<u>FINAL REPORT</u>

THE PRECIPITATION AUGMENTATION FOR CROPS EXPERIMENT: PHASE II

by

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I. INTRODUCTION

This report serves as the Final Report on Cooperative Agreement NAH87RAH07077 for the period of 16 June 1987 through 15 August 1988. The objectives/tasks of the project were as follows:

A. A broad objective was to continue exploratory field testing of certain aspects of a dynamic modification hypothesis for individual clouds generally developing into cloud clusters or already in a cluster. This objective was to include the design and planning for a field effort in late summer 1987, the actual field operations, and the ensuing analysis of the data collected. The specific tasks/objectives were:

   1. To measure the rate and duration of the conversion of water to ice in seeded and non-seeded control clouds;

   2. To determine if seeded cells (convective entities), defined in an objective manner, are enlarged vertically in comparison with non-seeded clouds, and whether this vertical growth produces increased echo intensity; and

   3. To discern if seeded entities stimulate interactions between adjacent clouds.

B. To continue studies of important effects of summer precipitation modification through models and field trials.

By late spring of 1987, it became apparent that the planned field effort for the late summer of 1987 would be an unwise choice, relative to conducting a more major field effort in 1988. The reasons for the delay included the fact that the HOT weather radar could not be ready for 1987 operations because the new signal processor would not be received from the manufacturer in time for the 1987 operations; second, the CHILL radar could not provide the desired differential reflectivity measurements, and further the CHILL radar would be in North Dakota limiting its presence to only August 1987; and needed funding for support of the T-28 cloud penetration aircraft was not available. For these reasons we decided to not launch a very limited late summer field operation in 1987, and to the concentration of our efforts into having a larger field program in 1988 in concert with the 3CP0 program. At that time we would be able to have both the HOT and CHILL radars operational for many studies of ZDR capability, dual doppler measurements, etc. As a result, the major dimensions of the 14-month effort covered under this Cooperative Agreement consisted of research activities in two areas; the planning for the major field experiment expected during the summer of 1988; and the extensive provision of informational assistance about weather modification to the general public, the scientific community, and Midwestern decision makers.

Two major events had a profound effect on what occurred during this project. As noted above, a portion of the project activities and funding were to be devoted to a major field experiment of clouds involving aircraft, radars, and other facilities during the summer of 1988. Unfortunately, the funding support for the companion effort needed to jointly support the sizable field effort which was to have begun during May 1988, could not be resolved in sufficient time to allow launching and conduct of the extensive (estimated cost $450,000) field effort. NOAA/ERL attempted to assist in this effort by providing $100,000 in July 1988, but it was too late to resurrect a major field effort. The final funding portion ($400,000) was received late in August 1988.

The second event that affected the dimensions of the 14-month project was the major spring-summer drought of 1988 in the Midwest. This drought developed during March-April 1988 in the Midwest. It consisted of much above normal maximum temperatures and very deficient precipitation throughout the spring and summer of 1988. This event brought great interest in weather modification and frequent requests for information and assistance in the Midwestern region concerning the status and use of weather modification. PACE staffing served as experts for government decision makers, agribusinesses, and the general public. Numerous requests from the news media from the Midwest and throughout the nation were handled. Weather modification and PACE were discussed by staff on three television programs including the Weather Channel. Sizable assistance was provided to the State of Ohio in their decisions and launching a seeding project (which was initiated in July 1988).

The result of these events and alterations in the proposed scope of the 14-month project leads to major conclusions. First, there is still an intense interest and need for information on weather modification capabilities in the Midwest. Secondly, the sizable field project planned for the summer of 1988 had to be cancelled. It is being planned for the summer of 1989, if the desired equipment can be obtained. How the 1989 field project will be conducted will depend on the status of the on-going drought. It is conceivable that the field operations in 1989 should be tailored to serve the needs and the opportunity afforded by drought conditions, if they continue.

A major accomplishment of this 14-month effort related to the extensive research being pursued on many topics. The highlights of the activities and key findings are summarized herein. However, many of the PACE findings are to be found in the numerous project publications. We are proud to report that during this project 23 scientific papers were published (or are in press), and 14 of these are in refereed prestigious journals. In addition, four major reports were generated dealing with downwind effects, basin modeling of rainfall, and drought.

In the following sections, each section is independent with its own set of tables and illustrations numbered 1 through X. Hence, the report has several table l's and figure l's.

II. WEATHER EFFECTS RESEARCH

The research involving effects of altered weather due to precipitation modification has moved forward in three studies. These included: 1) the testing of altered precipitation on controlled agricultural plots, 2) the regional-scale economic modeling of effects of additional precipitation on corn and soybean yields and livestock in the Midwest, and 3) development and testing of a basin-scale hydrologic model capable of monitoring the daily routing of rainfall and other hydrologic processes.

FIELD EXPERIMENTS TO EVALUATE THE EFFECTS OF RAINFALL ENHANCEMENT ON CORN AND SOYBEANS (Hollinger and Changnon)

Introduction

Determination of the value of added water on crop yields in Illinois and in turn to the state's economy has come from the use of crop yield-weather models based on historical records of yields and past weather conditions. These models rely on a variety of assumptions that make their results less than reliable in applying them to real world situations. Therefore, actual field experiments were established in 1987 and 1988 to evaluate the effects of differing amounts of additional rainfall on final crop yield. The plots are located under specially constructed rain shelters designed to be moved over the plot area during a rain event to exclude natural rainfall from the plots. When no precipitation is occurring, the shelters are moved off the plots so the plants experience the same weather as naturally growing crops in the region. An overhead sprinkler irrigation system is installed in the shelters so the time, amount, and quality of water applied to each plot can abe controlled. This system allows the establishment of an experimental design to test the validity of the model results in an actual field situation.

A description of the experimental method and treatments used in 1987 can be found in Changnon and Hollinger, 1988 (see publications). The 1988 experiment was the same as the 1987 with the exception that the corn and soybean plots were planted on 12 May and plant populations were over planted and then thinned to the desired 24,000 plants/ac and 150,000 plants/ac for corn and soybeans, respectively.

Results: 1987

Treatments in the movable shelter were started on 5 June 1987. At the time the treatments were started, the corn and soybean crop had just emerged. During the vegetative stage of growth the weather was hot and dry. Some differences in heights of the plants in different treatments were observed.

On 30 July the Urbana area experienced a 100-year storm when 114.3 mm of rain was received during a 4-hour period. At the time of the storm, the movable shelter was over the plots and no rain fell on the plots. However, due to the rapid rainfall rate, and the lay of the land, the plots were flooded for approximately 3 hours. During this time the soil moisture profiles of all the plots were recharged. At the time of this storm the corn was silking and the soybeans were beginning to flower. Therefore, during the critical corn growth stage of flowering the dry plots were recovering from any stress they were exposed to. As a result of the storm, all water treatments from 30 July to 9 August were suspended. During this interval, all rain was excluded from the shelter. These events provided a unique experiment relative to the effect of droughts during the vegetative growth stages of corn and soybeans.

Final yields were determined by harvesting the center two rows of each plot, weighing the reproductive and vegetative parts of the plants, adjusting the weight to 15.5% moisture and calculating the yield on a per hectare basis.

At the time the corn plots were harvested, the number of plants in the harvest area, the number of ears harvested, the number of rows per ear, and the number of kernels per ear were recorded. After the ears were shelled, the average weight per kernel and ear were calculated. The yield components of the soybean crop recorded were: (1) number of plants harvested; (2) number of pods per plant; (3) number of pods with at least one seed greater than 5 mm in diameter; (4) number of seeds per plant; and (5) the average weight of each seed.

Table 1 contains the change in various corn yield components between the dry, average, and wet summer scenarios, and their respective rainfalls augmented by 25%. The dry and dry plus 25% increased rainfall treatments have the lowest final plant populations. This treatment combination also showed the greatest increase in population between the augmented and corresponding non-augmented treatment. The increased population resulted in a decrease in the grain yield and is reflected in a decrease in the number of kernel rows. The normal and normal plus 25% increased rainfall treatment combination shows n increase in the total grain yield with increases in all the yield components. A decrease in final yield was seen between the wet and wet plus 25% rainfall augmentation treatment. This decrease could be due to increased wetness of the soil. Notice that in all cases, the final kernel eight is greater in the 25% rainfall augmentation treatments. This demonstrates that rainfall augmentation during the grainfill period will result in larger kernels.

Table 2 contains the yield components of the soybean treatments under the mobile shelters. Grain yields were increased by augmentation of the dry and wet season scenarios. The normal rainfall scenario with its corresponding augmented treatment showed a decrease in yield with additional rain. However, in this treatment combination the yields are larger than in either the dry or wet scenarios. In the case of the normal treatment combination the yield reduction is due to decreases in population and in final pod weight. The decrease in population in the dry and dry + 25% treatment combination would normally result in a yield decrease, especially with a decrease in the number of pods per plant. However these yield component losses were offset by a large increase in the pod weight.

The corn experiments in the open shelter (stationary shelter) were unusable due to severe lodging problems early in the season. The soybean yield results are shown in figure 1. In this study soybean yields decreased as total rainfall increased. This may be due to the continuous growth of soybeans on these plots in the previous 4 years resulting in unknown diseases and pests affecting this crop. These results would suggest that any disease would be encouraged by wet conditions.

Results: 1988

The corn plots planted in 1988 are near mid-dent stage. The open plots have ears on most of the plants but appear to be retarded in their development when compared to the plots in the mobile shelter. Since both groups of plots were planted at the same time, this can only be the result of the much drier soil conditions experienced in the open plots. The plants as a whole look very healthy considering the drought and heat stress they have been subjected to. This year, there have been no major insect problems with the corn crop; therefore, yield differences should show the actual affects of the different rainfall treatments.

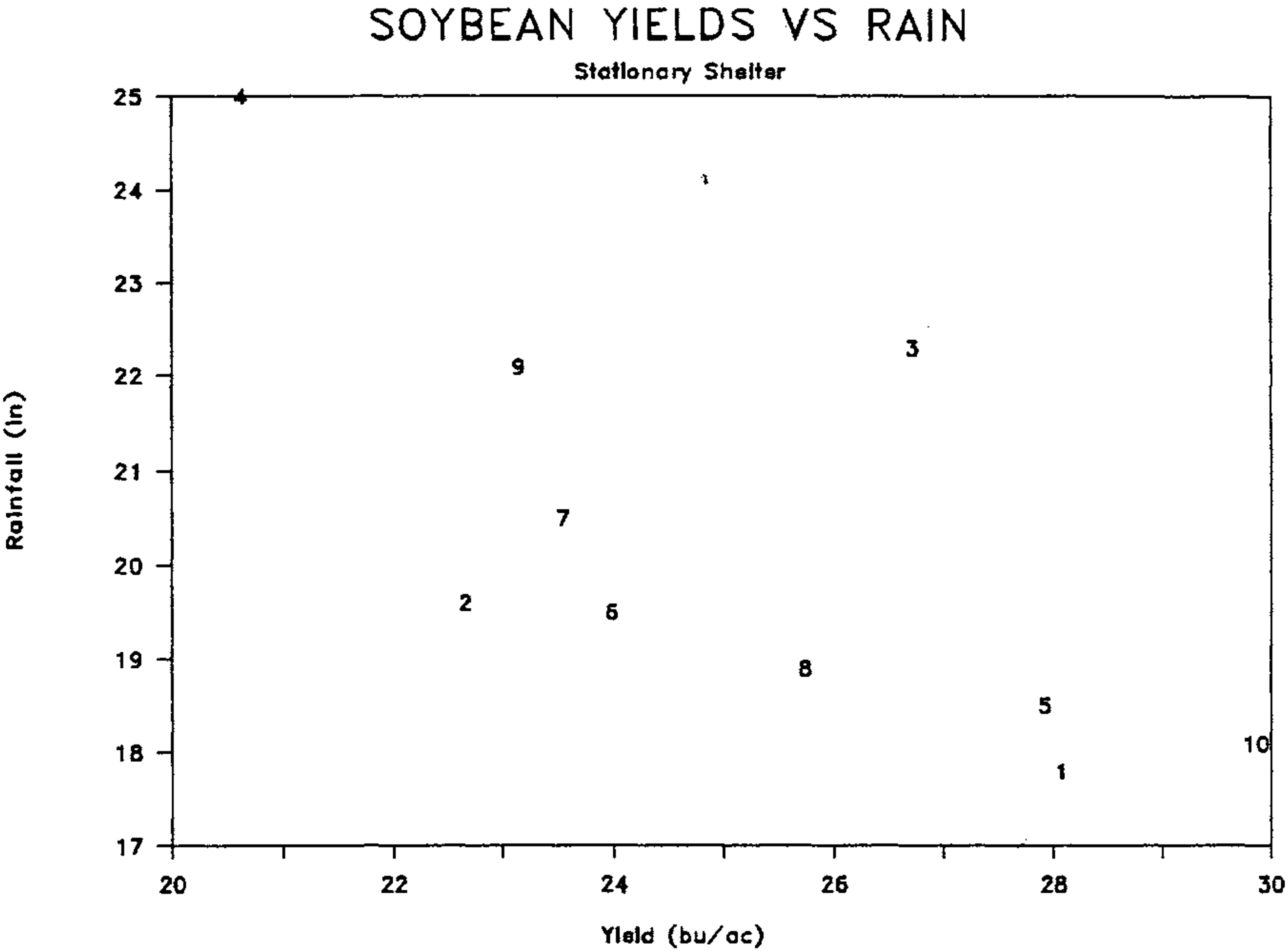

Figure 1. Soybean yield response to total rainfall in the stationary shelter from the 1987 experiments.

The soybean plots have stopped flowering and are in the process of filling the pods and maturing. The plots in the mobile shelter have more pods on each plant than those in the open and also are filling better. Final results of both the corn and soybean experiments for 1988 will be available in early 1989.

Table 1. Corn yield components and change between the augmented and non-augmented dry, average, and wet summer scenarios in the mobile shelters.

Treatment	Population (plants/ha)	Vegetative Mass (Mg/ha)	Grain Yield (Mg/ha)	No. Kernel Rows	No. Kernels/ Row	Kernel Weight (gms)
Dry	77,108	6.0	5.282	12.6	32.19	0.217
Dry + 25%	80,694	6.4	5.084	10.6	33.47	0.223
Difference	13,596	0.4	-0.198	-2.0	1.28	0.006
% Change	17.6	6.7	-3.7	-15.9	4.0	2.8
Normal	82,488	5.9	4.741	11.3	29.89	0.223
Normal + 25%	83,384	6.4	5.869	12.0	32.39	0.226
Difference	896	0.5	1.128	0.3	2.50	0.003
% Change	1.1	8.5	25.2	2.7	8.4	1.3
Wet	83,384	7.3	7.098	13.6	33.35	0.214
Wet + 25%	81,592	7.3	6.562	12.9	31.93	0.215
Difference	-1,792	0.0	-0.536	-0.7	-1.42	0.001
% Change	-2.1	0.0	-7.6	-5.1	-4.3	0.5

Table 2. Soybean yield components and change between the augmented and non-augmented dry, average, and wet summer scenarios in the mobile shelters.

