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PRELIMINARY INVESTIGATIONS OF A DYNAMIC SEEDING STRATEGY FOR OKLAHOMA CONVECTIVE CLOUDS

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ABSTRACT This article presents some early findings from on-going work investigating the seedability of Oklahoma convective clouds. Using the Great Plains Cloud Model (GPCM), predictions of maximum cloud height were compared for simulations of natural freezing, silver iodide enhanced freezing and dry ice enhanced freezing. Selected soundings were from time periods coinciding with airborne measurements of cloud microphysics which will allow for future evaluation of model realism. Climatological analyses indicated that representative meteorological conditions existed during these time periods. Preliminary indications suggest that opportunities for enhanced cloud growth due to seeding exist on days when cumulus clouds are present over Oklahoma and that a small advantage may result from the use of dry ice as compared to silver iodide.

I. INTRODUCTION

As part of Oklahoma's overall water resources development strategy, the Oklahoma Water Resources Board (OWRB) has presented a long term plan for utilizing and developing weather modification technology as a tool for water resources management in Oklahoma. This strategy is referred to as the Oklahoma Rainfall Enhancement Program (OREP). OREP takes the approach of utilizing today's best available cloud seeding technology, while at the same time remaining flexible enough to quickly incorporate advances in the technology.

The preliminary OREP seeding hypothesis was based on the static seeding concept as developed in HIPLEX (Bureau of Reclamation, 1979) and partially verified by Cooper and Lawson (1984) in Montana. Static seeding presumes that precipitation in seeded clouds occurs via initial diffusional growth of ice crystals to sizes where riming can commence, followed by subsequent evolution of the crystals into graupel. An increase in the total rainfall amount is expected through an increase in the average ice concentration to about 10 per liter, a concentration expected to be more efficient than the natural ice concentrations in converting condensate to precipitation. In addition, it is expected that the injection of ice into the cloud early in its lifetime will lead to earlier precipitation development, and to development of precipitation in some clouds that would not precipitate naturally (Mathis and Gibeau, 1985).

In contrast to this static approach, the design of the Southwest Cooperative Program Rainfall Enhancement Experiment for stimulating rainfall in West Texas, suggested a dynamic seeding approach (Jurica and Woodley, 1985). The conceptual model guiding the experiment invokes a chain of events beginning with the direct injection of an ice nucleant into supercooled updraft regions of convective cells. This on-top injection of the nucleant is expected to produce extensive and rapid glaciation of the updraft, resulting in release of latent heat of fusion, producing an increase in buoyancy and invigorating the cells' internal circulations, including downdrafts. The model predicts that seeded cells will grow taller, produce higher rain rates, last longer and produce more total rainfall. The enhanced downdrafts beneath the cells are expected to produce regions of enhanced convergence at the interface between downdraft outflows and the ambient flow which, in turn, will invigorate existing cells and/or produce new ones. This sequence of events is predicted to lead ultimately to a larger cloud system that lasts longer and produces more rainfall. This West Texas conceptual model is based in part on the FACE program (Florida Area Cumulus Experiment) which had a similar conceptual model and which produced increases in excess of 100% in rainfall on the scale of convective cells (Jurica and Woodley, 1985).

The results from the first year of the Southwest Cooperative Program, 1986, suggest that rainfall from the small meso-scale convective systems was increased due to silver iodide seeding suitable to produce dynamic effects. The apparent increases in rainfall, amounting to over 100%, were due to an increase in cell number, to an increase in mean cell height, and to an increase in total cluster area within the seeded systems. These apparent effects were consistent with an alteration and invigoration of the dynamics of the convective cells contained within the convective systems (Woodley et al., 1987).

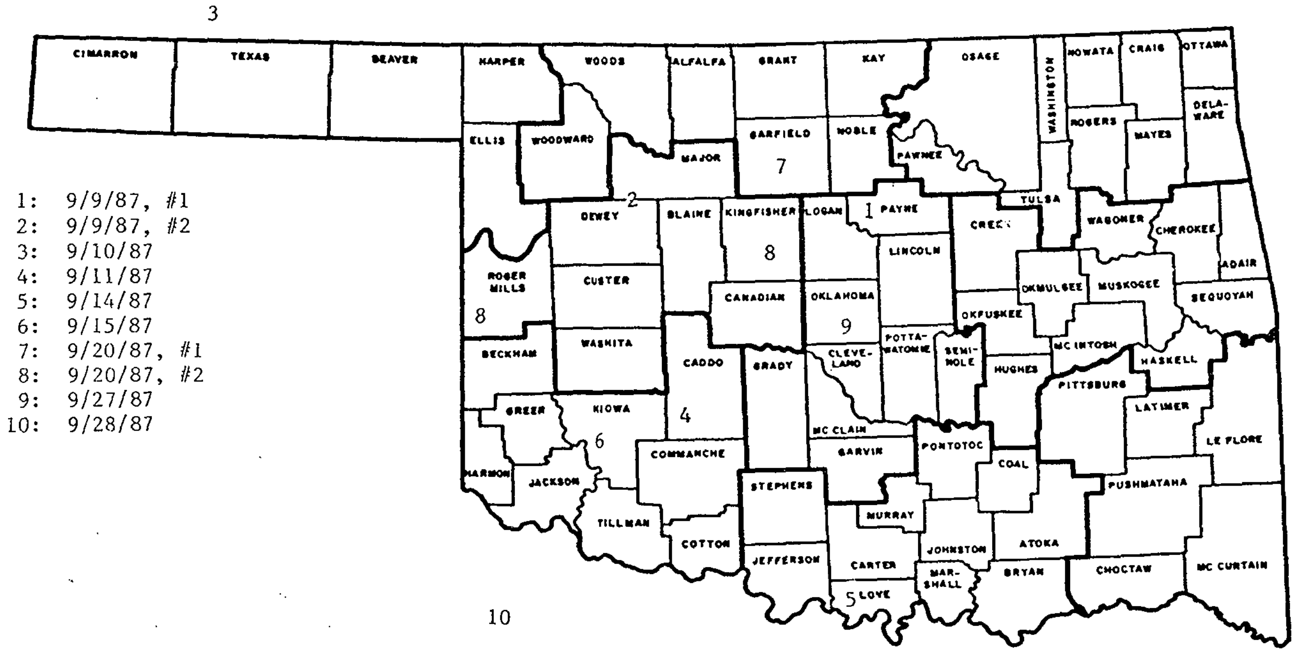
Additional results from 1987 suggest similar trends with a positive effect of AgI treatment on cell duration, maximum reflectivity, area, rain rate and rain volume. The largest effect was on mean total cell rainfall which increased between 50 and 146% (Woodley and Rosenfield, 1988).

