ANNUAL REPORT

ANALYSIS AND PLANNING FOR PRECIPITATION AUGMENTATION FOR CROPS EXPERIMENT

by

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ILLINOIS STATE WATER SURVEY

Cooperative Agreement NA90AA-H-0A175 for the period
September 1, 1990 to August 31, 1991
Atmospheric Modification Program, Environmental Research Laboratory
National Oceanic and Atmospheric Administration

Champaign-Urbana, Illinois
November 1991
Table of Contents

INTRODUCTION. ............................................................... 1
  1. Major Project Findings and Achievements. ......................... 3
     a. Information and Technology Transfer. ............................... 3
     b. Recent Publications .................................................. 6

PLANNED MODIFICATION OF PRECIPITATION PRODUCTION .............. 10
  1. Echo Core Behavior Research ....................................... 10
     a. Introduction ............................................................ 10
     b. Description of Echo Cores and Tracking Procedures ............. 11
     c. Echo Core Studies: Evaluation of the A Echo Cores ............. 13
     d. Summary .............................................................. 24
     e. References ............................................................ 25
  2. Cloud Physics Research ............................................... 26
     a. Introduction ............................................................ 26
     b. Background on First Ice in Natural Clouds ....................... 28
     c. The 1989 PACE Aircraft Data Set ................................ 36
     d. Typical Properties of PACE Clouds at the -10°C Level .......... 39
     e. Observations of First Ice in the Updrafts of PACE Clouds in 1989 .................................................. 42
     f. Review of Ice Initiation Mechanisms that May Operate in Illinois Cumulus ........................................ 47
     g. References ............................................................ 54
  3. Forecasting Research .................................................. 58
     a. Forecasting coalescence activity in Illinois Clouds using thermodynamic data ........................................ 58
     b. Quantitative Analysis of Mesoscale Lifting: The Divergence of Q ....................................................... 63
     c. References ............................................................ 66
  4. Seeding Effects Research .............................................. 67

INADVERTENT MODIFICATION OF THE ATMOSPHERE ....................... 72
  1. Urban Influences ....................................................... 72
  2. Contrails Research .................................................... 73

EFFECTS OF MODIFIED ATMOSPHERIC CONDITIONS ......................... 75
  1. Effect of Varying Summer Rainfall on Crop Yields in Illinois: Implications for Rainfall Modification .......................... 75
     a. Introduction ............................................................ 75
     b. Investigation of Rainfall-Crop Yield Relationships ............. 76
INTRODUCTION

The scientific research described herein was conducted within the context of the Precipitation-Cloud Changes and Impacts Project (PreCCIP) of the Illinois State Water Survey during the period September 1, 1990 to August 31, 1991. PreCCIP is an ongoing research effort, originally entitled Precipitation Augmentation for Crops Experiment (PACE). The overall goal of PreCCIP is to measure and understand the modification of atmospheric processes, resulting inadvertently from human activities or purposefully by cloud seeding, and to determine the impacts of altered weather and climate conditions on the hydrologic cycle, agricultural activities, and on the social and institutional structure of Illinois. Findings from the PreCCIP research concerning atmospheric processes and the effects of changed conditions are key inputs into a myriad of individual and institutional decisions affecting Illinois. They include major questions about 1) the application of cloud seeding to try to alter precipitation; 2) the magnitude and factors causing inadvertent climate change at the local and regional scales; 3) the types and importance of physical effects and socioeconomic impacts caused by altered weather; and 4) the monitoring, control, and regulation of activities leading to either purposeful or inadvertent modification of weather and climate. PreCCIP has thus embraced a wide range of scientific research including studies of physical processes in the atmosphere, research to define how additional summer rain alters a corn crop and shifts farm income, and how altered weather conditions affect local, state, and federal activities.
The research conducted during the past year was done on the basis of six major considerations. First has been the findings from past research, which has been structured in a step-by-step approach to develop an understanding of atmospheric processes and their modification. The research also focused on an ongoing analysis of a 1989 cloud modification experiment. The third factor affecting our research involved the status of our understanding of our research on effects of altered weather on various physical and socioeconomic systems. Staff capabilities and facilities available to the project were a fourth factor influencing the research. The needs for scientific information relating to altered weather and climate in Illinois and the Midwest were a fifth factor guiding our research. A sixth factor that greatly affected our research related to interactions with NOAA staff and awareness that future funding for the year after this project was to be delayed or withheld. This caused a reduction in effort in order to have funds available to address potential shortages during 1991.

This one year of research of PreCCIP focused on three broad topical areas which have been embraced throughout the past five years of the 12-year project. The first was a continuing study of cloud and precipitation processes. This is an essential part of understanding how to purposefully modify precipitation in Illinois and the Midwest. Our effort here concentrated on analysis of the 1989 seeding trials in Illinois. At this time, results are interesting but are not complete.
The second programmatic area of PreCCIP concerns **studies of inadvertent modification of weather and climate conditions** in Illinois and the Midwest. This research has addressed urban and lake influences on precipitation and studies of jet-induced contrails and their potential for creating cirrus cloud decks.

The third area of endeavor related to **studies of the effects of altered weather and climate conditions**. This research centered on studies of impacts on water resources including soil moisture, atmospheric moisture, and agriculture.

In the next section, "Major Project Findings and Achievements," we present a description of our recent efforts and major findings. Following this section, we present sections describing our major research endeavors, data collection, and instrument development.

1. Major Project Findings and Achievements

   a. **Information and Technology Transfer**

   As a state agency with mandated responsibilities to study the state's atmospheric and hydrospheric resources, and with a broad program of scientific research, the Illinois State Water Survey in general, and PreCCIP specifically, have a major responsibility to bring its findings to the broad user and the scientific communities. This has been done in three major ways.
The first of these relates to the education and training of undergraduate and graduate students. In our laboratory and in-house research studies, we have involved 6 undergraduate students (drawn from the atmospheric sciences, agriculture, geography, and computer sciences) in the various phases of the research. One graduate student has been involved in the project and done research relating to cloud physics.

The second major area of information and technology transfer has related to being a prime source of information, to the public and private sectors about weather modification throughout the Midwest. During the dry summer of 1991, project scientists responded to several calls for information from the press and government agencies in the Midwest. Talks addressing the science of weather modification were given at meetings. We have briefed state and federal agency staffs and agricultural interests about the status of our research. Certain members of the Illinois delegation to Congress who are interested in the project were briefed about the progress.

A third area of emphasis involves the provision of scientific and technical information about our research findings to the scientific community. To this end, all standard scientific channels have been used, including papers presented at scientific conferences, major reports, and papers published in scientific and technical journals. The project publications are itemized in the Section b of this chapter. There have been 10 papers based on project research published in the refereed scientific literature. In addition, 9 papers were presented at five national and international conferences over the past year, and in the past year, 12
papers have appeared in various conference proceedings and preprints (also documented in Table 1). Several papers are in preparation, including ones to the Journal of Atmospheric Sciences, Journal of Applied Meteorology, Nature, and the Journal of Weather Modification. Three papers, including one invited paper, will be presented at the Symposium on Weather Modification at the 1992 Annual Meeting of the American Meteorological Society. A major article presenting an in-depth description of the PreCCIP project and its findings appeared in the April 1991 issue of the Bulletin of the AMS.

In conclusion, the PreCCIP effort over the past year to provide project information to the major constituencies, as well as to provide meaningful education and training of undergraduate and graduate students, has been considerable. Furthermore, our interactions with the user communities in Illinois and the Midwest, as well as monitoring the field of atmospheric modification, have been utilized to continually assess the scientific direction of the project and to reformulate the research as needed. This effort is described further in the later section under "Program Management and Planning and Assessment."
b. Recent Publications

Refereed Journals and Reports


Non-Refereed Papers in Proceedings and Reprints


1. Echo Core Behavior Research

   a. Introduction

   During this research period, echo tracking of clouds treated during the 1989 PACE field program was completed. Echo tracking was made more exact in 1989 than it was in 1986 for several reasons. First, the loran-C navigation equipment on board the aircraft in 1989 provided a very accurate (within 1 km) aircraft location. An automated research aircraft tracking system (RATS) had been installed on the CHILL radar. These aircraft locations were recorded on the radar field tapes, providing an check on the Loran-C measurements. In addition, the 10-cm data collected by the CHILL radar, included reflectivity measurements with a minimum threshold of less than 10 dBZ, whereas in 1986 the threshold ranged from 12.5 to 20 dBZ. Finally, the tracking was simplified through the development of an interactive echo core, tracking program. The tracking procedure will be described in detail below. In 1989, several missions were specifically conducted in which the radar "painted" the aircraft flying a prespecified flight pattern, to calibrate the LORAN and RATS system.

   The computerized tracking software facilitated the subsequent core analysis. The echo cores were flagged and then the flagged data were retrieved for computation of co-variates and response variables. During this year, analysis of co-variates or predictor variables was initiated. This analysis has taken two approaches: first to look to the behavior
of the individual cores, with these cores as the statistical samples, and secondly to consider
the experimental units (the 28 km radius moving target centered on the treated group of
echoes) as the sample, and to examine the overall system within the unit and the mean
behavior of the cores within the unit, as was done with the 1986 echo core. As the 1989
project was designed primarily to look at the early cloud response to cloud seeding, this year
of analysis has concentrated on the individual cores. However, examination of the
experimental unit as a whole has commenced as well.

b. Description of Echo Cores and Tracking Procedures

The 1989 radar evaluation was made on the basis that clouds could be tracked as
individual echo cores, as was indicated by the 1986 radar analysis. There were several
instances in both years of multiple penetrations of cores, where the aircraft scientist observed
a new growth, but the radar only showed the continuation of an existing echo core. In 1989,
there were also 4 cases where the aircraft scientist observed a new growth and the radar
showed the aircraft to be on the edge of a large existing storm. In these cases, it was
assumed that the new growth was aliased by the existing storm and no tracking was
performed. Out of a total of 81 clouds, tracking was performed on 67 cores.

Merging of echo cores was as common in 1989 as it had been in 1986. At the time
of first echo detection, 48 out of 67 were already merged, that is they were either loosely
joined or strongly merged (Fig. 1). At the time of treatment, 52 out of 67 were merged.
In 1986, one of the cores formed out of the mass of an existing core. In 1989, at the time
Figure 1. Schematic history of an isolated, a loosely joined and a strongly merged echo core.
of first detection, the echo base could not be distinguished in 33 of the 48 merged cores. These strongly merged cores (at first detection) were easily distinguishable aloft, but formed on the edge of and actually above an existing system. These cores were trackable even at the low levels in subsequent volumes, but the beginning of the core had an ambiguous boundary with the adjacent parent core in the lowest levels.

The more easily tracked cores generally followed a pattern of 1) formation in the 3-6 km height range, 2) expansion in the vertical, 3) expansion in the horizontal, and 4) a drop of the echo core toward the surface. The expansion of the core and the drop in altitude of the maximum reflectivity core may proceed concurrently. This same model of growth was found in the mid to upper levels for the more complex cores and was assumed when making the more subjective decisions of beginning and ending the cores: After the surface reflectivity reached its peak from the previous core, the surface area/reflectivity of the next volume would be attributed to the current core. The current core's surface area/reflectivity would continue until it reached its peak and then the next volume area/reflectivity at the surface would be attributed to the successive core. The end points of many cores (both simple and complex) were defined in this way if they were succeeded by another core. Thus, the "total volumetric history" of the core and the rainfall from only that core is somewhat suspect. However, the echo core history at 4 km and above is generally clear throughout the history of the complex cores.
Echo cores were tracked until they dissipated or became indistinguishable from surrounding cloud reflectivities. This occurred after the time when the maximum height, area and reflectivity were reached. Thus, the response parameters are based largely on data up to the time when the maximum echo area, height and reflectivity were reached.

c. Echo Core Studies: Evaluation of the A Echo Cores

The 1989 sample includes 12 "A" type experimental units and 71 clouds/cores (4 with no echo). The echo core characteristics at the time of first echo and at the time of treatment have been examined to determine if differences existed in the sample of AgI and sand treated echo cores. Table 1 provides a list of the variables examined in detail. A complete list of variables is given in Appendix A. There are 35 AgI echo cores/clouds and 32 sand cores/clouds. The 4 no-echo clouds not included in the analysis reported on herein were AgI clouds.

i. First Echo Attributes

At the time when the cloud was first observed as an echo, no differences were observed in the distribution of the height of the top of the echo or in the height of the maximum reflectivity. The mean and median of the maximum reflectivity were larger for the sand clouds, though the difference was not significant. A two-sided Wilcoxon Rank Sum test for shift in distribution gave a p-value of .107 (Table 2). This difference can be observed in looking at the distribution of echo core reflectivity frequency for sand and AgI treated clouds, where 11 sand clouds and only 5 AgI cores were observed with reflectivities
Table 1. Variables describing the echo at the time of first echo and at the time of treatment. A threshold of 10 dBZ was used in all computations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEHtp10</td>
<td>First Echo Top Height (km)</td>
</tr>
<tr>
<td>FEmnDIA</td>
<td>First Echo Mean Diameter (km)</td>
</tr>
<tr>
<td>FEA10</td>
<td>First Echo Max Area (km²)</td>
</tr>
<tr>
<td>FEHMxz</td>
<td>First Echo Max Reflectivity Height (km)</td>
</tr>
<tr>
<td>FEmxz</td>
<td>First Echo Max Reflectivity (dBZ)</td>
</tr>
<tr>
<td></td>
<td>First Echo Status (strongly merged (SM), loosely jointed (LJ), isolated (I); Treatment Time Status (merged, isolated, no echo)</td>
</tr>
<tr>
<td>FECPt</td>
<td>Core Age at Treatment (min) - +/- 1 min. of treatment time of treatment**</td>
</tr>
<tr>
<td>CPHTp10</td>
<td>Echo Core Top Height at Treatment (km)</td>
</tr>
<tr>
<td>CPmnDIA</td>
<td>Echo Core Mean Diameter at Treatment (km)</td>
</tr>
<tr>
<td>CPA10</td>
<td>Echo Core Max Area at Treatment (km²)</td>
</tr>
<tr>
<td>CPMxz</td>
<td>Echo Core Max Reflectivity at Treatment (dBZ)</td>
</tr>
<tr>
<td>CPdiam56</td>
<td>Core Diameter at Flight Level at Treatment (interpolated to 5 or 6 km)</td>
</tr>
<tr>
<td>CPZ56</td>
<td>Core Max Reflectivity at Flight Level at Treatment (dBZ)</td>
</tr>
<tr>
<td>FltAltR</td>
<td>Flight level derived from the Radar (km agl)</td>
</tr>
<tr>
<td>FltAltA</td>
<td>Flight level derived from the Aircraft (km agl)</td>
</tr>
<tr>
<td>CPFEdH10</td>
<td>Change in Top Height from FE to Treatment (km)</td>
</tr>
<tr>
<td>CPFEdA10</td>
<td>Change in Max Area from FE to Treatment (km²)</td>
</tr>
<tr>
<td>CPFEdZ</td>
<td>Change in Max Reflectivity from FE to Treatment (dBZ)</td>
</tr>
<tr>
<td>CPFEdHdt</td>
<td>Rate of Change in Top Height from FE to Treatment (km/min)</td>
</tr>
<tr>
<td>CPFEdAdt</td>
<td>Rate of Change in Max Area from FE to Treatment (km²/min)</td>
</tr>
<tr>
<td>CPFEdZdt</td>
<td>Rate of Change in Max Reflectivity from FE to Treatment (dBZ/min)</td>
</tr>
</tbody>
</table>
Table 2. Sample size, mean, median and p-value derived from a Wilcoxon Rank Sum Test for the First Echo Parameters for AgI and Sand Treated Cores

<table>
<thead>
<tr>
<th></th>
<th>FEHtp10</th>
<th>FEHMxZ</th>
<th>FEMxZ</th>
<th>FEmnDIA</th>
<th>FEA10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AgI Sample</strong></td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Median</td>
<td>6.0</td>
<td>5.0</td>
<td>20.6</td>
<td>2.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Mean</td>
<td>6.0</td>
<td>4.8</td>
<td>24.7</td>
<td>2.2</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>Sand</strong></td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Median</td>
<td>6.0</td>
<td>5.0</td>
<td>28.5</td>
<td>3.2</td>
<td>11.0</td>
</tr>
<tr>
<td>Mean</td>
<td>6.3</td>
<td>4.8</td>
<td>29.5</td>
<td>3.1</td>
<td>12.2</td>
</tr>
<tr>
<td><strong>P-value</strong></td>
<td>.754</td>
<td>.711</td>
<td>.107</td>
<td>.000</td>
<td>.001</td>
</tr>
</tbody>
</table>
35 dBZ or greater (Fig. 2). The mean diameter and maximum area (at any given height) of first echoes were significantly different for the sand and AgI cores, with the sand cores having a larger mean and median. A statistical summary is presented in Table 2 and the distribution of values in Fig. 2. The Wilcoxon Rank Sum test assumes that all of the echo cores are independent samples. Because the randomization was by experimental unit, this is not strictly true. A rerandomization of the data is planned to recompute the significance levels.

ii. Echo Core Attributes at the Time of Treatment

Of the 35 AgI clouds that echoed, 6% were treated (> 1 min.) prior to an observed echo, 20% echoed first at the time of treatment (+/- 1 min.), and 74% were echoing prior to treatment (Fig. 2). Of the sand clouds, 12.5% were not echoing prior to treatment, 12.5% echoed first at the time of treatment, and again 75% were already echoing before treatment. Additionally, of the 35 AgI cores, 54% were raining at the time of treatment. Rain was assumed when an echo reached the 1 km level. 69% of the sand cores were raining at treatment. The no-echo value values for the clouds that had or would echo are included in the histograms presented (Fig. 3, 4 and 5), and in calculating the statistics (Table 3). The 4 AgI clouds that never echoed were excluded from the analysis.

Parameters representing the overall size of the core and the characteristics of the core at flight level were examined. In addition, growth rates computed between the time of first echo and the time of treatment for growth in terms of echo top height, maximum
Figure 2. Frequency Histograms for AgI and Sand Cores for echo top height, height of the maximum reflectivity, maximum reflectivity and mean diameter, at the time of first echo; and age of the core at the time of treatment.
Figure 3. FrequencyHistograms for Agl and Sand. Core echo top height, mean diameter, maximum reflectivity, core diameter and maximum reflectivity at the flight level, and aircraft altitude, at the time of treatment.
Figure 4. Frequency Histograms for Agl and Sand Cores for height of the echo top and the max area at treatment, and change and rate of change of height and area between first echo and the time of treatment.
Figure 5. Frequency histograms for Agl and Sand Cores for maximum reflectivity at treatment, and the change and rate of change of max reflectivity between first echo and treatment.
echo core area and maximum echo core reflectivity. Many of the echo parameters examined at the time of treatment had significantly different distributions according to a two-sided Wilcoxon Rank Sum test (Table 3). The mean and median values indicated that the sand
Table 3. Characteristics at the time of Treatment for the 35 AgI treated cores and the 32 sand cores. The P-value is derived from a two-sided Wilcoxon Rank Sum Test.

<table>
<thead>
<tr>
<th></th>
<th>AgI Sample</th>
<th></th>
<th>Sand Sample</th>
<th></th>
<th>P-val</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Mean</td>
<td>Median</td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>FECPt</td>
<td>4.7</td>
<td>6.0</td>
<td>6.6</td>
<td>8.8</td>
<td>.315</td>
</tr>
<tr>
<td>CPHtp10</td>
<td>7.0</td>
<td>6.1</td>
<td>8.0</td>
<td>7.1</td>
<td>.029</td>
</tr>
<tr>
<td>CPmnDIA</td>
<td>3.6</td>
<td>3.6</td>
<td>4.9</td>
<td>4.8</td>
<td>.006</td>
</tr>
<tr>
<td>CPA10</td>
<td>18.0</td>
<td>23.3</td>
<td>30.5</td>
<td>38.2</td>
<td>.010</td>
</tr>
<tr>
<td>CPMxZ</td>
<td>38.7</td>
<td>35.2</td>
<td>52.7</td>
<td>44.5</td>
<td>.020</td>
</tr>
<tr>
<td>CPFEdH10</td>
<td>.0</td>
<td>.6</td>
<td>2.0</td>
<td>1.8</td>
<td>.017</td>
</tr>
<tr>
<td>CPFEdH/dt</td>
<td>.0</td>
<td>.05</td>
<td>.19</td>
<td>.16</td>
<td>.072</td>
</tr>
<tr>
<td>CPFEdA10</td>
<td>8.0</td>
<td>17.4</td>
<td>19.0</td>
<td>27.0</td>
<td>.033</td>
</tr>
<tr>
<td>CPFEdA/dt</td>
<td>1.3</td>
<td>2.2</td>
<td>3.6</td>
<td>3.4</td>
<td>.038</td>
</tr>
<tr>
<td>CPFEdZ</td>
<td>10.3</td>
<td>11.4</td>
<td>17.6</td>
<td>17.6</td>
<td>.135</td>
</tr>
<tr>
<td>CPFEdZ/dt</td>
<td>1.5</td>
<td>1.6</td>
<td>2.0</td>
<td>2.0</td>
<td>.616</td>
</tr>
<tr>
<td>CPdiam56</td>
<td>3.2</td>
<td>3.0</td>
<td>4.5</td>
<td>4.2</td>
<td>.026</td>
</tr>
<tr>
<td>CPZ56</td>
<td>24.9</td>
<td>23.4</td>
<td>34.6</td>
<td>31.6</td>
<td>.027</td>
</tr>
<tr>
<td>FltAltR</td>
<td>5.65</td>
<td>5.64</td>
<td>6.05</td>
<td>5.94</td>
<td>.000</td>
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<tr>
<td>FltAltA</td>
<td>5.60</td>
<td>5.57</td>
<td>5.95</td>
<td>5.85</td>
<td>.000</td>
</tr>
</tbody>
</table>
cores were generally larger than the AgI cores. Though the means and medians suggested larger and more rapid growth for the three parameters, they were only significant at the .05 level for the change and rate of change of maximum area, and for change in maximum height.

The difference in the mean flight altitude for the AgI and Sand treated clouds was small, on the order of 300 - 400 m. However, this difference suggests that flight procedures were inadvertently compensating for the larger sand clouds by flying through them at a slightly higher altitude.

iii. Degree of Merger of the Core at First Echo

The numbers of echo cores that were merged at the time of first echo, are presented in Table 4. Approximately equal numbers of AgI and sand treated cores were strongly merged at first detection. These were the cores which grew above an existing core. More sand clouds were loosely joined at first echo, that is, joined at some level with another reflectivity volume, but having an individual core observed at all levels. At the time of first echo, 66% of the AgI cores and 78% of the sand treated cores were merged. There were no statistically significant differences in in echo top height and maximum reflectivity, at first echo and at treatment the AgI and sand treated cores when ordering the parameters by the degree of merger at first echo. In looking at the distribution of mean echo diameters, the sand cores appeared to have larger diameters than the AgI in all diameter categories (Fig.
Table 4. First Echo status: strongly merged (SM), loosely joined (LJ), isolated (I), and the mean and median first echo mean diameter (km), and the mean echo diameter at treatment time.

<table>
<thead>
<tr>
<th></th>
<th>AgI Sample</th>
<th></th>
<th>Sand Sample</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Mean</td>
<td>N</td>
<td>Median</td>
<td>Mean</td>
</tr>
<tr>
<td>FEmnDIA (km)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Str. Merged</td>
<td>2.5</td>
<td>2.6</td>
<td>18</td>
<td>3.3</td>
<td>3.4</td>
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<tr>
<td>Loose Joined</td>
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<td>1.9</td>
<td>5</td>
<td>3.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Isolated</td>
<td>1.6</td>
<td>1.8</td>
<td>12</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>CPmnDIA (km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Str. Merged</td>
<td>4.2</td>
<td>4.4</td>
<td>18</td>
<td>5.4</td>
<td>5.8</td>
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<td>Loosely Joined</td>
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<td>5</td>
<td>4.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Isolated</td>
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<td>2.8</td>
<td>12</td>
<td>3.9</td>
<td>3.7</td>
</tr>
</tbody>
</table>
6). However, the difference was significant at the .05 level only for the strongly merged cores, using the two-sided Wilcoxon Rank Sum Test. A difference in the mean diameter of sand and AgI treated echo cores also was found at the time of treatment, again in each degree merger category. The difference was similar at the time of treatment to that at the time of first echo. By the time the echoes were treated, 74% of the AgI treated clouds were merged, and 94% of the sand treated cores were merged.

iv. Echo Core Characteristics Stratified by Core Age at Treatment

Other studies have found that clouds react differently to treatment depending on the age of the echo at the time of treatment. Gagin and Rosenfeld (1986) in the evaluation of the FACE II echo data found that the echo cores treated within 5 minutes of first echo reacted more strongly to AgI than those treated after 5 minutes. Woodley and Rosenfeld (1989) found a similar result in the SW Texas experiment. In the sample of clouds from PACE 86, it was found that it is common in Illinois for echoes to be present below flight level for as much as 5-20 minutes prior to the echo extending upward to the treatment level (Westcott, 1989). For the three experimental units in 1986, the mean time from first echo to treatment was 17, 4, and 9 minutes respectively. The mean time from first echo at the flight level to treatment time, however, was 7.5, 4.6 and 7.3 minutes for those three units.