Treatment	**Population (plants/ha)**	**Grain Yield (Mg/ha)**	**No. Pods/ Plant**	**Pod Weight (gms)**
Dry	356,850	2.56	26.1	0.276
Dry + 25%	345,195	2.66	22.0	0.353
Difference	-11,655	0.10	-4.1	0.077
% Change	-3.3	3.9	-15.7	27.9
Normal	359,540	2.82	27.6	0.292
Normal + 25%	353,264	2.80	28.9	2.281
Difference	-6,276	-0.02	1.3	-0.011
% Change	-1.7	**-0.7**	4.7	-3.8
Wet	344,298	2.65	20.8	0.373
Wet + 25%	360,437	2.78	25.5	0.305
Difference	16,139	0.13	4.7	-0.068
% Change	4.7	4.9	22.6	-18.2

AGRONOMIC EFFECTS MODELING FOR MIDWESTERN PRECIPITATION CHANGES (Garcia and Changnon)

Funding for this PACE study lasted approximately two years. The resources were used primarily to employ a research associate and for computation costs. The funding generated several publications and presentations (see reference section).

The project was designed to examine the effect of precipitation enhancement on Midwest agriculture. The research design involved developing an econometric representation of the livestock, corn, and soybean complex. Weather variables were introduced through the agricultural production side of the model. The dynamic effects of changes in precipitation can be traced through the simulation.

The formulation generated in the research is a version of a model used to examine the interaction in the U.S. Feed/Livestock Complex (Offutt and Blandford, 1984). In order to address the primary concerns of this research (i.e., weather feedbacks in Midwest agriculture and regularity in supply), soybeans were incorporated into the demand analysis and the supply side was extended. The procedure used to include the soybean sector was similar to the original model. An important difference in the models comes from the disaggregation of the supply side which permits examination of the effect of temperature and precipitation at the crop reporting district level. Emphasis of this difference was a major focus of the research and awareness of the importance of this regionality question generated the bulk of the publications for this project. Offutt et al. (1985; 1987a; Garcia et al.,1987) examine the importance of the regional supply response in one form or another. Offutt et al. (1985; 1987b; Garcia et al. . 1987) discuss and quantify the importance of disaggregation in supply response when assessing the effects of changing precipitation and temperature. Offutt et al. (1987a) and Garcia et al. use the basic concept of regionality and economic models to identify that the distribution of gains as well as the total gains can be seriously affected as technology (be it weather modification or new high-yielding varieties) is introduced. Garcia and Hollinger (1985) is a more general piece that discusses the importance of considering changing weather in an integrated framework. The presentation (Preprint Volumes) and chapters in the final report were primarily progress reports. The PACE final report of 1987 provides a detailed description of the model. Another manuscript is still in progress. This effort extends the work in Offutt et al. (1985; 1987b; Garcia et al. . 1987) discussed above.

Publications

Garcia, P., S.E. Offutt and M. Pinar, 1985: Methodological Considerations for Assessing the Potential Benefits of Weather Modification in Illinois Agriculture. 17th Conference of Agricultural and Forest Meteorology. Preprint Volume, pp 169-172. Paper presented in Phoenix, AZ, May.

Garcia, P. and S.E. Hollinger, 1985: Modeling Crop and Weather Interactions. Illinois Research. 27, 8-10.

Garcia, P., S.E. Offutt, M. Pinar and S. Changnon, 1987: Crop Yield Behavior: Effects of Technological Advance and Weather Conditions. J. Clim. and Appl. Meteor., 26, 1092-1102.

Garcia, P., S.E. Offutt and S.T. Sonka: Assessing Agricultural Research Strategies. J. Production Agric., Forthcoming. Invited paper presented in the Department of Agricultural Economics at Purdue University.

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Offutt, S.E., P. Garcia and M. Pinar, 1987a: The Distribution of Gains from Technological Advance When Input Quality Varies. Am. J. of Agr. Econ., 69, 321-327.

Offutt, S.E., P. Garcia and M. Pinar, 1987b: Technological Advance, Weather and Crop Yield Behavior. North Central J. of Agric. Econ.. 9, 49-63.

HYDROLOGIC BASIN MODELING (Changnon)

A two-year effort done as part of PACE concerned the development of a basin-scale hydrologic model. It was designed to have the capability of monitoring the routing of daily rainfalls and other hydrologic conditions so as to discern the impacts of additional precipitation from cloud seeding. Simulations of various levels of increased rainfall were used with the model from six actual summers of the recent past, including three dry summers and three wet summers. This endeavor was brought to a successful conclusion and two reports summarizing the model and the effects studies were prepared, along with a scientific paper (see publication section).

III. ATMOSPHERIC RESEARCH AND PLANNING

PACE 1986 RESULTS: RADAR CHARACTERISTICS OF SEEDED AND CONTROL ECHOES IN ILLINOIS (Westcott)

1. Introduction

During July and August 1986, a field experiment was conducted in central Illinois as part of the exploratory phase of PACE. The experimental design . involved randomized cloud seeding and the use of radar data, some cloud microphysical aircraft data, and synoptic scale meteorological data as evaluation tools (Changnon, 1985; Changnon and Huff, 1987). 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, further compounding the difficulty in finding a seeding effect. Treatment with silver iodide (AgI) flares occurred during two of these flights with placebo flares on a third flight.

In all, 30 treatment passes were made through a total of 20 clouds with the intent of enhancing precipitation through dynamic seeding. It is postulated that the injection of seeding material (AgI) into the updraft near the top of a vigorous cloud containing a significant amount of supercooled water will cause glaciation to occur sooner in the life of a cloud and at a lower altitude. This then would result in the rapid release of latent heat, warming of the cloud, an increase in buoyancy and thus an enhancement of the vertical circulation, ultimately leading to an increase in the area, height, duration and rainfall production of the cloud (Braham, 1986a; Braham, 1986b; Simpson, 1980). By the very nature of this seeding technique, i.e., treating clouds that are selected because they are vigorously growing and thus likely to produce rain, seeding effects are difficult to detect.

An analysis based on radar reflectivity measurements determined that individual echo cores could be associated with the treated clouds, even near the treatment level at the time of treatment. Following from the initial dynamic seeding hypothesis, the seeding effect should result from the rapid release of latent heat and be manifested by enhanced vertical and horizontal growth, which should be easiest to detect in the behavior of the individual cores. It is assumed that AgI is so dispersed that by the time it has reached adjacent clouds, it is ineffective in releasing large amounts of latent heat. Thus, echo cores adjacent to the treated echo core but within the same echo, and adjacent echoes have been eliminated from this study, as their inclusion in the sample would likely mask any observable seeding effect. Dynamic effects postulated in the later steps of the seeding hypothesis which result from cell interactions (Simpson, 1980), are beyond the scope of this study and are not addressed.

Thus, the approach here has been to study the growth characteristics of the individual treated cores employing interpolated reflectivity measurements, much as in the Gagin, Rosenfeld, Lopez (1985) study. The objectives of this study are: 1) to determine whether discernible differences occurred in echo core characteristics between experimental units, and if so, whether these differences could be related to the differences in the general environment and/or possibly due to seeding effects; 2) to explore the usefulness of a variety of parameters related to the growth habits of clouds, in evaluating cloud seeding results. The small sample size whether considering the three experimental units or the 20 individual treated clouds, has precluded comment regarding the possibility of a seeding effect. However, the results from this first study have provided guidance in refining the PACE experimental field design, and in the development of evaluation criteria and analysis procedures.

2. Data Source and Methodology

Field Operations

The project operational center was located at the NSF/ISWS CHILL radar site in east-central Illinois (CMI). During the field program, 10-cm reflectivity data were collected at 512 range bins, each representing a 300 m deep (1° wide) disk, out of 150 km. The radar was operated in a 360° 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°C level was accomplished by a Cessna 421C Golden Eagle III aircraft with 20 gram AgI or placebo pyrotechnic flares. These flares were released in-cloud, but near cloud top where liquid water concentrations neared 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}. Aircraft positions were computed by both a Loran C and a VOR/DME system.

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. The location of the echo associated with the last cloud on August 26, could not be determined with any certainty and thus it was omitted from the analysis, leaving 19 echoes studied.

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 the treated clouds were manually tackled, 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 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 (reflectivities >15 dBZ), at the treatment time, and at the time the maximum value of a particular parameter was reached, 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 nd could have been underestimated by 0 to 5 minutes. 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.

Environmental Conditions

The meteorological environment under which these convective systems developed were described at length in Westcott (1987a, 1987b, 1988) and will not be repeated here.

3. Results Pertinent to Randomization

The randomization was such that the two afternoon units were actually seeded with AgI and the morning unit with the placebo. Due to the nature of the local environmental conditions, it was not unexpected that the morning echoes were smaller and shorter-lived than those from the other two units. A pronounced minimum in rainfall is found at 1000-1400 CDT, in this area of the country (Huff, 1971). It is common in the Midwest for nocturnal storms to diminish in strength in the early morning, possibly as a result of nocturnal storms reaching the end of their natural life cycle. This appears to be the case for the second experimental unit and was likely an overriding factor resulting in the differences in echo characteristics for the morning and afternoon storms. The variety of environmental conditions that can potentially control the dimensions of the clouds from day-to-day, as well as within a single day, indicates that in the Midwest it will be necessary to stratify echo parameters based on larger-scale atmospheric conditions in the evaluation of seeding effects. The use of such meteorological covariates in the design and evaluation of cloud modification has been long recognized (Simpson and Dennis, 1974).

The large number of dynamic and thermodynamic conditions occurring in the Midwest, also suggest that the evaluation can be strengthened by considering both a control and a seeded sample of clouds during any given convective period. With the 1986 design, the difference in the growth habits of seeded and natural clouds could not be distinguished. In addition, because of the variance found within a single thunderstorm line, a number of clouds must be treated in any given experimental unit to insure representative sampling.

4. Highlights of the Echo Core Analysis

The structure of 19 clouds occurring during three convective periods on two days in August 1986 have been examined using 10-cm reflectivity measurements. Treatment with AgI occurred during the two afternoon periods with a placebo during the morning period. The meteorological environment during each period was similar in that the echoes evolved under conditions of warm cloud bases and ample low-level moisture. Some echoes attained maximum reflectivities of 55 dBZ. However, differences in the strength of the dynamic forcing, thermodynamic stability, moisture availability, time of day, among other factors resulted in differences in the height of formation, growth rates, and in maximum areal coverage and top height of the treated echoes. The echoes did grow in a manner consistent with the general meteorological environment. While the small sample size limits comment on seeding effects, this study suggests criteria based on radar reflectivity which may be relevant for the evaluation of future Midwestern modification programs.

An examination of echo characteristics was made at the time of first detection at reflectivities >15 dBZ, and at the time of treatment, to serve as a base for comparison of changes in echo behavior following treatment. Observations indicated that differences in echo characteristics at these times likely either reflected differences in the meteorological environment or could be attributed to the age of the echo at treatment. The main findings in this comparison are as follows:

1. Even though the echoes were first observed at different heights with respect to the freezing level, only small differences were found in the peak reflectivity and area of the echoes at the time of their first detection, with the first echoes from Units 2 and 3 on August 26 taller, and slightly larger and stronger than those from Unit 1 on August 6 (Table 1).

2. At the time of treatment, larger differences between the units were observed in the reflectivity and area of the sample echoes. The echoes which were treated earlier in their growth stage (Unit 2) were in the mean smaller in horizontal extent and had lower reflectivities than those treated later (Table 2). However, the echo top heights at the time of treatment were smallest for Unit 1, even though they were on average 8 minutes older than those of Unit 3, and 13 minutes older than for Unit 2. The difference in height likely was due to differences in moisture availability, stability and dynamic forcing.

3. At the time of treatment, an echo was observed at 6 km, near the level of treatment for all clouds. The size and intensity of the echoes at 6 km appeared to be related more to the echo top height at treatment, rather than to the age of the echo. The stronger dynamic

forcing associated with the cold front probably accounted for the larger echoes at 6 km during Unit 3 (table 3).

The amount of growth following treatment appeared to be directly related to conditions prior to treatment, i.e., the growth still was dependent upon the environmental conditions and upon the time in the echo's development when it was treated. This suggests that in order to detect a seeding effect the post treatment growth rates need to be stratified by echo characteristics at first detection if, as here, this occurs prior to first treatment, or by conditions at the time of treatment. The main findings concerning the amount and rate of growth were:

1. In comparing the three experimental units, the average amount of growth in area and height following treatment were larger for the echoes which were largest on average at the 6 km level at the time of treatment (Tables 3, 4). Additionally, in examining the individual echoes within each experimental unit, the larger the echo at the time of treatment, the larger the maximum area reached.
2. In comparison with pre-treatment growth, the overall growth in terms of reflectivity and area subsequent to treatment appeared to be a function of the height of the initial echo formation and the age of the echo (Tables 1, 2, 4). The percent change in reflectivity and area after treatment was greatest for the youngest echoes found in the morning Unit 2 and least for the oldest echoes found in Unit 1.
3. Both pre-and post-treatment growth rates for all but one echo were positive. However, in many cases (50-75 percent), even for the morning unit when the echoes wee generally treated earlier in their development history, the post-treatment growth rates were smaller

than the pre-treatment rates (Table 5). It may be more appropriate to look for a reduction in the decrease of the growth rates rather than for explosive growth rates sometimes expected with dynamic seeding.

4. The growth rate of maximum reflectivities appeared to be more closely correlated with factors relating to the height of the echo rather than with factors relating to horizontal expansion (Table 6). However, large reflectivities were reached even with shorter echoes in the case of Unit 1, when both the cloud base height and the height of echo formation were lowest, possibly because of adequate time and supercooled water; in the case of Unit 2, for narrower echoes probably because of sufficient instability and moisture aloft.

5. For all units, only the average growth rate for area >35 dBZ was larger after treatment than the before, with 50 percent of the clouds having larger post-treatment rates (Table 5). This may in part reflect the longer time to reach the maximum areal coverage (Table 1). A pattern of reaching maximum values of reflectivity and echo top height first, followed by maximum values of area were found for each unit (Table 6), indicating that echoes continued to expand horizontally after reaching their maximum vertical extent, as indicated by Simpson, 1980.

These results suggest that it may be more appropriate to compare post treatment rates rather than differences between pre- and post-treatment rates. The differences in absolute growth or in the growth rates before and after treatment may be more useful in determining the point in the growth stage of an echo when treatment occurred than in deducing a seeding effect.

While radar measurements can provide the general growth characteristics of treated echoes, they alone will not resolve the basic questions relating to the potential usefulness of cloud seeding in this area of the country. The PACE program intends in future projects to combine in situ cloud physics aircraft measurements with the radar measurements in order to better address the many questions regarding the dynamic seeding hypothesis.