In an effort to evaluate potential opportunities for dynamic seeding in Oklahoma, Johnson (1982) prepared an analysis of area rawinsondes for the five year period 1976-1980. The "dynamic seedability" was evaluated using the Great Plains Cloud Model - GPCM (Hirsch, 1971). This one-dimensional, steady-state model uses temperature, humidity, and wind data from a specified rawinsonde observation to predict the values of various dynamical and microphysical parameters in a resultant cumulus cloud. Of primary interest is the additional height of cloud development present when glaciation is allowed to occur in warmer portions of the cloud (thus simulating a seeding effect), and this height change is synonomous with the term "dynamic seedability". The conclusions from this study were that there is a likelihood of dynamic seeding opportunities on most days, somewhere in western Oklahoma, during the summer months. Such findings for Oklahoma were consistent with those of Matthews (1981) who demonstrated that dynamic seeding opportunities appeared to exist in Montana, Kansas and Texas during the summer months of 1975-1977.

2. DYNAMIC SEEDABILITIES

As part of the continuing effort to develop the basis for a scientifically sound weather modification program in Oklahoma, the University of North Dakota Citation cloud physics aircraft research team came to Oklahoma to collect microphysical data for analysis. Data were collected during spring (May 27 through June 9) 1986 and late summer (September 9 through September 28) of 1987 at the sites shown in Fig. 1. The results of analyses of the 1986 sampling effort are reported in Poellot (1986) and summarized in Mathis (1987). The results from the 1987 sampling effort are reported in Poellot (1988) and Pflaum (1988). The analyses indicate that Oklahoma convective clouds appear to develop precipitation initially through a warm rain process. As continued vertical development occurs and the clouds reach lower temperatures, the drops freeze, subsequently evolving into graupel. The data also indicated that supercooled liquid water does not persist long enough to enable static seeding to work (see companion article in this journal by Poellot and Pflaum). However, an ample supply of supercooled liquid water exists initially, suggesting that a dynamic seeding approach might be more appropriate.

As a first step toward investigating this possibility, the GPCM was applied to soundings for the days during which the Citation was collecting data. This was done for two purposes: 1) To evaluate the dynamic seedability on days when it was known that seeding candidates



1: 9/9/87, #1
2: 9/9/87, #2
3: 9/10/87
4: 9/11/87
5: 9/14/87
6: 9/15/87
7: 9/20/87, #1
8: 9/20/87, #2
9: 9/27/87
10: 9/28/87

Figure 1: Flight Locations and Dates

existed, and 2) to compare the dynamic seedability of two hypothetical seeding treatments. Tables 1.1 - 1.12 represent compilations of the model predicted seedabilities (km) for various cloud radii. In the "natural cloud", the conversion to ice is effected linearly between -20 °C to -40 °C. In test one, designed to simulate seeding with AgI, the conversion to ice was shifted to warmer regions of the cloud and effected linearly between -5 and -25 °C. In test two, designed to simulate seeding with dry ice, the conversion of ice was shifted to even higher temperatures, and effected linearly between 0 and -15 °C. The abbreviations, OKC, AMA, and DDC stand for Oklahoma City, Amarillo and Dodge City, respectively. National Weather Service soundings for these 3 sites were used as input to the model. The letter M indicates that sounding data was missing.

It is seen that on days when convection existed: 5/27, 28, 31, 6/1, 2, 3, 6, 9, 1986; 9/9, 10, 11, 14, 15, 20, 27, 28, 1987, and sounding data was available, the opportunity for enhanced vertical development was present at least at one of the stations, often at all three. Enhancement of greater than 1 km was generally present for clouds of at least one size category.

The effects of changing the ice conversion temperature were relatively small but general trends were as follows:

a. When dynamic seedability was demonstrated in test 1, it was present in test 2 at a slightly enhanced value. However, it was not uncommon for small negative variations to occur as well.

b. When more substantial positive changes occurred from test 1 to test 2, they usually took the form of an expansion of effects to neighboring cloud sizes rather than any initiation of effects where none existed for test 1. There were two cases where test 2 produced a significant reduction as compared to test 1.

c. Spring days were slightly more responsive than fall days to the simulated seeding, a trend also noted by Johnson (1982).

In summary, according to GPCM predictions, opportunities existed for positive dynamic seeding effects on days when convection was present during the Spring of 1986 and Fall of 1987. In addition, the model suggested that a small advantage may result from dry ice seeding as compared to silver iodide seeding.

3. CLIMATOLOGICAL REPRESENTATIVENESS OF THE DATA COLLECTION PERIODS

In light of the short sampling periods and the lack of any historical record of cloud physics information in Oklahoma, a climatological perspective was needed for the observations and GPCM predictions. The following is an attempt to provide such a perspective.

3.1 The Spring Period (May 27-June 9, 1986)

The Spring thunderstorm season in Oklahoma is the period of greatest rainfall for the State. The transition from winter to summer is nearly complete by the end of May. Severe thunderstorms that develop in response to the interaction between transient disturbances in the jet stream and the warm moist air which dominates the State's surface weather, frequently spawn tornadoes, strong winds, and hail. Those same thunderstorms also produce locally heavy rains which supply water to the ripening wheat crop and runoff water into the lakes and ponds. The spring storm season then is a good time to find rain clouds in Oklahoma and to study their characteristics.

Clouds were sampled on 9 of the 14 days during the Spring 1986 sampling period. The aircraft was down for repairs on two additional days, one of which was marked by heavy rains in Norman (Poellot, 1986). Rainfall was reported within the western two-thirds of Oklahoma on each day of the sampling period (OCS, 1986a and OCS, 1986b). Eddy (1982) found that rain-producing clouds are normally present in western Oklahoma on 95% of the days in spring and summer. The reported frequency of raindays is not atypical for a short period of time, but the wide-spread nature of the rain in the 1986 period was.