As was stated earlier, about 75% of the clouds treated were echoing at or before treatment with about 50% of the clouds were echoing more than 5 minutes prior to treatment. Of the AgI clouds, about 26% echoed more than 10 min. before treatment, and
Figure 6. Frequency Histograms for AgI and Sand Cores for mean echo diameter at the time of first echo and at the time of treatment, stratified by the Degree of Merger at First Echo, strongly merged (SM), loosely joined (LJ), or Isolated (I).
of the sand clouds, about 40% echoed 10 min. prior to treatment. Echo parameters at the
time of treatment are presented for echo cores forming at or within 5 minutes of treatment
and for echoes forming more than five minutes before treatment (Table 5; Fig. 7). In
comparing changes in height, area and reflectivity between first echo and the cloud pass
time, only echoes forming before treatment are included in the group of echoes less than
5 minutes old (Table 5; Fig. 8 and 9).

The median value for sand cores was greater for all categories of echo parameters.
The differences were significant for those parameters specific to the time of treatment. The
magnitude of the difference in median values was comparable for those forming within 5
minutes and for those forming more than 5 minutes before treatment. That is, the
magnitude of the difference did not appear to increase for older echoes. Echo core growth,
(the change in height and area, and the rate of change of height from first echo to
treatment) was significantly larger for the sand than the AgI treated cores in the older
category of echoes. While the trend was also present in the younger cores the differences
were not found to be significant; possibly because the samples of cores was reduced by about
a third from the total sample in this comparison. As the difference between the height, area,
and reflectivity of sand and AgI treated cores was present for both age groups at the time
of treatment. Hence, the difference in the echo parameters at the time of treatment was
probably not dependent on the age of the echo core.
Table 5. Median values of echo parameters stratified by the age of the echo core at treatment. The P-value is from the Wilcoxon Rank Sum Test.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age ≤ 5 min.</th>
<th>Age &gt; 5 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AgI</td>
<td>Sand</td>
</tr>
<tr>
<td>Sample</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>CPHtp10</td>
<td>6.5</td>
<td>8.0</td>
</tr>
<tr>
<td>CPmnDIA</td>
<td>2.6</td>
<td>4.5</td>
</tr>
<tr>
<td>CPMxZ</td>
<td>26.2</td>
<td>46.9</td>
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<tr>
<td>Sample</td>
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<td>7</td>
</tr>
<tr>
<td>CPFEdH10</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>CPFEdH/dt</td>
<td>.34</td>
<td>.43</td>
</tr>
<tr>
<td>CPFEdA10</td>
<td>8.0</td>
<td>16.0</td>
</tr>
<tr>
<td>CPFEdA/dt</td>
<td>1.9</td>
<td>4.1</td>
</tr>
<tr>
<td>CPFEdZ</td>
<td>10.3</td>
<td>10.5</td>
</tr>
<tr>
<td>CPFEdZ/dt</td>
<td>3.6</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Figure 7. Frequency Histograms for Agl and Sand Cores for echo top height and maximum reflectivity, stratified by the age of the echo core at the time of treatment.
Figure 8. Frequency Histograms for Agl and Sand Cores for mean core diameter and the change in echo
maximum area between first echo and treatment, stratified by the age of the echo core at the time of treatment.
Figure 9. Frequency histograms for Agl and Sand Cores for the change and rate of change of echo top height between first echo and treatment time, stratified by the age of the echo core at the time of treatment.
d. Summary

Echo properties have been examined at the time of first echo detection and at the time of treatment. This examination has indicated that the sample of echo cores which received sand flares were initially larger, and more reflective than those treated with AgI flares. At the time of first echo, this difference was observed in the mean echo diameter and in the maximum echo area. At the time of treatment, the difference was observed in the echo top height, the maximum reflectivity, the diameter of the core, and in the diameter and maximum reflectivity at the flight level. Differences also were observed in the rate of change of maximum area between first echo and the cloud pass time, where the sand treated cores were growing more rapidly in area than the AgI treated cores.

The degree of merger of echo cores at first echo and the age of the echo at treatment were also examined. About 50% of the AgI and sand treated cores were strongly merged at first echo, that is, they could not be distinguished from their parent cloud at their lowest boundary. The difference in the echo parameters at the time of treatment did not appear to be dependent on the degree of merger, however. Likewise, the difference in echo parameters at the time of treatment did not depend on the age of the echo core at treatment. The echoes were stratified by those forming within 5 minutes of treatment, and those forming more than 5 minutes before treatment, and in both categories, the sand echoes were larger than the AgI cores for the parameters specific to the time of treatment.
e. References


2. Cloud Physics Research

   a. Introduction

   There have been several noteworthy accomplishments of cloud physics research during this period. Software that was in development for processing, displaying, and analyzing PACE aircraft data was completed. In particular, software for classifying 2D image data was completed. This software which has an objective and an interactive subjective mode discriminates between drops and graupel using least squares polynomial approximation to image perimeter data.

   Aircraft data on thermodynamic, kinematic and microphysical properties relevant to ice and precipitation production in mixed-phased clouds encountered during the 1989 PACE field program were processed during this research period. This processing includes data for clouds that received either sand or AgI treatment, candidate clouds, and penetrations at temperatures colder than 0°C of other natural clouds. Images in all of the 2D image records were classified. Data analysis has initially focused on meeting two broad objectives of the research on Planned Modification of Clouds and Precipitation. The first objective has been to supply data in support of analysis to discern seeding effects. The second objective has been to improve understanding about the natural in-cloud conditions for seeding, about the natural initiation of ice, and models of how these might be altered by AgI seeding. Three basic research activities concerning summertime convective clouds in the Midwest have been initially addressed. The first activity has been to conducted a thorough review
of the literature concerning mixed-phased clouds which have active coalescence processes and initiate ice at temperatures warmer and concentrations larger than expected from ice nuclei. The purpose of this activity has been to provide a context from which to interpret the 1989 PACE aircraft data. The second activity has been to typify the microphysical, kinematic, and thermodynamic structure of Illinois clouds at the -10°C (seeding) level. The 1984 aircraft data set is the first modern set of measurements of in-cloud conditions specific to Illinois of clouds that visually appear to be suitable for seeding. The third activity has been to address the problem of first ice production in Illinois type clouds. The goal of these research activities has been to develop a better understanding about in-cloud conditions and precipitation mechanisms to better address questions related the dynamic seeding hypothesis on how the introduction of AgI seeding material might alter natural sub-cloud scale processes in ways that might alter cloud scale behavior, and thereby augment rainfall.

The remainder of this section is divided into 4 parts covering preliminary results of the research conducted over the past year. The first part presents background information on previous measurements of clouds which are comparable to those in Illinois because they typically contain supercooled drizzle and rain drops prior to the initial production of ice. The next part reviews the 1989 PACE aircraft data set within in the context of sample size, operational procedures, and instrumentation. The next part describes typical properties of Illinois clouds at the -10°C level. The next part describes initial finding about the
production of first ice in summertime convective clouds in Illinois. The last part lists references sited in this section.

b. Background on First Ice in Natural Clouds

i. Warm-based, Deep Convective Clouds: Midwestern Cumuli

Observational and laboratory results of clouds studied in South-Central Missouri during Project Whitetop unquestionably provide the most relevant findings to Illinois clouds, outside studies conducted as part or in conjunction with PACE research. In fact, comparison between Whitetop findings and observations taken as part of the 1986 PACE field experiment (Czys 1991) show many similarities but data were for clouds that occurred in Indiana and Missouri. As part of Whitetop, observations of clouds were made over four summers, and several important findings were reported. There were three major findings from Whitetop that are relevant to Illinois clouds

1. Whitetop clouds frequently initiated precipitation in the form of drizzle-size drops through the warm-rain process (Brown and Braham 1963);
2. Snow pellets (graupel) were present in Whitetop clouds at temperatures as warm as -6°C (Hoffer and Braham 1962). Laboratory study of the freezing of drops from the melt of ice collected near the top of Whitetop clouds indicated that these pellets probably did not originate from heterogeneous freezing upon mineral nuclei;
(3) Study of the hydrometeors collected during 1960 and 1961 summers of Whitetop led to the conclusion that the snow pellets probably originated from freezing of the drizzle drops produced by the coalescence mechanism (Koenig 1963). This sequence of events was later referred to as the coalescence-freezing mechanism (Braham 1986).

ii. Warm-based, Deep Convective Clouds: Florida and Tropical Cumuli

Data collected in mixed phased regions near the tops of cumuli during the 1975 Florida Area Cumulus Experiment (FACE) showed that the initiation of ice typically followed the first appearance of supercooled drizzle and rain drops (Hallett, et al. 1978). Concentrations of supercooled cloud droplets were very high (> 500 cm\(^{-3}\) at -10°) which are more on the order of that expected for continental clouds. This stands as a major difference between Florida and midwest cumulus; supercooled cloud droplet concentrations are less at the -10° C level. Graupel was the dominate initial ice form, and occurred in concentrations as high as 10 L\(^{-1}\). After the development of graupel, large numbers of pristine crystals were observed, and these ice crystals were believed to have originated as splinters from a riming-splintering process.

More recently, precipitation development was traced in the top of an isolated maritime cumulus tower off the southeastern shore of Florida, using data from four penetrations at successively colder temperatures (Willis and Hallett 1991). The aircraft was flown to track the development of precipitation in an ascending parcel of cloudy air.
Supercooled drizzle and rain drops were observed to develop from accretion and coalescence in the cloud top volume. These observations may be the first direct measure of in situ precipitation development, not advection of particles by the updraft from lower cloud regions. Even more importantly, they may be the first direct evidence of the action of a coalescence process (presumably accretion and self-collection) solely involving supercooled drops.

Formvar replicator data showed that the ice appeared only after the first appearance of large supercooled drops, and consisted of graupel and partially frozen drops, just as was the case in Project Whitetop and FACE. No pristine ice was found in the replicator data. Two mechanism were proposed for ice nucleation: (1) mixing at cloud top which results in an excess wet bulb temperature that activates additional ice nuclei, and (2) conditions for rime-splintering. It is worthy to note that the course of ice development is quite different than the convective clouds observed in the 1975 FACE observations (Hallett et al. 1978) in that ice crystals were not observed in prolific numbers.

iii. Shallow Maritime Cumulus and Cumulus Congestus in the South Pacific

A series of reports have been made on precipitation development in maritime cumulus around the southern Pacific near Australia. In the first of this series was the reports on the characteristics of a single inversion limited cumuli off the south coast of Australia during the southern hemisphere spring (Mossop, et al 1968). This particular cumulus had a cloud base between 1.5 and 1.8 km, was entirely warmer than -4.5°C, and
produced a large number of columnar crystals. Although, the presence of these columnar crystals was emphasized, supercooled drizzle and rain drops were also present from the time of the first penetration, and initial ice forms (such as frozen drops and graupel) were also observed. Thus, although the observation of large numbers of columnar crystals was emphasized, the evidence was consistent with the development of ice along with, or following the production of supercooled drizzle and rain drops.

Next, Mossop, et al. (1970) reported on observations made in the upper region, approximately 0.3 km below cloud top, of small supercooled cumulus off the Tasmanian coast in May 1968 (southern Hemisphere Fall). A total of 114 clouds on 9 days were measured. Cloud base temperatures ranged from 5 to 0°C. Narrow clouds, those approximately less than 3 to 4 km in diameter, contained only liquid hydrometeors. Clouds with larger diameters contained ice. The relationship between the presence or absence of ice and cloud width was interpreted to indicate that the presence of ice was related to length of time that suitable conditions for ice production existed, and this in turn was a function of width. Graupel and ice crystals were the dominant first ice forms. Observed maximum ice concentrations of up to 100 L⁻¹ were reported, and found to be independent of cloud top temperature over the range -5 to -15°C. Such concentrations were greater than ice nuclei by a factor of 10³. Thus, these clouds were "generally capable of producing drizzle drops simultaneously with, or even preceding, the first precipitation through the ice phase."
Measurement of 53 southern hemisphere Fall and Winter maritime cumulus and stratocumulus sampled over or near the Australian mainland supported previous finding for similar south Pacific clouds (Mossop, et al. 1972). Penetrations were made approximately 0.3 km below cloud top. Cloud base temperatures ranged from 3 to 10°C for the cumulus, and were -3 to -10°C for the stratocumulus. Cloud depths were generally 2 km. As was the case for their earlier observations (Mossop et al. 1970), no evidence was found that ice concentrations were related to cloud top temperature as is shown in Fig. 1 reproduced from data provided in Mossop et al. (1970, 1972). Ice concentrations were found to increase with increasing cloud width (see Fig. 2 reproduced from Mossop et al., 1970, 1972).

Finally, Mossop (1985a) reported on observations of small cumuli, approximately 2 km deep, with base temperatures of about 5°C, top temperatures of about -10°C, and maximum liquid water contents of around 1 g m\(^{-3}\). Consistent with previous observations of this type of cloud in this geographic area was the that large supercooled drops (D > 300 μm) appeared at the -5°C level at about the same time as large ice particles, implying initial ice production through the freezing of supercooled drizzle and rain drops,

iv. Maritime Clouds of the Pacific Northwest

There have also been a series of papers on observations of maritime clouds that occur off and around the coast of the State of Washington. These clouds are in many ways similar to those observed over the southwest Pacific. The first report is from measurements taken on 11 days of orographic maritime clouds (Hobbs 1969) which showed that the ratio
Figure 1. Cloud summit temperature versus maximum ice crystal concentration.
Figure 2. Cloud width versus maximum ice crystal concentration.
of ice particles to ice nuclei in clouds actually decreased with decreasing cloud top temperature. This is noteworthy because it is the only observation for clouds of this type where a temperature dependence was observed for ice nucleation, and has not again been reported for any subsequent northeast Pacific cumulus.

Data have also been presented which showed that maximum ice concentration in mature and aging maritime bears no dependence on cloud top temperature (Hobbs and Rangno 1985). This observation was based on measurement of 90 cumuliform and 72 stratiform clouds. Maritime cumulus ranged in depth from about 1 to 5 km. Cloud base temperatures ranged from -6 to 10°C. Some these clouds had very cold tops, -20 to -25°C, with an occasional cloud top as cold as -30°C. Continental cumulus had ice concentrations higher than expected from ice nuclei, but show a temperature dependence roughly parallel to that for ice nuclei activity. A threshold parameter, $D_T$, representing the broadness of the supercooled cloud droplet spectrum showed that maximum ice concentrations were well correlated to the broadness of the cloud droplet spectrum. Maximum ice particle measurements were defined to be the peak values of the ice particle concentrations measured with an OPIC, and averaged over a time interval of at least 15 s. An obvious increasing relationship exists between $I_{MAX}$ and $D_T$ (see Fig. 3). The data also showed that as the concentration of cloud droplets with diameters greater than 20 μm increased so did $I_{MAX}$. 

$I_{MAX}$.
Figure 3. Threshold diameter versus maximum ice particle concentration.
The validity of invoking the mechanism of rime splintering (Hallett and Mossop 1974) to explain the discrepancy between concentrations of first ice and ice nuclei was called into question. The most damaging evidence was that only 65% of the clouds with enhanced ice concentrations met all the laboratory criteria for rime-splintering. Clouds most often did not meet criteria because they contained insufficient concentrations of cloud droplets less than $13 \mu m$. Some clouds did not meet the -3 to -8°C temperature criteria. Other ice initiation mechanisms were explored. It was concluded that fragmentation was probably not an important process. Contact nuclei was considered to be possible, since evaporation might have generated ice nucleating aerosol from complete evaporation of the smallest drops, and because conditions conducive to phoretic capture of contact nuclei can also occur. Freezing by evaporative shock when drops greater than $20 \mu m$ are subjected to the dry entrained air was also considered. However, it was later argued (Telford, et al. 1987) that the data from Hobbs and Rangno (1985) did not support the idea that "big" drops with ice will cause a rise in ice particle concentrations. Telford et al. argued that even though higher concentrations of "big" drops can be expected as cloud depth increases, (implying an increased time for coalescence), the data showed that average ice concentrations decreased with depths greater than 1 km.

Measurements of ascending tops of maritime cumulus congestus made 30 km from the Washington coastline have shown high ice particle concentrations development after the production of supercooled drizzle and rain drops, presumably by coalescence (Hobbs and
Rangno 1990). Ice concentrations were found to increase from 0 to more than 350 L$^{-1}$ in 9 minutes, and from less than 1 to approximately 1100 L$^{-1}$ within in 12 minutes. These rapid increases imply rates of ice production in excess of that conventionally expected from rime-splinter production. Hence these observations were again taken to cast doubt on the validity of invoking a rime-splintering process although a "super" rime-splintering process was not ruled out.

Extensive description of each penetration was given in Hobbs and Pangau (1990) which generally supported the observation that ice appeared in "prodigious" concentrations after the formation of supercooled drizzle drops. The production of ice in these clouds was viewed as a two stage process. Stage I was characterized by frozen drops ($< 400$ μm) and small graupel. Stage II was characterized by high concentrations of vapor grown ice crystals. It was hypothesized that the second stage of ice production occurred in localized pockets of cloud where supersaturation may be 5%-10% above water saturation, and that the removal of large numbers of cloud droplets may produce these large supersaturations. In these regions rapid ice nucleation was supposed to occur to produce ice crystal concentrations greatly in excess of those measured by ice nucleus counters, which are generally operated close to water saturation.

Hence previous observations of ice initiation in clouds with active supercooled coalescence process have several findings in common. One common finding is that first ice concentrations are not a function of cloud top temperature in clouds with active coalescence
processes. The production of ice usually follows the production of supercooled drizzle and rain drops. Ice enhancement ratios, the ratio of observed ice concentration to that expected from ice nuclei, of up to $10^3$ L$^{-1}$ have not been unusual and the dominate first ice form is usually frozen drizzle and rain drops, or graupel, suggesting these to be the source of first ice. Ice crystals have not been usually observed initially, but their complete absence can not be dispelled since capability to measure small ice has not always been adequate. None-the-less, ice crystals have usually been observed after the riming process has had time to operate. Finally, in-cloud conditions have not always been favorable for rime-splintering, so invoking a secondary process such as rime-splintering may not always be valid. Several other mechanistic explanations have been proposed to explain the discrepancy between first and ice nuclei, but none are completely satisfactory.

c. The 1989 PACE Aircraft Data Set

Table 1 summarizes the number of penetrations made during the course of the 1989 PACE field experiment. Aircraft data collection began on 7 May and end on 25 July 1989. The data reported on herein were obtained from penetrations at approximately the -10°C shortly after cloud top pasted through flight level. No penetrations are reported of clouds when their tops were greater than 5000 ft above flight level. Therefore, the data on the properties of updrafts mostly reflect the result of precipitation processes that occurred in rising parcels of cloudy air. In all, 121 different cloud penetrations have been processed, 68 penetrations of clouds with diameters $\geq 3$ km, and 53 penetrations of clouds with diameters
Table 1. Statistics on ALL EUs, All Updrafts for First Ice Data

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total penetrations</td>
<td>121</td>
</tr>
<tr>
<td>Total with cloud &gt;= 3 km</td>
<td>68</td>
</tr>
<tr>
<td>Total with cloud &lt; 3 km</td>
<td>53</td>
</tr>
<tr>
<td>&quot;A&quot; penetrations</td>
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</tr>
<tr>
<td>&quot;A&quot; penetrations with cloud &gt;= 3 km</td>
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</tr>
<tr>
<td>&quot;A&quot; penetrations with cloud &lt; 3 km</td>
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</tr>
<tr>
<td>&quot;B&quot; penetrations</td>
<td>20</td>
</tr>
<tr>
<td>&quot;B&quot; penetrations with cloud &gt;= 3 km</td>
<td>20</td>
</tr>
<tr>
<td>&quot;B&quot; penetrations with cloud &lt; 3 km</td>
<td>10</td>
</tr>
<tr>
<td>Total Updrafts</td>
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<tr>
<td>Total with cloud &gt;= 3 km</td>
<td>146</td>
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<td>Total with cloud &lt; 3 km</td>
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<tr>
<td>&quot;A&quot; updrafts</td>
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<td>&quot;A&quot; updrafts with cloud &gt;= 3 km</td>
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<tr>
<td>&quot;A&quot; updrafts with cloud &lt; 3 km</td>
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</tr>
<tr>
<td>&quot;B&quot; updrafts</td>
<td>47</td>
</tr>
<tr>
<td>&quot;B&quot; updrafts with cloud &gt;= 3 km</td>
<td>43</td>
</tr>
<tr>
<td>&quot;B&quot; updrafts with cloud &lt; 3 km</td>
<td>4</td>
</tr>
</tbody>
</table>
< 3km. The sample of clouds is roughly divided into two categories. The first category consists of clouds whose vertical motion easily carried cloud top to levels above 30,000 ft. These are refer to as "A" clouds or "A" penetrations. The second category consisted of clouds that were topping out at, or slightly above the -10°C level. These clouds are referred to as "B" clouds or "B" penetrations. There were 101 "A", and 20 "B" category clouds. Fifty eight of the 8 clouds had diameters ≥ 3 km, and 43 had diameters < 3 km. Of the 20 "B" clouds, 10 had diameters ≥ 3 km and 10 had diameters < 3 km.

A light twin engine airplane (Beechcraft Baron) was used to collect the in-cloud data. This airplane was equipped with a full compliment of cloud physics, thermodynamic and kinematic instrumentation. Cloud physics instrumentation included a Forward Scattering Spectrometer Probe (FSSP) set to measure cloud particles in the 0 to 45 μm diameter size range in 3 μm intervals, and Particle Measuring Systems (PMS) 2DC and 2DP optical array probes. Temperature was measured using a Rosemont and reverse flow thermometers. Dew point was measured using an EG&G cooled mirror hygrometer. Vertical wind was computed according to a method described by Lawson (1979) using measurements of the airplane angle of attack, pitch and vertical acceleration. Two estimates of cloud liquid water content were obtained, one computed from the FSSP data and another using a Johnson-Williams hot wire probe.
d. Typical Properties of PACE Clouds at the -10°C Level

The typical cloud in the sample of PACE89 clouds was an isolated cumulus congestus. These were usually feeder clouds, prior to merging with a cumulonimbus entity. Cloud diameters at the observational level, determined by using the FSSP data, ranged from 0.7 to 14 km, and averaged 3.8 km with sample standard deviation of 2.3. Figure 4 shows profiles of Vertical Wind, Thermal Buoyancy, and Liquid Water content from penetration 1 of cloud 8 on 23 July 1989 (or 723C08P1). Thermal buoyancy is the difference between in-cloud temperature and an environment temperature averaged over a 15 second length at a position approximately 5 km from cloud edge. Thermal buoyancy does not take into account loading by the solid and liquid condensate. Two measures of liquid water are given, the solid line is liquid water computed from the FSSP probe, and the dashed line shows liquid water indicated by the hot-wire probe.

Figure 5 shows two contour plots of the FSSP cloud droplet distribution. The upper plot is a contour of cloud droplet concentrations, and the lower plot is a contour of cloud droplet mass. Figure 6 shows a plot of precipitation-size particle size encountered along the penetration. Each solid circle represents an individual observation of a particle determined from either the 2DC or 2DP records. The upper panel was created from images which were classified has "drops" even though some images may have been recently frozen drops because they displayed a smooth circular outline. The lower panel was created from 2D images which were classified as ice, either graupel or large ice crystals. Data in the lower
Figure 4. Profiles of vertical velocity, thermal buoyancy, and liquid water content.
Figure 5. Contour plots of cloud droplet size distribution and cloud droplet mass distribution.
Figure 6. Diameter of precipitation-size particles versus time (position) in cloud.
panel of Fig. 6 roughly corresponds to data for graupel since concentrations of particles classified as ice crystals, aggregates, or fragments was extremely small. Figure 7 shows relative concentrations of 2DC and 2DP images classified as drops. Figure 8 is similar to Fig. 7 except that it applies to 2D data on ice. Relative concentrations are provided since sample volumes and particles counts were too small on a second-by-second basis to compute a statistically meaningful concentration.

There are several noteworthy features in Figs. 4 to 8 which are representative of properties of most of the other clouds in the sample. These features are:

1. A multiple updraft structure, usually with one main updraft (magnitude and strength) and with one or more adjacent updrafts, downdrafts, and shear zones;
2. Updraft velocity can be substantial with peaks up to 10 or 15 m s\(^{-1}\);
3. Thermal buoyancy is both positive and negative, and usually shows some correlation with the updraft and downdraft regions;
4. Positive Thermal buoyancies of up to 4°C were typical;
5. Liquid water contents of up to 3 g m\(^{-3}\), with minimum occurring in regions of downdrafts, and maximums associated with updraft regions, corresponding effects on the cloud droplet size and mass distribution were also appreciable;
6. A substantial amount of the condensate is in the form precipitation particles.

It was not unusual to encounter drops or graupel with diameters greater than
Figure 7. Relative concentration of liquid particles versus time (position) in cloud.
Figure 8. Relative concentration of precipitation size ice particles versus time (position) in cloud.
300 μm, and as is shown in Fig. 6 the production of very large rain drops up to 3 or 4 mm diameters were encountered. Note that the largest drops encountered on this penetration also correspond to the portion of the forward looking video tape that very large splash marks can be seen on the aircraft windshield. Hence, the large circular smooth images were probably correctly classified as drops. Note also that, because the observations are early in cloud life cycle, and because there was little cloud top above flight level, these drops were most likely produced by coalescence, rather than representing melted graupel.

(7) The substantial amount of condensate in the form of precipitation-size particles is indicative of substantial updraft loading.

