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DEVELOPMENT OF PHYSICAL EVALUATION TECHNIQUES FOR THE NORTH DAKOTA CLOUD MODIFICATION PROJECT

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Abstract. This paper is a summary progress report on the development of physical evaluation techniques aimed at assessing the effects of ice phase cloud seeding on summertime convective storms in North Dakota. The use of digitized 5-cm radar data, rawinsonde data, and one-dimensional cloud model results are discussed in this techniques development effort. These preliminary results suggest favorable tendencies toward successful rainfall enhancement. Various biases are presented and suggestions for further research are made.

1. INTRODUCTION

As a part of research under a federal-state cooperative program being conducted through NOAA, the South Dakota School of Mines and Technology is working to develop physical evaluation techniques for operational weather modification projects directed toward summer convective clouds. The modification emphasis in the North Dakota Cloud Modification Project is two-fold: a) seeding moderate-sized convective elements for rain enhancement; and b) seeding strong convection for reducing hail damage. To date, this evaluation research has been limited to a search for ways to estimate seeding effects on rainfall. The primary purpose of this paper is to report our progress toward this goal.

Specific objectives of the research efforts include:

a) Continued development of climatological information to assist in identifying the potential for weather modification activities.

b) Assessment of the effectiveness of the field operations in accomplishing the intended cloud seeding.

c) Assessment of the appropriateness of the dynamic seeding hypothesis using rawinsonde data processed through a numerical cloud model and radar data.

d) Development of evaluation techniques using digital weather radar data as the primary basis.

2. DATA COLLECTION AND PROCESSING

2.1 Radar Data

During the summers of 1980 and 1981, digital 5-cm weather radar data were recorded in conjunction with the North Dakota Cloud Modification Project (NDCMP) at two sites - Bowman and Parshall (Fig. 1). The radars used were the 5.4-cm sets with 2° antenna beamwidths that are also used to direct the NDCMP operations. A volume scan up to 15° elevation was made each 10 to 12 min, using 1° elevation increments. The data were recorded on magnetic tape for later reduction and analysis.

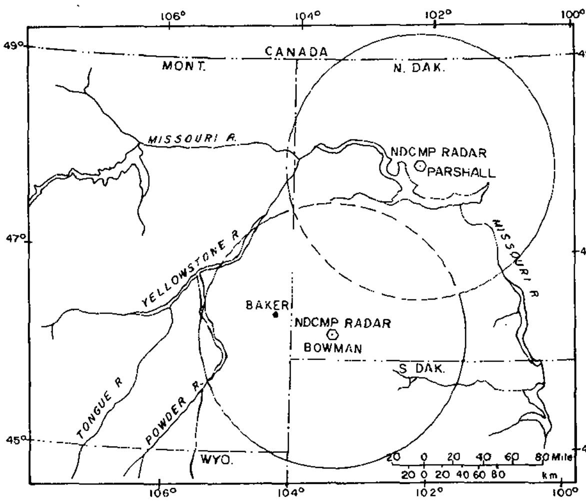

Fig. 1: Map showing the location of the two radar sites used to collect data for the NDCMP 1980 and 1981. Circles indicate 150 km range. The HIPLEX rawinsonde data were collected at Baker, MT, about 65 km west of Bowman.

Computer-generated map printouts of Z values were used to identify cell clusters. Tracks of the cloud seeding aircraft were plotted on the printouts to help determine which clusters were seeded and which were not seeded. Overlays of the target district boundaries were used to identify in-target versus out-of-target clusters. Maximum echo heights, maximum reflectivity factors, rain volumes, and other characteristics were then computed for each cluster.

Usable data were recorded from the Bowman radar on 7 days in 1980 and 51 days in 1981. The Parshall radar provided usable data for 18 days in 1980. The 1980 data were analyzed in an exploratory manner (Smith et al., 1982) but had only a small number (8) of seeded echo clusters. Calibration problems occurred with the Parshall radar in 1981, so most of the analysis presented here will be based on the Bowman 1981 data. In that data set, 583 clusters were identified from 32 days.