A persistent upper-level low pressure area lingered to the west of the State throughout the observational period. Frontal activity was generally weak, but the environment was favorable for the development of showers and thunderstorms in response to the small-scale disturbances which frequently are embedded in the wind flows that dominated the period. Since no fronts of any significance passed through the State, ample moisture was available to support convective activity. The study period was a wetter-than-normal two week interval, but not a period that could be characterized as an extremely wet period.

The atmosphere during the observational period tended to be cooler (by 3 °C at 850 mb and 700 mb and by 1 °C at 500 mb at Oklahoma City) than normal. The basic low-level moisture measures indicate that greater than normal moisture was available during the period. The stability, as measured by the Lifted Index and the Total Totals was near normal throughout the period. The K-index tended to be higher than normal, a reflection of the depth of the available moisture. Table 2 is a summary of the moisture and stability parameters during the field project.

The clouds sampled during the 1986 field period were found in an airmass that was generally unstable though not of the extreme instability associated with spring outbreaks of severe weather in western and central Oklahoma. A more normal two-week period would likely have resulted in, at least, one or two

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Table 4.1
Dynamic Seedability (Km): OKC
Test I

		Cloud radius (km)					
Date 1986	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
5/27	00	0.0	0.0	0.0	0.0	0.0	0.0
5/27	12	0.0	0.0	0.0	0.0	0.0	2.8
5/28	00	0.0	0.0	0.0	0.0	0.0	0.0
5/28	12	0.0	0.1	3.6	0.0	0.0	0.3
5/29	00	0.0	0.0	0.3	0.5	1.0	0.7
5/29	12	M	M	M	M	M	M
5/30	00	0.0	0.0	0.2	4.3	4.4	1.4
5/30	12	1.2	2.4	0.3	0.3	0.0	0.7
5/31	00	0.0	0.2	5.2	0.0	0.3	0.7
5/31	12	M	M	M	M	M	M
6/1	00	0.0	3.3	0.7	0.5	0.3	1.0
6/1	12	0.0	3.5	3.2	0.6	0.3	6.6
6/2	00	0.9	1.8	0.8	0.3	0.4	0.4
6/2	12	0.5	1.2	2.0	3.9	0.0	0.4
6/3	00	0.0	4.3	0.0	0.3	0.0	0.5
6/3	12	0.0	0.2	4.1	0.3	0.4	0.5
6/4	00	0.0	0.0	0.0	5.5	5.5	0.4
6/4	12	M	M	M	M	M	M
6/5	00	0.0	0.0	0.0	0.0	0.0	0.0
6/5	12	0.0	0.2	0.3	0.5	6.2	0.4
6/6	00	M	M	M	M	M	M
6/6	12	M	M	M	M	M	M
6/7	00	0.0	0.0	0.0	0.0	0.0	0.0
6/7	12	0.0	0.0	0.0	0.0	0.0	0.0
6/8	00	M	M	M	M	M	M
6/8	12	M	M	M	M	M	M
6/9	00	0.0	0.0	0.0	0.0	0.0	0.0
6/9	12	0.0	0.0	3.9	4.0	0.3	0.8

Table 4.2
Dynamic Seedability (Km): OKC
Test 2

		Cloud radius (km)					
Date 1986	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
5/27	00	0.0	0.0	0.0	0.0	0.0	0.0
5/27	12	0.0	0.0	0.0	0.0	0.0	2.8
5/28	00	0.0	0.0	0.0	0.0	0.0	0.0
5/28	12	0.0	0.3	3.4	0.0	0.0	0.5
5/29	00	0.0	0.2	0.5	0.7	1.0	0.7
5/29	12	M	M	M	M	M	M
5/30	00	0.0	0.0	4.0	4.1	4.4	1.7
5/30	12	1.4	2.4	0.3	0.3	0.0	0.7
5/31	00	0.0	4.8	5.2	0.0	0.3	0.7
5/31	12	M	M	M	M	M	M
6/1	00	3.3	3.3	0.7	0.5	0.3	1.0
6/1	12	0.0	3.5	3.2	0.6	0.3	7.0
6/2	00	1.1	1.8	0.9	0.3	0.4	0.9
6/2	12	1.3	1.4	2.2	3.9	0.0	0.7
6/3	00	0.0	4.0	0.0	0.3	0.0	0.5
6/3	12	0.0	1.9	4.1	0.3	0.4	0.5
6/4	00	0.0	0.0	0.0	5.2	5.5	0.8
6/4	12	M	M	M	M	M	M
6/5	00	0.0	0.0	0.0	0.0	0.0	0.0
6/5	12	0.0	0.5	0.5	1.7	6.2	0.8
6/6	00	M	M	M	M	M	M
6/6	12	M	M	M	M	M	M
6/7	00	0.0	0.0	0.0	0.0	0.0	0.0
6/7	12	0.0	0.0	0.0	1.9	3.5	0.0
6/8	00	M	M	M	M	M	M
6/8	12	M	M	M	M	M	M
6/9	00	0.0	0.0	3.4	4.0	0.3	0.8