Hence, these data typify clouds which initiated precipitation by coalescence. Furthermore, the coalescence process, involving accretion and self collection (Berry and Reinhardt, 1974), must have continued after the water was lifted above 0° C and supercooled. The lack of large pristine ice crystals, and presence of millimeter size graupel is also an indication that ice initiation was through the freezing of supercooled drizzle and rain drops, and that this observation is consistent with the coalescence freezing process (Braham, 1986), although the exact mechanism which caused the drops to nucleate ice is not yet known.
The data were first examined to determine if a relationship exists between the coldest possible cloud temperature and total concentration of "first" (detectable) ice. Such a relationship can be expected if the mechanism for ice initiation is temperature dependent as it would be if ice-forming nuclei (IFN) were solely involved. Figure 9 shows a plot of estimated cloud top temperature versus total ice concentration for each of the updrafts containing ice in the 1989 PACE sample. There are three notable features of Fig. 9: 1) total ice concentrations are not related to cloud top temperature, 2) the largest ice concentrations are not related to cloud top temperature, and 3) minimum concentrations are at least those expected from IFN.

The lack of evidence for a temperature dependence on concentrations of "first" ice may suggest that either 1) a temperature independent primary ice nucleation process was responsible for the production of ice, or that 2) a secondary process completely overwhelmed the initial conversion of supercooled water-to-ice. Finally, cloud top temperature is not a good predictor variable for the onset of detectable ice in midwestern clouds.

As mentioned earlier, maximum ice concentrations have been found to be well correlated with the broadness of the supercooled cloud droplet spectrum for mature and aging maritime clouds that were no colder than -6°C. (Hobbs and Rangno, 1985; Rangno and Hobbs, 1991). This relationship was shown in Fig. 3. As earlier indicated, \( I_{\text{MAX}} \) was
Figure 9. Estimated cloud top temperature versus total ice concentration.
defined to be peak value of the ice particle concentrations measured with an Optical Ice Particle Counter (OIPC). Ice concentrations were averaged over a time interval of at least 15 seconds (approximately 1 km of cloud penetration distance). Threshold diameter ($D_T$) was defined such that the cumulative concentration of droplets with diameters greater than or equal to 3 cm$^{-3}$ as measured with the FSSP and 10 cm$^{-3}$ as measured with the ASSP. The solid line in Fig. 3 was determined from a least squares fit to the data, and has the form:

$$I_{\text{max}} = \left( \frac{D_T}{18.5} \right)^{8.4}$$  \hspace{1cm} (1)

For comparison, we have plotted threshold diameter versus ice concentration for PACE89 cumulus, and this is shown in Fig. 10. It was not possible in our analysis to use the exact definitions of Rangno and Hobbs (1991) for $I_{\text{max}}$ or $D_T$ because an OPIC and an Axially Scattering Spectrometer Probe (ASSP) were not available for the 1989 PACE measurements. We therefore defined $D_T$ strictly on the basis of FSSP measurements such that the cumulative concentration of droplets with diameters greater than $D_T$ was 3 cm$^{-3}$. Furthermore, we used total ice concentration as defined in Fig. 9, since it was not possible to determine a statistically significant one second change in ice concentration within an updraft on the basis of 2D imaging data. The solid line in Fig. 10 is a plot of Eq. 1.

Figure 10 clearly shows that the largest ice concentrations in the updrafts of PACE89 clouds coincide closely with the maximum expected on the basis of threshold cloud droplet diameter. While the 1989 PACE data gives support to the idea that the largest ice
Figure 10. Threshold diameter versus total ice concentration.
concentrations may be linked to the broadness of the supercooled cloud droplets spectrum, the 1989 PACE data also show that there were many updrafts which have ice concentrations which fall between the minimum expected from primary ice nuclei and the maximum expected based on $D_T$. Thus, although $D_T$ may be a good indicator of the maximum ice concentration, it is not a good general indicator of ice concentrations.

The possibility that a secondary ice process such as rime-splintering was also explored. The rime-splintering mechanism was demonstrated in laboratory experiments that showed the ejection of secondary ice crystals when supercooled droplets froze onto an ice substrate (Hallett and Mossop 1974). Subsequent laboratory work indicated that certain physical criteria must be met for the process to operate. For example, the process has been determined to be temperature dependent in that ice splinters were produced at temperatures between -3 and -8°C, with peak production at approximately -5°C (Hallett and Mossop 1974). Droplets larger than 25 μm (Mossop and Hallett 1974) and droplets smaller than approximately 13 μm (Mossop 1978) must be present. The rate of ice splinter production has been found to be proportional to the rate of sweep out of droplets larger than 25 μm (Mossop 1976), and has been found to be sensitive to the velocity of the riming body (Mossop 1976). Finally, the rate of splinter production has been found in laboratory experiments to be influenced by the surface temperature of the riming body (Heymsfield and Mossop 1984; Foster and Hallett 1982) rather than by the environment temperature. Hence,
splinter production may occur anywhere that the surface temperature of the riming body falls in the temperature range of -3 to -8°C.

The possibility that a correlation might exist between concentrations of cloud droplets and ice concentrations was explored. Figure 11, 12, and 13 are plots of ice concentration versus concentration of droplets smaller than 13 μm, concentration of droplets larger than 25 μm, and total concentration of supercooled cloud droplets as indicated by the FSSP. Although the scatter in each figure is large, ice concentrations appear to decrease with increasing concentrations of droplets. The correlation coefficients for the data in each figure is 0.57, 0.52, and 0.60, respectively. The solid line through the data in each figure is a least squares fit. For the case of total ice concentrations, the equation for the least squares fit (y = 990.9 x \(^{-2.7}\)) can be rearranged to obtain the same general form as Eq. 1 or

\[
N_I = \left(\frac{N_d}{12.43}\right)^{-2.7}
\]

where \(N_d\) is the total concentration of supercooled cloud droplets per cm\(^3\), and \(N_I\) is the concentration (per liter) of ice larger than approximately 150 μm diameter.

Because reports from Project Whitetop (Braham, 1964), and more recently reports from maritime Florida cumulus (Willis and Hallett, 1991) have indicated that ice initiates after the presence of supercooled drizzle and raindrops. We extended our analysis to investigate for a relationship between the concentration of drops greater than 300 μm diameter and the concentration of ice. A plot of these two parameters is shown in Fig. 14.
Figure 11. Concentration of drops smaller than 13 μm diameter versus ice concentration.
Figure 12. Concentration of droplets larger than 25 μm diameter versus ice concentration.
Figure 13. Total concentration of cloud droplets versus ice concentration.
Figure 14 clearly shows that as the concentration of drops bigger than 300 μm increase so do ice concentrations. A least squares fit to the data yields an equation of the form

\[ N_I = \left( \frac{N_D}{0.22} \right)^2 \]  

Therefore, Eq. 3 may be a potentially better indicator of ice in midwestern clouds than Eq. 1 or 2 since it provides a general rule for ice concentration rather than a specific rule for maximum ice concentrations. The fact that ice concentrations do correlate very well with the concentration of drops greater than 300 μm is consistent with the hypothesis that ice originates from the freezing of supercooled drizzle and rain drops.

It is interesting to note that a similar relationship between the concentration of drops larger than 300 μm diameter and ice concentration somehow went overlooked in the data of Mossop et al. (1970, 1972). Figure 15 was created from data on mean and maximum ice concentrations tabularized, but not plotted in Mossop et al. (1970, 1972). The solid line in Fig. 15 is a least squares fit to the data and has the equation

\[ N_I = \left( \frac{N_D}{0.31} \right)^{.74} \]  

where \( N_I \) is concentration of ice per liter, \( N_D \) concentration of drops larger than 300 μm diameter.

Finally, Mossop et al. (1970, 1972) found that a relationship existed between cloud width and maximum ice concentration. They speculated that maximum ice concentrations
Figure 14. Concentration of drops larger than 300 μm diameter versus ice concentration from PACE 89.

\[ y = 19.9 \times^{2.0} \]
Figure 15. Concentration of drops bigger than 300 μm versus ice particle concentration for clouds in the S. Pacific.
generally increase with increasing cloud width because cloud width implicitly represented a
time for ice to develop under favorable conditions. For comparison, we have used mean
updraft speed and the depth of the 0 to -10°C layer to compute a time for a raising parcel
of air to ascend from 0 to the -10°C level and plotted this time versus the concentration of
ice observed in updraft. This plot is shown in Fig. 16. A least squares polynomial
approximation was applied to the data for polynomials of the order 1 through 5. A third
order polynomial was found to have the smallest variance to approximating the data.
Hence, although the data in Fig. 16 is scattered the best fit to the data has the equation

$$N_I = -0.009t^2 + 0.71t - 1.43$$

where t is time in seconds and $N_I$ is concentration per liter. As can be seen in Fig. 16, a
plot of this equation suggests that initially ice concentrations increase as more time becomes
available for ice production. Eventually, ice concentrations begin to decrease possibly
because updraft velocities become small, and hence, unable to transport the condensate load
aloft.

f. Review of Ice Initiation Mechanisms that May Operate in Illinois Cumulus

The observational evidence thus far obtained indicates that: (1) first ice occurs in
concentrations higher and at temperatures warmer than expected from conventional
measures of ice nuclei concentration, (2) first ice concentrations are independent of
temperature, (3) the species of first ice is usually in the form of frozen drizzle and rain
drops, and graupel; species such as vapor grown ice crystals are rare even though adequate
Figure 16. Time to travel from the 0°C isotherm to the -10°C isotherm versus ice concentration.
time is available for detection, (4) maximum ice concentrations are related the broadness of the distribution of supercooled cloud droplets; however, ice concentrations in general are not correlated with $D_T$, and (5) concentrations of "first" ice are positively correlated with concentrations of supercooled drizzle and rain drops. Therefore, the first appearance of ice in supercooled clouds seems to come about from the direct freezing of supercooled drizzle and rain drops, which is then followed by graupel growth by riming as was first indicated by data collected in Project Whitetop (Braham 1964). However, the exact mechanism(s) responsible for freezing the first few drops remains unclear.

Several mechanisms for ice nucleation will now be discussed,

i. Ice Nuclei Measurement Uncertainty

As is well known there are three primary modes of heterogeneous ice nucleation. Ice in clouds may nucleate heterogeneously by: (1) contact nuclei, (2) immersion nuclei, and (3) sorption nuclei. All three modes may simultaneously occur in clouds although one mode may dominate over the others depending upon physical conditions. It is generally agreed that no measurement technique adequately reproduces conditions for all modes of heterogeneous ice nucleation, and that more than one method must be employed in order to obtain a comprehensive measure. Therefore, the discrepancy between concentrations of first ice and ice nuclei may simply be related to a poor capability to measure ice nuclei, or that measurement techniques have not adequately reproduced special conditions, such as ultra-high water supersaturations, that may develop in localized regions in clouds. However,
the lack of any temperature dependence on ice concentration in the observational evidence in the PACE89 sample, and other observations in which a supercooled coalescence process were important (Czys, 1991), suggests that ice nuclei may be unimportant in the production of first ice in these clouds.

ii. Contact Nucleation

This mode of ice nucleation may eventually prove to be important for cloud regions, such as downdrafts and cloud edges, where mixing plays an important role and phoretic forces act to drive aerosol toward evaporating surfaces (Baker, 1991; Young, 1991). Rosinski and Morgan (1991) have recently proposed a plausible mechanism that begins with the evaporation of the smallest cloud droplets in mixing regions. This process results in the production of a transient population of sorption ice nuclei that may be active at temperatures as warm as -4°C. These residual ice nuclei may then act as contact nuclei in drop freezing by inertial capture or may act as condensation followed by freezing nuclei. Once nucleated these ice crystals may either grow undisturbed by vapor deposition, or may be captured by a supercooled drizzle or rain drop. However this mechanism probably does not explain the high ice concentrations in this analysis became observations were restricted to updraft regions where evaporative effects are minimal.

iii. Immersion Nuclei

In this mechanism ice initiates by the direct freezing from an ice nuclei immersed within the supercooled water. Assuming that measurement techniques have resulted in an
underestimation in the concentration of this type of nuclei, some temperature dependency in concentration can still be expected if this mode is dominant. Furthermore, drop freezing experiments conducted by Hoffer and Braham (1962) have shown the freezing temperature of the melt from ice collected near the top of cumulus clouds was considerably colder than the coldest possible temperature of the cloud; assuming that handling and preparation of the ice did not alter the activity of the immersed ice nuclei. Electron microscopy did not show the presence of clay mineral of the type found in the center of snow crystals by Kumai (1957, 1961). Thus, the onset of ice by immersion or contact nuclei could not be demonstrated.

The fact that first ice concentrations show no relation to cloud temperature may be an indication that natural ice nuclei are not important to the onset of ice. Also, the lack of temperature dependence in first ice concentrations may also be an indication that the discrepancy is not simply an underestimation of concentrations ice nuclei by conventional methods since the chemical physics of that nucleations process dictates temperature (and supersaturation) dependence. Supporting evidence is the finding that ice nuclei activity spectra takes on the same general form as that for CCN (Huffman 1973) concentrations in certain supercooled clouds without active coalescence processes, and that some clouds where supercooled drizzle and rain drops are not present do show a temperature dependence (Mossop 1985b). Rosinski and Morgan (1991) have reported from laboratory experiments that sorption ice-forming nuclei may be produced when cloud droplets evaporate, and that
the activity of these as ice nuclei is much higher if the nuclei are subjected to high water supersaturations. However, this mechanism should show an ice concentration dependence on temperature. The possibility that ice originated from the action of contact nucleation has also been ruled out on the basis of numerical simulation (Young 1974) as well as analytical consideration of phoretic forces (Baker 1991) which has indicated that nucleation should preferentially occur in regions of evaporation, such as downdrafts or cloud edges, not in updrafts where evaporative effects can be suspected to be minimal,

iv. Secondary Ice Production by Rime-Splintering

We have also investigated the possibility that a secondary ice production by rime splintering mechanism operated to account for the discrepancy between first ice and ice nuclei. In this mechanism, a few drizzle and or rain drops freeze in accordance with that expected from immersion and or contact nuclei. These frozen drops go on to accrete supercooled droplets to produce graupel particles. In the process of riming growth ice splinters are produced which subsequently may either nucleate other supercooled drizzle and rain drops. Some may survive and grow strictly by vapor deposition. The detection of large numbers of vapor grown columns and needles in the later stage of development of Florida cumuli (Hallett et al. 1978), as well marine stratocumulus (Hobbs and Rangno 1990) can be interpreted as residual ice from Hallett-Mossop which escaped from capture by supercooled drops.
As is fairly well known laboratory work has indicated that several criteria must be met to permit a rime-splintering process to operate. The process has been found to be temperature dependent, only operating in the temperature range from -3 to -8°C, peaking at about -5°C (Hallett and Mossop 1974). This temperature dependence has been found to be modified by the release of latent heat depending on whether conditions for wet or dry graupel growth exist. The mechanism has also been found to operating in the sensitive to the presence of cloud droplets less than 13 \( \mu \)m diameter (Mossop 1978), in addition to the criteria that droplets greater than 25 \( \mu \)m must also be present (Mossop and Hallett 1974). Apparently, the presence of these drop sizes determines the frailty of the rime as it grows on the graupel surface and thus is related to the rate of splinter production (Harris-Hobbs and Cooper, 1987). The extent to which this process is important in the production of ice in Illinois clouds is uncertain. On the one hand, Illinois clouds usually meet the criteria for the Hallett-Mossop mechanism, in that cloud passes through the -3 to -8°C level and that large and small supercooled cloud droplets are almost always present. However, as was shown in Figs. 11 through 13, a negative relationships was found to exist between cloud droplet and ice concentrations. Whether this negative trend contradicts a rime-splintering process, or reflects the effect of altered surface temperature of the rime particle by accretion and latent heat release deserves further consideration. However, the later may be unlikely since liquid water contents are generally much smaller than required for a surface
temperature effect according to laboratory and modeling results reported by Heymsfield and Mossop (1984).

v. Primary Ice Production by Collision-Freezing

The nucleation of ice in supercooled water dynamically, either by shock waves, sonic vibrations or mechanically is a well established fact (see for example Barnes 1906 or Dorsey 1938). The possibility that freezing may occur from collisions between supercooled drops probably first received attention as a possible ice initiation mechanism at the First Conference on the Physics of Cloud and Precipitation Particles (Blanchard 1957). Later, Hobbs (1965) speculated that collision and subsequent rapid freezing of supercooled fog droplets was a possible mechanism for the type of ice aggregates (two or more adhered spherical ice particles) photographed in supercooled fogs. Alkezweeny (1969) presented data from a Continuous Particle Replicator which apparently showed precipitation-size drops which may have frozen on contact with one another (in collision) prior to replication. This replicator data, collected in isolated cumulus around Flagstaff Arizona during the summer of 1968, is shown in the upper half of Fig. 17. Finally, Czys (1989) reported on simple laboratory experiments in which millimeter size supercooled drops where made to freeze by mechanical shock and examined cavitation as a possible mechanism for ice nucleation.

Motivated by these observational and laboratory findings, the 2DC and 2DP image records obtained during the 1989 PACE field experiment were examined for images which might have been created by the shadow of particles in the form of those identified by
Figure 17. Observational evidence of collision-freezing.
Alkezeeny (1969). The lower portion of Fig. 17 shows two image records, one from the 2DC and the other from the 2DP which contain examples (indicated by arrows) of these types of images dubbed "double images". The 2D image records from the 121 cloud penetrations have been examined for this form of particle image. A total of 98 double images were identified in 28 cloud penetrations. As part of the classification procedure the diameter of the large and small parts of double images were recorded and these diameter pairs are plotted in Fig. 18 as open triangles. The two solid squares are data reported by Alkezweeny (1969). Solid lines in Fig. 18 are lines of constant Weber Number, a non-dimensional measure of drop deformation and indicator of impact pressure. The shaded region corresponds to drop sizes where the impact pressure may be sufficient for cavitation, and hence, freezing (see Czys 1989). Fig. 18 suggests that if collision-freezing is represented by the images identified in the 1989 2D image records and the 1969 replicator data, then the mechanism may operate over a wide range of precipitation-size drops, but be limited to very high size ratios. Therefore, collision-freezing cannot yet be ruled out as a possible ice mechanism in Illinois clouds, and deserves further investigation.

\[ g. \quad \textbf{References} \]


Figure 18. Sizes of small and large particles from double images found in 2D data.


3. Forecasting Research

a. *Forecasting coalescence activity in Illinois Clouds using thermodynamic data*

A simple objective procedure to forecast the occurrence, tallness and coalescence activity of summertime convective clouds was developed and tested as part of the 1989 PACE field program. This procedure, based on use of morning values of the temperature of the convective condensation level \( T_{\text{CCL}} \) and potential buoyancy \( \text{PB} \), has been evaluated with respect to forecasting convective occurrence and tallness (Changnon et al. 1990; Scott and Czys 1989). During this research period, processing of aircraft data was completed, allowing for evaluation of the procedure to forecast the presence or absence of supercooled drizzle and rain drops at the -10°C seeding level. The presence of supercooled drizzle drops is one requirement for a cloud to be suitable for dynamic seeding because drops of this size represent a substantial reservoir of latent heat, act as graupel embryos when frozen, and act as a brake on the updraft. Therefore, prior knowledge about the potential presence or absence of supercooled drops at the seeding level is desirable.

The objective forecasting procedure used in the 1989 PACE field experiment was developed from the finding that the amount of coalescence activity in the convective clouds of Eastern Transvaal was strongly linked to thermodynamic conditions (Mather et al. 1986). From analysis of 3 years of microphysical measurements, 2D images of drops greater than 300 μm diameter were found at the -10°C level in 40% of 42 storms measured. Furthermore, the presence of supercooled drizzle and rain drops around the -10°C seeding
level was strongly related to cloud base temperatures (CBₜ) and buoyancies. Mather et al. defined a parameter called potential buoyancy (PB) as the difference at 500 mb between the pseudoadiabat through cloud base and the environment temperature. Potential buoyancy is a close cousin to Lifted Index. Figure 1 has been reproduced from Mather et al., and shows the separation between storms that had clouds with large (D > 300 μm) drops at the -10°C level, and storms that had clouds which did not, according to CBₜ and PB. In Fig. 1, open circles represent cases where the 2D imagery from a mission showed images of large drops, and x's indicate missions during which large drops were not encountered. Mather et al. determined a discriminator function, \( L \), from this data

\[
L = b_0 + b_1 CB_T + b_2 \Delta T_{500}
\]

where the coefficients \( b_0, b_1 \) and \( b_2 \) were chosen to maximize differences between drops and no drops when \( L = 0 \) (Panofsky and Brier 1958). Even allowing for the possibility that some of the large, smooth images that they interpreted to be liquid drops may have been recently frozen, the discriminator line in Fig. 1 provides a clear indication that the presence or absence of supercooled drizzle and rain drops at the -10°C level is related to cloud base temperature and potential buoyancy.

The distinct separation between days with clouds that develop supercooled drizzle and raindrops and those that do not, is physically related to the length of time for coalescence to operate, implicit in the CBₜ, PB parameter space. Cloud base temperature represents a depth between the cloud base and the 0°C isotherm. As cloud base becomes warmer, this
Figure 1. Buoyancy at 500 millibars versus cloud based temperature.
depth increases, and thus, a greater distance exists over which coalescence processes can operate, assuming that all other factors are equal. Potential buoyancy, unadjusted for the lessening effects of entrainment and condensate loading, implies an updraft velocity, and thus, constitutes a measure of the potential strength of the updraft. Thus, when cloud base temperature (distance) and potential buoyancy (velocity) are taken in combination, they represent a time or duration for coalescence to operate. If this time is short, either because the updraft velocity is large, or cloud base is cold, or both, the likelihood that the cloud will produce drizzle and rain drops before cloud top reaches the 0°C level is small. Hence, the likelihood that drizzle and rain drops will be produced improves as updraft velocity and depth between cloud base and 0°C combine to result in a longer time for coalescence to operate.

Therefore, the parameter space of Fig. 1 well represents physical variables related to the production of rain by coalescence, and we would thus expect the data on the presence and absence of drizzle and rain drops in convective clouds to separate according to CB_T and PB, regardless of the geographic location. Hence, the results shown in Fig. 1 for Eastern Transvaal should have application to Illinois particularly since the distribution of cloud based temperatures for Illinois (Johnson 1982) is very similar to those for South Africa (Mather et al. 1986). Thus, summer convective storms in Illinois should have supercooled rain drops present at -10°C on days when CB_T and PB intersect above L=0 in Fig. 1, and should be absent on days when CB_T and PB intersect below L=0. Evaluation
of \( L \) as a predictor of supercooled drizzle and rain drops is presented in the last part of this section.

In the development of our forecasting technique, use of \( CB_T \) was abandoned in favor of the temperature of the convective condensation level (\( T_{CCL} \)) since our experience indicated that this parameter is well correlated to \( CB_T \) and because it is easily obtained from the NWS morning sounding.

On each day during the 1989 PACE field program a value of \( L \) was computed using

\[
L = 8.6 - T_{CCL} + 1.72PB
\]

which is a specific solution for Eq. 1. In our procedure, we forecasted that at least some clouds encountered during a mission would have supercooled drizzle and rain drops at the -10°C seeding level if the value of \( T_{CCL} \) and \( PB \) in Eq. 2 produced a negative value of \( L \), which roughly corresponds to the region of open circles in Fig. 2. In developing this technique we speculated that the concentration of supercooled drizzle and rain drops may vary with \( L \). Otherwise, our objective forecasting procedure indicated that it was not likely for convective clouds to have supercooled drops bigger than 300 mm diameter at the -10°C level. Therefore, using \( T_{CCL} \) and \( PB \) with Eq. 2 provided an indication of the likely presence or absence of supercooled drops bigger than 300 mm at the -10°C seeding level.

To verify this forecast we kept daily track of \( T_{CCL} \) and \( PB \), and recorded whether supercooled drizzle and rain drops were present or absent at -10°C, whenever the aircraft was deployed to experiment with supercooled convective clouds. Figure 2 is a plot of the
Figure 2. Discriminator function, L, versus concentration of supercooled drops larger than 300 μm diameter.
discriminator function \( L \), specified by Eq. 2 versus concentrations of drops larger than 300 mm diameter observed in the updrafts encountered during the mission (open circles). The large vertically striped squares are plotted at the median values of the concentrations for each mission. A least squares polynomial approximation was applied to the median data for polynomials of order 1 through 5. A 3rd order least squares polynomial was found to best approximate the median values of drop concentrations and is written

\[
\log(N_{D>300}) = -3.5 \times 10^{-4}L^3 - 4.0 \times 10^{-2}L^2 - 5.4 \times 10^{-1}L - 2.1
\]  

(3)

where \( N_{D>300} \) is the concentration of drops (per liter) greater than 300 \( \mu \)m diameter, and \( L \) is the value of the discriminator function (Eq. 2) calculated from sounding data on the morning of each mission. The variance of this polynomial approximation was 0.40, the lowest variance for tests of polynomials of order 1 through 5. Substitution of Eq. 2 into Eq. 3 yields

\[
\log(N_{D>300}) = -10.0 - 2.3PB - 0.15PB^2 - 0.002PB^3 + 1.31T_{CCL} + 0.17PB \cdot T_{CCL} + 0.003PB^2 \cdot T_{CCL} - 0.05T_{CCL} - 0.002PB \cdot T_{CCL} + 0.004T_{CCL}^3
\]  

(4)

which yields supercooled drop concentration directly from values of \( PB \) and \( T_{CCL} \). Equation 4 has been plotted as a solid line in Fig. 2 and runs approximately through the median values.

