4	1.4	.8	.6	6	9	11	13
	N	6	5	6	6	6	5	6	5

Table 6. Sample mean (X), standard deviation (SD) and sample size (N) of the change in reflectivity, echo height and area, before (from first detection) and after (to time of maximum value) treatment.

Unit No.		Refl. Change Before (dBZ)	Refl. Change After (dBZ)	Top Change Before (km)	Top Chang After (km)	Area>15 Change Before (km^2)	Area>15 Change After (km^2)	Area>35 Change Before (km^2)	Area>35 Change After (km^2)
1	X	29.4	2.7	3.3	1.8	35.3	23.8	14.5	10.5
	SD	12.8	2.2	1.0	2.7	12.4	15.5	9.9	9.2
	N	4	5	4	5	4	5	4	5
2	X	11.4	18.5	1.3	2.0	7.4	28.2	2.9	11.8
	SD	10.5	10.5	1.3	1.6	6.3	18.4	4.2	10.2
	N	8	8	8	7	8	8	8	8
3	X	22.0	7.5	2.3	3.3	24.6	34.3	11.3	17.4
	SD	4.7	4.7	0.8	2.0	9.4	13.0	4.9	10.3
	N	6	6	5	5	6	6	6	6

Table 7. Sample mean (X), standard deviation (SD) and sample size (N) for before and (/) after treatment growth rates (zero values included). Number of echoes with post treatment rates larger (NPTL) than pre-treatment rates, compared to total sample (zero values not included).

Unit No.		Refl. (dBZ/min)	Echo Top (m/s)	Area $dBZ_z > 15$ (km^2/min)	Area $dBZ_z > 35$ (km^2/min)
1	X	1.8/1.0	3.4/1.4	2.1/2.4	0.9/1.5
	SD	0.8/0.9	1.5/2.8	0.3/1.2	0.5/1.7
	N	4 / 4	4 / 4	4 / 4	4 / 4
	NPTL	1:4	1:4	3:4	2:4
2	X	2.4/2.3	4.1/4.2	1.6/1.5	0.5/0.9
	SD	1.6/1.1	3.4/1.5	1.1/0.9	0.6/0.7
	N	8 / 8	7 / 7	8 / 8	8 / 8
	NPTL	1:6	0:5	0:6	3:6
3	X	2.7/1.4	5.0/3.2	3.0/1.7	1.4/1.5
	SD	1.4/1.8	2.3/4.6	1.5/0.6	0.8/0.8
	N	6 / 6	5 / 5	6 / 6	6 / 6
	NPTL	2:6	2:5	1:6	4:6

5.4 Summary

In summary, only small differences in first echo characteristics were found between days except for the height of formation. During Unit 1 when the echoes typically formed at a lower altitude and appeared to grow upward, the echoes were treated later in the history of the echo and generally after the echo had joined to the parent storm at low levels. In contrast, during the morning case (Unit 2), the echoes in general formed higher, appeared to grow downward and were treated earlier in the echo core growth period. The echoes from unit 3 formed at intermediate levels and were treated at intermediate times when compared to Units 1 and 2. All of the clouds, however, were typically treated within 5 minutes of reaching the treatment level. While it may be appropriate to treat in both cases, a comparison of the before and after changes in reflectivity, area and height may not be suitable evaluation parameters, unless the experimental units are stratified by echo age and the height of formation. The post treatment changes in the area and reflectivity may be more appropriate evaluation tools.

6.0 DISCUSSION

6.1 Randomization results

The seed / no seed decision for the experimental units was not disclosed in the result section of this paper to emphasize that the difference between the 3 units could easily have resulted from the natural meteorological influences. The randomization was such that the two afternoon units were actually seeded with AgI and the morning unit with the placebo. Without knowing the seeding decision, it seemed reasonable to conclude that the morning echoes were smaller and shorter-lived than those from the other two units.

In this area of the country, a pronounced minimum in rainfall is found at 1000 - 1400 CDT, (Huff, 1971). It is common in the Midwest for nocturnal storms to diminish in strength in the early morning, possible as a result of nocturnal storms reaching the end of their natural life cycle. This appears to be the case for this second experimental unit and was likely an overriding factor resulting in the differences in echo characteristics for the morning and afternoon storms. However, without stratifying the experimental units by local conditions, misleading results could have been obtained inadvertently, by either masking the true seeding signal or by attributing enhanced echo growth resulting from environmentally more favorable conditions to enhanced echo growth due to seeding.