Table 4.3
Dynamic Seedability (Km): OKC
Test I

		Cloud radius (km)					
Date 1987	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
9/9	00	0.2	0.5	1.0	0. 0	0.3	0.4
9/9	12	0.2	1.5	0.3	0.0	0.0	0.0
9/10	00	0.2	0.3	2.2	0.5	0.3	0.7
9/10	12	0.0	0.0	0.7	0.6	0.3	0.4
9/11	00	0.0	0.7	1.0	0.5	0.3	0.8
9/11	12	0.0	0.0	0.0	0.0	0.0	0.0
9/12	00	M	M	M	M	M	M
9/12	12	M	M	M	M	M	M
9/13	00	M	M	M	M	M	M
9/13	12	M	M	M	M	M	M
9/14	00	M	M	M	M	M	M
9/14	12	M	M	M	M	M	M
9/15	00	0.0	0.0	0.0	0.4	0.0	0.0
9/15	12	0.0	0.7	1.0	1.0	0.0	0.5
9/16	00	0.2	0.2	0.4	0.4	0.5	0.4
9/16	12	0.0	0.0	0.0	5.4	0.3	0.3
9/17	00	0.0	0.0	4.0	0.3	0.3	0.4
9/17	12	0.0	0.5	0.0	0.0	0.0	0.4
9/18	00	0.2	0.8	0.2	0.3	0.3	0.5
9/18	12	0.0	0.0	0.0	0.0	0.0	0.0
9/19	00	0.0	0.0	0.0	0.0	0.0	0.0
9/19	12	0.0	0.0	0.0	0.0	0.0	0.6
9/20	00	0.6	1.1	0.2	0.3	0.0	0.7
9/20	12	M	M	M	M	M	M
9/21	00	2.0	0.5	0.3	1.4	0.0	3.1
9/21	12	0.0	0.2	0.8	1.4	0.4	0.6
9/22	00	0.0	0.0	0.0	0.0	0.0	0.2
9/22	12	0.0	0.0	0.0	0.0	0.0	0.0
9/23	00	0.0	0.0	0.2	2.7	1.1	1.2
9/23	12	0.0	0.0	0.0	0.0	4.8	3.7
9/24	00	0.2	1.2	0.8	0.6	0.3	0.4
9/24	12	0.0	0.8	1.2	0.3	0.3	0.8
9/25	00	0.0	0.0	2.0	2.4	0.6	1.0
9/25	12	0.0	0.7	0.7	0.6	0.3	0.4
9/26	00	0.0	0.5	0.5	0.5	0.3	0.8
9/26	12	0.0	2.7	0.5	0.5	0.3	0.4
9/27	00	M	M	M	M	M	M
9/27	12	M	M	M	M	M	M
9/28	00	M	M	M	M	M	M
9/28	12	M	M	M	M	M	M

Table 4.4
Dynamic Seedability (Km): OKC
Test 2

		Cloud radius (km)					
Date 1987	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
9/9	00	0.5	0.5	1.0	0.0	0.3	0.4
9/9	12	1.3	1.5	0.3	0.0	0.0	0.4
9/10	00	0.6	0.7	2.2	0.5	0.3	0.7
9/10	12	0.0	0.2	1.2	0.8	0.3	0.8
9/11	00	0.2	0.7	1.0	0.5	0.3	0.8
9/11	12	0.0	0.0	0.0	0.0	0.0	0.0
9/12	00	M	M	M	M	M	M
9/12	12	M	M	M	M	M	M
9/13	00	M	M	M	M	M	M
9/13	12	M	M	M	M	M	M
9/14	00	M	M	M	M	M	M
9/14	12	M	M	M	M	M	M
9/15	00	0.0	5.7	0.0	0.4	0.0	0.0
9/15	12	0.0	0.7	1.3	1.0	0.0	0.5
9/16	00	0.2	0.4	0.6	0.7	0.5	0.8
9/16	12	0.0	0.0	0.0	5.4	0.0	0.3
9/17	00	0.0	0.2	3.8	0.3	0.3	0.8
9/17	12	0.2	0.9	0.0	0.0	0.0	0.4
9/18	00	0.5	0.8	0.2	0.3	0.3	0.5
9/18	12	0.0	0.0	0.0	0.0	0.0	0.0
9/19	00	0.0	0.0	0.0	0.0	0.0	0.0
9/19	12	0.0	0.0	0.0	0.0	0.0	0.9
9/20	00	0.6	1.3	0.2	0.3	0.3	0.6
9/20	12	M	M	M	M	M	M
9/21	00	M	M	M	M	M	M
9/21	12	0.1	0.5	1.1	1.4	0.6	0.6
9/22	00	0.0	0.0	0.0	0.0	0.6	0.5
9/22	12	0.0	0.0	0.0	0.0	0.0	0.0
9/23	00	0.0	0.1	2.9	2.7	1.1	1.2
9/23	12	0.0	0.0	0.0	0.0	4.8	3.7
9/24	00	0.4	1.4	0.8	0.6	0.3	0.9
9/24	12	0.0	1.0	1.2	0.6	0.3	0.9
9/25	00	0.0	0.0	2.0	2.7	0.6	1.0
9/25	12	1.8	0.9	0.7	0.6	0.3	0.8
9/26	00	0.0	0.9	0.5	0.5	0.3	0.8
9/26	12	0.0	2.5	0.7	0.5	0.3	0.4
9/27	00	M	M	M	M	M	M
9/27	12	M	M	M	M	M	M
9/28	00	M	M	M	M	M	M
9/28	12	M	M	M	M	M	M

Table 4.5
Dynamic Seedability (Km): AMA
Test I

Cloud radius (km)

Date 1986	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
5/27	00	0.0	0.0	0.1	0.0	3.2	3.5
5/27	12	0.0	0.0	0.0	0.0	0.0	0.0
5/28	00	0.0	0.0	0.0	0.0	0.0	0.0
5/28	12	0.0	0.0	0.0	0.0	0.0	0.0
5/29	00	0.0	0.0	0.1	0.0	0.2	0.5
5/29	12	0.0	0.0	0.0	0.0	0.0	0.0
5/30	00	0.0	0.0	0.3	1.5	2.0	1.5
5/30	12	0.0	0.0	0.0	0.2	0.2	0.8
5/31	00	0.0	0.0	0.3	1.2	2.7	0.6
5/31	12	0.0	0.0	0.0	0.0	6.5	5.9
6/1	00	M	M	M	M	M	M
6/1	12	0.0	0.3	0.9	1.7	3.6	0.6
6/2	00	0.0	1.2	4.3	0.0	0.0	0.4
6/2	12	2.9	0.7	0.3	0.0	0.0	0.3
6/3	00	0.0	0.0	0.2	0.0	0.2	5.2
6/3	12	0.0	2.3	0.0	0.0	0.3	0.4
6/4	00	0.0	2.6	0.0	0.0	0.0	0.7
6/4	12	M	M	M	M	M	M
6/5	00	0.0	0.0	0.0	0.0	0.0	0.0
6/5	12	0.0	0.0	5.5	0.3	0.0	0.4
6/6	00	M	M	M	M	M	M
6/6	12	M	M	M	M	M	M
6/7	00	0.9	0.0	0.3	0.0	0.0	0.4
6/7	12	0.7	0.7	0.3	0.6	0.4	0.8
6/8	00	M	M	M	M	M	M
6/8	12	M	M	M	M	M	M
6/9	00	0.2	2.6	2.6	2.8	3.0	2.8
6/9	12	0.0	0.4	1.0	1.6	0.3	0.8