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

Unit No.		Refl. (dBZ)	Ht. of Peak Refl. (km)	Echo Top (km)	Area dBZ >15 (km^2)	Ht of 0°C Isotherm (km AgI)
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	
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	
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

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) of the change in reflectivity, echo height 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 Change After (km)	Area >15 Change Before (km^2)	Area >15 Change After (km^2)	Area >35 Change Before (km2)	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 5. 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 (NPoTL) than pre-treatment rates (zero values not included).

Unit No.		Refl. (dBZ/min)	Echo Top (m/s)	Area dBZ >15 (km^2/min)	Area dBZ >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/.9	1.5/2.8	0.3/1.2	0.5/1.7
	N	4/4	4/4	4/4	4/4
	NPoTL	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
	NPoTL	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
	NPoTL	2:6	2:5	1:6	4:6

Table 6. Sample (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).

		Rate of Increase to Maximum				Time Elapsed to Maximum			
Unit No.		Refl. (dBZ/min)	Echo Top (m/s)	Area dBZ >15 (km^2/min)	Area dBZ >35 (km^2/min)	Refl. (min)	Echo Top (min)	Area dBZ >15 (min)	Area dBZ >35 (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

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CLOUD PHYSICS STUDIES (Czys)

1. Introduction

During July of 1986 exploration began of the mixed phased regions of cumulus clouds at the -10°C level. Over the course of 30 aircraft research hours, observations were taken at 41 natural clouds on 5 days and 3 treated clouds on 2 days. Over 70 penetrations were made in mostly young (tops between 500 and 1500' above flight level), warm-based ($T_B \approx 16$ C) cumulus occurring along the boundaries of organized mesoscale rain systems. Basic reduction and analysis of this data was initiated following the field activities. The initial analysis focused on the spatial variation of microphysical properties over entire penetration of natural, untreated clouds. These data are reported in the 1987 Final Report (Changnon, 1987) and do not include quantitative information about the condensate load from particles larger than about 50 μm.

A major undertaking, ongoing from the end of the 1986 field experiment, was the development of software for classifying and counting particle images recorded by the 2-D particle imaging probes to get estimates of liquid and solid water contents which included the largest precipitation particles. This task has recently been completed. Analysis of cloud microphysical data proceeded with focus on the content of the updraft portions of clouds. Viewing the data in this way gives a sense of the result of precipitation processes primarily driven by adiabatic release of water vapor in the presence of particle interactions. Thus a clearer picture of the available conditions for seeding emerges.

Several major findings are noteworthy from the 1986 data:

1. Direct evidence has finally been obtained for the existence of large amounts of supercooled coalescence rain at the -10°C level, indicating that a large untapped reservoir of energy is available in the form of latent heat for release by imposed glaciation.
2. The amount of supercooled water composing the cloud drop population (i.e., drops with diameter up to 45 μm) was found to be typically less than 0.5 g m^{-3}; somewhat less than the 1 g m^{-3} extrapolated from earlier observation in more vigorous clouds at warmer temperature.
3. In keeping with previous observations it was not unusual to find multiple updraft cores in younger clouds.
4. Almost every young cloud was determined to be negatively buoyant when the total condensate load is included in the calculation.
5. Initial ice concentrations within the updraft were found to be in excess of "typical" ice nuclei concentrations. The ice population was observed to be composed of mostly graupel (and possibly frozen drops). Vapor grown crystals were a rarity.
6. Even though ice concentrations are larger than expected, the mass of the solid water represents only a small fraction of the total condensate load in the updraft. Hence, the clouds are suitable for buoyancy enhancement by glaciogenic seeding leaving open the question as to how this enhancement is communicated vertically through the cloud.

With respect to finding 5 a new hypothesis for the origin of ice in midwestern cumulus was developed. The hypothesis simply stated is: Ice may originate in the warm-based cumulus of the Midwest from collisions between supercooled drizzle and rain drops. Exploratory tests of this hypothesis were conducted in the laboratory in cooperation with the cloud physics laboratory at The University of Chicago. This hypothesis opens a previously unexplored physical process that may prove to explain initial ice content in clouds that develop coalescence rain.

The Cloud Physics Studies of 1987 were successful in defining initial microphysical properties within updrafts. Properties of downdraft regions still need to be examined and information on the total conversion process of water to ice still needs to be gathered using means unrestricted by rapid cloud development to sizes beyond that considered safe for penetration by conventional aircraft. Therefore, future cloud physics studies need to fill in these gaps on the way to understanding microphysical alterations caused by seeding.

Presented in this chapter is a review of the results of the 1987 cloud physics studies. These studies focused on the natural initiation of ice and on the microphysical properties of the updraft portions of 11 different "warm-top" clouds, those having an estimated top temperature no colder than 13°C when penetrated. The clouds in this sample were individual, warm-based cumulus feeding into a larger organization of mature rain clouds easily reaching 30 to 40 kft.

2. Updrafts

An updraft was defined as any region in cloud where measured vertical winds were greater than 1 m s^{-1} for at least 3 continuous seconds. Thus, for a typical true air speed of 90 m s^{-1}, the minimum allowable updraft length was approximately 270 m. Of the 11 clouds, 30 distinct updrafts were identified.

The clouds, although observed during the very early part of their lifetime, were not composed of one extensive updraft, but rather were composed of several distinct regions of raising air surrounded by regions of sinking air. The number of updrafts per cloud ranged from 2 to as many as 6, with most clouds composed of either 3 or 4. As might be expected, larger clouds contained more updrafts. The general rule of thumb for this sample is to expect at least 1 updraft for each 1 km diameter of cloud. Updrafts were typically 600 m long, ranging up to 1530 m with one as large as 2520 m.

Before examining the features of specific updrafts, Fig. 1 is presented to show typical vertical velocity (A), thermal buoyancy (B), and FSSP liquid water content (C) profiles over the entire transect of one cloud penetration. The airplane first entered a region of negative buoyancy with slightly sinking air and then progressed into a region of mostly positive buoyancy and rising air. Liquid water content was fairly uniform over the transect and had an average of about 0.4 g m^{-3}. Three distinct updrafts can be identified: a minor region about 20 s after cloud entry; a major region at 30 s; and a secondary region at about 42 s. The positive vertical motion displayed at about 50 s is due to turning of the aircraft upon exiting of the cloud. Clearly, a cloud with this type of structure can be expected to have a uniform response to uniform treatment, rather internal response will depend upon the local availability of supercooled water and whether that portion of the cloud is negatively buoyant with sinking air or positive buoyant with rising air. Therefore, a larger net positive effect of seeding on buoyancy should be expected from clouds not only with large amounts of supercooled water but also those having the larger extent of positive buoyancy and updraft.

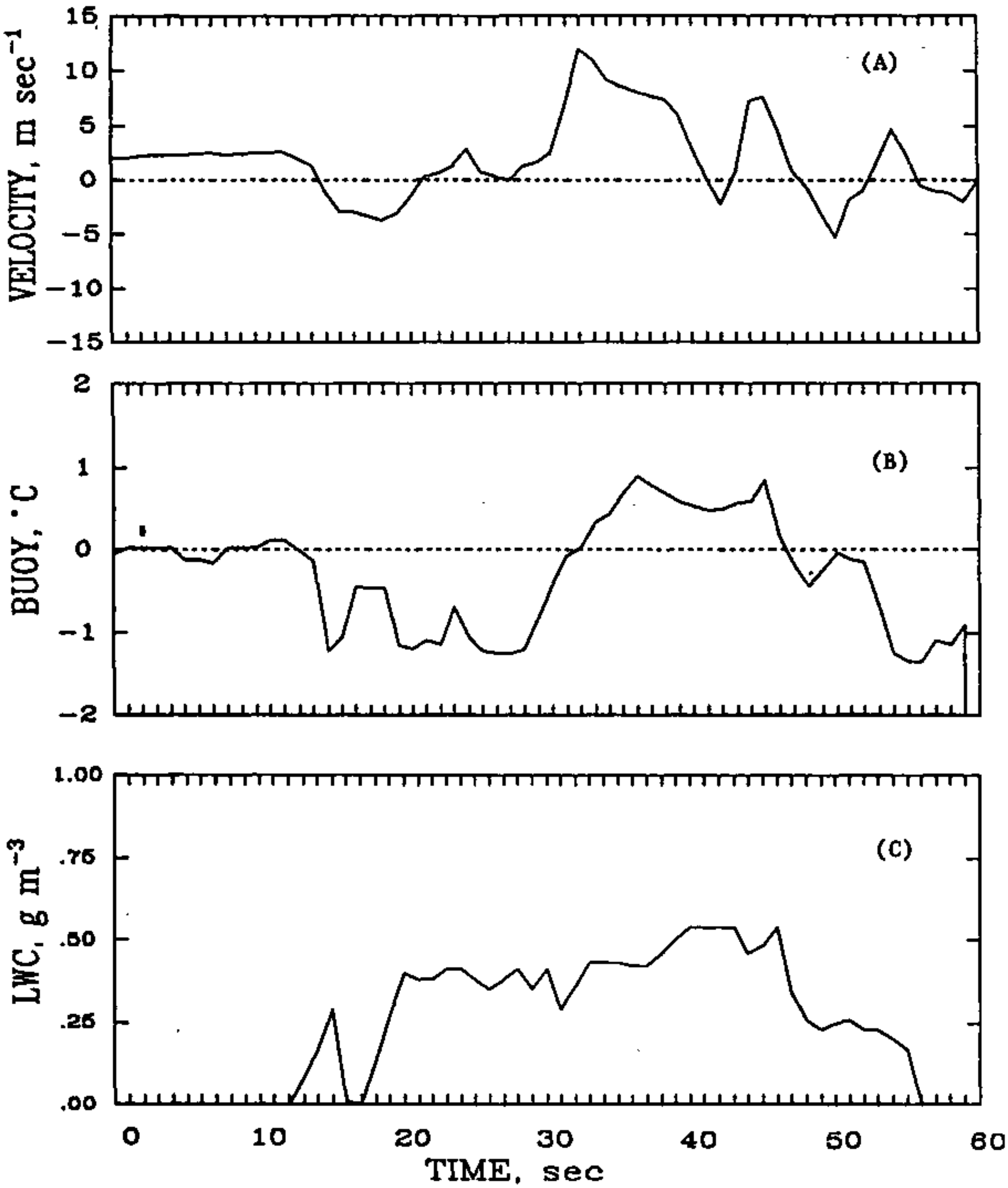

Figure 1. Profiles of vertical velocity (A), thermal buoyancy (B), and FSSP liquid water content (C) typically observed over an entire transect of a cloud penetration.

The distribution of mean velocities for the 30 updrafts is shown in Fig. 2. Some bimodality is evident in this small sample with a major peak, 50% of the data, falling in the 1 to 3 m s^{-1} category and a secondary maximum occurring in the 5 to 6 m s^{-1} category. As can be seen, mean updraft velocities ranged from 1 to 12 m s^{-1} with sampled average of 4.2 m s^{-1}. Thus on average any particle smaller than about 800 μm diameter would still tend to rise with the updraft.

3. Supercooled Water: Cloud Droplets

The amount of supercooled water in that portion of the size spectra representing drops smaller than about 50 lm diameter measured less than expected from previous observations of more vigorous midwestern clouds at warmer temperatures. Liquid water content was measured using a Forward Scattering Spectrometer Probe (FSSP) and hot-wire probe. All updrafts had at least some supercooled liquid water in the form of cloud droplets. The sample average amount from the FSSP is 0.3 g m^{-3} and never exceeded 0.7 g m^{-3}. Liquid water content measured using the hot-wire probe generally coincided with amounts indicated by the FSSP when contents were less than 0.5 g m^{-3}. The distribution from the hot-wire probe is more broadly distributed than that for the FSSP, up to 1.3 g m^{-3} , but averaged nearly the same, 0.4 g m^{-3}.

Figure 3 shows 3 visualizations of the cloud droplet spectra for the cloud profiles shown in Fig. 1. Each successive time interval represents approximately 90 m of horizontal space. The distinctive feature of the spectra is the bimodal structure perhaps resulting from entrainment. Typical of the other cloud droplet spectra, this spectra has a mean overall concentration and diameter of 190 cm^{-3} and 13 μm, respectively, The peak concentration was 55 cm" in the 3 to 6 μm category.

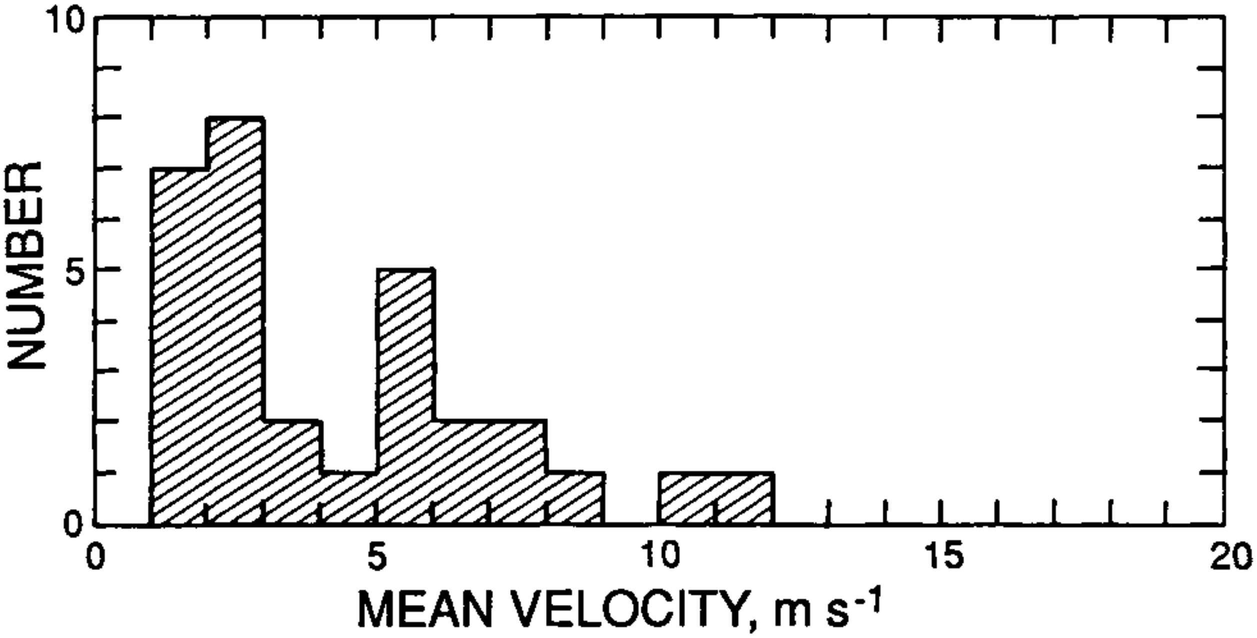

Figure 2. Distribution of mean velocity for 30 updrafts.