As can be seen in Fig. 2, supercooled drizzle and rain drops were encountered in the updrafts of clouds on almost every mission, and that the concentration of large drops increases with decreasing \( L \). The fact that no median values are plotted for values of \( L \)
greater than approximately zero indicates that many of the updrafts on these missions had concentrations of supercooled drizzle and rain drops which were either less than 0.001 L\(^{-1}\) or 0 L\(^{-1}\). Hence median values fall below the range of the y axis in Fig. 9.

The plot in Figure 2 also suggests that the concentration of large drops may begin to fall off as values of \(L\) exceed approximately -10. If accurate, we speculate that this is because it becomes more difficult for the atmosphere to carry an increasingly massive water load aloft. Finally, if we chose to define the presence or absence of large drops by a threshold of 0.001 L\(^{-1}\), then our observations are consistent with those determined for the Eastern Transvaal shown in Fig. 1. Therefore, it appears that the discriminator function, \(L\), developed for the Eastern Transvaal not only gave a good indication of the presence or absence of large drops, but also provided a good indication of the median concentration of large supercooled drops that were encountered in updrafts at the -10°C level of 1989 PACE clouds.

\(b. \quad \text{Quantitative Analysis of Mesoscale Lifting: The Divergence of } Q\)

As part of the forecasting research conducted over the past year, we have adopted a procedure to obtain quantitative estimates of mechanical lifting on the mesoscale as indicated by the divergence of \(Q\) (Hoskins et al. 1978). Developing a procedure for making quantitative estimates of vertical motion was important for two reasons. First, mechanical lifting is important in the development of convective cloud systems in the Midwest because thermal instability alone is usually only a necessary requirement (Huff, 1981). Secondly, the
analysis of seeding effects needed a method to quantitatively diagnose days as similar or
different with respect to vertical forcing.

The co-equation has been commonly used to express vertical forcing in the atmosphere
and is written

\[ N^2 \nabla_h^2 \omega + f^2 \frac{\partial^2 \omega}{\partial z^2} = f \frac{\partial}{\partial z} (V_g \nabla \zeta_g) - \frac{\phi}{\theta_o} \nabla_h^2 (V_g \nabla \theta) \]  

(5)

As is well known the co-equation expresses forcing of vertical motion by the derivative of
vorticity advection and the horizontal Laplacian of thermal advection. Hoskins et al. (1978)
has pointed out that the shortcoming of the co-equation in this form is that there can be
cancellation between these two terms, and the terms in isolation can be misleading when
attempting to diagnose magnitude, and under certain circumstances, the sign of the
vertical velocity.

In order to overcome this shortcoming, Hoskins et al. (1978) redrived the co-equation
taking into consideration the tendency for geostrophic motion to destroy thermal wind
balance. From this rederivation, a form of the co-equation which is identical to that on the
left hand side of Eq. 1 was obtained, but in terms of a parameter Q on the right hand side
or

\[ N^2 \nabla_h^2 \omega + f^2 (\partial^2 \omega/\partial z^2) = 2 \nabla.Q \]  

(6)

where Q is defined as the vector rate of change of horizontal potential temperature gradient
on a fluid particle from geostrophic motion alone. From this approach, vertical motion in

64
the atmosphere is forced solely by the negative divergence of $Q$. For ease of use, Hoskin et al. (1978) developed the equation for use in a Cartesian coordinate system with $x$ axis tangential to the potential temperature contour at the point where $Q$ is to be calculated and the $y$ axis points towards colder air. In this coordinate system, $\partial \theta / \partial x = 0$ and Eq. 6 becomes

$$Q = \left[ -\frac{\partial u_y}{\partial x} \frac{\partial \theta}{\partial x} - \frac{\partial u_x}{\partial y} \frac{\partial \theta}{\partial y} - \frac{\partial v_y}{\partial x} \frac{\partial \theta}{\partial y} - \frac{\partial v_x}{\partial y} \frac{\partial \theta}{\partial y} \right]$$

(7)

Initial analyses of $Q$ were conducted at 700 mb with the intention of identifying mid-level short waves, important to the initiation of convection on days with a conditionally unstable structure. Fig. 3 shows a spatial distribution of $Q$ vectors, and contours of $Q$ convergence for 23 June 1989. Areas of negative divergence correspond to areas of lifting motion.

It should be noted that clouds and or precipitation was reported for each area of negative convergence. Analysis of $Q$ vector maps were generated for each experimental unit day during the 1989 field program and these are shown in Appendix B. Analysis of the $Q$ vector maps suggests that convergence of $Q$ provides an excellent instantaneous indication of areas with precipitation in addition to a good objective measure of the strength of vertical lifting forces for use in analysis of seeding effects.
c. References


4. Seeding Effects Research

During this period we initiated research directed toward understanding the effects of AgI seeding on cloud (echo core) behavior. Our first step in this analysis was to review the literature to determine which predictor and response variables had been used in previous summertime cloud seeding experiments. The purpose of this review was to assist in selecting analysis variables for the 1989 PACE data set such that meaningful comparisons could be made with previous summertime cloud seeding experiments. The review focused on six past experiments: (1) Australian Isolated Cumulus Cloud Project, (2) Project Whitetop, (3) Stormfury, (4) Florida Area Cumulus Experiment, (5) Florida Area Cumulus Experiment - re-evaluation, and the (6) South West Texas Cooperative Project. Table 1 lists response variables used in previous experiments. In Table 1 a "+" indicates a positive response even though it may not have been statistically significant, an "0" indicates no response, a - indicates a negative response. Blank cells in Table 1 indicate that particular response variable was not included in the experiment. Table 2 lists predictor variables from the same experiments listed in Table 1.

The next step in our analysis was to create a master set of predictor and response variables for the 1989 PACE experiment. Variables were selected if they (1) described important characteristics about the cloud/echo core at the time of treatment that indicate of future cloud growth, (2) responses that could be compared to results from previous experiments, or (3) responses that can be expected according to the dynamic seeding
hypothesis. Predictor variables originated from aircraft, radar, and synoptic data. In all we identified a grand total of 182 variables, 149 of which were predictor variables and 33 of which were response variables. A glossary of these variable names and definition is given in Appendix A.

We then initiated analysis to determine if the population of sand and AgI treated clouds were similar at the time of treatment, and thus, could be expected to experience similar future cloud growth. A summary of the results of this analysis is given in Appendix B. In brief, we found that the clouds had some differences in their properties at the time of treatment in ways which might influence future cloud growth; sand treated clouds were found to be generally "brighter" and more vigorous. We also found that the suitability of the clouds for dynamic seeding may have changed over the course of the experiment, at least according to a subjectively established set of criteria. Hence, these preliminary findings illustrate that the large inherent natural variability in conditions from the microscale, to cloud scale, and the mesoscale makes it extremely difficult to obtain to similar populations, inspite of following a randomization scheme which provided us with about equal numbers of sand and AgI treated clouds, and provided a set of alternating sand and AgI treated experimental units. Hence, future research has been focused on developing a satisfactory methodology which will account for the difference in the sand and AgI clouds at treatment, and thus make comparison of the response of the two populations to seeding provide an indication of seeding effect.
Summary of Evaluation Parameters from "Single Cloud," Warm Cloud Base Projects

Table 1. Response Variable Used in Previous Summertime Cloud Seeding Experiments

<table>
<thead>
<tr>
<th>Response Variables</th>
<th>AICC</th>
<th>WTp</th>
<th>StF</th>
<th>FaceS</th>
<th>Face2</th>
<th>SWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>First echo tops</td>
<td></td>
<td>o</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># Echoes reach ground</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Estim. Rain</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max RER near cld base</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Max Area near cld base</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Refl. near cld base</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td>o</td>
</tr>
<tr>
<td>Duration of echo/eld</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Max echo/eld top</td>
<td></td>
<td>o</td>
<td>o</td>
<td>+</td>
<td>+</td>
<td>o</td>
</tr>
<tr>
<td>Avg. amt of cld growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td># echoes/elds wh/grow</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td># merger events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>

+ indicates positive response, no matter how (insignificant
o indicates no difference
- indicates negative response
x indicates the data were examined for seeded clouds only

AICC - Australian Isolated Cumulus Cloud Project
WTp - Whitetop - area experiment - re-eval of simple cores
StF - Stormfury - single cloud
FaceS - Florida Area Cumulus Experiment - single cloud experiment
Face2 - Florida Area Cumulus Experiment - re-eval of area exper.
SWT - South West Texas Cooperative Project
### Table 2. Predictor Variables Used in Previous Summertime Cloud Seeding Experiments

<table>
<thead>
<tr>
<th>Predictor Variable/Project</th>
<th>AICC</th>
<th>WTp</th>
<th>StF</th>
<th>FaceS</th>
<th>Face2</th>
<th>SWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cld Top T &gt;-10 C</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cld Top T &lt;-10 C</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Time Fe to CP &lt;5 min</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time FE to CP &gt;5 min</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily Max Top 20-40 kft</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily Max Top &gt;40 kft</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Clds Grow &gt; 31 kft</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time during seeding</td>
<td>-</td>
<td></td>
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</tr>
<tr>
<td>Time 0-5 hr post</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days w/ S winds</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Days w/ W winds</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Time: seed to 40 min</td>
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<td>Shear prevent growth</td>
<td>-</td>
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<tr>
<td>Sounding types:</td>
<td></td>
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</tr>
<tr>
<td>Suppressed Growth</td>
<td>-</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cut off tower Growth</td>
<td>-</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Explosive Growth</td>
<td>+</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Large Natl Cld Growth</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echo Cover &lt; 12.7%</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Echo Cover &gt;12.7%</td>
<td>-</td>
<td>-</td>
<td></td>
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</tr>
<tr>
<td>Predictor Variable/Project</td>
<td>AICC</td>
<td>WTp</td>
<td>StF</td>
<td>Face S</td>
<td>Face 2</td>
<td>SWT</td>
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<td>---------------------------</td>
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</tr>
<tr>
<td>Rel. Humid Layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>cld base to 700 mb</td>
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<td>+</td>
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<tr>
<td>700 mb to 500 mb</td>
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<tr>
<td>Static Stab. Layers</td>
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<td></td>
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<tr>
<td>cld base to 700 mb</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 mb to 500 mb</td>
<td></td>
<td>+</td>
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<td></td>
<td></td>
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<tr>
<td>500 mb to 400 mb</td>
<td></td>
<td>-</td>
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<td></td>
</tr>
<tr>
<td>400 mb to 200 mb</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large burners</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td>Small burners</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flares &lt;9</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flares &gt;9</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
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</tbody>
</table>
INADVERTENT MODIFICATION OF THE ATMOSPHERE

The rapidly growing interest in the subject of global climate change has raised concern and renewed interest in the Midwest, and Illinois specifically, about the causes, magnitude, and consequences of inadvertent weather modification. That is, those atmospheric processes that are altered by human activities and in turn, can lead to changes in clouds and precipitation over local to mesoscale areas. Water Survey research during the 1970s and early 1980s addressed effects of major metropolitan areas, power plants, and jet contrails on clouds and precipitation.

1. Urban Influences

As a result of growing state interests in inadvertent weather and climate modification, project scientists have directed increased attention to these processes. In 1988 we initiated research on several key questions as yet unresolved. For example, METROMEX precipitation data from the transition seasons (fall and spring) and winters of 1971-75 were utilized to investigate for the first time the possible existence of urban influences at St. Louis on precipitation during these seasons (Changnon et al. 1990a). Prior research of urban effects on clouds and precipitation had focused on the summer season. These recent studies revealed that the St. Louis metropolitan area, over a 5-year period, had led to increased fall precipitation by 17% in downwind areas, increased spring precipitation by 4%, but had not influenced the winter precipitation at any detectable level. Furthermore, the enhancement during the fall and spring seasons occurred only during convective periods. Because
convective rainfall represents 72% of the total average precipitation in the Midwest, it is important to understand and estimate the impacts of urban modification of weather conditions.

2. Contrails Research

Another area of research initiated during 1990 and pursued in 1991 concerned the effect of jet contrails leading to the development of widespread cirrus. Potential effects of contrails on cloud cover has been found, based on surface observations. Project scientists recently initiated studies utilizing satellite data to identify U.S. regions of major contrail incidence in a 3-year study period (De Grand et al. 1990). This probing study has revealed that the Midwest, the southwestern U.S., and the northwestern U.S. were the nation's primary areas for contrail-induced outbreaks of cirrus shields. This information has allowed us to launch more definitive studies of the development and temporal evolution of contrails into major cirrus shields in the Midwest. Since cirrus clouds can affect precipitation formation and are key elements in the global energy balance, improved understanding of the dimensions of aircraft effects on cirrus in the Midwest is a key topic under investigation.

The objective of this research has been to investigate many cases when areas of persistent contrails developed into broad cirrus shields. Project-related research in 1990-91 consisted of a study to determine prime regions for contrail formations utilizing satellite data for 1977-79. This research provided three major findings including: 1) that the major regions for contrail formation in all four seasons were located in the Midwest, the Southwest,
and the Pacific Northwest; 2) that the seasonal variations in the contrail occurrences were largely a function of latitudinal shifts in the westerlies and jet stream position; and 3) that for incidences of major contrail-cirrus outbreaks, the general tropospheric temperature and moisture conditions were distinctly different from those just before and after the extended contrail-cirrus period.

The ongoing contrail-cirrus climate research included: 1) study of contrail persistence and temporal evolution utilizing 1985-87 satellite data; and 2) evaluation of the atmospheric conditions required for contrail formation (satellite and conventional atmospheric data). We obtained, for the period of April 1985-April 1987, the 2.7-km resolution DMSP imagery to inventory contrail occurrences over the U.S. for each mid-season month (e.g., January, April, July, and October). The 1-km DMSP data are limited for this time period. However, the 2.7-km data enabled major contrails to be identified. We then obtained AVHRR 1.1-km resolution digital data for contrail outbreak times, as identified from the periods based on the DMSP analysis. The AVHRR data are from NOAA-9 and NOAA-10. They overlap from the period November 1986 to present, and then have different ascending and descending times (NOAA 9: 1420 and 0220 local time; NOAA 10: 1930 and 0730). Thus, for those months, we are analyzing the temporal evolution of contrails into cirrus shields.
1. **Effect of Varying Summer Rainfall on Crop Yields in Illinois: Implications for Rainfall Modification**

   **a. Introduction**

   During this past research period, data collected during 1987 to 1990 from the agriculture plots were integrated and analyzed. This section reports on the results of this analysis. The analysis addressed two issues. First, to define the influences of varying amounts of summer rainfall on Illinois corn yields and soybean yields. Second, to discern how altered rain levels and resulting changes in crop yields, relate to various other climatic, operational, economic, and legal factors that collectively affect rain modification endeavors in Illinois and other areas of similar climate and soils.

   Increases in rainfall during the summer season (June through August) were applied to agricultural plots located in central Illinois to measure the range of yield outcomes during 1987-1990. The objective was to gain insight as to the best and worst water treatments (amount and timing) for use in the design, operations, and the evaluation of purposeful weather modification experiments. The results also were seen to have value in gaining a better understanding of weather-crop relationships, and for estimating the effects of future climate changes and irrigation applications of water.

   Frequency of days with severe storm warnings in central Illinois, classified according to different levels of rainfall, were determined to define how these events would affect rain
modification endeavors. Climatic analyses were performed to define the rain-day conditions during summer since the rain enhancement-yield testing was based on different rain levels. Operational needs to modify (seed) clouds in a typical project area were also determined.

b. Investigation of Rainfall-Crop Yield Relationships

i. Field Project Description

The agricultural plots used in this study were located on the South Farm of the University of Illinois in Champaign, Illinois. These plots are on prairie soils (silty clay loam) typical of those found in the Corn Belt. Sixty plots were used for the 4-year experiment. Thirty plots were assigned for soybean testing and 30 for corn. The variety of corn was a Mo17 x B73 Cross, and a Williams variety of soybeans were grown. Each plot was 3 x 3 meters and had a separate sprinkler located in its center. The water applied to each of the 60 plots was controlled by a system that used de-ionized water delivered from the central control and supply system.

There were ten water treatments selected for application to the corn and to the soybeans. Three plots, selected at random, received each water treatment. For example, three plots got treatment #1 for corn, and three plots received water treatment #1 for soybeans. The operations were conducted during June 1 - August 31 of each year. After each rain occurred and was measured upon its ending, the increased water amounts were applied according to the treatment design and actual amount of rain which had fallen.
The treatments were selected based on a wide range of rainfall enhancement capabilities which might someday exist in Illinois. Cloud seeding results with summer rainfall in other climatic zones suggested that rainfall increases under certain rain conditions, might be developed to be in the range of 10 to 25% increases above the naturally-occurring summer rainfall. Thus, we chose to apply water increases including 10%, 25%, and 40% of actual rainfall. The treatments chosen are listed in Table 1. Three were uniform applications of 10%, 25% and 40% to all rains that occurred in the summer. Others selected were increases added only to light rains (≤0.1 inch), only to moderate rains (0.1 to 1.0 inch), and only to heavy rains (>1.0 inch). The range of treatments chosen bracketed all possible outcomes for purposeful rainfall modification as to magnitude of the increase and the rainfall conditions during which increases might occur or be agriculturally desirable,

ii. Field Conditions During 1987-1990

The field experiment was conducted during 1987-1990. A 4-year sample is at the mercy of the weather conditions which occurred before, during and after the experiment. Previous research has suggested that the most critical rainfall for corn and soybeans in Illinois is during June through August (Changnon and Huff 1971). In most years, the growing season in the deep prairie soils begins with adequate soil moisture. Seldom does any significant moisture depletion occur during the late April - May portions of the growing season. Thus, rainfall during June, July, and August is considered most critical of the growing season and with the greatest impact on crop yields.
Table 1. Definitions of Rainfall Treatments Used on Agricultural Plots for all Rain Events (Days) During June through August.

<table>
<thead>
<tr>
<th>Treatment I.D.</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Actual rainfall</td>
</tr>
<tr>
<td>2.</td>
<td>Actual plus 10% to all rains</td>
</tr>
<tr>
<td>3.</td>
<td>Actual plus 25% to all rains</td>
</tr>
<tr>
<td>4.</td>
<td>Actual plus 40% to all rains</td>
</tr>
<tr>
<td>5.</td>
<td>Added 40% to &lt;.25 cm rains (0.1 inch)</td>
</tr>
<tr>
<td>6.</td>
<td>Added 40% to daily rains in range of 0.25 (0.1 inch) - 2.54 cm (1.0 inch)</td>
</tr>
<tr>
<td>7.</td>
<td>Added 40% to rains ≥ 2.54 cm (1.0 inch)</td>
</tr>
<tr>
<td>8.</td>
<td>Added 10% only to rains ≥ 2.54 cm (1.0 inch)</td>
</tr>
<tr>
<td>9.</td>
<td>Added 10% to daily rains in range of 0.25 - 2.54 cm (0.1 to 1.0 inch)</td>
</tr>
<tr>
<td>10.</td>
<td>Added 25% to daily rains in range of 0.25 - 25.4 cm (0.1 to 1.0 inch)</td>
</tr>
</tbody>
</table>
Assessment of the temperature conditions experienced during the past four years has revealed that a wide range of temperature conditions were experienced as shown in Table 2. These ranged from near record high temperatures during 1988 to much below average conditions in 1990. Also shown in Table 2 are the number of days with 90° or higher temperatures in each year and the average number. These temperatures reflect the major crop stress days. Their highly varying counts reveal the wide range of temperature conditions sampled in four years, from hot (1988 and 1991), to near average, to cool (1989 and 1990).

The lower portion of Table 2 presents the precipitation conditions experienced during 1987-1990. These also reveal a very wide range of amounts, from near average summer rainfall in 1989 to the second driest summer on record in 1988. Above average rainfall occurred in 1987 and 1989. The frequencies of moderate (>0.5 inch) and heavy (> 1.0 inch) rain days are also shown since they too are critical to crop yields.

The summers of 1987 and 1989 presented an interesting contrast, one being relatively warm and wet, and the other being relatively cool and comparably wet. The summer of 1988 was an extremely hot and dry summer, whereas the summer of 1989 had very average summer weather conditions. The relatively short sample of summer weather conditions provided a wide range of conditions.
Table 2. Monthly Weather Conditions at Champaign during 1987-1991 and their Climatological Departures

<table>
<thead>
<tr>
<th></th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean dep&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>Days &gt;90°</td>
<td>Mean dep&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>Days &gt;90°</td>
</tr>
<tr>
<td>1987</td>
<td>+2.7</td>
<td>8</td>
<td>+0.4°</td>
<td>9</td>
</tr>
<tr>
<td>1988</td>
<td>+1.5</td>
<td>16</td>
<td>+2.9</td>
<td>18</td>
</tr>
<tr>
<td>1989</td>
<td>-0.4</td>
<td>4</td>
<td>±0</td>
<td>7</td>
</tr>
<tr>
<td>1990</td>
<td>+0.2</td>
<td>6</td>
<td>-2.0</td>
<td>4</td>
</tr>
<tr>
<td>1991</td>
<td>+3.9</td>
<td>11</td>
<td>+1.0</td>
<td>12</td>
</tr>
<tr>
<td>1851-80 Avg temp</td>
<td>71.9°</td>
<td>75.2°</td>
<td>73.1°</td>
<td>73.4°</td>
</tr>
<tr>
<td>1951-80 Avg days ±90°</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Dep&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>Days &gt;1in.</td>
<td>Total Dep.</td>
<td>Days &gt;1in.</td>
</tr>
<tr>
<td>1987</td>
<td>+1.07</td>
<td>3</td>
<td>+3.5</td>
<td>1</td>
</tr>
<tr>
<td>1988</td>
<td>-3.60</td>
<td>0</td>
<td>-0.71</td>
<td>1</td>
</tr>
<tr>
<td>1989</td>
<td>+1.10</td>
<td>2</td>
<td>-2.57</td>
<td>0</td>
</tr>
<tr>
<td>1990</td>
<td>+4.41</td>
<td>3</td>
<td>-0.72</td>
<td>1</td>
</tr>
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<td>1991</td>
<td>-3.26</td>
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<td>4.35</td>
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</tr>
<tr>
<td>Average</td>
<td>3.92</td>
<td>1</td>
<td>4.35</td>
<td>1</td>
</tr>
</tbody>
</table>

(1) Monthly mean temperature expressed as departure from 1951-80 average.
(2) Monthly total rainfall expressed as departure from 1951-80 average.
There were certain operational problems experienced at the plots during the four years. In July 1987 a strong thunderstorm with major downdrafts caused considerable blowdown damages to the corn crop. The damage was so great that it terminated the 1987 corn experiment.

In late July 1987, there was a 4.5-inch rainfall of short duration which nearly flooded the soybean plots. No rain treatments were applied after this singular event. In 1988, the spring and early summer were exceptionally warm and dry, and by late June the corn plants were withering and dying. To save the plants, additional water applications amounting to 1.6 inches were applied to all corn plots between June 18 and 22. This effectively increased the natural rainfall.

iii. Analysis of Yields

Two ways were used to assess the effects of the different rainfall treatments on the crop yields. One was based on an intercomparison of the average yields obtained over the sampling period for the ten treatments. The second approach sought to measure the consistency of the treatments performance; that is, their relative performance (yield level) in the individual years. This was important because it is possible for a treatment to provide good yields in two of three years but produce relatively bad yields in another year, or vice versa, depending on the actual weather conditions experienced. The performance of a treatment between years varies depending upon the level and timing of the natural rainfall. That is, a large rainfall increase in a dry summer may be very beneficial to crop yields,
whereas as that same increase during a wet year may be detrimental by making the soils too wet and decreasing yields.

We compared the ranking of the average yields for the total experimental period, and we compared their performance based on the individual annual yields and their consistency between years.

iv. Corn Results

a. Rank Scores of Annual Corn Yields

Table 3 presents the relative ranks of each treatment for the three years of corn experimentation, 1988-1990. For each treatment, the annual yields were ranked, and these rank scores were summed to form a rank sum. These sums were then ranked and compared (Table 3). For example, the no-increase rainfall treatment (Treatment I.D. #1 in Table 1) produced a yield that ranked eighth highest amongst the ten treatments in 1988. Then, the no-increase rain-related yield ranked third best in 1989 and in 1990. The rank sum score of these three ranks was 14. Treatment 8, (10% increases to ≥ 1-inch rains), which had a rank sum score of 10, had the best performance treatment.

Several conclusions can be reached from these rank scores. First, only three rainfall treatments performed better than the no-rain increase treatment. These were treatments 8, 9, and 10. The individual annual ranks shown in Table 3 were then inspected for relative consistency, classed as those being generally all high, all low, or mixed. One of the three better performing rain treatments, 10, showed the greatest consistency from year-to-year.
Table 3. Analysis of Annual Corn Yields 1988-90

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1989</th>
<th>1989</th>
<th>1990</th>
<th>Sum of Ranks</th>
<th>Rank of Sum Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>14</td>
<td>3-4</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>28</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1</td>
<td>9</td>
<td>16</td>
<td>6-7</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>7</td>
<td>7</td>
<td>16</td>
<td>6-7</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>15</td>
<td>5</td>
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<tr>
<td>6</td>
<td>10</td>
<td>5</td>
<td>6</td>
<td>21</td>
<td>9</td>
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<tr>
<td>7</td>
<td>5</td>
<td>10</td>
<td>4</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>8</td>
<td>5</td>
<td>14</td>
<td>3-4</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>
The best performing treatment, number 8 with the lowest rank sum score, was excellent in two years (1989 and 1990) but poor (7th) in 1988. The other relatively good treatment, number 9, was best in 1988 but its yield was low ranked in 1989 and in the middle of the yield values of 1990. Hence, treatments 8 and 9 were less consistent from year-to-year than was treatment 10.