Table 4.6
Dynamic Seedability (Km): AMA
Test 2

Cloud radius (km)

Date 1986	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
5/27	00	0.0	0.0	0.7	2.8	3.2	3.7
5/27	12	0.0	0.0	0.0	0.0	0.0	0.0
5/28	00	0.0	0.0	0.0	0.0	0.0	0.0
5/28	12	0.0	0.0	0.0	0.0	0.1	0.1
5/29	00	0.0	0.4	0.4	0.6	0.8	1.1
5/29	12	0.0	0.0	0.0	0.0	0.0	0.0
5/30	00	0.0	0.1	0.9	1.7	2.0	1.5
5/30	12	0.0	0.1	0.1	0.3	0.9	2.4
5/31	00	0.0	0.2	0.8	1.4	2.7	0.9
5/31	12	0.0	0.0	0.0	5.4	6.5	6.2
6/1	00	M	M	M	M	M	M
6/1	12	0.2	0.6	1.2	2.3	3.6	0.6
6/2	00	0.5	1.4	4.0	0.0	0.0	0.4
6/2	12	2.5	0.7	0.3	0.0	0.0	0.7
6/3	00	0.0	0.2	0.3	0.2	6.1	5.8
6/3	12	0.0	2.2	0.0	0.0	0.3	0.4
6/4	00	0.0	2.4	0.0	0.0	0.0	0.7
6/4	12	M	M	M	M	M	M
6/5	00	0.0	0.0	0.0	0.0	0.0	0.0
6/5	12	0.0	5.4	5.5	0.3	0.0	0.4
6/6	00	M	M	M	M	M	M
6/6	12	M	M	M	M	M	M
6/7	00	1.1	0.0	0.3	0.0	0.0	0.4
6/7	12	0.9	0.7	0.3	0.6	0.4	0.8
6/8	00	M	M	M	M	M	M
6/8	12	M	M	M	M	M	M
6/9	00	1.7	2.4	2.6	2.8	3.0	3.1
6/9	12	0.0	0.7	1.2	1.6	0.3	0.8

Table 4.7
Dynamic Seedability (Km): AMA
Test 1

Cloud radius (km)

Date 1987	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
9/9	00	0.0	0.3	0.4	0.8	1.2	0.4
9/9	12	0.2	0.7	2.0	0.8	0.3	0.4
9/10	00	1.5	0.6	0.6	0.7	0.6	0.7
9/10	12	0.2	0.6	0.2	0.3	0.0	0.4
9/11	00	1.2	0.5	0.3	0.0	0.3	0.4
9/11	12	5.1	0.3	0.0	0.0	0.0	0.3
9/12	00	M	M	M	M	M	M
9/12	12	M	M	M	M	M	M
9/13	00	M	M	M	M	M	M
9/13	12	M	M	M	M	M	M
9/14	00	M	M	M	M	M	M
9/14	12	M	M	M	M	M	M
9/15	00	0.0	0.2	0.4	0.8	1.5	0.8
9/15	12	0.3	0.2	0.4	0.2	0.2	0.8
9/16	00	0.0	0.0	0.0	0.0	3.3	2.6
9/16	12	0.0	0.0	3.7	3.6	3.5	0.9
9/17	00	0.0	0.2	0.0	0.2	0.2	0.2
9/17	12	0.4	0.5	0.3	0.0	0.0	0.4
9/18	00	0.6	1.1	0.3	0.0	0.0	0.5
9/18	12	0.2	0.5	0.9	1.5	5.1	4.5
9/19	00	0.0	0.0	0.0	0.0	0.0	0.0
9/19	12	0.0	0.2	0.3	0.0	0.0	0.4
9/20	00	0.0	0.0	0.3	0.0	0.3	0.4
9/20	12	M	M	M	M	M	M
9/21	00	M	M	M	M	M	M
9/21	12	0.0	0.3	0.8	1.3	0.2	0.6
9/22	00	0.0	1.4	1.2	1.1	0.6	1.3
9/22	12	0.1	1.2	0.2	0.0	0.2	0.6
9/23	00	0.0	0.0	0.0	0.0	0.0	2.8
9/23	12	0.0	0.2	3.3	3.7	0.3	0.7
9/24	00	0.2	2.3	0.3	0.3	0.0	0.4
9/24	12	0.5	1.4	2.2	0.5	0.6	1.0
9/25	00	0.2	1.8	0.3	0.3	0.3	0.8
9/25	12	0.5	2.9	0.3	0.3	0.3	0.4
2/26	00	0.0	2.8	1.2	0.6	0.3	0.4
2/26	12	0.8	0.0	0.0	0.0	0.0	0.4
9/27	00	M	M	M	M	M	M
9/27	12	M	M	M	M	M	M
9/28	00	M	M	M	M	M	M
9/28	12	M	M	M	M	M	M

Table 4.8
Dynamic Seedability (Km): AMA
Test 2

Cloud radius (km)