2.2 Rawinsonde Data

Rawinsonde data from Baker, Montana, were available from the Bureau of Reclamation's HIPLEX-1 project (Silverman, 1980). Usually, 1500 GMT soundings were made 6 days per week, with other runs as needed based on convective activity in eastern Montana.

These rawinsonde data were used as input to a one-dimensional, steady-state numerical cloud model (Hirsch, 1971). Seeded and non-seeded model runs were compared to help assess the potential for dynamic seedability in the NDCMP.

2.3 Aircraft Data

Seeding aircraft crews maintained records of their flight paths, seeding rates and times; they also recorded periodic updraft speed measurements and estimates of cloud base height and temperature. The University of North Dakota provided a Cheyenne aircraft in 1981 equipped to measure cloud liquid water concentrations and ice particle concentrations. It was also equipped for cloud seeding.

3. ANALYSIS AND DISCUSSION

3.1 Radar Climatological Information

The radar printouts were examined to identify the time and location of initial radar echoes from cloud clusters. No obvious prevalent region of echo generation was revealed. A peak in convective activity was found in the late afternoon (2100-0000 GMT), and a minimum in the early morning hours (1200-1500 GMT), as shown in Fig. 2.

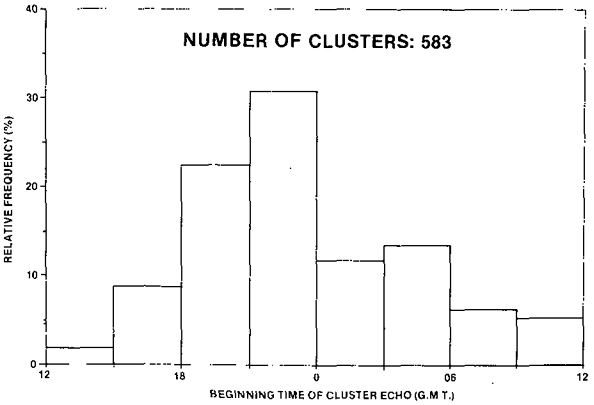

Fig. 2: Relative frequency distribution of the beginning times of cluster echoes for June-August 1981, Bowman data.

Frequency distributions of echo durations for seeded and non-seeded cloud clusters are compared in Fig. 3. It is evident that the seeded clusters had longer lifetimes when compared to the non-seeded clusters. This difference is primarily attributed to the priority given to the seeding of strong echo clusters for hail suppression in the NDCMP.

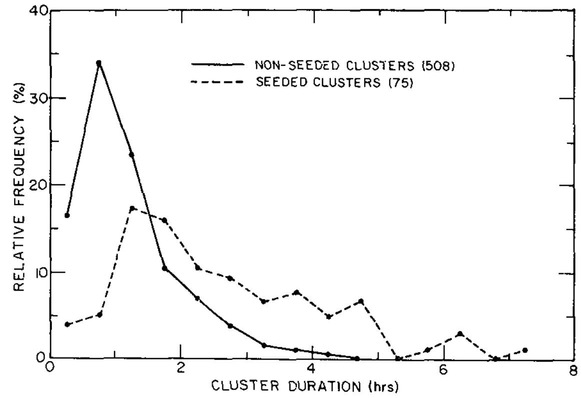

Fig. 3: Frequency distributions of seeded and non-seeded echo durations; Bowman 1981 data.

3.2 Assessment of Operational Effectiveness

Some of the cloud seeding operations were examined to assess the effectiveness in responding to opportunities and in following the operations manual procedures. Examination of cloud seeding records and aircraft flight times showed that the modification activities followed well the frequency of observed radar echoes -- an expected observation.

The response to the first priority of seeding -- hail suppression -- was found to be quite good. At times rain enhancement opportunities were passed by during hail suppression operations. This procedure follows the desires of the local ranchers and farmers who request that hail suppression attempts take priority over rainfall seeding.