The data suggests that several stratifications might be useful: stratification according to time of day (morning and afternoon), or by the mean height of echo formation, or by the strength of the surface convergence, stability, or moisture availability.

However, the echo core area and height at the time of treatment, seemed to be good indicators of the subsequent growth of the echo core, particularly when the age of the echo at treatment was considered. If sufficient cases are sampled in future midwestern experiments, it may be possible to normalize the expected growth by examining the mean echo characteristics at the time of treatment.

6.2 Cloud behavior

The large reflectivities observed at the time of treatment were not wholly unexpected due to the abundance of moisture, the importance of coalescence processes and the rapidity with which drizzle and rain drops form in the Midwest (Braham, 1964). The indication of positive growth rates following treatment in 18 out of the 19 cloud suggests that actively growing clouds were treated. The slower growth rates following treatment and as the echo matured may indicate that in this area of the country, the initial seeding effect may be evidenced by a reduction in the rate of decrease of the growth rather than for explosive growth rates often expected with seeding (Orville, 1986). Aircraft measurements taken during July 1986 also suggest this (Czys and Weaver, 1987).

However, the absence of explosive growth may also result from treatment occurring too late in the echo history to be of value. To better address this question, the design of the 1989 field program included a seeding aircraft with instrumentation to detect microphysical and dynamic properties of the cloud at treatment. Knowing the buoyancy and the updraft speed of the cloud, as well as the amount of cloud above the treatment level and the echo history may allow a better prediction of the expected post treatment growth for both natural and seeded clouds.

The within storm variability of echo core characteristics at the time of treatment, may be related to the very dry conditions above 4.5 km, on 6 August. It also may indicate that while visually the actively growing cumulus clouds are similar in appearance, they may have distinctively different cloud properties depending on their age and the progress of precipitation growth process at the time of treatment. This is suggested by the observations of Koenig (1963). Such differences will likely result in different responses to cloud seeding. Radar measurements in conjunction with in-situ aircraft measurements of hydrometeor size and phase distributions also may provide a basis for the prediction of individual cloud response to seeding.

6.3 Experimental unit

Study of the echo core characteristics has provided a means to examine the earliest dynamic response of the cloud to glaciogenic seeding. It is important to note that much of the rainfall from these clouds occurred following the time when the echo cores had merged with newer cores or with the more mature, less actively dynamic portion of the storm, so that they could no longer be distinguished. This is observed in many severe storms, as well as in non-severe storms (Westcott and Kennedy, 1989). Thus, it is difficult to derive a straight forward echo core versus rainfall relationship. Additionally, as suggested by Simpson (1980), the seeding effect may result in enhanced downdrafts, leading to enhanced low-level convergence and the development or invigoration of adjacent clouds. Because the individual clouds are not necessarily independent at least for rainfall computations, the experimental unit must encompass an area that includes storms cells immediately adjacent to the treated clouds.

As in past projects, the initial approach to the rainfall studies was designed on an area wide basis. However, a drawback to that definition of the experimental unit is that much of the area included in the analysis may not be affected by the seeding agent, thus reducing the likelihood of detecting an effect. In order to balance these two effects, the experimental unit has been refined and is similar to one developed for the Southwest Texas Cooperative Project Rosenfeld and Woodley (1989). In our case, the unit will be defined as a circle with a 28 km radius surrounded by a 28 km buffer, centered on the weighted mean position of the treated clouds, and moving with the mean cell motion (Changnon, et. al., 1989). An advantage to this approach is that it may be possible to have more than one experimental unit (upwind and well separated in time and space) during a given rain period, thus providing a larger experimental sample. However, even without a second unit that could serve as a control, in most cases rainfall coverage is not confined to a small area and radar derived rainfall trends within the experimental unit could be compared with that outside the unit.

Finally, to assure that the mean echo parameters discussed in earlier sections are representative of the experimental unit, a large number of clouds need to be sampled and the distribution of values must be considered as well. This would be consistent with typical operational seeding programs, where seeding is applied to as many clouds as possible.