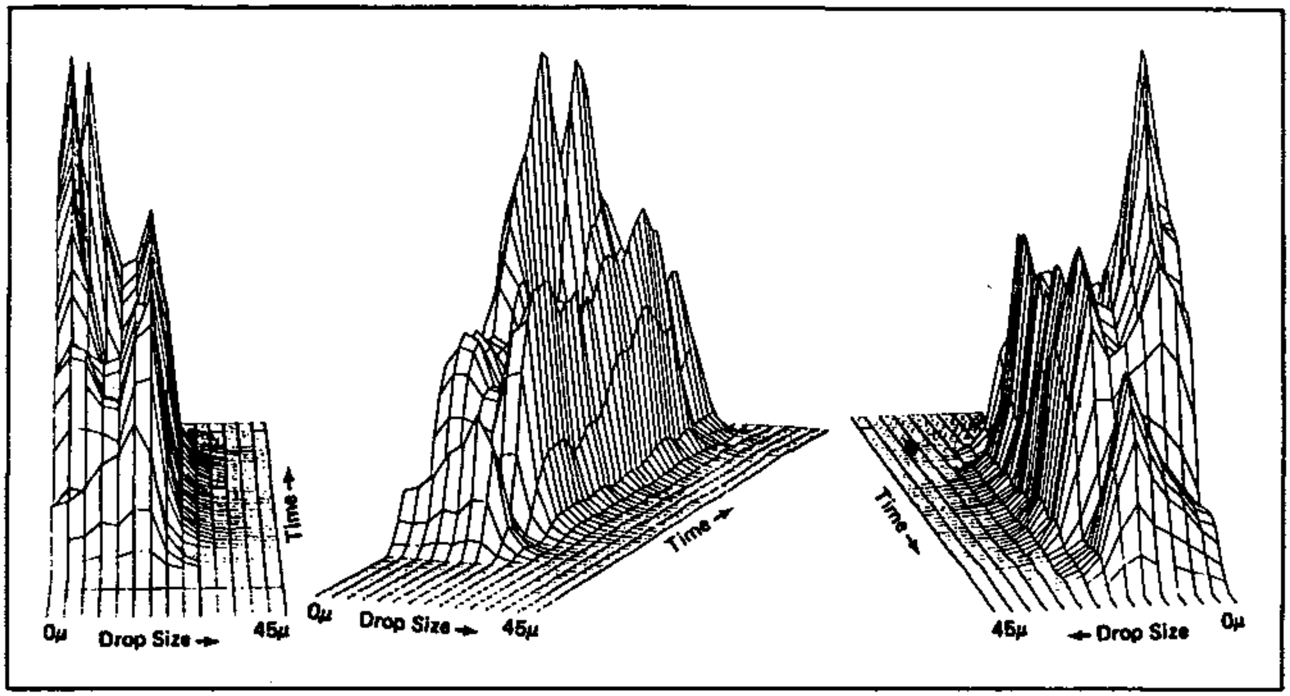

Figure 3. Three visualizations of the cloud droplet spectra from the cloud with profiles shown in Fig. 1.

4. Supercooled Water: Drizzle and Rain Drops

Supercooled water in the form of drizzle and rain drops was found in each of the 30 updrafts. The amount of this water has been estimated using the image records of a 2DC (25 to 800 $\mu\mu m$) and a 2DP (200 to 6400 μm) optical array probe using software developed at the ISWS. This interactive software provides and extremely conservative lower bound to the true amounts present since only complete, axis-symmetric shadows of smooth particles eclipsing at least a several diode width of the illumination beam were allowed to be interpreted as water drops. Errors were made that would lead to an over estimation of water contents form an inability to distinguish between liquid and frozen drops. A forward looking video camera has been useful in identifying regions with large supercooled drops and noticing occasional "drop-out" of 2D data, particularly during times of heavy supercooled rain indicated by splashing on the windshield. Hence, the estimates provided here also have great uncertainty at the lower bound and should be viewed with caution.

The distribution of total supercooled liquid water, based on data from the FSSP, 2DC and 2DP probes, averaged 1 g m^{-3}, ranged from greater than zero to just greater than 6 g m^{-3}, and had most of the data falling in the categories from 0.4 to 1 g m^{-3} . A similar distribution, with average of 1.1 g m^{-3}, is produced if data from the hot-wire probe is used in place of that from the FSSP. As shown in Fig. 4, supercooled drizzle and rain drops made up more than half the total mass of the supercooled water load in almost half of the updrafts observed. Approximately 1/3 of the updrafts had total water content mass composed of 60% or more supercooled drizzle and rain drops.

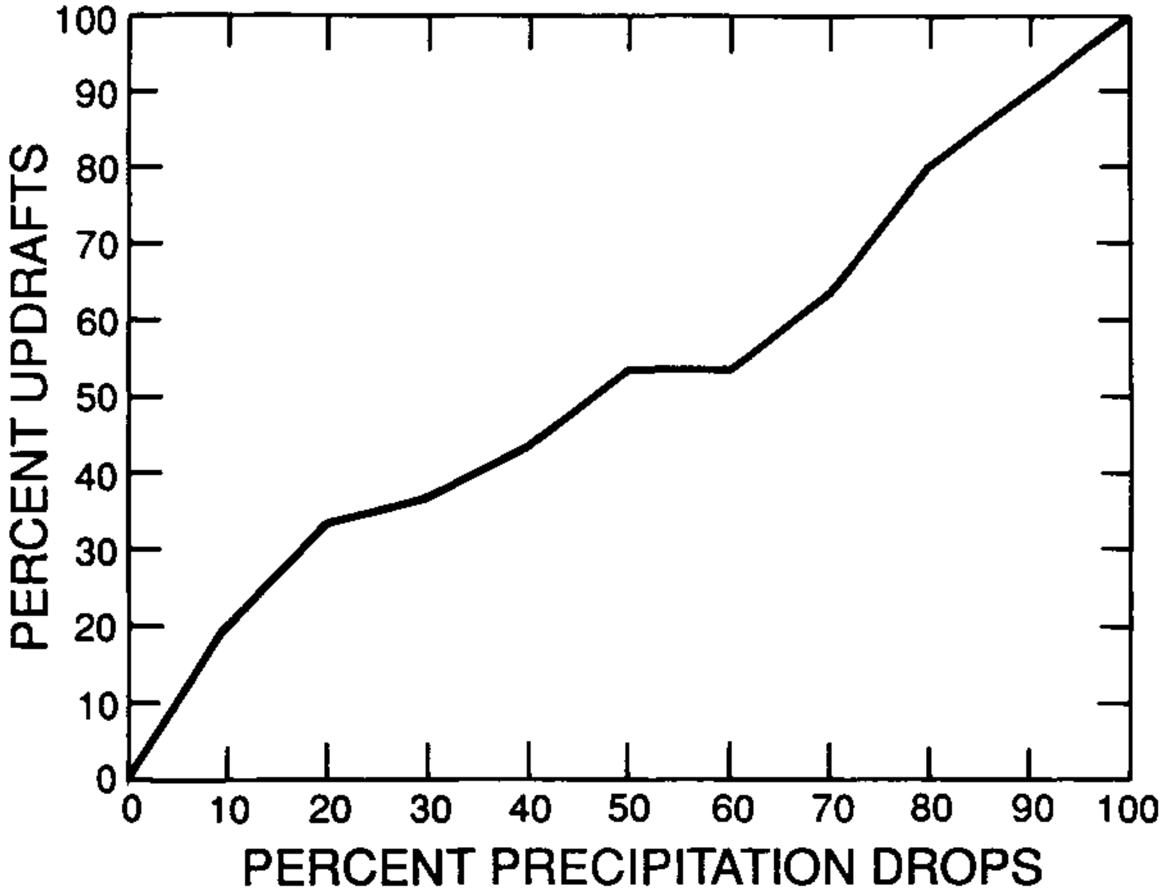

Figure 4. Cumulative distribution of percent mass of precipitation drops in updrafts.

5. <u>Ice</u>

Estimates of the kind and amount of ice in each updraft have also been made using data from the 2D probes. Ice particle images were classified as being either graupel, vapor grown ice crystals or crystal fragments. An image was classified as a graupel particle if it had a complete, quasi-spherical or conical shape with ragged outline that shadowed several diodes by its major and minor axis. Images were classified as ice crystals when their shape resembled either a complete columnar, stellar, dendritic or hexagonal form. An image was classified as a fragment it had the appearance of part of an ice crystal.

A coalescence-freezing precipitation mechanism (Braham, 1986), beginning with the freezing of a few supercooled drizzle or rain drops followed by rimming and ending with the production of precipitation-size graupel particles, appears to have operated in these updrafts. Graupel was the most common ice image in the 2D record. Stellar, dendritic and hexagonal shapes in the image record are absent. The occasional appearance of rectangular solid and hollow images suggest the presence of columnar crystals in low concentration. However, because these images are preferentially oriented with respect to the diode array, they are suspected of being artifacts.

Graupel often occurred in concentrations larger than would be expected from a one-to-one correspondence with ice nuclei. Shown in Fig. 5 are mean graupel concentrations versus size for each updraft determined from the 2DC and 2DP records. For graupel in the 2DC size range, concentrations span from zero to slightly greater than 15 ℓ^{-1}. Fifty percent of the updrafts produced 2DC graupel in concentrations greater than 1 ℓ^{-1}. Graupel concentrations in the DP size range were considerably less than 1 ℓ^{-1}, averaging just .04 ℓ^{-1} and ranging up to .11 ℓ^{-1}. Of the thirty updrafts the 2D records suggest that 5

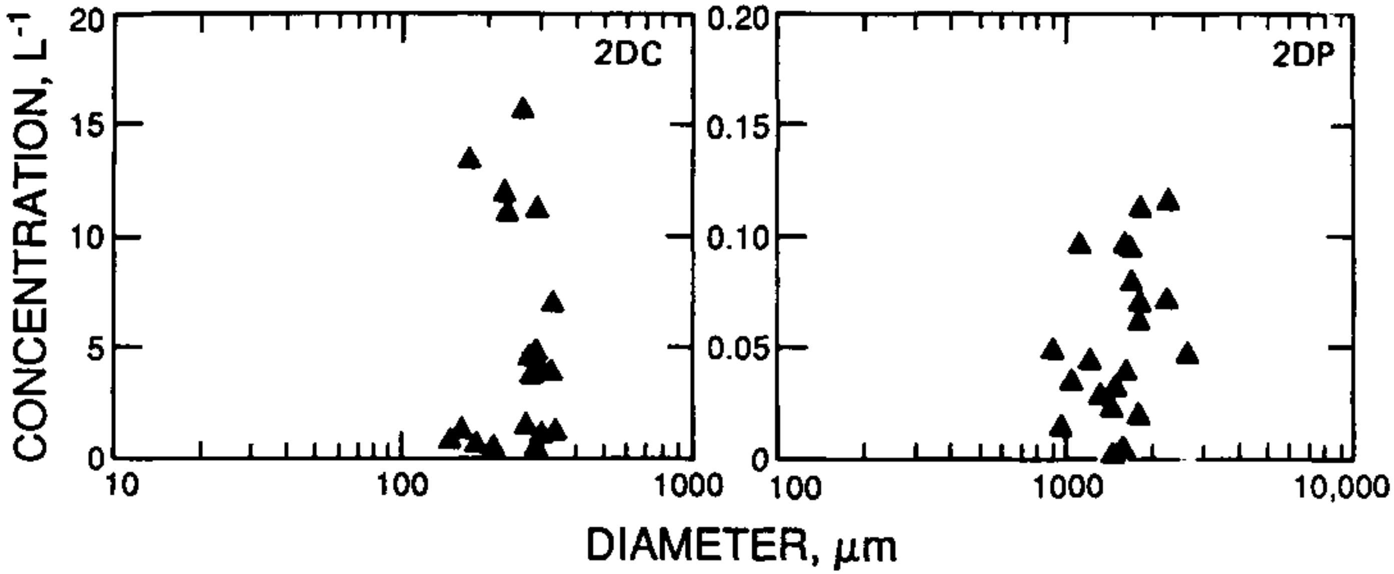

Figure 5. Graupel concentration versus size as determined from the 2DC and 2DP image records.

produced no ice at all, 16 generated ice in both the 2DC and 2DP size range, 4 had only 2DC ice, and 5 originated in the 2DP size range. Aside from the uncertainty introduced by the particle classification scheme, it would be possible to observe only large (2DP) graupel if the process began with the freezing of very large drops.

Although ice was found in concentrations greater than typical ice nuclei concentration, the total mass of water in the liquid state was found to exceed that in the frozen state in almost all of the updrafts. Data from the FSSP, 2DC and 2DP were combined to determine the total liquid water content (LWC) and solid water content (SWC) of each updraft.

As shown in Fig. 6, 26 of the 30 updraf ts had liquid water mass per unit volume of air exceeding the ice mass in the same unit volume. Thus, even though ice process is proceeding more rapidly than a process involving only simple heterogeneous freezing of supercooled drops by ice nuclei, in the initial stage, glaciation does not overwhelm the liquid water in the short time and air parcel has to rise from 0 to -10°C. Thus, with supercooled water accessible in a broad spectrum of sizes, a "cold-rain" collection process must precede and then accompany graupel growth by riming. Recognition that an active collection process involving supercooled drizzle and rain drops has led to the hypothesis that the first few frozen drops may originate directly from drop collisions diminishing the necessity for ice nuclei to trigger glaciation. A laboratory investigation was conducted to explore this idea and is discussed in the next few sections.

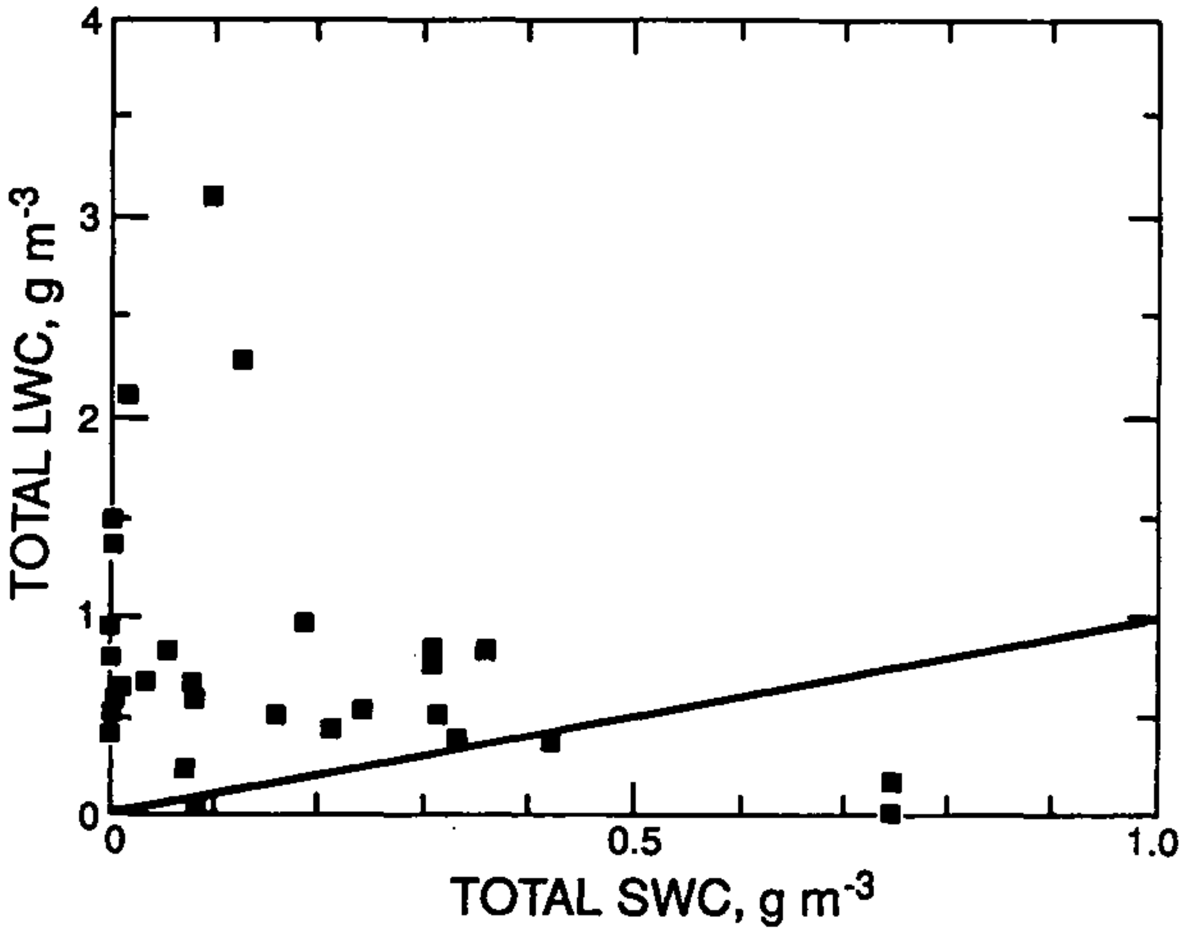

Figure 6. Solid water content versus liquid water content for each of the thirty updrafts.