The rank sum scores were used to identify the treatments that gave poor corn yields. Analysis of the scores reveals that treatment 2 with a score of 28 was the worst, followed by treatment 6 with a score of 21. Inspection for consistency amongst the poorer performing treatments also reveals that treatments 2 and 6 were consistently low in all three years.

b. Evaluation of Average Corn Yields

Table 4 presents the average 3-year corn yields (1988-1990) for the 10 treatments. The treatments have been ranked from high to low based on the 3-year average yield. For example, treatment 10 with an average yield of 184 bushels per acre ranked highest. The most positive yield increases, classed as the treatments producing 6 bushels per acre or more above the no increase (natural) rainfall levels, included treatments 10, 9, and 4. The treatments providing "good" increases in yields, defined as at least two bushel per acre or more, were treatments 5, 7 and 8. Two of the treatments provided yields that were much lower than the that resulting from natural rainfall. These were treatments 2 and 6.
Table 4.  Ranks of Average Corn Yields for 1988-1990.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>bu/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>#10 (25% - 0.1 to 1.0 inch)</td>
<td>184</td>
</tr>
<tr>
<td>#9 (10% - 0.1 to 1.0 inch)</td>
<td>183</td>
</tr>
<tr>
<td>#4 (40% - to all rains)</td>
<td>182</td>
</tr>
<tr>
<td>#5 (40% to &lt;0.1 inch)</td>
<td>180</td>
</tr>
<tr>
<td>#8 (10% to &gt;1.0 inch)</td>
<td>180</td>
</tr>
<tr>
<td>#7 (40% to &gt;1.0 inch)</td>
<td>178</td>
</tr>
<tr>
<td>#3 (25% to all rains)</td>
<td>177</td>
</tr>
<tr>
<td>#1 (no increase)</td>
<td>176</td>
</tr>
<tr>
<td>#6 (40% to 0.1 to 1.0 inch)</td>
<td>172</td>
</tr>
<tr>
<td>#2 (10% to all rains)</td>
<td>162</td>
</tr>
</tbody>
</table>
c. **Summary**

The corn yields associated with the nine added rainfall treatments were assessed based on both their annual rank scores and their average yields. Based on this analysis, and on the consistency in the annual yield ranks, treatment 10 appears best in providing corn yield increases and for performing well in all years. There were two treatments that provided yield decreases and poor performance in all years. These were treatments 2 and 6.

v. **Soybean Analysis**

The same analysis was done for added water treatments to soybeans. Table 5 presents the rank of the annual yields for the years 1987-1990. For example, the yield with treatment 1 (no increase in natural rainfall) ranked second best in 1987, then fifth highest in 1988, first in 1989, and fourth in 1990, providing a sum of rank scores of 12. The scores based on the sum of rank reveal that the no-increase treatment to soybeans, over this 4-year period, was the best performing treatment. Only treatment 7 (40% more on days with > 1 inch) was as good overall and as consistently good in all years as was treatment 1.

a. **Rank Score Analysis**

The best rated treatments included treatments 1, 3, 5, 7, and 10. These five treatments all had similar close scores, ranging between 12 and 18, as shown in Table 5. Inspection of those that had relatively consistent ranks from year-to-year reveals that treatments 1, 3, and 7 were the most consistent. Treatments 5 and 10, which had low sums
Table 5. Analysis of Annual Soybean Yields during 1987-1990

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1987</th>
<th>1988</th>
<th>1989</th>
<th>1990</th>
<th>Sum of Ranks</th>
<th>Rank by Sum Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>13</td>
<td>1-2</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>5</td>
<td>29</td>
<td>7-8</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>2</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>31</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>13</td>
<td>1-2</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>29</td>
<td>7-8</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>9</td>
<td>1</td>
<td>7</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>4</td>
<td>10</td>
<td>3</td>
<td>18</td>
<td>5</td>
</tr>
</tbody>
</table>
(good scores), had major inconsistencies, each with two high ranking yield years and one low ranking yield year. For example, the yield with treatment 5 ranked third in 1987, third in 1988, then ninth in 1989, and then second in 1990. The annual yield responses are shown in figure 1. One notes how the yields tended to increase with total summer rainfall, at least up to about 16 to 17 inches. Thereafter, yields decreased as conditions become too wet.

The yields with the other five treatments, 2, 4, 6, 8, and 9, all had much higher rank scores and with scores very similar, 26 to 31. Treatments 2, and 6 were consistently bad in all years. Treatments 4 and 8 were each bad in two years but were near the middle of the yield distribution in two other years.

b. Average Soybean Yield Evaluation

Table 6 presents the rank order of the average yields from the ten treatments to soybeans. The no-change treatment was the best with an average yield of 44.63 bushels per acre. However, there were four treatments with yields very close to this value, with close defined as being within two bushels per acre of the best performance. These four better performing treatments were 3, 5, 7, and 10. The treatments producing the lowest yield responses, defined as those 4 or more bushels per acre below the best, were treatments 2, 4, 6, and 8.
Fig. 1. Relationships of soybean yields during 1987-1990, as grown on the open agricultural plots, with the ten rainfall treatments applied each year.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (no change)</td>
<td>44.63</td>
</tr>
<tr>
<td>3 (25% to all rains)</td>
<td>44.21</td>
</tr>
<tr>
<td>10 (25% to 0.1 - 1.0 inch)</td>
<td>43.16</td>
</tr>
<tr>
<td>5 (40% to &lt; 0.1 inch)</td>
<td>43.07</td>
</tr>
<tr>
<td>7 (40% to &gt; 1.0 inch)</td>
<td>42.39</td>
</tr>
<tr>
<td>9 (10% to 0.1 - 1.0 inch)</td>
<td>41.56</td>
</tr>
<tr>
<td>8 (10% to &gt; 1.0 inch)</td>
<td>40.30</td>
</tr>
<tr>
<td>6 (40% to 0.1 - 1.0 inch)</td>
<td>40.08</td>
</tr>
<tr>
<td>4 (All rains get 40%)</td>
<td>39.90</td>
</tr>
<tr>
<td>2 (All rains get 10%)</td>
<td>39.74</td>
</tr>
</tbody>
</table>
c. **Summary**

The best performing treatments for soybean yields during 1987-90 was no rainfall increase or 40% more to 1-inch rain days. They had high average yields and the they were consistently good performers in all four years. Treatment 7 (40% increases to rainfalls of 1-inch or more) rated best in 1988 and 1990, whereas treatment 10 rated first in 1987, third in 1990, and fourth in 1988. Treatments 5 and 10 were also generally good for soybeans but were less consistent between years than treatments 3 and 7. The treatments rated worst for soybean yields were 2, 4, 6, and 8.

vi. **Discussion**

Field studies of the effects of increased summer rainfall levels on crop yields were conducted in central Illinois during a 4-year period, 1987-1990. Sixty plots on the University of Illinois South Farms, each with an individually controlled watering device, were used for experiments with corn and soybeans.

The summer seasons experienced during this 4-year period provided a wide spectrum of weather conditions, ranges often not sampled in such a short period. The 1987 summer was relatively warm and quite wet; the 1988 summer had near record hot and dry conditions; the 1989 summer was notably average in both temperatures and rainfall, and the 1990 summer was cool and very wet. The conditions bracket well the hot/dry, normal, and cool/wet variety of summer seasons found in central Illinois over a period of many years. Although the sample size was relatively short from a climate standpoint, it sampled widely
varying conditions that affect these crops in varying ways. The 4-year sampling conditions for soybeans is considered adequate to define the rainfall-yields relationships. The 3-year sample for corn, with the loss of 1987 data due to crop damage from winds, is not as large as desired. The inclusion of the 1991 data when available, will be helpful for further defining the corn-rainfall relationships.

The ten rainfall treatments chosen provided a wide range of outcomes for rainfall increases, varying from 10% up to 40%, and bracketing the range of all possible rain enhancement capabilities envisioned for the Illinois area. These various levels of rain increase were applied to days with light rains only, to only days with moderate rains, and to only the days with heavy rains, as well as to all rain days during each summer. The range of treatments utilized encompass all possible outcomes desired.

The information generated from these experiments is seen as useful in three areas of application, in addition to obtaining improved knowledge of weather-crop yield relations. The findings have value 1) to decisions relating to irrigation applications; 2) to the design, operation, and evaluation of rainfall modification endeavors; and 3) to studies attempting to assess the influence of future climate change on Illinois crop yields.

a. **Assessment of Treatments to each Crop**

The value of the results for translation to irrigation operations apply to the findings for each crop. One can control separate water applications either to corn or to soybeans, seeking to optimize the effects of additional water.
The corn yield-rainfall results reveal that to achieve consistent benefits, treatments 10 and 9 were the best, closely followed by treatment 8. Analysis of average yields for the 3-year period supported these outcomes indicating that treatments 10 and 9 were the best. Treatments 2 and 6 were undesirable for enhancing corn yields in all years. Interpretation of these outcomes reveals that added water to increase corn yields is best when more water is applied to days when the natural rainfall is heavy, an inch or more, or when the natural daily rainfall is moderate, between 0.1 and 1.0 inch. Corn yields, on the average, were not benefitted by applying 40% increases to moderate rainfalls (0.1 to 1.0 inch), or 10% increases to all rains. Collectively, these results for corn indicate one should apply moderate rain (water) increases on days with moderate rainfall to gain yield benefits.

Analysis of the soybean responses revealed that in most years the no-rain increase or 40% to 1-inch rains were the overall best outcomes. However, there were two rain addition treatments that, in some years, were better. These included treatment 10 (25% to 0.1 to 1.0 inch rains), and treatment 3 (25% to all). The worst rain treatments for soybeans were 2, 4, 6, and 8. These related to too much water in the moderate rain range, or too small amounts of additional water. The important finding from the soybean-rain outcomes was that on a year-in and year-out basis, either no increase in rainfall or 40% to days with an inch or more rain were the best treatments. In dry years such as 1988, rain increases are needed with 40% to 1-inch being the best choice with other good choices being 25%
increases to all rains, and 40% increases to rains of 0.1 to 1.0 inch range.

b. Assessing Treatments Based on Consideration of Both Crops

The findings, as they apply to the utilization of precipitation modification, or for analyzing the possible impacts of climate change, must include an assessment of the treatments for both crops considered jointly. This means assessment of the treatments that are relatively good to yields of both crops and those relatively bad to both crops.

The performance of the ten treatments was classed, based on their rank sums and on the rank of the average yields, from high to low for both corn and soybeans. These values are shown in Table 7. This reveals very mixed outcomes for most treatments. The only relatively good treatment for both crops is treatment 10, with treatments 2 and 6 the worst for both crops.

c. Implications for Precipitation Enhancement in Illinois

The results relating to how corn and soybean yields responded to the ten different simulated rainfall treatments during summer were used in an analysis of precipitation modification. This analysis attempted to consider the scientific questions of rainfall modification, the results relating to the effects of added rainfall on crop yields, and other climatic, economic, logistic, and legal factors that affect precipitation modification activities.

Rainfall Modification Considerations: One must first couple climatic values of rain-days frequencies and the amount of rainfall they produce with the crop yield results to consider all other factors influencing the outcome. Rain-yield results indicated that the
Table 7. Assessment of Rain Treatments and Crop Yields

<table>
<thead>
<tr>
<th>Rank</th>
<th>Corn</th>
<th>Soybeans</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (best)</td>
<td>#10</td>
<td>#1</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
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<td>8</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>10 (worst)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
optimum rainfall increase in all years was 25%, with yield increases occurring if 25% increases occurred in the heavier rainfall events, typically those ≥0.2 inch.

Involved in a mix of what the climate presents and the crop yield responses to added rainfall, are these other factors. They include the capability of seeding clouds during different types of rain days; the logistic implications of this including aircraft and other facilities required to deliver seeding materials to candidate clouds; and the resultant costs and benefits.

In addition to these climatic, logistic, and economic factors, are the public relations and legal aspects of cloud seeding. The current Illinois law regulating cloud seeding activities does not allow seeding in areas during periods when severe weather warnings exist. This has been done to reduce public concerns that cloud seeding leads to damaging severe storms. This situation, in effect, reduces the number of opportunities for seeding.

*Effects of Varying Rainfall Increases:* An assessment of the three various levels of rainfall increases, including 10%, 25%, and 40%, was done since these represent the ultimate capabilities being sought by weather modification research. The treatments involving 10% rain increases included 2, 8, and 9. The assessment of the performance of the 10% increase treatments revealed they generally were not desirable. The 10% increase to all rains (treatment 2) is rated the worst of all ten treatments in both crops. Treatment 8 (10% to ≥ 1-inch rains) was good for corn yields but bad for beans; and treatment 9 was also good for corn and bad for beans. Thus, one could conclude that although 10% increases are not
helpful to both crops, 10% increases on days with moderate to heavy rains helped corn but, in turn, hurt soybean yields. One would clearly not recommend use of a weather modification capability that only achieved area-wide 10% increases in summer rainfall.

The assessment of the yields associated with 25% increases in rainfall also was based on two treatments, plus a synthesization of the value of 25% increases to rains greater than 1 inch. Treatment 10 (25% increase to rains of 0.1 to 1 inch) was easily the best overall rated treatment to both crops of the ten tested. Treatment #3 (25% increases to all rains) rated good on beans but weaker for corn yields. Data from treatments 7 and 8, which represent 10% and 40% increases in rain events of 1 inch or more, respectively, were used to interpolate results for corn and soybeans with a 25% increase to these heavy rains. Interpolation of their rank scores indicated that a 25% increase in rain days of ≥ 1-inch would rate in the "good category" (estimated rank of 4 on a scale of 1 to 10). The results indicate that 25% increase in 1-inch or heavier rainfalls is highly desirable. In summary, soybean yields are helped by 25% rain increases applied in all classes of rain days, and corn yields are helped by 25% increases on days of moderate to heavy rains, but not in light rains.

The analysis of 40% rainfall increases was based on three treatments, 4, 5, and 7. These bracketed a wide range of rainfall conditions. The outcomes of the results of 40% increases revealed a very mixed yield response. The 40% increases on days with light rain had some value. However, 40% increases on all rain days, or just on heavy rain days,
presented very different outcomes between the two crops. For example, 40% increases to all rains was rated as good/average treatment for corn yields but a bad treatment for soybeans. Conversely, a 40% increase on days with 1 inch or more rainfall rated as good for beans but bad for corn. However, it is important to note that 40% increases are beneficial to both crop yields during extremely hot/dry summers like that in 1988.

*Value of Modifying Rainfall in Different Daily Rainfall Classes:* Another way to use the yield results for the assessment of rainfall modification activities is to classify the outcomes by the daily rainfall amounts, including light, moderate, and heavy rain days. Yield results indicated that there is little value in increasing light rains (0.01 to 0.1 inch) unless 40% or larger rain increases can be accomplished. Increases in rainfall on days of moderate rainfall (0.1 to 1.0 inch) are useful to crops if increases of 25% can be achieved. Increases of 40% tend to damage soybean yields.

Increases in rainfall on heavy rain days (≥1.0 inch), other than in a dry summer, produce very mixed outcomes. Small increases, 10% to these heavy rain days, show benefits to corn but not to soybeans, whereas 40% increases are helpful to beans but of very little value to corn yields. Interpolation of the effect of 25% increases to heavy rains indicated this level of increase would be useful to both crops if it was produced on heavy rain days. In general, the results do not give encouragement for cloud seeding unless increases of 25% can be achieved.
Climate Factors: First, and relevant to interpretation of the crop yield data, one must consider the frequencies of rainfalls (days of rain) in various class intervals during the summer. The average rainfall conditions during June-August include the frequency of rain days and amounts of rain associated with them. The 0.01-0.1 inch class of rainfall at a point includes 8 rain days during the 92-day summer, and these 8 days produce, on the average, 0.55 inch of rainfall. The second class considered, 0.11 to 0.5 inch per day, has 9 days with rain in this class interval. These 9 days produce 2.9 inches of rain on the average. The third class considered were days with rainfalls ranging from 0.51 to 1.0 inch. Rains in this range occur on 5 days per summer and they produce, on the average, 3.65 inches of rainfall. The fourth class of rain days considered were those producing 1.0 inch or more. Rains in this range occur on the average, 3 days per summer, and these 3 rain days produce 4.0 inches of the total average summer rainfall. The summer total average values are 25 rain days producing 11.1 inches of rain, the long-term (1895-1991) average.

The climatology of the areal distribution of summer rainfall must be considered. For example, an area that would undergo cloud seeding to increase rain (typically 1,000 to 2,000 square miles) never has uniform rainfall amounts on summer rain days. Statistical analysis of summer-day rainfall values indicates that, on the average, rain days in a 2,000 square-mile area with a maximum point rainfall of 0.5 to 1.0 inch experience less than 0.1 inch over 55% of the area. This means that half of the area when a 25% increase in rainfall of 0.1- to 1-inch could be produced to aid crop yields, would not experience a benefit. That is, the rain-
yield relationships did not indicate yield increases at the lower rain (<0.1 inch) levels. On
days when the maximum point rainfall in the area (2000 mi²) is >1.0 inch; the area of ≤0.1
inch is on the average, 36% of the area. Typically, only 10% of the area receives ≥ 1 inch
when one inch or more occurs. These point-area relationships of rainfall coupled with the
rain-yield results, indicate that the economic value of attaining a desired rain increase over
an area, given a 25% increase could be accomplished to all rain in the area, would occur to
about 50% to 65% of the area on any given day.

Another climatic factor that affects the analysis of seeding opportunities and rainfall
increase potential, is the incidence of precipitation at night. On the average, 46% of all the
summer precipitation in Illinois occurs during nocturnal hours 2000 to 0600 LST (Changnon
and Huff, 1981). Current seeding technologies involving aircraft depend upon visual
observations of the clouds along with other measurements. Obviously, visual cloud
observations relating to cloud seeding can not be made during nocturnal hours. Thus,
candidate rain events occurring during the nocturnal hours can not be considered as
potential seedable conditions.

**Effects of Severe Storm Warnings:** An east-central Illinois area of 5,000 mi² was
considered to be a potential an operational area for a cloud seeding project in order to
simulate and assess the influence of curtailed seeding operations on days when warnings
exist. This is essential from a public relations standpoint and necessary from a legal
standpoint in Illinois.
The number of severe storm warnings occurring on rain days in different rain class intervals (maximum point value of >1.0 inch, >0.5 inch, and ≥0.1 inch) was calculated for the 1986-1990 period. This revealed that 19% of all days with ≥0.1 inch maximum point rains in the area had warnings, 32% of all days with ≥0.5 inch had warnings, and 46% of all days with ≥1.0 inch rains had warnings.

**Incidence of Seedable Echoes:** Since the rain-crop yield results showed benefits came from increasing rains on days with moderate to heavy rains, we investigated the radar-echo statistics using two years of data. This information is relevant because the cloud seeding approach apt to be successful requires an aircraft to either deliver seeding material at cloud base or inside the growing cells of each cloud. Each individual echo (cloud) was considered a cloud suitable for seeding in this simulation analysis over a 5000 mi² area of a presumed project. Prior studies for hail suppression endeavors (Changnon and Morgan, 1976) had indicated the need for 12 seeding aircraft for a 2,000 mi² area in Illinois. Depending on the type of aircraft used, and the residence times required at each cloud, this analysis revealed there would need to be 4 or 5 high-level, high-performance jet aircraft available for cloud seeding in a 5,000 mi² area. Operations would typically last 5 to 6 hours. This leads to a high cost of operations based on flight costs of $1,000 per hour per aircraft.

**Examples of Integrating Modification Factors:** An analysis of rainfall modification opportunities for the two most promising rain-day classes detected from the crop yield-
rainfall analysis was pursued. This included the 0.1-1.0 inch daily rainfall events, and the > 1.0 inch daily rainfall events. The analysis of these two classes of conditions follows.

On the average, there are 14 rain days in the class of 0.1 to 1.0 inch rainfall during the summer. These produce 6.5 inches of rainfall on the average. Twenty percent of these days would not be available for cloud seeding due to severe weather warnings. Twenty percent of 14 days is 3 days, leaving 11 days with rainfall for modification. However, 46% of these events are not available for seeding because they occur at night, removing 5 more days from consideration, leaving 6 days for potential rainfall increases. The average rainfall per day (for these 14 days) is 0.48 inch. With 6 days as opportunities, there is 2.9 inches available for precipitation modification. Since the crop yield results indicate a 25% increase is desirable, the modification of these 6 days, and their 2.9 inches, would produce 0.72 inch of additional water. This increase would be only 6% of the summer total rainfall.

Notably, the 2.9 inches available for modification due to these various constraints, is much less than the total of 6.6 inches tested in this category during the 1987-90 field trials with corn and soybean yields. In fact, the potential increase represents 44% of the potential tested (2.9 - 6.5); thus, less than half of the yield increase obtained with this simulation treatment (25% of 0.1 to 1.0 inch) could be achieved. The average gain in corn yields (above the base rainfall) was 8 bu/acre, and application of 44% means that a 3 to 4 bu/acre (from a base of 176 bu/acre) gain is all that is possible. The soybean gain would be negligible, less than 1 bu/acre, on the average. The average yields increase across the 2000 mi$^2$ area would
be less because 50% of the area typically receives less than 0.1 inch which shows no yield effects with 25% increases.

A similar analysis was done for the rainfall days on which > 1.0 inch rainfall occurred. The crop yield field results indicated that increases on these days could be significant in increasing crop yields, particularly those of soybeans. The >1.0 inch amounts occur, on the average, on 3 summer days and produce 4.0 inches of rainfall. However, one of these three days available for rainfall modification is lost due to severe storm warnings. Another one of the three days is lost because it occurs at night and cannot be modified. Thus, there is only one heavy rain day available to be modified. The average daily rainfall on these days is 1.3 inches. If one assumes that a major rain increase of 40% could be attained, this would add a total of 0.52 inch, or 4% of the summer total average rainfall. Importantly, the amount to be increased, 1.3 inches, is 33% of the total rain in this rain-day class. Thus, the yield increase associated with rains 40% increases in rains of ≥ 1-inch would be about 1/3 of that found in the 1987-1990 field trials from this treatment. This would be 2 to 3 bu/acre to soybean and no increase to corn. These outcomes must be further considered on a regional basis. This shows that only about 50 to 65% of the area would realize the rain benefit because of the low rainfall in 35% to 50% of the area (and negligible yield effect) in the remaining area. Thus, the economic value is lessened.
c. **Conclusion**

This integration of agricultural, climatic, logistic, economic, and legal factors affecting rainfall enhancement for crop yield increases reveals that crop yield increases resulting from additional rainfall would be considerably less than those calculated from the field simulations. Basically, the increased crop yields with a 25% increase for the 0.1-1.0 inch moderate rain days would be 44% of the total yield increase found through experimentation, and the 40% increase with the >1.0 inch days would be only 33% of the simulated increase. The crop yield increases that could be realistically expected over a typical-sized area experiencing rainfall modification would be even less due to the spatial distribution of rainfall in the summer with any seeding induced additions to light rainfall exhibiting little positive yield effect. The costs to modify all, or most seedable clouds during moderate to heavy rain events, and given that 25% increases could be accomplished, would be large. Multiple aircraft requirements with sophisticated instrumentation would cost at least $0.5 million per summer to ensure a quality field project over 5000 mi$^2$. The average rain-induced increase of 2 bu/acre in corn yields (and essentially none in soybeans) realized over half the area would equate to about 350,000 additional bushels. At a price of $2/bu, the benefit would be $0.7 million, barely more than estimated project costs.

A rainfall increase in a hot/dry summer, if scientifically possible, would be best served by adding 40% increases to rains of 1 inch or more, or 25% increases to all rains. Unfortunately, hot-dry summers have few candidate rain days, particularly in the moderate
to heavy rain-day categories. Further, these two rain treatments are not a good choice for summers that have near average or above average rainfall. Thus, the selection of what is the best treatment for a given type of summer also requires the skill to predict the summer rainfall conditions at the outset of summer, a skill which does not currently exist.

Collectively, these findings do not support a strong case for the value of rainfall enhancement, even at an optimum potential capability of 25% to 40% above natural summer rainfall. Clearly, the benefits would increase if rainfall increases could be accomplished at night.

d. References


2. Weather Effects on Crop Yields

   a. Description of 1990 Experiment

   The fifth and final year of the corn and soybean experiments in the rain shelters were conducted this year. The design was the same as in previous years with one shelter containing corn and soybean plots, and two shelters containing the planting date and plant population experiment. The 1991 experiments were established without any problems, and the first water treatments were applied on schedule. The natural rain plots in the open unsheltered area were scaled down from previous years and included only 0%, 10%, 25%, and 40% additions to all rains during June, July, and August. Data from the 1991 experiments were not available for this report.

   Analysis of the effects of enhanced rainfall as simulated by water applications have been reported in several papers published this year (See Appendix D and E for papers). We are in the process of writing an in-depth description and analysis of the experiment. The major preliminary findings are:

   1. The response of soybeans to additional rainfall was variable from year to year, with the greatest response occurring in 1989 after a dry summer and an incomplete recharge of soil moisture during the 1988-1989 winter.