7. CONCLUSIONS

The structure of 19 cumuliform clouds occurring during 3 convective periods on two summer days in 1986 were examined using 10-cm reflectivity measurements. In particular, the growth of these echoes in terms of area, height and reflectivity was determined so that they could be evaluated for their usefulness as stratification criteria to aide in distinguishing cloud seeding effects from differences due to natural meteorological conditions.

The two seeded periods occurred during the mid to late afternoons of August 6 and 26, and the non-seeded period occurred on the morning of August 26. While the seeded echoes in the mean were longer-lived and larger in area than the non-seeded, it was felt that any seeding effect present would have been outweighed by overriding differences in the local environmental conditions. Because of the variety of conditions under which summer convection can develop in the Midwest, the strength of the dynamic forcing and the airmass characteristics during any given rain period must be taken into account in the evaluation procedures. Echo height and area parameters at the time of treatment appeared to be related to the maximum value attained by the echo cores of those same parameters, suggesting they may be used as a means of normalizing the experimental units.

Additionally, it was found that echo core growth rates following treatment for the small sample of both seeded and control cases were positive but slower than the rates prior to treatment. This suggests that instead of explosive growth sometimes expected with dynamic cloud seeding, it may be that cloud seeding in this area of the country results in a decrease in the reduction of growth rates.

It also was found that to make inferences regarding a causal relationship between cloud seeding and rainfall, it was necessary to account for the influence of neighboring clouds. In addition, because only a small portion of the target area is treated, and because of the small number of experimental units accumulated using the synoptic rain period as the sampling unit, the experimental unit was redefined as suggested by the work of Rosenfeld and Woodley, 1989.

Finally, while radar measurements provide general growth characteristics, they alone will not resolve the basic questions relating to the potential usefulness of cloud seeding in this region of the country. Coordinated aircraft and radar measurements are warranted to better address the many questions regarding the dynamic seeding hypothesis.

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APPENDIX Table of Individual Echo Core Characteristics