6. Experiments on the Mechanical Nucleation of Supercooled Water

An exploratory investigation into the supercooling and freezing of distilled deionized water was conducted using a drop-freezing apparatus similar to that described by Hoffer and Braham (1962). In each of four experiments about two dozen millimeter-size drops were placed on a chrome stage smoothly coated with petroleum jelly. A clear plastic awning was used to guard the drops from dust. The stage was then placed in an open-top cold box and the drops were slowly cooled below 0°C.

Data were obtained at constant temperature for drops cooled to -10°C and for drops cooled to -15°C. The air temperature in the vicinity of the drops was -13°C and -16°C, respectively. After the drops had been cooled to these temperatures a length of time was allowed to elapse before mechanical shocks were transmitted to the cooling stage by repeated tapping of the stage tray with a plastic mallet.

In Fig. 5, the cumulative number of frozen drops is plotted as a function of time for two runs (distinguished from each other by the dashed and solid line) for drops cooled to -10°C. Fig. 8 is similar to Fig. 7 except the drops were cooled to -15°C. The time at which the drops began to receive mechanical shocks were arbitrarily selected and is indicated by the arrow. As can be seen in Fig. 7 and 8, undisturbed, most of the drops remained supercooled for lengths of time far in excess of the 6 minutes or so allowed to a cloudy air parcel raising from 0 to -10°C at ≈ 8 m s . In the experiment, at -10°C only 5 drops in 24 froze during the 32 minutes preceding mechanical disturbance and for the other run only 4 drops in 24 froze during 87 minutes. At -15°C, 8 drops froze in 35 during 68 minutes and 8 of 27 drops froze during 58 minutes.

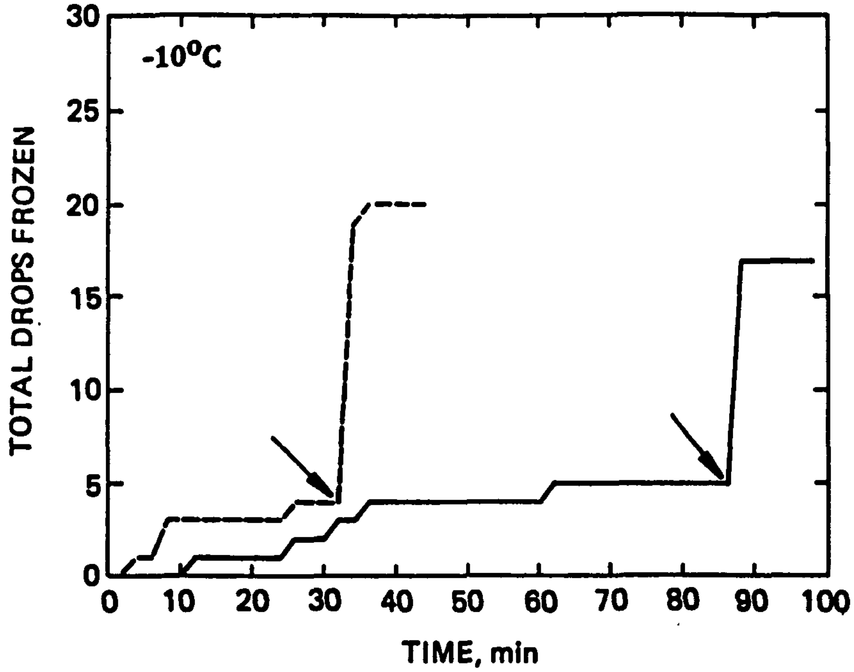

Figure 7. Cumulative number of frozen drops with time for a supercooling of -10°C.

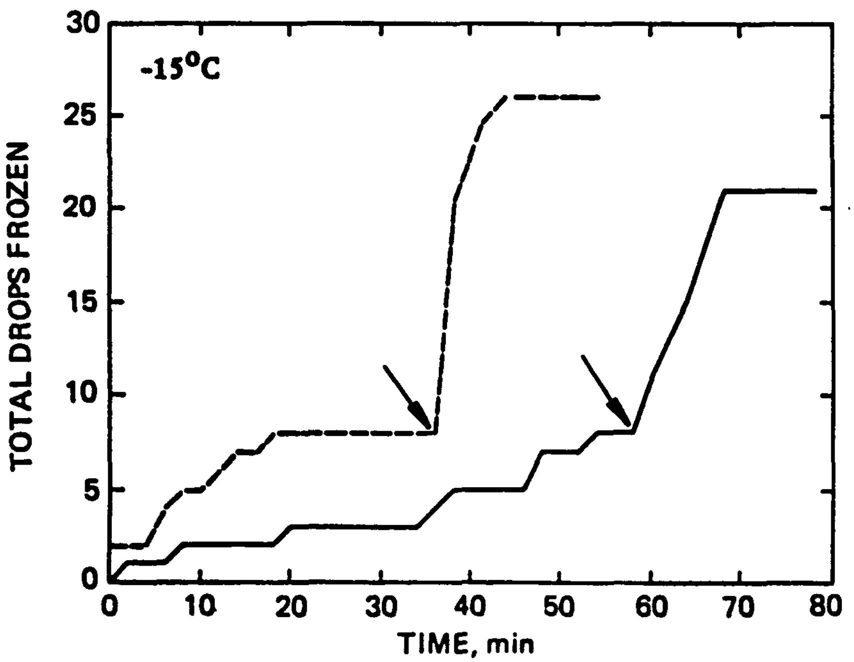

Figure 8. Cumulative number of frozen drops with time for a supercooling of -15°C.

As can also be seen in Fig. 7 and 8, the number of drops that freeze jumps sharply in both runs at -10°C so that nearly all of the drops become frozen within a few minutes. Virtually identical results were obtained in the experiment using drops supercooled to -15°C. These drastic increases in the number of frozen drops, precisely at the onset of mechanical shocks, suggest that freezing occurred by more than chance.

The results of this experiment serve to demonstrate that it is possible for mechanical shock to cause freezing. It thus appears feasible that a similar process may operate in clouds. However, these experiments did not adequately model the forces acting on drops in clouds and are subject to the uncertainty that frost growth on the substrate supporting the drops may have nucleated the water. Clearly, additional experiments at warmer temperatures using drops in free fall are desired to develop an understanding of this phenomenon with regard to collisions between supercooled drops in clouds.

7. The Mechanism of Mechanical Ice Nucleation

Two facts have been recognized to suggest that ice nucleation is either aided or caused by cavitation. As pointed out by Goyer et al. (1965), the freezing of supercooled water can be triggered by sonic intensities of 1 or 2 W cm" . Thus, for at least the effect of sonic waves, cavitation should precede freezing. However, disagreement exists over the basic physical sequence of events that end with the formation of a stable ice lattice. Some have proposed that evaporation into the bubble causes sufficient cooling to nucleate ice, others have suggested that a transient pressure wave generated at bubble collapse shifts the melting temperature and thus somehow causes ice nucleation. Yet others have proposed that the pressure wave in itself causes ice nucleation (see Hunt and Jackson, 1966). It is presently proposed that adiabatic cooling of the bubble causes ice nucleation and this mechanism is explored in the next few paragraphs.

True cavitation is the formation of a *void* or cavity within a liquid in the absence of impurity. Thus, for an absolutely pure liquid, cavitation occurs when forces are sufficient to tear the molecular bonds of the liquid (i.e., when the tensile strength of the liquid is exceeded). However, all liquids, no matter how carefully prepared for experimentation, contain a certain amount of dissolved and undissolved gas in addition to solid impurities.

As the molecules of the liquid vibrate, localized pockets of vapor are constantly formed and destroyed. The strength of the liquid is weaker at these locations. Thus, preferential sites for nucleation continuously flicker into and out of existence. If the liquid is subjected to either a sufficient pressure decrease (a temperature increase or both) cavity growth occurs and the physical effects in the locale thereafter depend on the rate of cavity growth and collapse relative to the rates of air dissolution and diffusion in water.

Net adiabatic cooling can be expected in the vicinity of the bubble whenever the cavity expands faster than air molecules can be added to. If this happens then the number of molecules in the cavity can be considered nearly constant as the volume increases. Thus, the expansion is adiabatic and cooling is produced.

Once a bubble forms its collapse will always be limited by the rate at which the air composing it can dissolve back into the water. Thus, volume decreases roughly correspond to a loss of gas molecules to the liquid. This is a slow process as indicated by the diffusivity of air in water. Epstein and

Plesset (1950) estimated that 7 s are required for a 10 *um* air bubble to dissolve in water.

The amount of the cooling in the vicinity of the bubble may be estimated from Piosson's equation. Assuming that the bubble nucleus is a spherical cluster of molecules with radius of 10 angstroms and that the bubble reaches a maximum spherical radius of 0.5 μm, a temperature decrease on the order of 100°C is calculated for an environment pressure of 500 mb and pressure jump across the bubble given by the ratio of surface tension to maximum bubble curvature.

A temperature change of this size suggests that enough cooling may occur for homogeneous nucleation. Therefore, if conditions in clouds prevail to cause a bubble within a supercooled drop, ice may nucleate spontaneously. However, bubble expansion may not be ideal and some addition of gas molecules to the bubble should be expected. In this case, enough cooling may still be produced to activate a submerged ice nuclei.

Admittedly, the physical sequence of events from bubble formation to freezing area based on conjecture, but adiabatic temperature changes appear feasible. And since bubble formation should precede ice nucleation anyway, the occurrence of cavitation may at least have predictive value. Therefore, a key question arises as to whether collisions between supercooled drops in clouds produce negative pressure differences which are sufficient to cause cavitation.

8. Application of Mechanical Ice Nucleation to Clouds

Although threshold for cavitation in water has been determined experimentally using mechanical and sonic systems, it is difficult to apply much of this information to conditions in clouds. Experiments with mechanical systems have used water in bulk and have generally not given quantitative results. Although the experiments of Young and Van Sicklen (1916) provide quantitative data, and acceptable way to convert their results for application to drop collision in clouds could not be found for this writing.

The intent of previous investigators using sonic systems to determine tensile strength has promoted the use of extremely pure water. Therefore many of the reported threshold values are suspected of being far in excess of what might be expected for drops in clouds. Of the experiments that have reported sonic intensity for what may have been heterogeneous nucleation, none provide all the information needed to convert their results to equivalent mechanical energies or pressure differences. An exception is the work of Goyer et al. (1965), but their data is not for thresholds. Thus, for the present paper it was possible to only roughly establish criteria for cavitation and hence collisional drop freezing in clouds.

The pressure difference between environment and drop for homogeneous cavitation is given by Apfel (1981) as:

$$P_E - P_I = (8\sigma/9)[3\sigma \;/\; 2(P_I + 2\sigma/R_B)R_B{}^3]^{1/2} \qquad (1)$$

where P_E is the environment pressure, P_I the internal pressure of the water drop, σ the surface tension of water, and R_B the maximum bubble radius. Substituting values appropriate for precipitation size drops at -10°C into Eq. 1 yields a threshold for cavitation of approximately 500 mb. This value is clearly an upper limit since Eq. 1 does not include the effects of dissolved gas, solid impurity or viscosity, factors which would tend to permit a bubble to form at a lower pressure difference.

The experimentally determined lower limit of 5 mb reported by Hueter and Bolt (1955) for aerated tap water subjected to sonic waves is probably closest to that for cloud and rain water. Actual thresholds may be lower given the difficulty of bubble detection and the fact that cloud and rain drops may contain larger amounts of impurities. Therefore, the criteria used here for cavitation within drops of clouds are collisions in which either or both drops eventually experience a negative pressure difference with respect to the environment greater than 5 mb for heterogeneous nucleation or greater than 500 mb for homogeneous events.

In the numerical simulation of drop rebound Foote (1975) has shown that an intricate pressure field evolves within a drop from impact to maximum deformation. Similarly complicated pressure fields must evolve from coalescence although these have not yet been calculated. Foote gives detailed results for the rebound of a spherical drop 1.19 mm diameter impacting a wall at 30 cm $^{s-1}$. The collision is characterized by a Weber Number of 1.42. The Weber Number gives a non-dimensional measure of drop deformation from the ratio of impact pressure to curvature pressure. The larger the Weber Number the greater the deformation.

Foote (1975) illustrates the evolution of an internal pressure field (difference between environment and drop where a negative difference indicates an internal pressure greater than environment) and surface capillary wave. Initially, just above the point of impact, at the bottom of the drop, the pressure field takes the form of a sharp spike with maximum and minimum of 35 and 2.5 mb, respectively. Simultaneously, a surface wave in the form of a ring propagates away from the point of impact. With these features an internal circulation also develops and evolves. At the time of maximum deformation when the capillary wave reaches the top of the drop and the internal circulation just below reverses, a nearly uniform pressure field is shown with maximum and minimum of 3.8 and -2.3 mb, respectively.

The pressure difference calculated in the final integration step of Foote's model does not exceed the criteria for heterogeneous cavitation set herein (i.e., -5 mb), but is large enough to suspect that sufficient pressure differences may be reached for rebounds characterized by larger Weber Numbers. Such collisions should have greater deformation, a larger amplitude capillary wave and thus result in larger negative pressure differences between drop and environment.