   2. Corn responded to increased rainfall during all the years of the experiment. A strong year-to-year variability indicates that there is an additional variable affecting corn yields.
3. The mean air temperature from planting to tassel initiation affected the final yield of corn. Higher temperatures during this period resulted in decreased corn yields. The reduced yields were due to a reduction of the number of kernel rows per ear, and the number of kernels per row.

4. Increasing all rains by 40% resulted in increased corn yields when total summer rainfall was below 15 to 16 inches. Additional rainfall above 15 to 16 inches resulted in decreased yields as a result of the soils being too wet.

The preliminary results are significant in that they indicate that the response to precipitation enhancement varies from year to year, and this experiment will help to define those summers when precipitation enhancement will be most beneficial.

3. Effects of Altered Soil Moisture on Clouds and Precipitation

The objective of this research was to make quantitative evaluations of the effect of drought-induced soil moisture deficits on evapotranspiration (ET) during summer. Measurements of ET made during the 1988 drought had revealed substantial reductions (25%-50%) compared to what would be expected under adequate soil moisture conditions. These results suggested that the interaction of crop growth, soil moisture, and ET could be a major limiting factor in summer rainfall production in drier seasons since soil moisture is an important source of water vapor for clouds. Hence, this research has great potential implications for more effectively assessing the cloud seeding potential in dry seasons, as well as understanding inadvertent modification of clouds and rain in dry periods.
A field experiment was established in central Illinois in July 1991 to further investigate the possibility of altered ET on clouds and precipitation with measurements of the components of the surface energy budget. Central Illinois experienced very dry conditions in June 1991, which allowed significant soil moisture deficits to develop by early July. Project equipment was placed in a cornfield near Champaign, Illinois for the period July 5, 1991 to August 25, 1991. This equipment consisted of eddy correlation sensors to measure surface fluxes and instruments to measure other meteorological variables. Measurements of sensible and latent heat flux showed the effects of soil moisture deficiencies. Mid-day Bowen ratios, (the ratio of sensible heat flux to latent heat flux) were in the range of 0.5 to 0.6 during early July, indicating more sensible and less latent heat flux as compared to values of 0.1 to 0.3 for more adequate soil moisture.

Substantial rains (60 mm) fell during mid-July. These rains had a significant impact on the surface energy budget; mid-day Bowen ratios were reduced to 0.1. The contrast in the surface energy budget before and after the July rains was also revealed by the infrared temperature measurements of the canopy. Before the rains, canopy temperatures were 1.5 to 3 °C higher than the air temperature, whereas afterwards canopy temperatures were 0 to 1°C less than the air temperature.

Dryness persisted from late July through August, and mid-day Bowen ratios rose to 1.0 to 1.5. These very high ratios are indicative of the impact of soil moisture deficiencies on the surface energy budget. This represents sensible heat fluxes up to four times greater
than what would be expected under normal soil moisture conditions. Latent heat fluxes, by
contrast, were one-half to two-thirds of normal. These large Bowen ratios were
accompanied by canopy temperatures 2 to 4°C warmer than the air temperature.
FACILITY DEVELOPMENT - HOT RADAR

The HOT radar data system has been used to review field tapes collected during 1989 PACE experiments. Sequential color photographs have been taken of the low level PPI scans at 10 minute intervals, for 15 operational days from May 25 to July 25, 1989. These data have provided analysis personnel with an overview of the complete precipitation pattern in the PACE target area. In addition to their use on the PACE analysis, the photographs have been reviewed to delineate appropriate storm periods for the examination of high precipitation supercell storms as part of the Cooperative Research to Improved Operational Forecasting of Midwestern Severe Weather project supported by the UEAR Cooperative Program for Operational Meteorology, Education and Training (COMET).

Significant improvements were made to the HOT radar during the 1991 research period. A 72 db step attenuator (12 db/step) to increase the dynamic range of the digital processing system which is used for processing and storing of radar observations was purchased and installed. Also, a standby low-noise R-F amplifier, has been procured for substitution in case of failure of the original unit.

The process of renewing the F.C.C. license is in progress at the time of writing of this report. The F.C.C. area frequency coordinator is reviewing our frequency request and considering reassignment of our present frequency. The anticipated frequency assignments of the NEXRAD network may eventually require a change of our assigned frequency.
During the past 20 years the CHILL and HOT radar systems were controlled by the Illinois State Water Survey. Common documentation was used for many parts of the radar systems. However, with the relocation of the CHILL system to Fort Collins, Colorado, it has become necessary to prepare documentation for the HOT system. This process is ongoing and should be completed during the next period.
PROGRAM MANAGEMENT AND PLANNING

A continuing and essential aspect of this project has been the scientific guidance and overall project management. Continuing assessment of the research has involved weekly and monthly staff meetings to assess findings. Our programmatic assessments have included a broad perspective on all relevant scientific advances in weather modification and attention to new issues, such as global climate change, that are of great concern to Illinois. The ever-growing concerns of the State of Illinois over the potential of climate change due to man's effects on the atmosphere, indicate that a good understanding of cloud and precipitation processes and how they may be changed, either purposefully or inadvertently, is very relevant.

Program management has included numerous interactions with NOAA staff. We made project presentations in Boulder, Colorado and Norman, Oklahoma and had discussions about the project with NOAA staff in Boulder, Los Angeles, Silver Springs, and Denver (all separate meetings). NOAA visitors to Illinois included the Head of OAR, the Program Manager, and two staff from the grants office. Two staff members visited the NOAA Springfield project in Oklahoma.

Project staff provide briefings requested by members of Congress in Illinois and in Washington, D.C. Our program interactions also included three meetings with leaders and top scientists of the other states involved in the Atmospheric Modification Program.
APPENDIX A: GLOSSARY OF PREDICTOR AND RESPONSE VARIABLES

Documentation of Variable Names

UP_Dia  Diameter of the updraft (m) (aircraft's mean airspeed times the number of seconds of updraft).
Mean_VW  Mean vertical velocity (vertical wind) of the updraft (ms⁻¹).
Max_VW  Maximum vertical velocity during the updraft (ms⁻¹).
Mean_ThV  Mean virtual potential temperature of the updraft (K).
Max_ThV  Maximum virtual potential temperature during the updraft (K).
U_flrs  Number of flares in the updraft.
Mean_TBuoy  Mean thermal buoyancy (°C) (= Mean_ThV - Env_ThetaV).
Max_TBuoy  Maximum thermal buoyancy (°C) (= Max_ThV - Env_ThetaV).
Load_W  Loading from water (liquid) (°C) (1°C / 2.5 gm⁻³).
Load_I  Loading from ice (solid) (°C) (1°C / 2.5 gm⁻³).
Buoy_Enh  Buoyancy enhancement (°C).
NBuoy  Net buoyancy (°C) (= Mean_TBuoy - Load_W - Load_I)
PBuoy  Potential buoyancy (°C) (= NBuoy + Buoy_Enh).
SWC-frac  Fraction of solid water content [SWCd / (Mean_JWC + LWCd + SWCd)].
Cld_Dia  Diameter of cloud (m).
#_Ups  Number of updrafts in cloud (updraft = ≥ 1 ms⁻¹ for at least 3 consecutive seconds).
%_Updraft  Percent of cloud which is updraft.
C_flrs  Number of flares in the cloud.
%_in_Up  Percentage of flares released in any updraft.
#_SECs  Number of seconds of the longest updraft.
Env_ThetaV  Mean virtual potential temperature of the environment (K) (i.e., 10 consecutive second mean within 1 minute prior to cloud).

Env_TC Temperature of the environment (°C) (i.e., 10 consecutive second mean within 1 minute prior to cloud).

Mean_JWC Mean liquid water content of the updraft from the JW probe (i.e., cloud droplets) (gm⁻³).

Max_JWC Max liquid water content during updraft from the JW probe (gm⁻³).

Mean_FWC Mean liquid water content of the updraft from the FSSP probe (i.e., cloud droplets —> D < 45  μm) (gm⁻³).

Max_FWC Max liquid water content during updraft from the FSSP probe (gm⁻³).

Mean_Dia Mean diameter of cloud droplet particles (from FSSP data) (m).

Max_Dia Max diameter of cloud droplet particles (m).

Thres_Dia Threshold diameter (from Hobbs, 1990) —> defined such that the total concentration of droplets with diameters > Thres_Dia is 3 cm⁻³ (as measured by the FSSP probe) (m).

Mean_Conc Mean concentration of cloud droplets in the updraft (cm⁻³).

Max_Conc Max concentration of cloud droplets in the updraft (cm⁻³).

Mean_Conc_D<13 Mean concentration of cloud droplets < 13  μm in the updraft (cm⁻³).

Mean_Conc_D >=25 Mean concentration of cloud droplets ≥ 25  μm in the updraft (cm⁻³).

CPA56 Area at flight level at cloud pass (km²).

CPZ56 Max reflectivity at flight level at cloud pass (dbZ).

CPDia56 Diameter of echo at flight level at cloud pass (km).

FltAltR Radar (RATS) derived aircraft flight level at cloud pass (km).

FltAltA Aircraft derived aircraft flight level at cloud pass (km).

FEHtp10 Top height of the 10 dbZ contour at first echo (km).

FEdepth10 Depth of the 10 dbZ contour at first echo (km).

FEA10 Max area of the 10 dbZ contour at first echo (km²).
<table>
<thead>
<tr>
<th>FEVol10</th>
<th>Volume of the 10 dbZ contour at first echo (km$^3$).</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEMxZ</td>
<td>Max reflectivity at first echo (dbZ).</td>
</tr>
<tr>
<td>FEHMxZ</td>
<td>Height of max reflectivity at first echo (km).</td>
</tr>
<tr>
<td>FECPt</td>
<td>Time from first echo to cloud pass (min).</td>
</tr>
<tr>
<td>CPHtp10</td>
<td>Top height of the 10 dbZ contour at cloud pass (km).</td>
</tr>
<tr>
<td>CPA10</td>
<td>Max area of the 10 dbZ contour at cloud pass (km$^2$).</td>
</tr>
<tr>
<td>CPMxZ</td>
<td>Max reflectivity at cloud pass (dbZ).</td>
</tr>
<tr>
<td>CPHMxZ</td>
<td>Height of max reflectivity at cloud pass (km).</td>
</tr>
<tr>
<td>CPA.L1</td>
<td>Area at 1 km level at cloud pass (km$^2$).</td>
</tr>
<tr>
<td>CPZ.L1</td>
<td>Max reflectivity at 1 km level at cloud pass (dbZ).</td>
</tr>
<tr>
<td>CPAL6</td>
<td>Area near flight level (6 km) at cloud pass (km$^2$).</td>
</tr>
<tr>
<td>CPZ.L6</td>
<td>Max reflectivity near flight level (6 km) at cloud pass (dbZ)</td>
</tr>
<tr>
<td>CPdia.L6</td>
<td>Diameter of echo near flight level (6 km) at cloud pass (km)</td>
</tr>
<tr>
<td>CPFEdA10</td>
<td>Change in area of the 10 dbZ contour from first echo to cloud pass (km$^2$).</td>
</tr>
<tr>
<td>CPFEdH10</td>
<td>Change in height of the 10 dbZ contour from first echo to cloud pass (km).</td>
</tr>
<tr>
<td>CPFEdZ</td>
<td>Change in max reflectivity from first echo to cloud pass (dbZ).</td>
</tr>
<tr>
<td>CPFEdA/dt</td>
<td>Rate of change of max area from first echo to cloud pass (km$^2$ min$^{-1}$).</td>
</tr>
<tr>
<td>CPFEdH/dt</td>
<td>Rate of change of echo height from first echo to cloud pass (km min$^{-1}$).</td>
</tr>
<tr>
<td>CPFEdZ/dt</td>
<td>Rate of change of max reflectivity from first echo to cloud pass (dbZ min$^{-1}$).</td>
</tr>
<tr>
<td>FEmndia</td>
<td>Mean diameter of echo at first echo, averaged in height (km).</td>
</tr>
<tr>
<td>CPmndia</td>
<td>Mean diameter of echo at cloud pass, averaged in height (km).</td>
</tr>
<tr>
<td>FEtptmp</td>
<td>Top of echo temperature at first echo (°C).</td>
</tr>
<tr>
<td>FEmztmp</td>
<td>Temperature at the height of the max reflectivity at first echo (°C).</td>
</tr>
<tr>
<td>FEtoFR</td>
<td>Time from first echo to first rain (min).</td>
</tr>
</tbody>
</table>
CPtoFR  Time from cloud pass to first rain (min).
FRtoMxRFx  Time from first echo to max rain flux of echo core (min).
MxRFx  Max rain flux of echo core ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
TotRNVOL  Total rain volume of echo core ($10^{10} \times \text{cm}^3$).
RFxtCPeu  Experimental unit rain flux at cloud pass ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
RFxt-15eu  Experimental unit rain flux at 15 minutes prior to cloud pass ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
RFxDifeu  Change in experimental unit rain flux from a) 15 minutes prior to cloud pass to b) at cloud pass ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
AtCPeu  Experimental unit echo areal coverage at cloud pass (km$^2$).
At-15eu  Experimental unit echo areal coverage 15 minutes prior to cloud pass (km$^2$).
ADifeu  Change in experimental unit echo areal coverage from a) 15 minutes prior to cloud pass to b) at cloud pass (km$^2$).
RFxtCPtn  Total network rain flux at cloud pass ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
RFxt-15tn  Total network rain flux at 15 minutes prior to cloud pass ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
RFxDiftn  Change in total network rain flux from a) 15 minutes prior to cloud pass to b) at cloud pass ($10^{10} \times \text{cm}^3 \text{hr}^{-1}$).
AtCPtn  Total network echo areal coverage at cloud pass (km$^2$).
At-15tn  Total network echo areal coverage 15 minutes prior to cloud pass (km$^2$).
ADiftn  Change in total network echo areal coverage from a) 15 minutes prior to cloud pass to b) at cloud pass (km$^2$).
MaxH10  Maximum height of the 10 dbZ reflectivity contour (km).
MaxA10  Maximum area of the 10 dbZ reflectivity contour (km$^2$).
MaxZ  Maximum reflectivity (dBZ).
FEMXtMxH  Time from first echo to max height (min).
FEMXtMxA  Time from first echo to max area (min).
FEMXtMxZ  Time from first echo to max reflectivity (min).
CPMXtMxH: Time from cloud pass to max height (min).
CPMXtMxA: Time from cloud pass to max area (min).
CPMXtMxZ: Time from cloud pass to max reflectivity (min).
MXFEdA10: Change in max area of the 10 dBZ contour from first echo to max area (km$^2$).
MXFEdH10: Change in height from first echo to max height of core (km).
MXCPdA10: Change in area of the 10 dBZ contour from cloud pass to max area (km$^2$).
MXCPdH10: Change in height of the 10 dBZ contour from cloud pass to max height (km).
MXFEdA/dt: Rate of change of max echo area from first echo to max area (km$^2$ min$^{-1}$).
MXFEdH/dt: Rate of change of echo height from first echo to max height (km min$^{-1}$).
MXCPdA/dt: Rate of change of max echo area from cloud pass to max area (km min$^{-1}$).
MXCPdH/dt: Rate of change of echo height from cloud pass to max height (km min$^{-1}$).
MXFEdZ: Change in max reflectivity from first echo to max reflectivity (dBZ).
MXCPdZ: Change in max reflectivity from cloud pass to max reflectivity (dBZ).
MXFEdZ/dt: Rate of change of max reflectivity from first echo to max reflectivity (dBZ min$^{-1}$).
MXCPdZ/dt: Rate of change of max reflectivity from cloud pass to max reflectivity (dBZ min$^{-1}$).
m100: Tallest max radar echo top within 100 nm of CMI observed between 1130 and 2030 CDT at the NWS site (MMO, STL, EVV) closest to the echo (kft).
m80: Tallest max radar echo top within 80 nm of CMI observed between 1130 and 1830 CDT at the NWS site (MMO, STL, EVV) closest to the echo (kft).
temp: Surface temperature (°C) (this and the following synoptic variables are all from 0700 CDT Peoria sounding).
dpt: Surface dew point temperature (°C).
ct: Convective temperature using average mixing ratio in lowest 100 mb (°C).
dbar: Average dew point temperature in lowest 100 mb layer (°C).
plcl: Pressure of lifting condensation level (LCL) using averaged data in lowest 100 mb (mb).
tlcl  Temperature of LCL using averaged data in lowest 100 mb (°C).

hlcl  Height of LCL using averaged data in lowest 100 mb (m).

pccl  Pressure of convective condensation level (CCL) using averaged data in lowest 100 mb (mb).

tccl  Temperature of CCL using averaged data in lowest 100 mb (°C).

heel  Height of CCL using averaged data in lowest 100 mb (m).

pres1 Pressure of 0°C level (mb).

hgt1 Height of 0°C level (m).

pres2 Pressure of -10°C level (mb).

hgt2 Height of -10°C level (m).

dh38 Height difference between height of -3°C level and -8°C level (m).

pw  Precipitable water between the surface and 500 mb (cm).

dir1 850 mb wind direction (degrees).

spd1 850 mb wind speed (ms⁻¹).

dir2 500 mb wind direction (degrees).

spd2 500 mb wind speed (ms⁻¹).

L  Raindrop size discriminant function based on tccl and pb calculations.

cpe  Coalescence precipitation efficiency; relative size of L (%).

pb  Synoptic (parcel) potential buoyancy (°C).

li  Lifted index (measure of latent instability).

ki  K-index (heat differential and moisture depth in the lower levels of the atmosphere).

mki Modified K-index.

jef Jefferson index (measure of instability).

msh Modified Showalter index (measure of instability).
Sweat index (measure of instability).

Pressure at the top of "positive" area of rawinsonde (mb).

Convective available potential energy (m$^2$s$^{-2}$).

Vector difference in wind at 4 km and average wind in lowest 500 m (ms$^{-1}$).

Bulk Richardson number, calculated using CAPE and vshr.

80 nm radius area (not including Indiana, centered on CMI) 24 hr (80-85% 7:00am obs) station averaged precipitation which fell on the day prior to the experimental unit.

80-100 nm radius area (not including Indiana, centered on CMI) 24 hr (80-85% 7:00am obs) station averaged precipitation which fell on the day prior to the experimental unit.

80 nm radius area (not including Indiana, centered on CMI) 24 hr (80-85% 7:00am obs) station averaged precipitation which fell on the experimental unit day.

80-100 nm radius area (not including Indiana, centered on CMI) 24 hr (80-85% 7:00am obs) station averaged precipitation which fell on the experimental unit day.

Maximum diameter of supercooled liquid rain/drizzle drop particles (i.e., water, and D > 150 µm) in the updraft (µm).

Total concentration of water particles (L$^{-1}$).

Total 2D probes particle count in Tconc_W.

Total concentration of water particles > 300 µm (L$^{-1}$).

Total 2D probes particle count in Tconc_W3.

Liquid water content by method I (i.e., discrete) (gm$^{-3}$).

Maximum diameter of ice particles (D > 150 µm) in the updraft (µm).

Concentration of graupel particles in the updraft (L$^{-1}$).

Total 2D probes particle count (of graupel) in Tconc_g.

Concentration of ice fragment particles in the updraft (L$^{-1}$).

Total 2D probes particle count (of ice fragments) in Tconc_f.
Tconc_i Concentration of ice crystal particles in the updraft (L⁻¹).

2D_Cnti Total 2D probes particle count (of ice crystals) in Tconc_i.

Tconc_I Total Concentration of ice particles in the updraft (L⁻¹).

2D_CntI Total 2D probes particle count (of graupel, fragments and crystals) in Tconc_I.

Tconc_Po Concentration of particles with polarization signal > 0 in the updraft (L⁻¹).

2D_CntPo Total 2D probes particle count (of particles with polarization > 0) in Tconc_Po.

SWCd Solid water content by method I (i.e., discrete) (gm⁻³).

FeStat Indicator of core merging at first echo (0 ≡ no echo at that time, 1 ≡ separate at all levels, 2 ≡ joined at some levels but can see base & top, 3 ≡ joined at lower levels but can see top, 4 ≡ no echo ever).

CpStat Indicator of core merging at cloud pass (0 ≡ no echo at that time, 1 ≡ isolated, 2 ≡ merged, 4 ≡ no echo ever).

pdeg Degree of polynomial used to determine velocities and accelerations of echo top before, at, and after cloud pass (the following 6 variables).

v_bef Velocity of echo top 2 minutes before cloud pass (km min⁻¹).

v_cdp Velocity of echo top at cloud pass (km min⁻¹).

v_aft Velocity of echo top 4 minutes after cloud pass (km min⁻¹).

a_bef Acceleration of echo top 2 min. before cloud pass (km min⁻²).

a_cdp Acceleration of echo top at cloud pass (km min⁻²).

a_aft Acceleration of echo top 4 minutes after cloud pass (km min⁻²).

FEHbs10 Base height of the 10 dbZ contour at first echo (km).

FEbsTmp Temperature at base of echo at first echo (°C).

dA/dt-PO/PR Ratio of rate of change of max area from a) cloud pass to time of max area and b) first echo to cloud pass (a/b).

dH/dt-PO/PR Ratio of rate of change of echo height from a) cloud pass to time of max height and b) first echo to cloud pass (a/b).
\[ \frac{dZ}{dt} \] \[ \frac{PO}{PR} \]

- Ratio of rate of change of max reflectivity from a) cloud pass to time of max reflectivity and b) first echo to cloud pass (a/b).

\[ \frac{dA}{PO/PR} \]

- Ratio of change of max area from a) cloud pass to time of max area and b) first echo to cloud pass (a/b).

\[ \frac{dH}{PO/PR} \]

- Ratio of change of echo height from a) cloud pass to time of max height and b) first echo to cloud pass (a/b).

\[ \frac{dZ}{PO/PR} \]

- Ratio of change of max reflectivity from a) cloud pass to time of max reflectivity and b) first echo to cloud pass (a/b).

\[ N_0_W \]

- Water size distribution intercept.

\[ \lambda_W \]

- Water size distribution slope.

\[ LWC_c \]

- Liquid water content by method II (i.e., continuous; area under the line defined by \[ N_0_W \] and \[ \lambda_W \]) (gm^{-3}).

\[ N_0_I \]

- Ice size distribution intercept.

\[ \lambda_I \]

- Ice size distribution slope.

\[ SWC_c \]

- Solid water content by method II (i.e., continuous; area under the line defined by \[ N_0_I \] and \[ \lambda_I \]) (gm^{-3}).
APPENDIX B: CALCULATED Q VECTORS AND DIVERGENCE OF Q FOR EXPERIMENTAL DAYS IN THE 1989 PACE FIELD PROGRAM
APPENDIX C: RESULTS FROM THE 1989 CLOUD SEEDING EXPERIMENT IN ILLINOIS
RESULTS FROM THE 1989 CLOUD SEEDING EXPERIMENT IN ILLINOIS

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1. INTRODUCTION

Preliminary results of exploratory cloud seeding experimentation to increase rainfall conducted in Illinois during the summer of 1989 are the subject of this paper. This field experiment was conducted as part of the Precipitation Augmentation for Crops Experiment (PACE) which was begun by the Illinois State Water Survey in 1978. PACE has continuously addressed two fundamental questions relating to precipitation enhancement in Illinois: 1) can it be accomplished, and 2) is it worth doing?

An organized long-term project to investigate these two questions was initiated by the State of Illinois for several reasons. First, research simulating the effects of precipitation enhancement in Illinois suggested that marked benefits could occur, principally to agriculture, in the form of increased and stabilized crop yields (Huff and Changnon 1972). Secondly, a series of operational cloud seeding projects developed in the Midwest during the 1970s with local agricultural backing raised fundamental questions in the agricultural sector, as to whether cloud seeding could change rainfall and what the effects might be (Changnon and Hsu 1981). Third, results of inadvertent weather modification studies in Illinois, and from cloud seeding research in other locations, along with major technological advances in weather radars and cloud physics instrumentation were encouraging factors for improved field research. Additionally, some success in modifying clouds believe to be similar to those in Illinois had been achieved in Florida and the Dakotas (Changnon 1980).

PACE was designed with two major components: meteorological studies, and weather impacts studies (see Changnon et al. 1991 for a comprehensive description of the design of PACE). The meteorological components of PACE addressed five areas of activity including: 1) design and evaluation of experimentation, 2) cloud studies, 3) precipitation studies, 4) synoptic weather analyses including predictor variables and covariates, and 5) modification and seeding hypotheses development. PACE was designed as a three phase effort. Phase 1 was an assessment of historical data and existing results and did not involve seeding trials (Ackerman et al. 1978). Phase 2 of PACE began in 1986 and is still in progress. The first efforts involved designing initial experimental seeding trials. The principal elements of field projects conducted in Illinois during the summers of 1986 and 1989 included an operational forecasting effort, the use of meteorological and seeding aircraft, weather radars, and special soundings involving the NCAR/CLASS system. Unfortunately, the 1986 sampling was limited to 23 clouds due to the lack of daytime cloud activity during the July-August operational period. However, the results encouraged further testing of the seeding hypothesis by field experimentation.