echo core no.	echo characteristics at first detection: peak refl (dBZ)	ht of peak refl (km)	echo top ht (km)	peak area >15 dBZ (km2)	peak area >35 dBZ (km2)	echo characteristics at first treatment: time since first dtctn (min)	peak refl (dBZ)	ht of peak refl (km)	echo top ht (km)	peak area >15 dBZ (km2)	peak area >35 dBZ (km2)	time since first dtctn at6km (min)	refl at 6km (dBZ)	area >15 at 6km (km2)	echo characteristics at time of maximum value: time to reach max refl (min)	max refl (dBZ)	time to reach max top (min)	max top ht (km)	time to reach maxarea dBZ>15 (min)	max area >15 dBZ (km2)	time to reach maxarea dBZ>35 (min)	max area >35 dBZ (km2)
date= 8/ 6/86						treatment time period= 1613 - 1705									experimental unit= 1							
1	22	1.0	3	5	0	12.0	55.0	2.0	7.0	27.0	14.0	3.0	23	10.0	12.0	55	12.0	7	16.5	31	16.5	18
2	17	2.0	4	4	0	20.0	56.0	3.5	8.0	55.0	26.0	14.0	48	21.0	20.5	57	29.0	11	24.5	71	24.5	44
3	25	3.0	5	8	0	14.0	35.5	1.5	7.0	38.0	2.0	5.5	16	2.0	21.0	40	15.0	7	21.0	59	21.0	4
4	57	6.0	2	32	18	M	57.0	2.0	6.0	45.0	25.5	5.0	22	11.5	M	60	M	12	M	88	M	48
5	15	3.0	4	3	0	20.0	47.0	2.5	7.0	41.0	16.0	10.0	25	1.0	24.0	52	20.0	7	27.0	76	28.5	22
date= 8/26/86						treatment time period= 0958 - 1133									experimental unit= 2							
6	28	4.0	5	4	0	8.5	54.0	5.5	9.0	18.0	6.5	7.5	52	14.5	14.5	68	M	M	14.5	25	14.5	10
7	25	6.0	6	3	0	0.0	25.0	6.0	6.0	3.0	0.0	2.0	25	3.0	16.0	52	16.0	10	33.0	40	20.0	17
8	07	4.0	5	1	0	3.5	24.5	4.5	6.5	10.0	0.0	2.5	21	9.0	13.0	45	5.0	7	30.0	56	16.5	11
9	22	6.0	7	10	0	2.5	33.5	6.0	8.0	16.0	2.5	4.5	35	15.5	9.0	62	18.0	12	26.5	36	14.0	16
10	15	5.0	5	1	0	6.5	38.0	4.0	6.0	13.0	2.5	5.0	27	9.0	18.0	45	14.0	7	30.0	33	22.0	8
11	15	6.0	6	1	0	1.0	18.0	6.0	6.5	3.5	0.0	1.0	18	1.0	13.0	45	5.0	7	21.0	30	17.5	6
12	37	5.5	8	23	1	0.0	37.0	5.5	8.0	23.0	1.0	3.0	33	20.0	8.0	57	8.0	11	16.0	83	12.5	35
13	32	5.0	6	6	0	8.0	52.0	4.0	8.0	22.0	11.5	11.0	42	22.0	8.5	54	11.0	9	16.0	31	16.0	15
date= 8/26/86						treatment time period= 1558 - 1828									experimental unit= 3							
14	25	4.5	6	11	0	7.5	47.5	5.0	8.0	35.0	11.0	8.0	39	24.5	18.0	57	21.0	11	24.0	65	18.0	27
15	22	4.0	7	7	0	5.0	48.0	4.5	9.5	32.0	13.5	5.5	46	32.0	7.0	57	15.0	13	36.5	84	15.5	29
16	27	3.0	4	3	0	15.0	42.0	3.0	M	13.0	2.1	7.0	26	5.0	23.5	55	M	M	48.0	46	48.0	19
17	20	3.0	5	8	0	9.0	47.0	4.5	7.0	37.0	11.0	5.0	45	18.0	13.5	57	21.5	13	29.5	73	21.5	45
18	32	4.0	4	2	0	9.5	50.0	3.5	7.5	40.5	16.0	7.0	42	20.0	15.5	52	32.0	11	24.0	82	20.0	36
19	30	4.5	6	4	0	10.0	53.5	3.5	7.5	25.0	14.0	11.5	42	12.0	8.0	55	8.0	8	19.5	38	12.0	16

M : missing
km2 : km x km

"REVIEWED"

8. REFERENCES

Ackerman, B. and R. Y. Sun, 1985: Predictions by two one-dimensional cloud models: a comparison. J. Clim. Appl. Meteor., 24, 617-628.

Ackerman, B. and N. E. Westcott, 1986: Midwestern convective clouds: a review. J. Wea. Mod., 18, 87-94.

Braham, R. R., Jr., 1986: The cloud physics of weather modification. Part I - Scientific basis. WMO Bulletin, 35, 215-222.

Braham, R. R., Jr., 1986: The cloud physics of weather modification. Part II - Glaciogenic seeding for precipitation enhancement. WMO Bulletin, 35, 308-315.

Braham, R. R., Jr., 1964: What is the role of ice in summer rain-showers? J. Atmos. Sci., 21, 640-646.

Byers, H. R., L. J. Battan and R. R. Braham, Jr., 1953: Observations and measurements on natural and artificial rain from convective clouds. Proc. Toronto Meteor. Conf., 262-268.

Changnon, S. A., Jr., 1985: Illinois weather modification program: PACE. Preprints, 10th Conference on Planned and Inadvertent Weather Modification, AMS, Boston, 315-319.

Changnon, S. A., Jr., 1978: Vertical characteristics and behavior of radar echoes. In Summary of METROMEX, vol. 2. Causes of Precipitation Anomalies. ISWS Bulletin 63, 274-279.

Changnon, S. A., Jr., 1976: Effects of urban areas and echo merging on radar echo behavior. J. Appl. Meteor., 15, 561-570.

Changnon, S. A., Jr., R. R. Czys, F. A. Huff, E. A. Mueller, J. B. Nespor, R. W. Scott and N. E. Westcott, 1989: Operations Manual for the Precipitation Augmentation for Crops Experiment - 1989. ISWS, 56 p.