Figure 9 is a Weber Number (WE) diagram calculated over the wide range of large and small drops typically observed in clouds. In Fig. 3 each contour is a line of constant WE and was calculated using the equation:

$$WE = (\rho_w r \Delta V^2)/\sigma \qquad (2)$$

where p_w is the density of water, ΔV^2 is the differential terminal velocity of the drops and σ is the surface tension of water. This expression is slightly different from that used by Foote (1975) in that he used drop diameter to characterize a deformation radius for collision between two equally sized drops. Here the radius of the smaller drop (r) has been used since it better characterizes the deformation radius for collision between dissimilarly sized drops (Ochs et al., 1986).

Without the benefit of a numerical model such as Foote's it was not possible to know explicitly which combinations of drop sizes (i.e., Weber Numbers) will have associated with them a collisionally induced pressure difference sufficient to cause cavitation. Thus in Fig. 9, it is not possible to know exactly which combinations of drop sizes might favor freezing from collision. Therefore, the assumption was made that a simple linear relationship exists between Weber Number and the eventual development of a negative pressure. Based on this assumption and that $\Delta P = 0$ when $WE = 0$, a

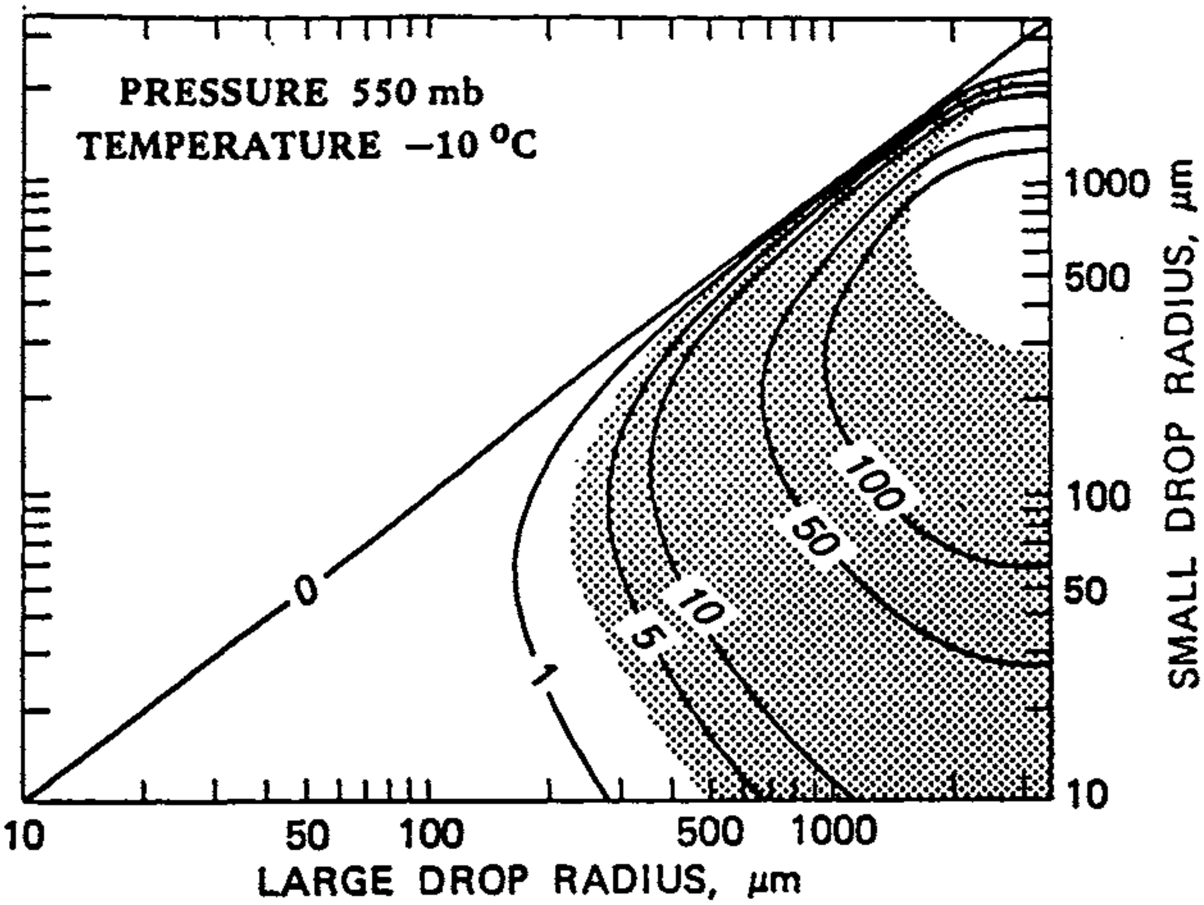

Figure 9. Weber Number diagram calculated over the meteorologically important range of drop sizes in clouds. Shaded area denotes collisions between large and small drops for which cavitation may result.

negative pressure difference greater than 5 mb was deduced for collisions characterized by Weber Numbers greater than about 3 and ΔP's > -500 mb for WE's > 300.

Figures 5-9 suggest that cavitation is possible for drop collisions in clouds over a wide range of large and small drop sizes once precipitation-size collector drops form. The stippled area in Fig. 9 delineates the region of WE greater than 3 and hence the large and small drop sizes for which cavitation (i.e., freezing) may be suspected. The absence of stippling for large drops (R > 1000 μm) and small drops (r > 300 μm) indicates collisions with sufficient energy for drop break-ups as determined in the investigations of Whelpdale and List (1971) and are not of present interest. Use of Eq. 2 produced a maximum Weber Number of ≈280, just smaller than suspected for the homogeneous bubble nucleation.

9. Collision-Freezing and Drop Interaction Results

As a parcel of air rises from the warm base of a midwestern cumulus the drop spectrum broadens from an active warm-rain process that does not necessarily cease as the air in the updraft cools to temperatures below 0°C. Figure 9 indicates that the collisional-freezing process may start out slowly, but accelerates as the spectrum of supercooled drops broadens through the "warm-rain" process. Figure 9 also suggests that drizzle size drops must be produced before the collision-freezing process may initiate since WE does not reach the lower threshold for cavitation (i.e., WE = 3) until a large drop of about 250 μm radius is produced. Thus, clouds that do not develop supercooled drops as large as 200 or 300 μm should not have first ice concentrations in excess of ice nuclei concentration if no other secondary ice process is operating. Data from 1986 and future data will be used to address this issue.

As 250 μm large drops are produced only a narrow range of small drops sizes are associated with WE >3. Thus early in the process only a few selected collisions will have sufficient pressure differences and may result in freezing. As collection proceeds and larger and larger drops are produced the range of small drop sizes with WE > 3 widens. Hence, more collisions may result in freezing. As the largest drops are produced (i.e., R > 1000 μm) collision with almost any size small drop is characterized by a WE » 3 and thus almost all collisions should be accompanied by bubble formation and freezing.

Although Fig. 9 signals that a collisional-freezing process may occur in clouds, it does not tell how coalescence, bounce, or temporary coalescence will participate in producing frozen drops. We can suspect that not all coalescences will result in frozen drops, but aircraft observation taken in a Langrangian mode should be obtained in the future to explicitly compare the drop size spectrum at 0°C to ice concentrations at -10°C. Laboratory work is needed to address the question of which coalescences, if any, result in freezing and why.

The possibility of drop rebound in clouds at temperatures below 0°C presents additional questions. For example, when a collision between supercooled drops results in bounce then is it the large drop, small drop, both, or neither that freezes and why? Clearly, from the nature of the collection process, glaciation along with broadening and depletion of the available supercooled drops will proceed differentially depending on which drops freeze in bounce.

The possibility of the temporary coalescence of supercooled drops raises similar questions since the event produces resultant drops nearly equal in size to the parents. More intriguing, is that temporary coalescence may produce a satellite drop particularly if the cloud reaches an appropriate electrical state (Czys. 1987). Is the satellite drop liquid or ice? Recent data obtained using drops in free at room temperature and pressure indicates that satellite drops smaller than 80 m radius are produced (Czys and Ochs, 1988). Small frozen satellite drops produced from temporary coalescence may have great impact on subsequent glaciation since they are prime candidates for capture by supercooled drizzle and rain drops.

10. Buoyancy and Condensate Loading

Net parcel buoyancy is determined not only by the moist density difference between it and the environment, but also by the amount of load it carries in the form of water and ice particles. For saturated conditions at -10°C and 500 mb, 2.5 g m^{-3} of water content is roughly equivalent to 1°C of negative buoyancy. Using this approximation and estimates of total LWC and SWC, net buoyancies have been calculated for each updraft.

Figure 10 shows the appreciable effect of condensate loading on parcel buoyancy. For each updraft, buoyancy was calculated assuming a load free water saturated parcel in an environmental at 50% relative humidity (open circle), and was calculated again including the influence of condensate load (solid circle). Buoyancy reductions between 0.2 and 0.4°C occurred for 70% of the updrafts with largest reductions being 2.5°C. These reductions are probably greater than shown considering the conservative way solid and liquid water contents were determined.

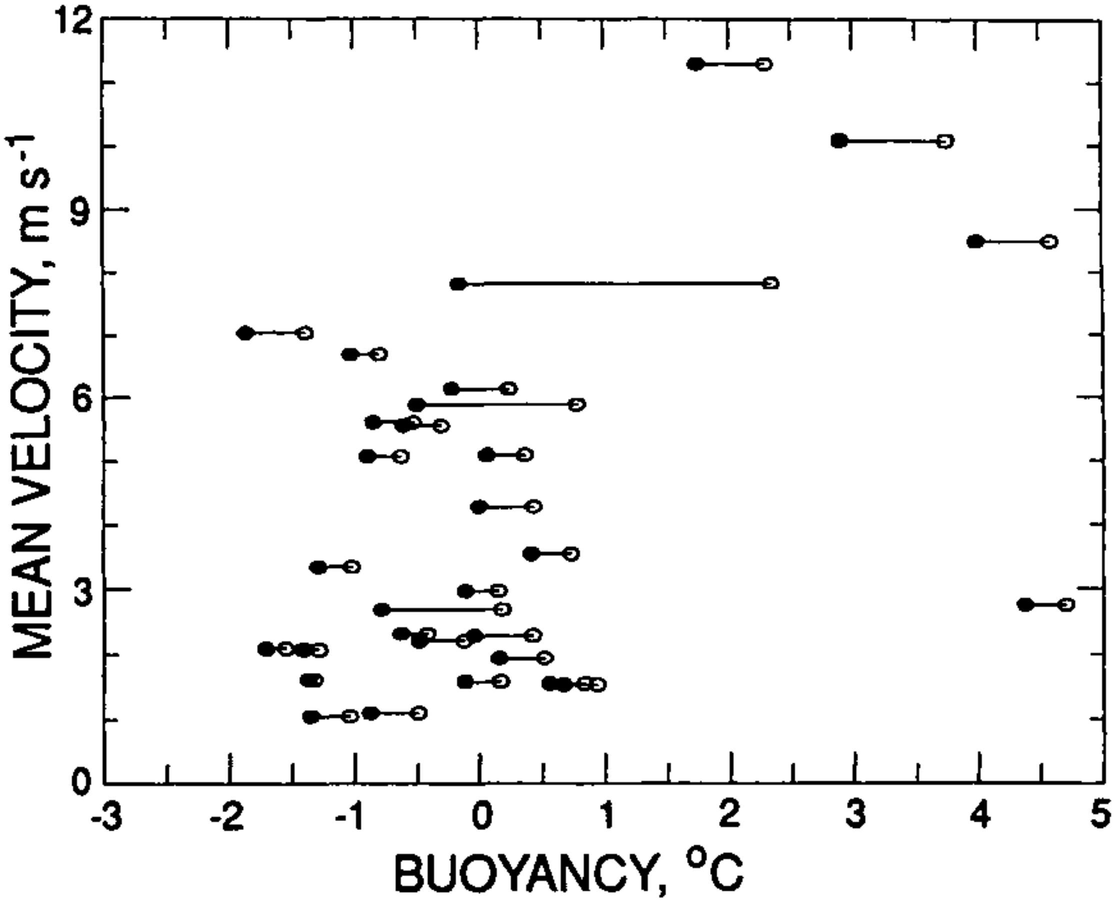

Figure 10. Observed cloud buoyancy with (solid circle) and without (open circle) total condensate loading.

11. Potential Glaciogenic Buoyancy Enhancements

Figure 11 shows as solid circles observed buoyancy including condensate loading and some potential buoyancy as open circles calculated from the scheme provided by Orville and Hubbard (1973) and is plotted against mean updraft velocity. The data show no strong relationship between mean updraft velocity and buoyancy although three stronger updrafts tended to be the most buoyant. The interesting feature of Fig. 11 is that many of the updrafts only show small buoyancy increases assuming that all of their supercooled liquid water content is frozen instantaneously and isobarically. Clearly, real buoyancy enhancement due to seeding would be smaller since large drops, those which will make the largest contribution from the release of latent heat, can require many seconds to completely freeze. Inspection of Fig. 11 shows that a few updrafts can be expected to have a much greater response, larger than about 1°C, to seeding than many of the others. This difference in response gives one indication of why statistical evaluation of seeding effects border around the insignificant level. Data organized in the way of Fig. 11 may be useful in sorting cloud responses observed by radar to give a stronger signal of buoyancy enhancement by imposed glaciation.

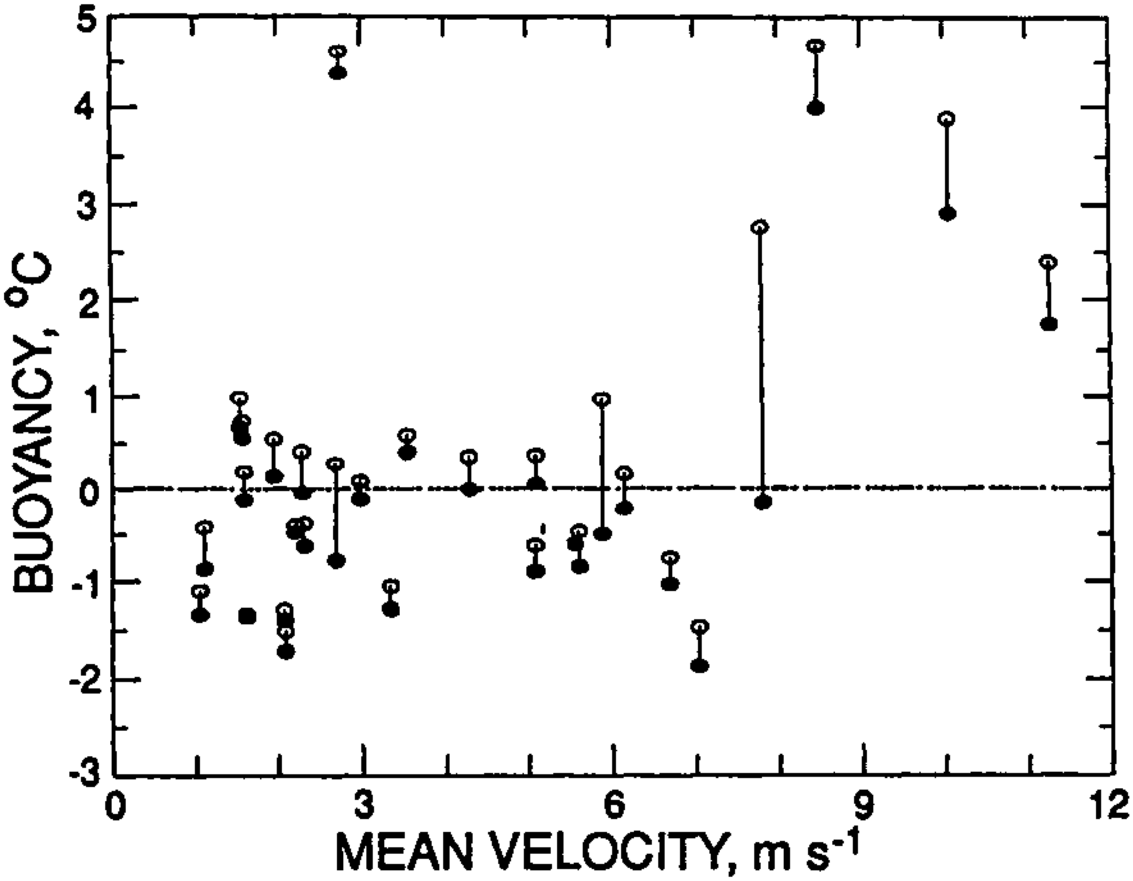

Figure 11. Observed buoyancy with loading (solid circle) and potential buoyancy enhancement (open circle) calculated assuming the water freezes instantaneously and isobarically.