2. THE 1989 HELD PROJECT

The field experiment conducted in Illinois during 1989 studied natural cloud behavior and cloud reactions to AgI seeding. Operations began on 8 May and ended on 11 August, and were divided into two periods. Period 1 (8 May - 31 May) was devoted to monitoring the conversion of water-to-ice in clouds treated with either AgI or sand. Period 2 (1 June - 7 August) was devoted to studies of reactions of clouds and cloud systems to seeding. The study area of the field project included central Illinois as shown in Fig. 1.

2.1 Facilities

The plane used for cloud physics and cloud seeding was a twin engine Beach Craft Baron leased from Colorado International Corporation. The aircraft was used to make in-cloud measurements of cumulus congestus as they reached the -8 to -15°C levels, and to simultaneously release cloud treatment flares (some AgI, some placebos of sand) according to a predetermined randomization scheme. The airplane was equipped with Rosemont and reverse-flow temperature, cooled-mirror dew point, pressure, vertical winds, Johnson-Williams hot-wire liquid water content, FSSP cloud droplets spectra, precipitation-size particles by 2DC and 2DP imaging. The airplane also carried a rack containing 200 pyrotechnic flares for cloud treatments.
A T-28 aircraft of South Dakota School of Mines and Technology and staff participated in the project in May. The aircraft was intended to be used to monitor water-to-ice conversions at constant temperatures as a cloud evolved. Being armored, the aircraft could penetrate into cloud regions containing hail and severe turbulence, and thus, provided in-cloud data from more mature and potentially severe cloud stages.

Two radars were involved in the 1989 PACE field program, the CHILL radar and the Illinois State Water Survey's HOT radar. Both radars transmit at 10-cm wavelength with a beam width of 1° for the CHILL and 1.5° for the HOT. Further details on the facilities used are available elsewhere (Changnon et al. 1991).

2.2 Design
The field project was designed to achieve two primary objectives: 1) to obtain data on the largest possible sample of clouds (treated and natural); and 2) to address early steps of dynamic seeding hypothesis by focusing on initial cloud reactions. Operational procedures were designed around five weather, cloud, and facility readiness situations. The five experiments were of two general classes, either 1) the collection of data about natural cloud and precipitation processes by the project aircraft and/or radar when seeding was inappropriate for various reasons, or 2) the randomized treatment of clouds (using AgI or placebos) under three experimental variations that differed according to available cloud sizes and/or equipment.

Under the second class, there were two top priority experiments. Missions in the first experiment involved randomized treatment of cumulus congestus clouds expected to reach at least 30,000 feet (9145 meters) in height. This experiment was referred to as the "large cloud experiment." Clouds in this experiment were cumulus congestus towers either forming individually or in association with a larger, sustaining cloud system. The "large cloud experiment" included simultaneous collection of radar and aircraft data on treated clouds. The second experiment, titled the "small cloud experiment", involved randomized treatment of cumulus congestus clouds which were growing above approximately 20,000 feet (6095 m), but not surpassing 30,000 feet (9145 meters) in height. These were typically cumulus congestus towers growing individually. The "small cloud experiment" included simultaneous collection of radar and aircraft data on treated clouds. We followed all of the operation procedures of the "large cloud experiment" in the "small cloud experiment", except "small" clouds were penetrated at least once after treatment in order to obtain a limited amount of direct measurements of seeding agent effect on in-cloud conditions. Initial results of randomized treatments in the "large cloud experiment" are the subject of this paper.

2.3 Randomization
Although the use of randomization in cloud seeding experiments has been questioned, it has been used in PACE because we consider it to be an essential means of gathering trustworthy data when people are involved in making critical analytical choices and assessments. The treatment randomization was based on "floating" experimental units, initially defined by a single congestus cloud or a group of congestus clouds behaving as an entity (see Fig. 2). The concept of a "floating" experimental unit was adapted from that used in cloud seeding operations in
West Texas (Rosenfeld and Woodley 1989). The radius of each unit where treatments were delivered was set at 28 kilometers from an initial cloud treatment point, and each unit typically swept out an oblate-shaped area during its lifetime. All clouds in the unit received the same seeding material, and the design allowed selection of up to 4 units during any operational period of up to 3 hours. An annular buffer area of 30 km around the treatment area was maintained to address concerns over physical and chemical interactions between units. A 50/50 randomization was set on experimental units rather than blocking AgI/sand choices into cloud pairs, because of the exploratory nature of the experiment. Balancing was achieved by randomizing experimental units in pairs. Therefore, no more than two experimental units in a row received the same treatment material. Separate randomization schedules were designed for the “large” and “small” cloud experiment to further maintain balance. The in-flight meteorologist who selected the clouds (and hence the experimental units) was blind as to the type of treatment being applied, and all processing and quality control of aircraft, radar and meteorological data was completed with blindness to the type of treatment used in the experiment unit (either sand or AgI flares).

2.4 Flight Procedures

In the large cloud experiment, aircraft and radar operations were launched at the first satellite, radar, and/or visual indication of cumulus initiation. These were days when the morning forecast predicted clouds to be warm-based (preferably around 16°C) and to grow to at least 30,000 ft (9145 m). When the aircraft arrived at a potential seeding area, a candidate cloud was selected to meet the following visual criteria: a) cloud top just passing through 20,000 ft, with potential for reaching 30,000 ft and beyond; b) a cumulus congestus (hard, blocky) appearance; c) be at least 2 kilometers in diameter; and d) show little or no vertical tilt. A test penetration of a candidate cloud further helped establish whether neighboring clouds could be considered suitable for treatment. In cloud properties had to include: 1) moderate updrafts, preferably 2 to 4 m s\(^{-1}\), 2) large amounts of supercooled water (approximately 1 to 6 g m\(^{-3}\)), a presence of supercooled drizzle and rain drops in the updrafts; and 4) little or no indication of ice, particularly in the updrafts.

All subsequent clouds in an experimental unit received the same treatment at -10°C level, as specified by the predetermined randomization schedule. Treatment flares containing AgI or sand were delivered, with every attempt to release flares only in the updraft regions at a rate of approximately 1 flare every 5 to 10 seconds, or approximately every 500 to 1000 meters of cloud updraft. The aircraft was typically positioned between 1000 and 5000 feet (300 to 1500 m) below the cloud top with the intent to release at least 20 grams of seeding material to the volume of the cloud updraft in the levels of -10 to -3°C. During these operations, the radars were operated in a sector scanning mode that provided detailed three dimensional portrayal of the echoes approximately once every 4 minutes with 1 or 2, 360 low elevation scans in between sector scans. After 10 or more clouds were treated, a decision was made to either remain with or leave the experimental unit for another. Typically, the experimental unit was abandoned and another one sought with the aid of the radar.

3. PRELIMINARY RESULTS FOR “LARGE” CLOUDS

Initial analysis of the 1989 data has involved three steps. First, was the extensive effort to process, quality control, and digitize the raw data and a large set of derived variables. These included all the various atmospheric synoptic variables determined from soundings and surface data analysis, an assortment of variables determined from the aircraft data as to in-cloud conditions, dosage, and variables determined from the 3-dimensional radar echo measurements, such as echo heights, core size, rate of growth, and maximum reflectivity. This endeavor yielded a grand total of 182 predictor and response variables for each of the 71 large clouds in the 1989 sample. Of these 182 variables, 149 were predictor variables and 33 were response variables.

Table 1 presents the number of clouds treated and the treatment material by date and experimental unit number. Of the 71 large clouds penetrated and treated, 4 had no distinguishable echo, even though the radar apparently operated properly. Thus, there were 67 large clouds sampled on 9 days representing 13 experimental units, as indicated in Table 1. The randomization scheme produced a good balance between treatment type by experimental units and clouds. Seven experimental units were treated with silver iodide and six with the placebos (sand). Of these 67 clouds (echo cores), 35 were treated with silver iodide and 32 with sand. Thus, our randomization scheme

<table>
<thead>
<tr>
<th>Date</th>
<th>Experimental Unit Number*</th>
<th>Number of Clouds / Echoes (with Radar)</th>
<th>Treatment Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 19</td>
<td>02</td>
<td>4</td>
<td>Sand</td>
</tr>
<tr>
<td>June 1</td>
<td>05</td>
<td>4</td>
<td>AgI</td>
</tr>
<tr>
<td>June 23</td>
<td>11</td>
<td>7</td>
<td>AgI</td>
</tr>
<tr>
<td>June 23</td>
<td>12</td>
<td>Out of Target</td>
<td>AgI</td>
</tr>
<tr>
<td>June 23</td>
<td>13</td>
<td>7</td>
<td>Sand</td>
</tr>
<tr>
<td>July 8</td>
<td>17</td>
<td>5</td>
<td>Sand</td>
</tr>
<tr>
<td>July 8</td>
<td>18</td>
<td>6</td>
<td>AgI</td>
</tr>
<tr>
<td>July 11</td>
<td>19</td>
<td>4</td>
<td>AgI</td>
</tr>
<tr>
<td>July 19</td>
<td>20</td>
<td>3</td>
<td>Sand</td>
</tr>
<tr>
<td>July 23</td>
<td>22</td>
<td>10</td>
<td>AgI</td>
</tr>
<tr>
<td>July 24</td>
<td>23</td>
<td>5</td>
<td>Sand</td>
</tr>
<tr>
<td>July 25</td>
<td>24</td>
<td>8</td>
<td>Sand</td>
</tr>
<tr>
<td>July 25</td>
<td>25</td>
<td>4</td>
<td>AgI</td>
</tr>
</tbody>
</table>

* Other numbered units were for other experimental classes.
seems to have worked well numerically, producing an approximate 50/50 split between sand and AgI treated clouds which alternated over the course of the field experiment.

The next major step in the analysis was to focus attention on the 149 predictor variables and on similarities and differences between clouds treated with sand and those treated with AgI at the time of treatment. Figure 3 shows histograms for three predictor variables which we considered to be fundamental describers of the state of the echo core at the time of treatment. Shown is data for the mean diameter of the echo core at treatment (CPdiam), the height of the top of the echo core at treatment (CPmaxH), and the maximum reflectivity of the echo core at treatment (CPmaxZ). Inspection of Fig. 3 reveals that the sand treated clouds had several echo cores that were wider, or taller or more reflective at treatment that AgI treated clouds. These perceived differences are all statistically significant at more than the 0.05 level. Statistically significant differences were also found between sand and AgI treated clouds at first echo (FE). For example, some of the sand clouds changed height from FE to treatment more quickly than AgI treated clouds, and sand clouds also had a few larger, accelerations in echo top vertical motion than AgI clouds. However, the height of the top of the first echo, defined by the 10 dBZ contour, was about the same for sand and AgI clouds.

The important finding of these comparisons was that two populations of clouds randomly selected were statistically significantly different from one another (at first echo and treatment) in many physical respects that might govern future cloud growth; despite achieving numerical and temporal balance in cloud selection. In fact and as shown in Table 1, six of the experimental units (June 23, July 8, July 25) were from the same dates and weather systems. Nevertheless, our sample of 67 clouds, randomly selected, gave us some fairly different clouds in the sand sample than in the AgI sample, reflecting a classic example of the "bad draw." Clearly, any future comparison of the sand and AgI clouds in response variables would provide little useful information as to potential seeding effects unless this bias can be satisfactorily taken into account.

The third stage of the analysis has attempted to address the problem of the bad draw revealed by predictor variable analysis. Our analysis has moved to investigate cloud characteristics before treatment and at treatment so as to define, in various subjective and objective ways, a set of AgI and sand treated clouds that were similar at treatment and thus, comparable.

Our initial and preliminary empirical approach has been to define a set of "seedability" criteria physically consistent with the dynamic seeding hypothesis. From the aircraft, radar, and meteorological based data, 21 variables were selected from the list of 149 predictor variables. Table 2 lists this set of "seedability" criteria and the threshold limits we set to derive a "Seedability" Index. As seedability criteria, we chose updraft diameter (variable number 1 of 182), mean vertical wind (2), and percent of cloud with updraft (17) as indicators of the organization of a cloud's vertical circulation. We reasoned that narrow clouds or clouds with many small updrafts, or clouds with weak updrafts had circulations that were poorly organized, and therefore would not respond too favorably to dynamic conditions. The third stage of the analysis has attempted to address the problem of the bad draw revealed by predictor variable analysis. Our analysis has moved to investigate cloud characteristics before treatment and at treatment so as to define, in various subjective and objective ways, a set of AgI and sand treated clouds that were similar at treatment and thus, comparable.

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![Figure 3. Histograms showing selected fundamental describers of echo core state at treatment.](image-url)
seeding. We chose net buoyancy (12) because we reasoned that if a cloud was either too negatively or too positively buoyant then the forces acting on these clouds may be so large as not to be appreciably modified. We chose the presence of supercooled drizzle or raindrops (147) and the absence of ice (14) since these are required according to the dynamic seeding hypothesis for release of latent heat and beneficial loading of the updraft. Echo parameters related to clouds that tended to reach their maximum of height (88), area (89), and reflectivity (90) after treatment and the existence of an echo at treatment (48). We chose the rate of change of height from first echo to treatment (60), mean diameter at treatment (62) and height at treatment (49) to establish similar echo core behavior at treatment. We chose the temperature of the CCL(U3), potential buoyancy (127), coalescence activity index (125), and Richardson Number (137) to include similarity in the meteorological setting for the convection. For each of these 21 variables, including the dosage rate (18, 15 with 17 and 19), we further established a threshold value, as shown in the right column of Table 2.

In this analysis based on seedability criteria selected empirically, we had to remove some of the 67 clouds because of a lack of data on the critical variables. Seven of the clouds, for various reasons, had no updraft data and these were deleted. Three of the remaining clouds had no echo data, and another four had no 2D data, resulting in a sample of 53 clouds, 25 treated with silver iodide and 28 with sand.

For each cloud, we added the number of times the cloud met a criteria, and then computed the percent criteria met of the total possible 21 criteria. These percentages are an index indicating, for an individual cloud, its tendency towards being "seedable." Thus, any two or more clouds would be considered similarly seedable even though they may not have a one-to-one correspondence in the individual criteria they met. The resulting values for the 53 clouds, plotted in a temporal sequence, appear in Figure 4.

<table>
<thead>
<tr>
<th>Variable Number</th>
<th>Variable Name</th>
<th>Limit(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UP_Dia</td>
<td>≥ 1000</td>
</tr>
<tr>
<td>2</td>
<td>Mean_VV</td>
<td>2 &lt; VW &lt; 8</td>
</tr>
<tr>
<td>17</td>
<td>%_Updraft</td>
<td>≥ 33%</td>
</tr>
<tr>
<td>12</td>
<td>Net_Booy</td>
<td>3 ≤ b ≤ +3</td>
</tr>
<tr>
<td>11</td>
<td>Booy_Enh</td>
<td>≥ 0.4</td>
</tr>
<tr>
<td>147</td>
<td>LWC</td>
<td>&gt; 0.0</td>
</tr>
<tr>
<td>14</td>
<td>SWC_frac</td>
<td>≤ 0.5</td>
</tr>
<tr>
<td>88</td>
<td>CPMXtMxH</td>
<td>≥ -2</td>
</tr>
<tr>
<td>89</td>
<td>CPMXtMxA</td>
<td>≥ -2</td>
</tr>
<tr>
<td>90</td>
<td>CPMXtMxZ</td>
<td>≥ -2</td>
</tr>
<tr>
<td>48</td>
<td>CPMxZ</td>
<td>&gt; 0 min</td>
</tr>
<tr>
<td>167</td>
<td>Aceel</td>
<td>-0.5 ≤ a ≤ +0.5</td>
</tr>
<tr>
<td>60</td>
<td>CPFEDz/dt</td>
<td>2.0</td>
</tr>
<tr>
<td>62</td>
<td>CPmndia</td>
<td>≥ 15</td>
</tr>
<tr>
<td>49</td>
<td>CPIIimxZ</td>
<td>≤ 1 or &gt; 1.5</td>
</tr>
<tr>
<td>113</td>
<td>T_CCI</td>
<td>&gt; 14</td>
</tr>
<tr>
<td>127</td>
<td>PB</td>
<td>≥ 2</td>
</tr>
<tr>
<td>123</td>
<td>L</td>
<td>≤ 0</td>
</tr>
<tr>
<td>137</td>
<td>Ri</td>
<td>≥ 50</td>
</tr>
<tr>
<td>18, 19, 15, 17</td>
<td>Doseage 1</td>
<td>&lt; 2.25 fl/km</td>
</tr>
<tr>
<td>19</td>
<td>Doseage 2</td>
<td>&lt; 66.67% in up</td>
</tr>
</tbody>
</table>

Figure 4. Temporal variation of the Seedability Index.

This temporal series of an empirically-derived seedability index reveals two interesting findings. First, there appears to have been a temporal shift in "seedability", at least for the criteria we selected and the threshold values we subjectively established. To the extent our selection of criteria and threshold is valid. Fig. 4 clearly shows that clouds may have had less seedable conditions in June and early July (treatment sequence or clouds 1 thru 27), and more seedable conditions thereafter; indicated by percentages generally between 70 and 80% for clouds 1 thru 27, and percentages generally above 80% after the last cloud (cloud number 27) on 19 July.

The second important finding relates to the two days (July 8 and July 25) that pairs of experimental units were obtained (see Table 1). Comparison of the sand values of seedability index with those for AgI (denoted in Fig. 4 as open and solid circles, respectively) reveals considerable differences between the first and second experimental units on each of these paired dates. The clouds in the initial unit on both days received a sand treatment, and the seedability index shows that the sand-treated clouds in the initial experimental unit of both days may have been more favorable for seeding than were those in the second experimental unit, both of which were treated with silver iodide. On these two days, the experimental units were separated in space by roughly 50 kilometers and in time by less than 40 minutes. These in-storm differences in clouds further demonstrate the problem of obtaining comparable samples even within storm periods.
4. DISCUSSION AND CONCLUSION

At this preliminary stage of our analysis, it is too early to make declarations about seeding effects in the 1989 data sample. This must wait development of a satisfactory methodology for selection of comparable clouds based on pre-treatment conditions. However, the findings do illustrate the large inherent natural variability in the conditions of clouds objectively selected on the basis of criteria. The net consequence for the 1989 PACE field experiment was to randomly select two populations of clouds with some very different individual characteristics. Hence, evident is the old dilemma of the "bad draw" as one reminder of why it has been so difficult to avoid some controversial moments in many historical weather modification experiments, even after going to great lengths to carefully randomize selection of clouds for experimentation. The interpretation of the seeding effect in the Illinois sample clouds from 1989, based strictly on all AgI treated clouds versus all sand treated clouds would not indicate a positive seeding effect. However, a careful and detailed analysis of the pre-treatment conditions has revealed that this is not how the evaluation should be pursued.

Acknowledgement. The findings reported in this paper are the result of many years of work by many people. In particular, the authors thank Bob Scott, Mary Schoen Petersen, and Nancy Westcott for the major contribution they made to the preparation and analysis of the 1989 PACE field data. This research was supported as part of the Atmospheric Modification Program under NOAA cooperative agreement COM NA90AA-H-0A175.

5. REFERENCES

APPENDIX D: STUDIES OF EFFECTS OF INCREASED RAINFALL IN CROP PRODUCTION
STUDIES OF EFFECTS OF INCREASED RAINFALL IN CROP PRODUCTION

by

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1. INTRODUCTION

A key problem encountered in the middle decades of weather modification research and development (R&D) was a lack of definitive information about the physical effects and socioeconomic impacts of purposeful weather modification. The early research commitments rested on a belief that a capability to modify the weather would be beneficial, with essentially all winners and no losers.

After two decades of R&D, this perception came under question for two major reasons. First, the environmental movement of the late 1960s asked probing questions about all forms of environmental modification and the consequences thereof. After spending $80 million on research in weather modification from 1956 to 1970, practically no resources had been devoted to analyzing the consequences of modified weather on the hydrologic cycle, biological systems, or on society.

A second unfortunate aspect of this lack of definitive impact research during the 1950s and 1960s was that growing questions in OMB, GAO, and elsewhere about the federal expenditures for R&D could not be answered with credible environmental or economic analyses. All too often, very simplistic economic analyses had been done such that "an inch of rain in July is worth 50 million bushels of corn in Iowa, and with corn @ $3.00 a bushel, this is worth $150 million. Cloud seeding at 10 cents per acre would cost only $1.3 million for an entire summer." Economists in the Office of Management and Budget and elsewhere in Washington were not convinced by such simplistic analyses. In fact, these approaches raised broader questions about the entire field of weather modification research.

The two basic questions that should have been addressed from the beginning were "will weather modification work," and "is it worth doing." Unfortunately, only the first question was being addressed. When the answers to that question were not forthcoming, for a variety of scientific and technical reasons, it became extremely important to adequately answer the value question for federal R&D expenditures.

2. BACKGROUND

When the Illinois State Water Survey, as the state's leading atmospheric resources research agency, concluded in 1969 that it was necessary to consider the potential of weather modification in Illinois it had the benefit of these past scientific endeavors and errors to guide it. Thus, the 20-year effort in Illinois to address the potential of precipitation modification in the Midwest began by addressing the aforementioned impact assessment problems. Results in this paper reflect the most recent research efforts to answer the question, "is weather modification worth doing"?

Briefly, the early Survey research to address this question looked into three areas: the effects on water resources, the effects on agriculture, and the state policy issues related to weather modification. Water and agriculture were the two most weather-sensitive activities in Illinois, hence the focus on them. Research during 1969-74 revealed that the potential benefits to the state's water resources were negligible unless extensive precipitation enhancement could be accomplished during droughts, and that potential seemed unlikely. However, research into agricultural effects revealed that the enhancement of summer rainfall, done at critical times during the growing seasons of corn and soybeans, could be beneficial. Research on policy issues led us to develop model legislation for the control and regulation of purposeful cloud seeding projects in the state.

The agricultural research accomplished during 1969-74 focused on the use of crop yield-weather regression models. Models were developed at county and regional levels to assess the effect of altering monthly and seasonal precipitation. These regression models showed that summer rainfall increases of 25% would provide sufficient increases in corn yields, 5 to 10%, to justify a cost of a then typical cloud seeding project with a sizable profit. Benefit-cost ratios were about 5:1.

This information became critical in guiding the further research of the Illinois State Water Survey in the field of purposeful weather modification. It should be noted that similar assessments were made relating to hail suppression. We found that unless an extremely high technology could be achieved, a capability to reduce hail by 60% or more, which was seen as scientifically very unlikely, the benefit-cost ratio would be negligible. The hail results, coupled with the agricultural rain results, were the factors that focused Water Survey efforts in purposeful cloud seeding research after 1976 on the study of summer rainfall enhancement.

The Survey launched, in 1978, a new research program entitled "Precipitation Augmentation for Crops Experiment" (PACE). It was designed to explore the potential for summer rainfall enhancement and to pursue studies of the rainfall effects. The effect studies since 1985 have focused on definitive analyses of the effects of altered rainfall on the hydrologic cycle, the economy, and on crop growth processes and yields.
A major finding relevant to the development of a rain enhancement capability came from the analysis of the open plots data. An increase of 40% in all rains gave the greatest increases in corn yields, at least up to a level of 15 to 16 inches of summer rainfall. Beyond that level, additional rainfall caused yield reductions as the soils became too wet.

Figure 1 portrays the relationships of total summer rainfall to the soybean yields during 1987-1990 on the open plots. This seasonal total rain approach masks effects related to the timing of certain rainfalls (e.g., to soybeans, a 1-inch rain in June is less important than one in August). Nevertheless, it reveals important tendencies. The results indicate 1) that too much rain, amounts greater than 15 to 18 inches, is not beneficial; 2) that 25% increases to all rains was better than 40% to all rains in all but one year, and 3) that 40% increase only for rains > 10 inch was the best treatment in two of the four years (1988 and 1990) and relatively good in 1989. The overly wet conditions of 1987 made most added water treatments undesirable - only one treatment gave yields that exceeded the yield achieved with natural rains.

Figure 1. Relationship of soybeans yields during 1987-1990, as grown on the open plots, with the ten rainfall treatments applied each year and seasonal total rainfall.

Rain Shelter Plots. Soybean yield response to precipitation augmentation in the rain shelters was very variable (Table 1). Over the entire 4 year experiment, soybean yields increased as the water applied increased. However, in 3 of the 4 years yield increases were not significantly different across the various water treatments in the mobile shelter experiments. The only year that yields consistently increased with increased water application was 1989. Due to a dry 1988-89 winter soil moisture conditions at the start of the 1989 growing season were drier than in the other 3 years, especially in the deeper profiles. Additional analyses are being conducted to determine the reason for no soybean yield response to increased water applications.
As a function of temperature revealed a strong effect of temperature during the first 25-30 days of growth. During with year and planting date within years (Table 3). Preliminary analyses of the yield and yield component data that responded to increased water application was recharge between growing seasons). The only corn yield augmentation in mobile shelters.

Table 2. Corn grain yield (bu/ac) relative to precipitation augmentation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Dry</th>
<th>Average</th>
<th>Wet</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>71.3</td>
<td>68.7</td>
<td>63.6</td>
<td>68.6</td>
</tr>
<tr>
<td>1988</td>
<td>161.9</td>
<td>151.3</td>
<td>165.5</td>
<td>182.9</td>
</tr>
<tr>
<td>1989</td>
<td>165.4</td>
<td>175.4</td>
<td>175.4</td>
<td>188.2</td>
</tr>
<tr>
<td>1990</td>
<td>143.5</td>
<td>146.6</td>
<td>158.5</td>
<td>153.4</td>
</tr>
<tr>
<td>Mean</td>
<td>135.5</td>
<td>135.5</td>
<td>140.8</td>
<td>150.8</td>
</tr>
</tbody>
</table>

Final corn yield and corn yield components varied with year and planting date within years (Table 3). Preliminary analyses of the yield and yield component data as a function of temperature revealed a strong effect of temperature during the first 25-30 days of growth. During this period, the number of leaves that will be on the plant is being determined, thus the photosynthetic capacity of the plant throughout the growing season is being determined.