Date 1987	Time (GMT)	0.5	1.0	1.5	2.0	3.0	10.0
9/9	00	0.0	0.3	0.5	1.0	1.2	0.4
9/9	12	0.4	0.9	2.2	1.1	0.3	0.4
9/10	00	1.5	0.6	0.6	0.7	0.6	0.7
9/10	12	0.2	0.6	0.2	0.3	0.0	0.4
9/11	00	1.1	0.5	0.3	0.0	0.3	0.4
9/11	12	4.8	0.3	0.0	0.0	0.0	0.7
9/12	00	M	M	M	M	M	M
9/12	12	M	M	M	M	M	M
9/13	00	M	M	M	M	M	M
9/13	12	M	M	M	M	M	M
9/14	00	M	M	M	M	M	M
9/14	12	M	M	M	M	M	M
9/15	00	0.0	0.3	0.5	1.0	1.7	0.8
9/15	12	0.5	0.2	0.4	0.2	0.2	1.1
9/16	00	0.0	0.1	2.3	2.6	3.3	2.6
9/16	12	0.0	0.5	1.9	3.6	3.5	0.9
9/17	00	0.0	0.2	0.2	0.3	0.3	0.5
9/17	12	0.5	0.5	0.3	0.0	0.0	0.4
9/18	00	0.6	1.1	0.3	0.0	0.0	0.5
9/18	12	0.3	1.1	1.4	2.8	5.1	4.5
9/19	00	0.0	0.0	0.0	0.0	0.0	0.0
9/19	12	0.0	0.2	0.3	0.0	0.0	0.4
9/20	00	0.0	0.0	0.3	0.0	0.3	0.4
9/20	12	M	M	M	M	M	M
9/21	00	M	M	M	M	M	M
9/21	12	0.0	0.6	1.1	1.5	0.2	0.8
9/22	00	0.0	1.1	1.4	1.1	0.6	1.3
9/22	12	0.1	1.4	0.2	0.0	0.2	0.6
9/23	00	0.0	0.0	0.0	0.0	0.0	3.1
9/23	12	0.0	1.3	3.3	3.7	0.3	0.7
9/24	00	1.0	2.3	0.3	0.3	0.0	0.4
9/24	12	0.7	1.6	2.2	0.5	0.6	1.0
9/25	00	0.4	1.8	0.3	0.3	0.3	0.8
9/25	12	0.9	2.9	0.3	0.3	0.3	0.4
9/26	00	0.0	2.8	1.2	0.6	0.3	0.4
9/26	12	0.0	0.0	0.0	0.0	0.0	0.4
9/27	00	M	M	M	M	M	M
9/27	12	M	M	M	M	M	M
9/28	00	M	M	M	M	M	M
9/28	12	M	M	M	M	M	M

"REVIEWED"

Table 4.9
Dynamic Seedability (Km): DDC
Test 1

Date 1986	Time (GMT)	Cloud radius (km) 0.5	1.0	1.5	2.0	3.0	10.0
5/27	00	0.0	0.1	0.1	3.9	3.8	3.1
5/27	12	1.3	0.0	0.2	0.0	0.0	0.5
5/28	00	0.0	0.0	0.0	0.0	0.0	0.0
5/28	12	0.0	0.0	0.0	5.7	5.7	1.4
5/29	00	0.0	0.0	0.3	0.5	4.2	0.5
5/29	12	0.0	0.0	0.0	0.0	0.0	0.0
5/30	00	0.0	0.0	0.3	0.8	3.0	1.1
5/30	12	0.0	0.2	1.0	1.8	0.9	1.4
5/31	00	0.0	0.0	0.0	0.0	0.2	0.2
5/31	12	0.0	0.0	0.5	0.5	2.6	1.2
6/1	00	0.3	1.3	1.8	0.5	0.0	0.4
6/1	12	0.0	0.0	1.6	0.3	0.0	0.4
6/2	00	0.0	0.0	0.0	0.0	0.0	0.4
6/2	12	0.2	0.2	0.0	0.0	0.2	0.7
6/3	00	0.0	0.8	1.4	3.9	0.0	0.4
6/3	12	0.0	1.1	1.4	4.6	4.7	0.7
6/4	00	0.0	6.1	0.3	0.4	0.0	0.5
6/4	12	M	M	M	M	M	M
6/5	00	0.4	0.3	0.0	0.4	0.0	0.0
6/5	12	0.3	0.7	1.7	1.0	0.3	0.4
6/6	00	M	M	M	M	M	M
6/6	12	M	M	M	M	M	M
6/7	00	3.8	0.3	0.0	0.0	0.0	0.5
6/7	12	0.4	0.9	0.5	0.3	0.3	0.8
6/8	00	M	M	M	M	M	M
6/8	12	M	M	M	M	M	M
6/9	00	0.2	1.2	1.2	1.1	1.1	1.3
6/9	12	0.0	0.2	1.7	2.2	0.3	1.0

Table 4.10
Dynamic Seedability (Km): DDC
Test 2

Date 1986	Time (GMT)	Cloud radius (km) 0.5	1.0	1.5	2.0	3.0	10.0
5/27	00	0.0	3.4	3.5	3.7	3.8	3.5
5/27	12	1.3	0.0	0.2	0.0	0.0	0.5
5/28	00	0.0	0.0	0.0	0.0	0.0	0.0
5/28	12	0.0	0.0	0.0	5.7	5.7	5.1
5/29	00	0.0	0.0	0.6	1.4	4.0	0.5
5/29	12	0.0	0.0	0.0	0.0	0.0	0.0
5/30	00	0.1	0.3	0.8	1.7	3.2	1.1
5/30	12	0.0	0.5	1.4	1.8	0.9	1.4
5/31	00	0.0	0.1	0.2	0.2	0.3	0.5
5/31	12	0.1	0.3	0.6	0.9	2.8	1.2
6/1	00	0.7	1.5	1.8	0.5	0.0	0.4
6/1	12	0.0	0.0	1.4	0.0	0.0	0.4
6/2	00	0.0	0.0	0.0	0.0	0.0	0.7
6/2	12	0.3	0.2	0.0	0.0	0.2	0.7
6/3	00	0.0	1.1	1.6	3.6	0.0	0.4
6/3	12	0.0	1.1	1.6	4.0	4.7	0.7
6/4	00	0.0	6.1	0.3	0.4	0.0	0.5
6/4	12	M	M	M	M	M	M
6/5	00	0.6	0.3	0.0	0.4	0.0	0.0
6/5	12	0.5	0.9	1.7	1.0	0.3	0.4
6/6	00	M	M	M	M	M	M
6/6	12	M	M	M	M	M	M
6/7	00	2.0	0.3	0.0	0.0	0.0	0.5
6/7	12	0.6	1.1	0.8	0.6	0.3	0.8
6/8	00	M	M	M	M	M	M
6/8	12	M	M	M	M	M	M
6/9	00	0.7	1.2	1.2	1.2	1.3	1.5
6/9	12	0.0	0.7	1.9	2.2	0.6	1.0