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FORECAST ANALYSIS RESEARCH (Scott)

1. Introduction

The logistics involved in conducting a successful weather modification program in which clouds are treated via aircraft depend heavily on accurate forecasts of suitable weather events. This is important not only to alert participants of an approaching opportunity and to warm of impending storms that are dangerous to personnel and aircraft, but also to provide adequate "downtime" for flight debriefing, maintenance and repair of equipment, and relaxation for the participants.

The success of the forecasting effort during the 1986 PACE field program was made possible by rapid access of substantial amounts of meteorological data from a variety of sources. Use of a high-speed computer grea'tly shortened the time required for processing forecasting products, producing analyses of digitized data that typically were a part of only post-experimental analyses in the past. Additionally, satellite data transmissions centered on Illinois were frequent and available for use in near real-time. Therefore, the system allowed for development of very short-term forecasting capabilities: nowcasting. This provided immeasurable assistance to the forecaster in determining the chances of weather modification opportunities in a rapidly-changing environment and to the field coordinator in deciding on flight activities.

The forecasting system has been further improved since the 1986 field program providing even faster analysis products by modification of computer programs and by the addition of higher speed modems between the Water Survey's computer and the field headquarters. In addition, the development of more objective approaches toward forecasting of rainfall occurrence, and in particular, the intensity of convection to be expected was attempted.

2. Investigations into Numerical Analyses

Forecasters used a variety of data sources to arrive at the conclusion that precipitation is to be expected in a given area during a prescribed period of time. To a large extent, this is a subjective process. However, over the years, many attempts have been made to objectively predict rainfall through numerical analyses of selected meteorological observations linked closely to rainfall.

This was attempted for PACE in a post-experimental analysis for each day of the summer months during 1986-87. Five precipitation indices which estimate rainfall occurrence based on an analysis of data from individual upper air soundings, were calculated at two rawinsonde observation sites surrounding the PACE operations area. Empirically-derived threshold values relate each of these indices to rainfall with larger values indicating greater probabilities of convective precipitation (the type of rainfall of interest to weather modification). Using 0700 CDT sounding data, these results were then related to rainfall occurrence between 1200-2100 CDT observed from three local NWS radar sites. Results show that forecasts of precipitation based solely on these numerical indicators verified 70-80% of the time. Similar success was found in predictions of no rain.

However, due to the physical characteristics of clouds that are required for optimum treatment opportunities in weather modification research, it is important to know not only if the rain will be convective, but also the intensity level the convection is expected to generate. Again using the indices data set, when all five predicted precipitation, radar echo tops generally exceeded 30,00 feet with half of these occurrences exceeding 50,000 feet. On the other hand, when no or just one index indicated rainfall, tops were usually under 20,000 feet or, more often than not, rain did not occur.

Thermodynamic calculations on the upper air soundings have yielded other evidence showing moderate success in predicting convective potential. Comparisons were made between certain thermodynamic parameters calculated from morning soundings and the maximum afternoon echo top observed in the PACE network for the summer months of 1986 and 1987. Two of the better relationships are shown in Figures 1 and 2.

Figure 1 shows a comparison between the potential buoyancy of the atmosphere (a measure of the free vertical movement an air parcel ha in relation to its environment, frequently initiated by an upward mechanical displacement force such as surface heating or frontal lifting) and an estimate of the temperature at the base of convective clouds that are expected to form during the day. Intuitively speaking, relatively warm temperatures at cloud base and a calculation of positive buoyancy would be required for good convective activity. This is precisely indicated in the figure with some apparent propensity for the highest tops to cluster. Most of the tops in excess of 40,000 feet occurred with a positive potential buoyancy and cloud base temperature greater than 12°C. Although cells over 50,000 feet are generally too large to investigate, the data represent the highest top of the afternoon inside the target; other cells at different areas and times may be very suitable for treating. Therefore, the day could be forecast as one expected to develop working conditions, but with the warning that some cells may become quite strong.

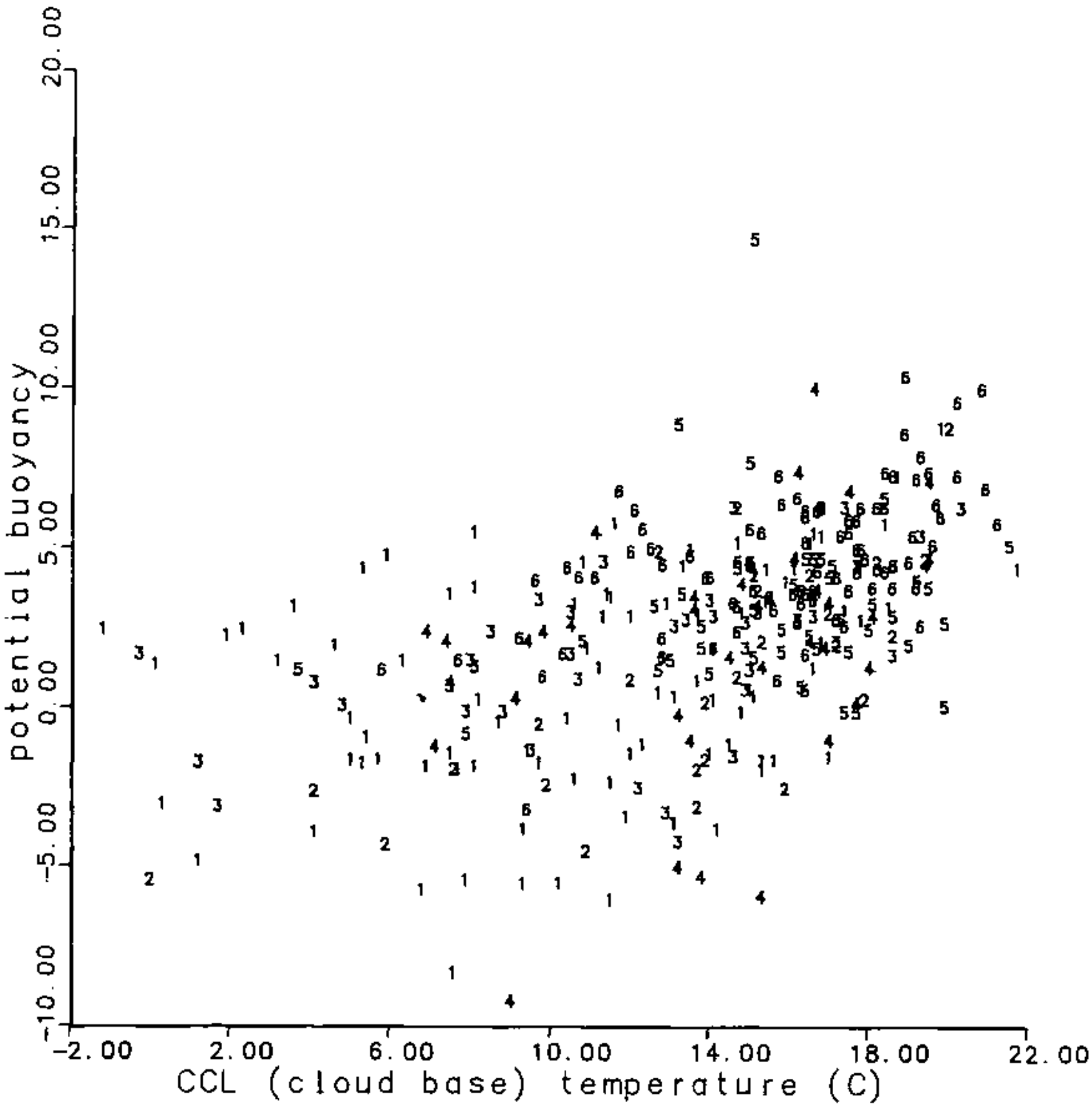

Figure 1. Comparison between the convective condensation level (CCL) temperature and the potential buoyancy of the atmosphere at Peoria and Salem, Illinois at 0700 CDT from June-August, 1986-1987. Data points are stratified by the maximum radar echo tops on each day between 1200-2100 CDT as observed by NWS radars in St. Louis, Missouri, Marseilles, Illinois, and Evansville, Indiana. (1 = no echoes; 2 = echo tops < 20,000 ft; 3 = tops 21,000-30,000 ft; 4 = tops 31,000-40,000 ft; 5 = tops >50,000 ft)

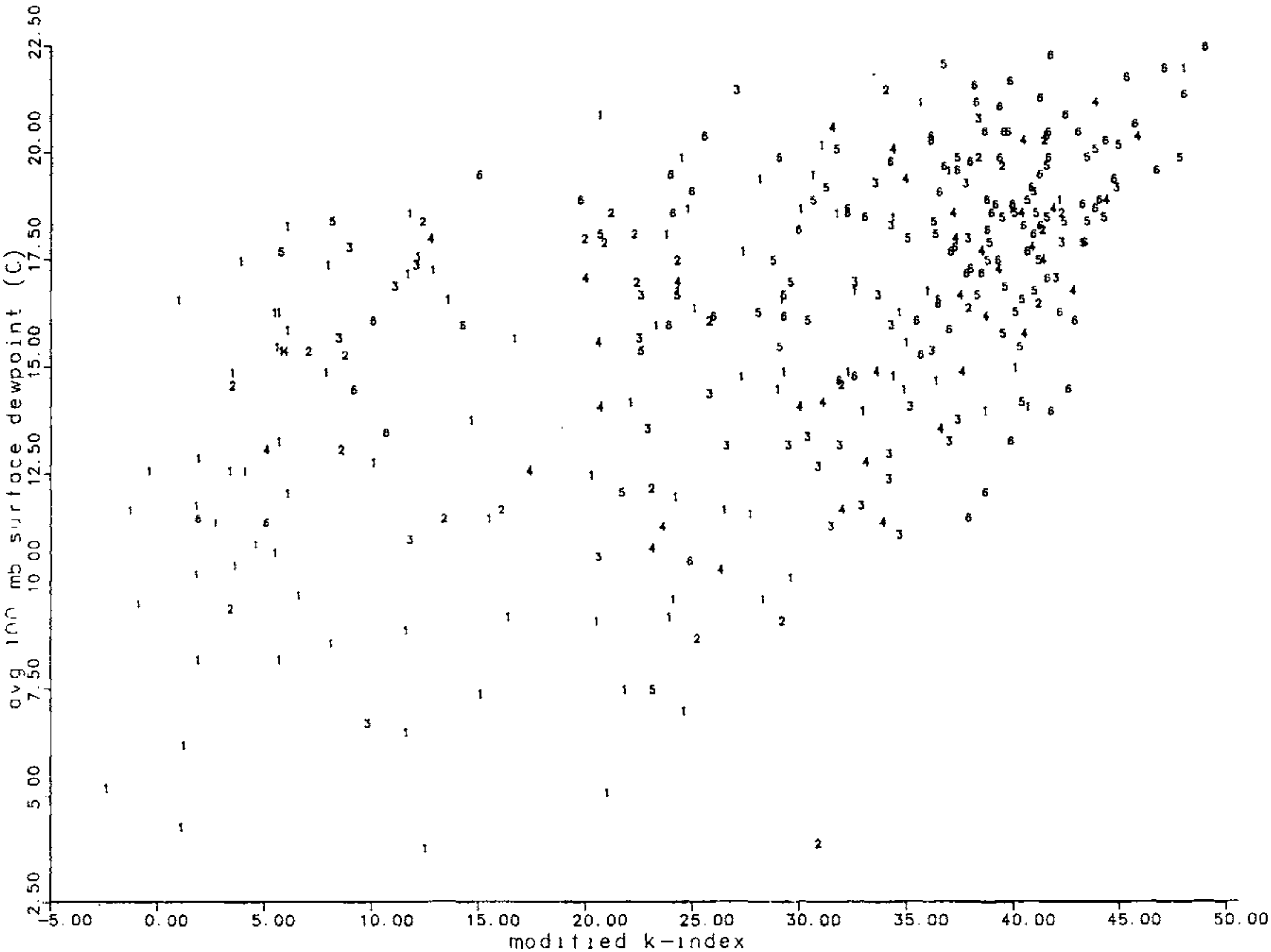

Figure 2. Comparison between Modified K stability index and the average dewpoint of the lowest 100 mb of the atmosphere at the same sites and times described in Figure 1.

Elsewhere on the figure, prediction of maximum echo tops, given observed abscissa and ordinate values, is less clearly defined but still useful. Positive buoyancies with cloud base temperatures from 6-12°C show many mid-level cloud tops which cold be worked freely without fear of becoming too large. The remainder of the figure shows a high likelihood of no echoes and the forecaster would need to depend on other products to support a convective forecast.

A similarly-constructed graph is shown in Figure 2 and relates a precipitation index (one which incorporates low-level moisture and low- and mid-level temperature) to near-surface moisture values. Again, highest tops clustered in one general area, specifically when index values exceeded 298 and near-surface dewpoints were greater than 15°C. Similarly, index values less than 23 and dewpoints less than 13°C tended to indicate a frequent occurrence of no echoes. Elsewhere, mid-level cloud tops predominate.

Although the largest numbers of occurrence of no echoes are grouped in the regions defined, they occur over the whole domain of both the charts while the highest echoes are located predominately in the outlined regions. This suggests that particular threshold values of the meteorological parameters are nearly essential for deep convection, but other factors may exist that will prevent storm formation.

3. Bi-Modal Echo Top Relationships

Radar data from the METROMEX experiment, conducted during the summer months of 1971-1975 in and around St. Louis. Missouri, show that a bi-modality exist in the distribution of half-hour radar echo tops. A pronounced minimum in the number of tops between 31,000-35,000 is obvious in the data set. A similar distribution is observed in maximum daily echo tops in both the

METROMEX and PACE86 data sets. A full analysis is in progress. However, initial results indicate that on the days when lower tops existed, the vertical lifting mechanisms in the atmosphere were either weak or nonexistent. Nevertheless, as much as one-half of the days showed sufficient liquid water content and potential buoyancy to support the precipitation that developed, much of which was lightly convective.