Changnon, S. A., Jr., and F. A. Huff, 1987: The design of the 1986 Illinois weather modification experiment. J. Wea. Mod., 19, 77-81.

Czys, R. R., 1988: Microphysical characteristics of warm based cumuli: Observations at -10 C. Preprints, 10th internat. Conf. on Cloud Physics, Deutscher Wetterdienst, FRG, 64-69.

Dennis, A. S., A. Koscielki, D. E. Cain, J. H. Hirsch, and P. L. Smith, Jr., 1975: Analysis of radar observations of a randomized cloud seeding experiment. J. Appl. Meteor., 14, 897-908.

Dixon, M. J., and G. K. Mather, 1986: Radar evaluation of a randomized rain-augmentation experiment - some preliminary results. Preprints, 10th Conf. on Wea. Modif., AMS, Boston, 139-141.

Gagin, A., D. Rosenfeld, and R. E. Lopez, 1985: The relationship between height and precipitation characteristics of summertime convective cells in south Florida. J. Atmos. Sci., 42, 84-94.

Huff, F. A., 1971: Distribution of Hourly Precipitation in Illinois. ISWS Circular 105, 23 pp.

Koenig, L. R., 1963: The glaciating behavior of small cumulonimbus clouds. J. Atmos. Sci., 20, 29-47.

Kraus, T. W., Jr., R. T. Bruintjes, J. Verlinde, and A. Kahn, 1987: Microphysical and radar observations of seeded and non-seeded continental cumulus clouds. J. Clim. and Appl. Meteor., 26, 585-606.

Mathews, D. A., 1981: Natural variability of thermodynamic features affecting convective cloud growth and dynamic seeding: A comparative summary of three High Plain sites from 1975 to 1977. J. App. Meteor., 20, 971-996.

Morrison, B. J., G. K. Mather, and G. Morgan, 1986: Aircraft observations of target turrets on multicellular storms showing radar response to dry ice seeding. Preprints, 10th Conf. on Wea. Modif., AMS, Boston, 204-209.

Ochs, H. T., III, and R. J. Semonin, 1979: Sensitivity of a cloud model to an urban environment. J. Appl. Meteor., 18, 118-1129.

Orville, H. D., 1986: Review of Dynamic Mode Seeding of Summer Cumuli. In Meteor. Mono. 21(43), AMS, Boston, p. 43-62.

Rosenfeld, D. and W. L. Woodley, 1989: Effects of cloud seeding in west Texas. J. Appl. Meteor., 28, 1050-1080.

Simpson, J., 1980: Downdrafts as linkages in dynamic cumulus seeding effects. J. Appl. Meteor., 19, 477-487.

Simpson, J., G. W. Brier, and R. H. Simpson, 1967: Stormfury cumulus seeding experiment 1965: Statistical analysis and main results. J. Atmos. Sci., 24, 508-521.

Simpson, J., and W. L. Woodley, 1971: Seeding cumulus in Florida: new 1970 results. Science, 172, 117-126.

Simpson, J., and A. S. Dennis, 1974: Chapter 6. Cumulus clouds and their modification. Weather and Climate Modification, John Wiley and Sons, Inc., N.Y., 229-281.

Smith, P. L., J. R. Miller, Jr., J. M. Hirsch, and H. D. Orville, 1986: Dynamic versus microphysical effects of seeding: some cloud model and radar observations. Preprints, 10th Conf on Wea. Modif., AMS, Boston, 175-178.

Towery, N. G. and S. A. Changnon, Jr., 1970: Characteristics of hail producing radar echoes in Illinois. Mon. Wea. Rev., 98, 346-3553.

Westcott, N. E., and P. Kennedy, 1989: Cell development and merger in an Illinois thunderstorm observed by Doppler radar. J. Atmos. Sci., 46, 117-131.

Westcott, N. E., 1989: Properties of echoes at first detection resulting in - multicelled rainstorms. Preprints, Internatl. Symposium on Hydrological Applications of Weather Radar., Univ. of Salford, Salford, paper E-2, 8 p.

Westcott, N. E., 1987: Radar Echo Studies. In Chapter 4. Precipitation Augmentation for Crops Experiment: Exploratory Research, Year 1. Final Report for NA-86RAH05060, ISWS, 61 p.