Table 4.11
Dynamic Seedability (Km): DDC
Test 1

Date 1987	Time (GMT)	Cloud radius (km) 0.5	1.0	1.5	2.0	3.0	10.0
9/9	00	0.2	0.2	0.0	0.3	0.3	0.4
9/9	12	0.3	0.9	0.5	0.3	0.0	0.0
9/10	00	0.7	0.3	0.0	0.3	0.0	0.4
9/10	12	2.6	0.0	0.3	0.0	0.0	0.0
9/11	00	3.9	0.0	0.0	0.0	0.3	0.4
9/11	12	1.3	2.2	0.3	0.0	0.0	0.4
9/12	00	M	M	M	M	M	M
9/12	12	M	M	M	M	M	M
9/13	00	M	M	M	M	M	M
9/13	12	M	M	M	M	M	M
9/14	00	M	M	M	M	M	M
9/14	12	M	M	M	M	M	M
9/15	00	0.7	1.1	0.5	0.3	0.0	0.8
9/15	12	0.4	0.2	0.2	0.2	0.3	0.7
9/16	00	0.5	1.2	0.2	0.2	0.3	0.3
9/16	12	M	M	M	M	M	M
9/17	00	0.0	0.0	0.0	0.0	0.0	0.5
9/17	12	0.7	0.6	0.2	0.3	0.3	0.4
9/18	00	0.6	0.2	0.2	0.0	0.0	0.4
9/18	12	0.0	0.0	0.0	0.0	0.0	0.0
9/19	00	0.0	0.0	0.0	0.0	0.2	3.2
9/19	12	1.2	0.7	0.4	0.2	0.0	0.4
9/20	00	0.5	0.4	0.4	0.2	0.3	0.7
9/20	12	M	M	M	M	M	M
9/21	00	M	M	M	M	M	M
9/21	12	0.0	0.1	0.1	0.3	0.5	0.6
9/22	00	0.1	0.9	1.1	1.1	1.3	1.4
9/22	12	0.0	0.0	0.0	0.0	0.0	0.0
9/23	00	0.0	0.0	0.0	0.0	0.0	0.9
9/23	12	0.0	0.0	0.0	0.0	0.0	0.0
9/24	00	0.0	0.6	2.1	0.3	0.0	0.5
9/24	12	0.0	0.0	0.0	0.0	0.0	0.8
9/25	00	0.2	0.8	1.4	0.5	0.3	0.8
9/25	12	0.0	0.0	0.0	0.0	0.0	0.0
9/26	00	0.4	1.2	0.7	0.5	0.3	1.0
9/26	12	3.5	0.3	0.3	0.0	0.0	0.4
9/27	00	M	M	M	M	M	M
9/27	12	M	M	M	M	M	M
9/28	00	M	M	M	M	M	M
9/28	12	M	M	M	M	M	M

Table 4.12
Dynamic Seedability (Km): DDC
Test 2

Date 1987	Time (GMT)	Cloud radius (km) 0.5	1.0	1.5	2.0	3.0	10.0
9/9	00	0.5	0.2	0.0	0.3	0.3	0.4
9/9	12	0.5	0.9	0.5	0.3	0.3	0.0
9/10	00	0.7	0.5	0.0	0.3	0.0	0.4
9/10	12	2.2	0.0	0.3	0.0	0.0	0.5
9/11	00	3.9	0.0	0.0	0.0	0.3	0.4
9/11	12	1.3	2.2	0.3	0.0	0.0	0.4
9/12	00	M	M	M	M	M	M
9/12	12	M	M	M	M	M	M
9/13	00	M	M	M	M	M	M
9/13	12	M	M	M	M	M	M
9/14	00	M	M	M	M	M	M
9/14	12	M	M	M	M	M	M
9/15	00	0.9	1.4	0.5	0.3	0.0	0.8
9/15	12	0.4	0.4	0.2	0.2	0.3	0.7
9/16	00	0.7	1.4	0.2	0.2	0.3	0.6
9/16	12	M	M	M	M	M	M
9/17	00	0.0	0.0	0.0	0.0	0.0	0.5
9/17	12	0.6	0.6	0.5	0.3	0.3	0.4
9/18	00	0.5	0.2	0.2	0.0	0.0	0.4
9/18	12	0.0	0.0	0.0	0.0	0.0	0.0
9/19	00	0.0	0.1	0.2	0.2	0.3	3.6
9/19	12	1.2	0.9	0.4	0.2	0.3	0.4
9/20	00	0.5	0.4	0.4	0.5	0.3	0.7
9/20	12	M	M	M	M	M	M
9/21	00	M	M	M	M	M	M
9/21	12	0.1	0.3	0.3	0.5	0.6	1.0
9/22	00	0.6	1.1	1.3	1.3	1.5	1.6
9/22	12	0.0	0.0	0.0	0.0	0.0	0.0
9/23	00	0.0	0.0	0.2	0.3	5.0	1.2
9/23	12	0.0	0.0	0.0	0.0	0.0	0.0
9/24	00	0.0	0.8	2.4	0.3	0.4	0.5
9/24	12	0.0	0.0	0.0	0.0	0.0	0.8
9/25	00	0.2	0.8	1.6	0.5	0.6	0.8
9/25	12	0.0	0.0	0.0	0.0	0.0	0.0
9/26	00	0.4	1.2	0.7	0.5	0.3	1.0
9/26	12	3.2	0.0	0.3	0.0	0.0	0.4
9/27	00	M	M	M	M	M	M
9/27	12	M	M	M	M	M	M
9/28	00	M	M	M	M	M	M
9/28	12	M	M	M	M	M	M

major systems which produced severe thunderstorms. Those major systems would then be followed by 2 or 3 days of quiescence. The clouds encountered were probably different from the seasonal norms in that they grew with less explosiveness, grew in a deeper moisture field, and were more numerous than would be considered typical. The sampling period was representative of a relatively moist mid-spring period.