These days appear to be good potential opportunities for modification. Although the atmosphere here is unable to support development of deep convection, the positive thermodynamic conditions may allow significant enhancement within treated cloud elements since seeded clouds theoretically grow due to a heat release created by the seeding process. It is likely that further analysis of the data will indicate which of the days are best suited for investigation, however actual flights into these clouds will be necessary to determine their weather modification potential.

4. Suppression of Convection Moving into Dry Airmasses

During PACE86, an interesting forecasting situation developed over the area. A synoptic-scale rainband move across the central U.S. during 12-16 August 1986, accompanied by deep convective clouds to heights of 40,000-50,000 feet. As the rainband moved into the lower Midwest (including the PACE network), the precipitation changed its character from convective to stratiform. Echo tops dropped to 20,000-25,000 feet. After passing through this region, deep convection once again formed in the Ohio and Tennessee River Valleys.

The reason for the change in the nature of the rainfall was a mesoscale pocket of dry air in the middle troposphere that had moved into the western Gulf States behind a cold frontal passage on 10-11 August. The dry pocket remained intact for several days and slowly moved northward, encountering the approaching rainband from eastern Oklahoma to Illinois on 14-15 August, and change the character of the airmass preceding the rainband, thereby reducing its convective potential. Although the dry air was quite visible in individual soundings, it was less visible on the standard meteorological charts and, in addition, moisture advection confined to a narrow layer near 850 mb helped conceal its importance.

The case is significant for forecasters as it points out the importance to fully investigate the vertical structure of the atmosphere in the prediction of convection. Standard charts may be insufficient when used alone for this purpose.

INVESTIGATION OF EXTENDED-AREA SEEDING EFFECTS (Woodley and Scott)

This study dealt with the evaluation of a method developed to assess potential extra-area effects of seeding. Selected rain-day cases from PACE 1986 were investigated.

The Griffith/Woodley satellite rain estimation method was used for the analysis. This procedure was developed during a study of cumulus development in Florida, but has been modified and used also over the tropical Atlantic and the High Plains of North America. In general, the procedure combines infrared satellite imagery with dense networks of raingage data to provide estimates of precipitation in regions where raingage instrumentation is sparse. The gage data is apportioned to the region of coldest cloud tops in a scheme believed to be consistent with the reality of rainfall distribution beneath convective storm systems.

A case study approach was used with the PACE studies to evaluate the performance of the technique. Two densely-packed rainfall networks, hourly recording data covering metropolitan Detroit, Michigan, and daily observed rainfall totals over all of McLean County, Illinois were used to comparison with infrared satellite imagery over both regions. The following tentative conclusions have been made:

1. The technique likely will provide useful rain estimates for the midwestern United States over periods of a week or longer for areas covering at least 3,000 km , satellite precipitation estimates accurate to 10% relative to gage data appear quite possible.
2. It is unlikely that the technique will provide daily rainfall estimates that are accurate to better than a factor of two.
3. Derivation of rainfall from individual convective cloud systems is not possible with this technique due to the course resolution of the satellite data and short lifetimes of the smaller convective clouds.
4. Satellite rain estimates generally exceed raingage measurements prior to rain apportionment scheme.
5. Adjustment of the satellite rain estimates with a one-dimensional cloud model produces a considerable improvement in their accuracy relative to raingage measurements.

IV. PLANNING FOR OPERATIONS FOR PACE 88

A major activity of this 14-month project concerned on the potential conduct of a major field experiment during the summer of 1988 in central Illinois. Portions of the funding of this cooperative agreement, plus sizable funding from a future cooperative agreement slated to begin in June 1988, were to be combined to provide the necessary funds for this effort. Considerable activity during this 14-month project was given to the planning for this 3-month field effort (late May-August 1988). Also involved were extensive negotiations for use of equipment with a series of other institutions including NOAA/ERL (primarily relating to securing funding, and use of the P-3 aircraft); contractors for aircraft services; the Desert Research Institute and the South Dakota School of Mines and Technology relating to the T-28 aircraft funding and operations; and the National Center for Atmospheric Research to obtain permission to use certain field facilities including the CLASS sondes and the T-28 aircraft, the use of which is under the authorization of the RFF of NCAR.

The critical and unfortunate aspect of the PACE 88 design effort and arrangements was that essential funding for the project, slated to come in a cooperative agreement from NOAA/ERL in June, could not be provided by NOAA. Federal funding uncertainties involving OMB, DOC, and NOAA led to continuing uncertainties over receipt of the funding. This issue was not resolved until late July and the funding totaling $400,000 was not received until late August. These uncertainties made it impossible to implement a major field program wherein commitments to various contractors had to be made in April and early May 1988.

PLANNING ACTIVITIES (Changnon)

The decision to conduct a field experiment in atmospheric chemistry in central Illinois by the Department of Energy laboratories during the fall of 1987 led to a unique opportunity to combine PACE 88 facilities and measurements with those of this sizable field project. The 3CP0 experiment was designed and conducted from mid-May to late June 1988. It provided PACE with an outstanding opportunity to gather considerably more information about cloud microphysics and dynamics than the PACE project could possibly collect. The PACE staff was actively involved with the 3CP0 groups from three laboratories and several other universities during the fall, winter, and spring of 1987-88. We attended several joint project planning meetings in October 1987, January 1988, and March 1988.

A major planning session for PACE was conducted in Champaign-Urbana in February 1988. Those attending included Dr. Ruben Gabriel of the University of Rochester (a consultant to the PACE project), Dr. William Woodley (also a consultant to the PACE project and a presumed participant in the PACE-88 field project), Dr. Donald Griffith of North American Weather Corporation, and Dr. Roger Reinking, Program Manger from ERL/NOAA. The general concept of the planning that evolved was to have a three-month project involving two aircraft (a cloud seeding aircraft and a cloud physics aircraft), the T-28 cloud penetration aircraft for 3 to 4 weeks, the HOT and CHILL radars throughout, and CLASS sondes and data from 3CP0 which included time on the NOAA P-3 aircraft. A portion of the three-month effort would overlap with the 3CP0 program during June 1988. Elaborate operational planning was done for the dual project efforts with 3CP0 and with the ensuing PACE-only efforts during July and August 1988.

The activation of the field program required the issuance of contracts to corporations which had been on the two aircraft requests issued in March 1988. A go/no-go decision had to be made by May 12 in order to issue these contracts which totalled more than $250,000. When it became apparent by May 12 that NOAA was unable to decide on whether to fund the cooperative agreement (slated to begin July 1988) and which provided a portion of this essential funding, the major field operations slated for 1988 were cancelled. However, ERL/NOAA attempted to partially aid us by providing $100,000 in late June 1988. The net result of these efforts were the operation of the CHILL radar during portions of June and July to collect data on natural cumulus clouds that could be used for enlarging our three-dimensional sample of echo data. The synoptic weather data and sounding data collected during 3CP0 and the limited July radar operations will be used in ensuing research to better define the forecasting criteria and the behavior of unseeded echoes. In the net, an outstanding opportunity to collect cloud data was missed in 1988. True, a major drought had occurred but within 100 miles of Champaign (the planned study area), many excellent cloud opportunities occurred during the late June-late August 1988 period. Furthermore, opportunities to sample clouds during drought conditions was missed.

DESIGN FOR PACE 1988 (Huff and Changnon)

Prior to cancellation of the 1988 PACE Field Program in May 1988, considerable effort was devoted to establishing sampling procedures for the program. Tentative decisions were made after consultation with PACE staff members and outside advisors to the project. Finalizing of procedures was postponed after cancellation of the summer program, but the information developed will form a firm basis for designing future operations.

In our initial field experiment during summer 1986, we randomized on the basis of storm days to completely eliminate the contamination factor. However, it was recognized that this approach would yield only a very limited number of samples during a seasonal experiment, and make verification of seeding effects exceedingly difficult and, consequently, controversial at best. Therefore, it was decided to seek multiple samples on each storm day which could be subject to randomization and reliable verification of treatment results. Based on available information on intercloud contamination and the size of our experimental area, it was tentatively concluded that contamination effects would be most effectively minimized by requiring a separation of 20 km or more between candidate experimental units, and stipulation that concurrent units could not exist downwind of each other.

In order to maximize sample size and cover a wide range of atmospheric conditions, sampling procedures had to provide for accommodating experimental units ranging from a single cloud to cloud groups moving as a unit. Also, logistical limitations would result in some cloud clusters not being completely treated, so handling of these had to be determined. Decisions had to be made on the definition of what constitutes a cluster. Based on past studies of radar clusters in Illinois, it was tentatively decided that the unit sampling size could be defined as a radius of 20 km about the center of the initial qualifying echo. The experiences of Woodley (project consultant) in Texas indicate this area could be effectively treated by a single aircraft.

In consideration of statistical sampling requirements (sampling and analysis), it is necessary to designate all analytical classifications as much as possible prior to initiation of the field experiment. Groups of macroscale and mesoscale parameters important to verification and evaluation were compiled to meet this requirement. Also, it is required to identify all "response variables" we wish to use prior to the experiments. For example, this would include such radar parameters as rain flux, echo area, echo height, reflectivity, rain rate and duration of cloud treatment in both treated and untreated experimental units.

Consideration had to be given to how cloud (radar echo) mergers and splits are to be handled in the sampling and analytical phases. Methods of logically blocking and balancing the experimental units had to be made for randomizing purposes in order to insure representative samples from the seeding experiments. In our case, it was also necessary to randomize for several types which included (1) single aircraft experiments aimed at rain enhancement, (2) two-aircraft seeding aimed at rain enhancement, (3) three-aircraft operations in which both cloud physics and rain enhancement experiments are being conducted, and occasional operation of the cloud physics aircraft outside the 90-km operational range.

All of the various factors mentioned above require careful attention if successful weather modification experiments are to be achieved. Past climatological studies, especially those pertaining o radar echo climatology, which have been carried out under PACE and other Illinois Water Survey research have proven exceptionally useful in designing the PACE experiments. As indicated earlier, the 1988 design was not completed. Some of the tentative decisions made for the 1988 program need to be reviewed and, other requirements need to be studied further before final decisions are made for later experiments.

HOT RADAR SYSTEM (Nespor)

The HOT radar system which will be extensively used in PACE field operations to collect 3-dimensional echo reflectivity and doppler data was a project area of continuing activity. This included extensive work on the 40-ft trailer which houses the operational center of the radar and on the radar components. This trailer installation allows the potential of future portability of the HOT. The trailer was extensively modified during the 14-month period to allow for air conditioning and soundproofing, and to house these complex functions. The modification of the trailer and the installation of the radar components in it were completed.

Another HOT radar activity related to the establishment of a site for its operations. A 40-ft steel tower has been provided by the Illinois State Water Survey for mounting the antenna at the University of Illinois Airport. This also involved negotiations including formal requests to the University of Illinois Airport officials and to the Federal Aviation Agency for the installation. Permission was received during the spring of 1988 for this installation.

By August, the HOT radar was nearing an operational status. The major difficulty experienced has been the tower on which the radar was to be installed. When the radar was placed on the tower it was obvious that there was a stability problem making its operation potentially useless. Measurements of height (i.e., the elevation angle of the antenna) would have been meaningless.

A structural engineer from the University has been consulted to determine the proper remedy for this situation and recommendations have been made. These consist of welding stiffening plates in a number of the critical areas of the tower as a short-term solution. These corrections were made and helped stiffen the tower so that the flexing was reduced considerably. A longer-term solution is now being considered by the structural experts.

It is desirable to enclose the antenna in an existing fiberglass radome to protect the antenna in the advent of large hail. Unfortunately, the addition of this radome will also increase the wind loading on the structure which in turn increases the need for additional stability of the tower. The solution to this problem has not been determined, but it will probably result in guy wiring the legs of the tower. The solution also addresses the safety aspects of the installation.

A number of other radar-related projects have been accomplished during the past year. These include the construction of the radio frequency chain for the transmitter and receiver, the reconstruction of the receiver section from the CHILL system to include the wide range linear receiver and the phase detectors and analog to digital converters, software modifications to the CHILL system to operate the HOT system on the Microvax II system without the additional Microvax I system that is a part of the CHILL radar. Although there was a minimum of new design in these projects, there was considerable staff time involved. With the limited staff available, the time to accomplish all of these changes was greater than expected.

The radar will be operational during the fall of 1988 so that some data on the fall convective elements can be collected. There will be additional work accomplished during the winter to ensure all systems to be in good operational condition for the 1989 spring/summer operations.

V. FUTURE ACTIVITIES AND PLANS

The unfortunate delay in funding in 1988 and the resultant inability to conduct the planned field project, led to several programmatic alterations. The new cooperative agreement for the period of mid-August 1988 through October 1989 will consist of three major activities.

First, will be research. The atmospheric research will focus on the radar and synoptic weather data collected during the limited operations of 1988. Historical echo data collected by the University of Chicago during METROMEX will be studied as a part of the forecasting research. Work will continue on the development of computer programs to track individual echoes. The crop yield data from the agricultural plots of 1988 will also be analyzed and interpreted.

Planning will begin for a major field experiment with clouds during 1989. The dimensions of this effort will depend on available funding, the status of the drought, and the availability of desired facilities. We are requesting through NCAR for the use of the CHILL radar during portions of the summer, and for use of two CLASS sondes. We are also requesting use of the T-28 aircraft for a 3- to 4-week period during May-August 1989. The activities and timing of the field operations in PACE 89 will be interfaced with those of HAILSWATH II since certain facilities are desired by both projects (the CHILL and T-28). The agricultural test plot experiments.

A third aspect of the envisioned program will be the conduct of the field operations. Again, if the drought persists into 1989, this could greatly affect the type of operations conducted. The project will be sensitive to how the drought and needs for additional rainfall is related to the design of the project.

VI. PUBLICATIONS AND ASSISTANCE PROGRAMS

The severe drought that developed during the spring and continued through the summer of 1988 brought on sizable efforts to provide information and assistance concerning weather modification and precipitation enhancement. It should be recalled that PACE was designed by the Illinois State Water Survey and the agricultural scientists in the Agricultural Experiment Stations of the University of Illinois, Purdue University for Indiana, Michigan State University for Michigan, and Ohio State University for the State of Ohio. This commitment to a four-state effort resulted in the need to supply considerable advice and documents to interests in Ohio, Indiana, and Illinois. All three states suffered severe agricultural drought during the spring and summer of 1988. This prompted intense interest by government decision makers, local officials, agribusinesses, and the news media. Numerous documents were provided to the personnel and numerous telephone conversations were conducted. Changnon traveled to Ohio for a one-day meeting with state and bank officials to provide information on weather modification. A subsequent operational cloud seeding project was launched in Ohio during July and August. Interested farmers and agribusiness leaders visited the State Water Survey during the summer to see facilities and gather further information.

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