Table 3. Corn yield and yield components as affected by date of planting.

<table>
<thead>
<tr>
<th>Date of Planting</th>
<th>Yield (bu/ac)</th>
<th>Rows/Ear</th>
<th>Kernels/Row</th>
<th>Kernel Mass (gm)</th>
<th>Vegetative Mass (gm/plant)</th>
<th>Cob Mass (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 28, 1987</td>
<td>77.7</td>
<td>12.1</td>
<td>32.2</td>
<td>0.390</td>
<td>64.5</td>
<td>14.8</td>
</tr>
<tr>
<td>May 12, 1988</td>
<td>173.5</td>
<td>13.6</td>
<td>43.2</td>
<td>0.233</td>
<td>93.0</td>
<td>22.4</td>
</tr>
<tr>
<td>May 13, 1989</td>
<td>201.9</td>
<td>16.1</td>
<td>39.0</td>
<td>0.243</td>
<td>95.0</td>
<td>24.7</td>
</tr>
<tr>
<td>May 31, 1989</td>
<td>156.6</td>
<td>16.2</td>
<td>33.9</td>
<td>0.200</td>
<td>91.1</td>
<td>20.3</td>
</tr>
<tr>
<td>May 24, 1990</td>
<td>163.2</td>
<td>14.2</td>
<td>38.8</td>
<td>0.246</td>
<td>77.6</td>
<td>18.7</td>
</tr>
<tr>
<td>May 28, 1990</td>
<td>162.5</td>
<td>14.0</td>
<td>40.1</td>
<td>0.262</td>
<td>79.8</td>
<td>22.5</td>
</tr>
<tr>
<td>June 5, 1990</td>
<td>145.3</td>
<td>13.0</td>
<td>35.1</td>
<td>0.280</td>
<td>85.7</td>
<td>18.8</td>
</tr>
<tr>
<td>Mean</td>
<td>154.4</td>
<td>14.2</td>
<td>31.9</td>
<td>0.265</td>
<td>96.8</td>
<td>20.3</td>
</tr>
</tbody>
</table>

The relationship between the average daily maximum temperature during the early growth period and the yield components were similar to the mean temperature response. However, the variance explained by the average daily maximum temperature was less than that explained by the mean temperature. Quadratic relationships between the average daily maximum temperature and the yield components were not significantly different from the linear relationships.

An important finding was the quadratic response of final yield to the average daily minimum temperature (Figure 2). This quadratic relationship indicates an optimum temperature during the spring for maximum corn yields. The relationship with the minimum temperature and the mean temperature during the early growth period provides a tool to estimate the potential benefits of precipitation enhancement on final corn yields.
5. SUMMARY

An important result was that the increases of 40% to just the one inch or heavier rain events, typically 4 or 5 events per summer, often gave relatively high yield increases. Furthermore, the increases of 10% to 40% to the lighter rain events provided no appreciable yield changes.

The important consequence of these findings for our research on rain modification capabilities is that cost-effective increases in the yields of corn and soybean crops grown in the prairie soils of Illinois, which embrace 2/3 of the state, will depend upon producing moderately sizable increases in rainfall on days when relatively heavy rain is already occurring. Sizable increases in rainfall on days when the rainfall is light, less than 0.10 inch, are essentially inconsequential for producing any measurable effect on crop yields. In sum, this means that cloud seeding to increase rainfall in Illinois will have to make sizable increases on days when atmospheric conditions are producing point rainfalls of 1.0 inch or more and area mean rainfalls of 0.5 inch or more. This finding constricts the conditions favorable for modification, both due to night storms (50% of these events occur at night), and the incidence of severe weather during heavier rain events (40% of all events have declarations of severe weather warnings).

These results are in general agreement with the studies of crop yields downwind of St. Louis. Crop yields in the area (2,000 mi² area cast of St. Louis) noted to have increased summer rainfalls were analyzed. The target area had yields that had become sizably greater over time and as the city grew, than did the surrounding counties. An important meteorological finding in the METROMEX related analysis of rainfall was that the urban effects were most active in enhancing rains when well-organized natural rains occurred producing area-average rainfalls in excess of 0.5 inch. This helps verify the findings from the 1987-1990 open plot studies. It also indicates that mature, well-developed rain-producing systems of the summer seasons can be altered and enhanced over sizable areas if urban-like influences on the atmosphere could be induced to occur.

The failure of soybeans to produce consistently greater yields to increased rainfall in the rain shelters indicates limited possibilities of increasing final soybean yields with intentional weather modification. However, the rain shelter experiments do indicate increased final corn yields with intentional weather modification.

An important finding relative to weather modification is the early season temperature response of corn. This finding provides a tool to evaluate the potential benefit of enhanced precipitation due to weather modification to corn early in the season before water becomes limiting. In cases of high daily minimum temperatures during the early growth stage, corn yields will be decreased regardless of how much additional rain intentional weather modification might produce. Additional analyses need to be conducted to determine how temperature and rainfall interact in dry, average, and wet summers to enhance corn yields when the early growing season has been warm or cool. Such analyses will help to determine how intentional or unintentional weather modification will affect yields under an anticipated warmer climate, and will assist in planning of intentional weather modification operations.

Acknowledgements. This research was performed with partial support from NOAA under Cooperative Agreement NA A89RAH09096, and with support of the State of Illinois and University of Illinois. The help of Lois Staggs, Gene Ziegler, and Wayne Banwart is appreciated.

LITERATURE CITED

APPENDIX E: RESPONSE OF CORN YIELD COMPONENTS TO SIMULATED PRECIPITATION AUGMENTATION
RESPONSE OF CORN YIELD COMPONENTS TO SIMULATED PRECIPITATION AUGMENTATION

Steven E. Hollinger and Stanley A. Changnon

Illinois State Water Survey
Champaign, Illinois 61820

1. INTRODUCTION

Crop-weather regression relationships have been used frequently to estimate crop productivity under varying weather conditions. In Illinois, these models have shown that an increase in rainfall due to weather modification would result in increased returns for producers (Garcia et al., 1990). Such modeling relies upon spatially and temporally averaged historical data, and introduces uncertainties in the results. These models also fail to demonstrate the physiological response of the crop to the timing of enhanced rainfall (Changnon, et al. 1989). Hence, we have sought, through field trials and controlled water applications, to define how various weather conditions and other management practices affect corn yields in Illinois.

Corn (Zea mays L.) yields are determined by a number of components that can be affected by management practices and weather at different times throughout the growth of the crop. The yield components include plant density, the number of kernel rows per ear, the number of kernels per row, and the kernel mass.

Plant density is determined to a great extent by the density of seeds planted. The density is modified to some extent by the soil moisture and temperature conditions during germination and emergence of the young plants. As plant density increases the yield of each plant will tend to decrease as the plants compete for water and nutrients. Generally, as plant density increases, yields over a large area will also increase. However, there is an optimum population above which higher plant densities begin to decrease area yields due to large reductions in the yields of individual plants. These yield reductions occur in the form of increased barrenness, reduced numbers of kernel rows per ear, reduced numbers of kernels per row, and reduced kernel mass.

The total number of kernels per plant (determined by the number of kernel rows per ear and number of kernels per row) and kernel mass can also be reduced by unfavorable weather during different parts of the growing season. For example, the number of kernel rows per ear is determined approximately 30 days after planting (Hollinger, 1981). Therefore, stresses due to weather and/or plant competition during this period may result in reduced numbers of kernel rows.

The potential total number of kernels per row, and thus the potential total number of kernels per ear, is determined during the period beginning 30 days after planting until approximately 2 weeks after pollination.

Before pollination, the plant is developing kernel primordia. The number of primordia developed determines the potential maximum number of kernels. If the plant experiences a stress during pollination the number of primordia fertilized will be reduced. Stress during the critical 2 weeks following pollination results in the abortion of kernels and a reduction in the number of kernels that mature (Grant et al., 1989; Eck, 1986; Harder et. al., 1982).

During the grain filling period (2 weeks after pollination to maturity) the final mass of each kernel is being determined. Stress during this period will not result in abortion of kernels, but will result in reduced kernel size which translates into reduced yields.

This paper reports the results of a 3 year study to determine the response of the various yield components to precipitation augmentation through weather modification. The yield increases experienced are related to the yield components to determine the growth period when precipitation augmentation is realized by the crop.

2. METHODS

Moveable shelters were used to preclude any natural rainfall from plots of corn during the summers of 1987, 1988, and 1989. Water to the crop was applied through a sprinkler system mounted in the moveable shelters that allowed the application of different amounts of water on each of the plots. Six rainfall treatments were applied to the 3x3m plots to simulate typical dry, normal, and wet summers and each typical year's rainfall augmented by 25% in central Illinois (Changnon and Hollinger, 1988). Totals of June, July, and August rainfall applied to represent the typical summers are shown in Table 1.

Corn (hybrid MO17xB73) was planted on 28 May 1987 at a density of 83,980 plants/ha, 12 May 1988 at a density of 64,220 plants/ha, and 12 May 1989 and 26 May 1989 at populations of 64,220 and 83,980 plants/ha. Four rows at a spacing of 0.76m were planted in each plot. The crops were fertilized at normal recommended rates each year, and weeds removed from the plots by hand hoeing.

Table 1. Total June, July, and August rainfall applied to represent typical dry, average, and wet summers in east-central Illinois.

<table>
<thead>
<tr>
<th>Summer</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>160</td>
</tr>
<tr>
<td>Dry + 25%</td>
<td>200</td>
</tr>
<tr>
<td>Average</td>
<td>279</td>
</tr>
<tr>
<td>Average + 25%</td>
<td>319</td>
</tr>
<tr>
<td>Wet</td>
<td>381</td>
</tr>
<tr>
<td>Wet + 25%</td>
<td>476</td>
</tr>
</tbody>
</table>

1Also Assist, Professor, Department of Agronomy, and Professor, Department of Orography, University of Illinois, Urbana, Illinois.
response to the increased rainfall occurred during the period of silking to 2 weeks following silking.

The number of rows per ear is determined when the plant is between the 5 to 10 leaf stage of growth (approximately 30-40 days after planting). During this early growth stage soil moisture is usually not a limiting factor in east-central Illinois and the plants are small enough that competition for sunshine is insignificant at the lower plant density treatment. The reduced number of kernel rows per ear in the higher plant density treatments indicated that at these populations, there was some competition occurring for nutrients or sunshine. It is not likely that water was limiting during the early growth stages, because the number of kernel rows per ear across a relatively constant across the rainfall treatments.

The different planting dates results in the application of different water amounts during the various growth cycles. Therefore, the data may provide some insight into the effect of water applications during different growth stages. The water application for each growth stage was determined by computing the growth stage intervals using the modified growing degree day method (Cross and Zuber, 1972) and the estimates of the growing degree days necessary to reach the various growth stages (Table 4). The amount of water applied to the crop during each stage was determined by summing the water applied during the growth stage.

The effect of different water application amounts on corn car yield components was determined by creating a linear correlation table (Table 5). All yield components were positively correlated with the quantity of water applied during the tassel initiation to ear initiation growth period. Vegetative mass was positively correlated with water application throughout the season. Final yield was negatively correlated with water application from planting to tassel initiation, and positively correlated with water application during all the other growth periods except for the growth period between car initiation and the end of row set.

The number of kernel rows per ear was positively correlated with the water application during the tassel initiation to ear initiation growth period and the period from the end of row set to silking. The later correlation is due to the high positive correlation between the amounts of water applied during the period from tassel initiation and ear initiation and the period from end of row set to silking. Because the number of rows is determined by the "end of row set" the significant correlation between the amount of water applied during the period from end of row set to silking and the number of kernel rows per ear is a spurious correlation and does not have any physiological significance.

Water amounts applied during the growth period from planting to tassel initiation were negatively correlated with the number of kernels per row and kernel mass. The number of kernels per row was positively correlated with the quantity of water applied during the tassel initiation to car initiation, end of row set and silking, and silking to August 31 growth periods. It is impossible to determine which periods have the most effect on the number of kernels per row because of the high correlations of water application amounts during the various growth periods.

The effects of enhanced rainfall through weather modification on final yield can be further evaluated by studying the changes in the components that contribute to the actual final yield (mass and number of kernels per fertile plant, and mass and number of kernels per nubbin), and those components that reduce the final yield from a potential maximum yield. Maximum potential yield is the product of the total number of plants, the number of kernels per fertile car, and the measured kernel mass for each treatment. The effects of the rainfall treatments on barrenness and number of nubbins and the associated yield reductions are shown in Table 6. At the lower plant densities, increasing the typical summer rainfall by 25% in dry years reduced the barrenness, while increased rainfall in the average and wet summer rainfall treatments tended to either increase or not change barrenness. At the higher plant densities, barrenness was reduced by increasing the rainfall by 25% during dry, average and wet summers.

The number of nubbins decreased in the average summer with increasing rainfall, while the increase in rainfall in the dry and wet summer treatments resulted in

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**Table 4. Growing degree days required to complete the various corn growth stages (Adapted from Hollinger, 1981)**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Growing Degree Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting to Tassel Initiation</td>
<td>311</td>
</tr>
<tr>
<td>Tassel Initiation to Ear Initiation</td>
<td>81</td>
</tr>
<tr>
<td>Ear Initiation to End of Row Set</td>
<td>144</td>
</tr>
<tr>
<td>End of Row Set to Silking</td>
<td>208</td>
</tr>
</tbody>
</table>

---

**Table 5. Correlation table of water applications between different corn growth stages and yield components.**

<table>
<thead>
<tr>
<th>Water Application</th>
<th>Yield Component</th>
<th>Stage</th>
<th>Growing Degree Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant to Tassel Initiation</td>
<td>Number of Kernels/Row</td>
<td>Planting to Tassel Initiation</td>
<td>311</td>
</tr>
<tr>
<td>Tassel Initiation to Ear Initiation</td>
<td>Number of Kernels/Row</td>
<td>Tassel Initiation to Ear Initiation</td>
<td>81</td>
</tr>
<tr>
<td>Ear Initiation to End of Row Set</td>
<td>Number of Kernels/Row</td>
<td>Ear Initiation to End of Row Set</td>
<td>144</td>
</tr>
<tr>
<td>End of Row Set to Silking</td>
<td>Number of Kernels/Row</td>
<td>End of Row Set to Silking</td>
<td>208</td>
</tr>
</tbody>
</table>

*Significantly different from 0 at α = 0.05*
Table 2. Corn yield components and final yield for each rainfall and plant density treatment.

<table>
<thead>
<tr>
<th>Yield Component</th>
<th>160 Rainfall (mm)</th>
<th>229</th>
<th>347</th>
<th>381</th>
<th>475 Population Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Density</td>
<td>65.364</td>
<td>65.364</td>
<td>64.556</td>
<td>65.364</td>
<td>64.017</td>
</tr>
<tr>
<td>Harfen Plants</td>
<td>1.346</td>
<td>1.346</td>
<td>1.013</td>
<td>1.013</td>
<td>1.013</td>
</tr>
<tr>
<td>Nubbins</td>
<td>3.498</td>
<td>4.308</td>
<td>3.228</td>
<td>1.077</td>
<td>808</td>
</tr>
<tr>
<td>Kernel row/ear</td>
<td>15.0</td>
<td>15.4</td>
<td>15.0</td>
<td>15.7</td>
<td>16.0</td>
</tr>
<tr>
<td>Kernels/row</td>
<td>38.0</td>
<td>37.7</td>
<td>38.8</td>
<td>39.4</td>
<td>41.0</td>
</tr>
<tr>
<td>Kernels/plant</td>
<td>569.8</td>
<td>566.0</td>
<td>582.3</td>
<td>618.1</td>
<td>641.8</td>
</tr>
<tr>
<td>Kernel weight (g)</td>
<td>0.236</td>
<td>0.239</td>
<td>0.296</td>
<td>0.296</td>
<td>0.300</td>
</tr>
<tr>
<td>Yield (mg/ha)</td>
<td>10.52</td>
<td>10.68</td>
<td>11.14</td>
<td>11.97</td>
<td>12.34</td>
</tr>
</tbody>
</table>

The center 2.4m of the 2 middle rows of each plot were harvested at maturity. The number of kernel rows per car and the number of kernels per row were counted. The total number of kernels per ear was computed by multiplying the number of kernel rows per ear by the number of kernels per row. Kernel weight was determined by dividing the total weight of grain harvested from each plot by the total number of kernels in each plot.

3. RESULTS

Mean yields of the low plant density treatments (64,220 plants/ha) increased as the summer water applications increased (Table 2). The same trend of increasing yields occurs in the high plant density treatment (83,980 plants/ha), however, the increases are not as consistent as those observed in the low population. The stage of growth when water treatments affected final yield can be found by studying the yield components that comprise the final yield. The response of each yield component to the 6 rainfall treatments is also shown in Table 2. Plant density, number of barren plants, and number of plants with incompletely formed ears (nubbins) are expressed on a hectare basis. The number of kernel rows per ear was determined by computing the sum of the kernel rows per ear for each plot and dividing by the total number of plants in the plot (includes barren plants and plants with nubbins).

Plant density had the greatest effect on the various yield components. The higher plant density resulted in an increase in barrenness and number of nubbins, and a decrease in number of kernel rows per ear, kernels per plant, and kernel mass. This effect is due to the increased plant competition for water, nutrients, and light at the higher plant densities.

Computing the ear yield components (kernel rows per ear and kernels per row) on the total plant population results in an underestimate of the actual number of kernel rows per ear and kernels per row on fully fertile ears. The numbers of kernel rows per ear, number of kernels per row, and the number of kernels on the fertile ears are computed by dividing the number of kernels per plot less then number of kernels contributed by the nubbins by the number of plants with fully developed ears (Table 3). The number of kernels per row on the fertile ears is slightly less than the number of kernels per row computed when the kernels on the nubbins are included.

Nubbins do not have any defined rows, therefore, in determining the number of kernel rows per ear a nubbin was reported as having 0 rows and 'X' kernels, where X is the number of kernels on the nubbin. Therefore, the number of kernels per row on fertile car (Table 3) is greater than the number of kernel rows per ear reported in Table 2.

Barrenness, defined as plants with no ears on them and plants with only small nubbins as ears, decreased as water application increased regardless of population. The higher populations resulted in greater barrenness over all water application treatments. The fact that barrenness decreased with increasing water application indicates that the plants in higher populations and lower water application treatments were competing for the available water. Therefore, one benefit of precipitation enhancement by weather modification is healthier plants resulting in decreased barrenness.

The number of kernels per fertile plant increased with increased water application in the low plant density treatment (Table 3). This increase in the number of kernels is due to a corresponding increase in the number of kernels per row. The increase in kernels per row indicates that the

Table 3. Number of kernel rows per ear, number of kernels per row on the fertile cars, and the number of kernels per nubbin.

<table>
<thead>
<tr>
<th>Yield Component</th>
<th>160 Rainfall (mm)</th>
<th>229</th>
<th>347</th>
<th>381</th>
<th>475 Population Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel rows/ear</td>
<td>16.2</td>
<td>16.3</td>
<td>16.6</td>
<td>16.2</td>
<td>16.2</td>
</tr>
<tr>
<td>Kernels/row</td>
<td>37.7</td>
<td>37.4</td>
<td>38.6</td>
<td>39.3</td>
<td>41.0</td>
</tr>
<tr>
<td>Kernels/plant</td>
<td>611.5</td>
<td>609.9</td>
<td>622.2</td>
<td>623.6</td>
<td>657.7</td>
</tr>
<tr>
<td>Kernel weight (g)</td>
<td>69.5</td>
<td>56.8</td>
<td>62.0</td>
<td>57.7</td>
<td>51.7</td>
</tr>
<tr>
<td>Yield (mg/ha)</td>
<td>10.70</td>
<td>51.3</td>
<td>85.1</td>
<td>76.5</td>
<td>72.9</td>
</tr>
</tbody>
</table>

The center 2.4m of the 2 middle rows of each plot were harvested at maturity. The number of kernel rows per car and the number of kernels per row were counted. The total number of kernels per ear was computed by multiplying the number of kernel rows per ear by the number of kernels per row. Kernel weight was determined by dividing the total weight of grain harvested from each plot by the total number of kernels in each plot.

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Computing the ear yield components (kernel rows per ear and kernels per row) on the total plant population results in an underestimate of the actual number of kernel rows per ear and kernels per row on fully fertile ears. The numbers of kernel rows per ear, number of kernels per row, and the number of kernels on the fertile ears are computed by dividing the number of kernels per plot less then number of kernels contributed by the nubbins by the number of plants with fully developed ears (Table 3). The number of kernels per row on the fertile ears is slightly less than the number of kernels per row computed when the kernels on the nubbins are included.

Nubbins do not have any defined rows, therefore, in determining the number of kernel rows per ear a nubbin was reported as having 0 rows and 'X' kernels, where X is the number of kernels on the nubbin. Therefore, the number of kernels per row on fertile car (Table 3) is greater than the number of kernel rows per ear reported in Table 2.

Barrenness, defined as plants with no ears on them and plants with only small nubbins as ears, decreased as water application increased regardless of population. The higher populations resulted in greater barrenness over all water application treatments. The fact that barrenness decreased with increasing water application indicates that the plants in higher populations and lower water application treatments were competing for the available water. Therefore, one benefit of precipitation enhancement by weather modification is healthier plants resulting in decreased barrenness.

The number of kernels per fertile plant increased with increased water application in the low plant density treatment (Table 3). This increase in the number of kernels is due to a corresponding increase in the number of kernels per row. The increase in kernels per row indicates that the
Table 6. Effects of enhanced precipitation on yield components and their contribution to final yield during typical dry, average, and wet summers. Numbers in the table have units of Mg/ha. (Note: Negative numbers indicate yield decreases and positive numbers indicate yield increases.)

<table>
<thead>
<tr>
<th>Rainfall Treatment</th>
<th>Low Plant Density</th>
<th>High Plant Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>Dry 125% Diff</td>
<td>Avg 125% Diff</td>
</tr>
<tr>
<td>Yield Potential</td>
<td>11.31 11.52 +0.21</td>
<td>11.89 12.45 +0.56</td>
</tr>
<tr>
<td>Barrenness</td>
<td>-0.23 -0.14 0.09</td>
<td>-0.23 -0.31 0.06</td>
</tr>
<tr>
<td>Nubbin number</td>
<td>-0.54 -0.69 -0.15</td>
<td>-0.52 -0.19 0.33</td>
</tr>
<tr>
<td>Nubbin size</td>
<td>0.07 0.07 0.00</td>
<td>0.08 0.02 -0.06</td>
</tr>
<tr>
<td>Kernel mass/ear</td>
<td>10.42 10.42 0.15</td>
<td>11.05 11.94 0.89</td>
</tr>
<tr>
<td>Actual Yield</td>
<td>10.54 10.69 0.15</td>
<td>11.13 11.96 0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td>Wet 125% Diff</td>
<td></td>
</tr>
<tr>
<td>Yield Potential</td>
<td>12.63 13.21 0.58</td>
<td></td>
</tr>
<tr>
<td>Barrenness</td>
<td>-0.16 -0.16 0.00</td>
<td></td>
</tr>
<tr>
<td>Nubbin number</td>
<td>-0.15 -0.39 0.24</td>
<td></td>
</tr>
<tr>
<td>Nubbin size</td>
<td>0.01 0.05 0.04</td>
<td></td>
</tr>
<tr>
<td>Kernel mass/ear</td>
<td>12.31 12.61 0.30</td>
<td></td>
</tr>
<tr>
<td>Actual Yield</td>
<td>12.32 12.66 0.34</td>
<td></td>
</tr>
</tbody>
</table>

more nubbins at the low plant density. At the high plant density, the number of nubbins was decreased in the dry summer, unchanged in the average summer, and increased in the wet summer when an additional 25% of rainfall was applied.

Increased rainfall resulted in larger fertile ear and nubbin size in all treatments regardless of the population with the exception of the average rainfall treatment with low plant density and the high plant density treatment in the wet summer rainfall treatment. In the first instance, the size of nubbins was reduced while in the second the size of the fertile car was reduced. In both cases, the reduction was due to reduced numbers of kernels on the ear or nubbin.

4. SUMMARY

Three years of controlled rainfall experiments in rain shelters were conducted in central Illinois to determine the effect of enhanced rainfall due to weather modification during typical dry, average and wet summers on final corn yields. Final corn yields were increased by an additional 25% of rainfall in each of the typical summer scenarios at both high and low plant densities, except for the wet summer at high plant densities. Final yield increases were due to decreased barrenness, reduced numbers of incompletely formed ears, and increased fertile ear size. These responses indicate that the greatest effect of increased rainfall was felt at the time of pollination and the 2 weeks following pollination.

The experiments show that a benefit to Illinois agriculture could be realized by a reliable weather modification technology in all summers. The greatest benefits occur in the average years with lesser benefits in the drier and wetter summers.

Acknowledgments: We gratefully acknowledge the contributions of Wayne Bauw and Eugene Zregler for managing the rain shelter and field plot studies. This research was supported through NOAA under cooperative agreement COMM-A89RAH09996.

5. REFERENCES


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