3.2 The Late Summer Period (September 9-28, 1987)

Summer in Oklahoma dies hard, but in normal times the oppressive heat of August gives way to a milder September. The jet stream typically begins to work its way southward during September, bringing with it an occasional surface frontal system. Rainfall in Oklahoma generally increases during the transition from summer to fall. Overall rainfall is not normally as great in the fall as during the spring storm season. Rainfall is sometimes increased dramatically by remnants of tropical disturbances, either from the Gulf of Mexico or from the Pacific Ocean via Mexico, which occasionally enter Oklahoma as they become incorporated into the mid-latitudinal weather systems.

Western portions of Oklahoma received near normal rainfall during the first half of the sampling period, but the last half was much wetter than normal. By the end of the month total precipitation in each of the six climate divisions in the western two-thirds of the State was 1 to 2 inches above the monthly norm (NOAA, 1987). Rainfall was reported somewhere in the experimental area on every day from the 6th through the 22nd. Significant storm systems moved across the State on the 9th, the 14th and 15th, the 18th and on the 27th of the month (OCS, 1987).

The Oklahoma City 1200 GMT rawinsonde observations are summarized in Table 3. The average soundings were somewhat cooler and more stable than normal, although individual events differed greatly from those means. Available moisture averaged less than normal. The events that produced the greater-than-average rainfall differed little from those typically observed in September. The frequency of rainfall events of interest to the sampling effort was greater than normal. Rain-producing storms that were sampled were probably similar in nature, though greater in number than would be expected in a typical September.

In summary, a few differences existed between historical means and the clouds sampled in Spring 1986 and Fall 1987. However, these differences were small and it is probable that observed microphysical characteristics and predicted dynamic seedabilities can be considered representative of an "average" spring and fall in Oklahoma.

4. SUMMARY

Oklahoma convective clouds, observed during the periods May 27 - June 9, 1986 and September 9-28, 1987, appear to be representative of clouds typically encountered during these seasonal time periods. The GPCM, initiated with soundings from Oklahoma City, Amarillo and Dodge City, indicated some opportunity for dynamic seedability on all days when convection was observed. Comparison of model runs simulating silver iodide seeding and dry ice seeding suggested a small advantage to the dry ice. Further studies will be done to check the model's realism by comparing predicted water content values to in-situ cloud microphysical measurements. Stratification of response variables to predicted natural cloud height will also be examined.

The microphysical mechanisms observed in Oklahoma convective clouds suggest that the initial development of precipitation occurs via collision-coalescence. This sequence is similar to that previously identified in the clouds from the Texas HIPLEX region. Additionally, the observed Oklahoma clouds contained supercooled water in amounts equal to or greater than the amounts reported for Texas HIPLEX clouds.

In view of the growing evidence suggesting increased rainfall in Texas HIPLEX as the result of a dynamic seeding approach, further investigation of this strategy for Oklahoma clouds seems warranted.

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Table 2. Comparison of May 27-June 9, 1986 OKC Rawinsonde Parameters to Historical Data (1976-1987)

	Historical		1986		
Parameter	mean	st. dev.	mean	min	max
Freezing level (km)	4.17	0.51	3.85	2.71	4.67
-5C isotherm (km)	4.92	0.50	4.79	3.56	5.63
-10C isotherm (km)	5.59	0.53	5.64	4.31	6.58
CCL Height (km)	2.56	1.03	3.51	3.17	4.17
CCL Temperature (°C)	10.71	5.30	12.96	5.66	17.89
Precip Water (cm)	2.84	0.73	3.28	1.84	3.95
Mixing Ratio (g/kg)	10.74	2.87	11.70	7.36	14.63
Lifted Index	0.40	5.20	0.40	-1.30	3.10
K-Index	24.50	11.90	32.50	27.30	36.50
SWEAT Index	219.70	124.30	173.40	104.60	232.00
Total Totals Index	46.30	8.50	46.40	42.90	50.50
T at 850 mb (°C)	16.70	5.20	13.20	6.60	17.40
TD at 850 mb (°C)	8.80	5.50	10.80	4.00	16.10
T-TD at 850 mb (°C)	8.00	5.30	2.40	0.70	7.00
T at 700 mb (°C)	7.40	3.70	4.20	-1.90	8.00
TD at 700 mb (°C)	-3.90	7.70	1.40	-5.50	5.40
T-TD at 700 mb (°C)	11.30	8.40	2.80	0.20	6.00
T at 500 mb (°C)	-10.50	2.30	-11.10	-18.90	-10.30

Table 3. Comparison of September 1987 OKC Rawinsonde Parameters to Historical Data (1976-1987)

	Historical		1987		
Parameter	mean	st. dev.	mean	min	max
Freezing level (km)	4.32	0.53	4.06	3.25	4.61
-5C isotherm (km)	5.16	0.41	4.99	4.28	5.35
-10C isotherm (km)	5.88	0.42	5.75	4.98	6.21
CCL Height (km)	2.97	1.13	4.47	1.81	5.86
CCL Temperature (°C)	9.88	6.46	6.34	-4.42	15.46
Precip Water (cm)	2.97	0.93	2.33	0.99	3.94
Mixing Ratio (g/kg)	10.54	3.18	8.85	4.82	13.18
Lifted Index	2.00	5.80	3.60	-3.80	11.30
K-Index	23.50	14.00	19.20	-10.10	37.50
SWEAT Index	191.70	92.70	145.30	21.30	266.60
Total Totals Index	43.60	8.20	42.60	23.00	53.80
T at 850 mb (°C)	16.90	4.20	15.80	8.60	19.80
TD at 850 mb (°C)	8.70	6.90	5.50	-15.80	14.20
T-TD at 850 mb (°C)	8.30	6.30	10.30	0.80	30.00
T at 700 mb (°C)	7.50	2.80	5.40	0.60	8.80
TD at 700 mb (°C)	-3.50	9.00	-7.30	-24.60	4.20
T-TD at 700 mb (°C)	11.00	9.00	12.70	1.20	30.00
T at 500 mb (°C)	-9.10	2.40	-10.70	-15.70	-7.70