The usual seeding was conducted with one Lohse-type generator or one or two flares used in a cloud for rain enhancement seeding. For hail suppression, two generators were normally burned continuously in conjunction with periodic flare ignition. The periodicity was based primarily on the storms' intensity, the availability of flares, and the desired seeding rate. More detailed assessment of the NDCMP operations may be found in reports by Smith et al. (1981, 1982).

3.3 Cloud Model Studies and Estimation of Dynamic Seedability

The Baker, Montana, rawinsonde data were used as input to the Hirsch (1971) one-dimensional, steady-state cloud model. The model simulates cloud response to ice phase seeding by invoking earlier freezing of the liquid water available as compared to unseeded model clouds. The seeded clouds experience "exponential" freezing between -5 and -25C and the non-seeded clouds between -20 and -40C.

The response to seeding is estimated by determining the increased cloud growth and/or increased vigor of the updraft predicted by the model. Both increased cloud top height (ΔH)* and

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*Here ΔH is defined as the difference between seeded and non-seeded cloud top height predictions, and ΔW is the difference in maximum updraft speeds.

increased updraft speed (ΔW)* in seeded clouds are interpreted to be dynamic seeding responses. Examination of the model output for 39 days in 1981 showed that 36 of the days gave some prediction of increased cloud growth and 33 days showed increases in updraft speeds. Figure 4 shows the frequency distribution of the maximum ΔH values.

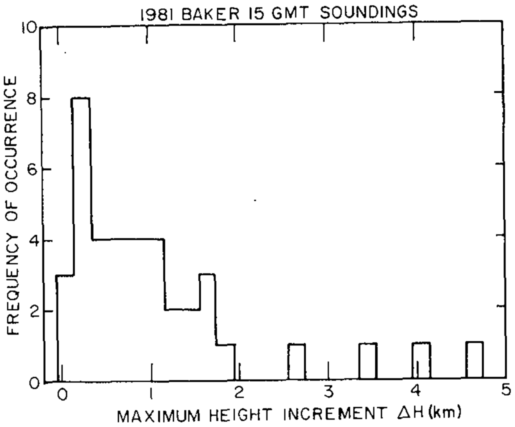

Fig. 4: Frequency distribution of the daily maximum cloud growth due to seeding for any initial updraft size according to the model output.

In the North Dakota Pilot Project (NDPP) and the Rapid Project, cloud model ΔH and ΔW values were used for stratification to assist in identifying sets of convective days which appeared to show favorable rainfall tendencies when comparing seeded and unseeded samples (Dennis et al., 1975; Chang, 1976). The distribution of ΔH values (Fig. 4) is similar to that found in the NDPP, which suggests a reasonable frequency of opportunities for dynamic seeding in the NDCMP. On the other hand, the growth in excess of 2 km commonly found in the FACE area (Woodley et al., 1982) is rare in North Dakota. [That difference is due in part to differences in the way the respective models simulate glaciation.]

3.4 Radar Data Analysis

3.4.1 Echo height vs. rain volume. Figure 5 shows a plot of cell cluster maximum echo height (MEH) values versus total storm radar estimated rain volume (RERV) values. This graph verifies the expectation of increased rainfall production by taller storms, which is a basic tenet of the dynamic seeding hypothesis. This result agrees well with a previous northern High Plains study (Dennis et al., 1974). Ewald (1983) suggests that using both echo height and echo duration as the predictor variables, in place of the single-valued MEH, may improve the relationship.

The preponderance of seeded echoes in the upper portion of the graph is attributed to the selection bias. That is, the project meteorologists selected tall and intense hail-threat cloud clusters over any others for treatment. This follows the procedures set down in the NDCMP operations manual (North Dakota Weather Modification Board, 1980). However, most of the points for seeded echoes lie above the regression line, which may be some indication of an increase in rainfall due to the seeding.

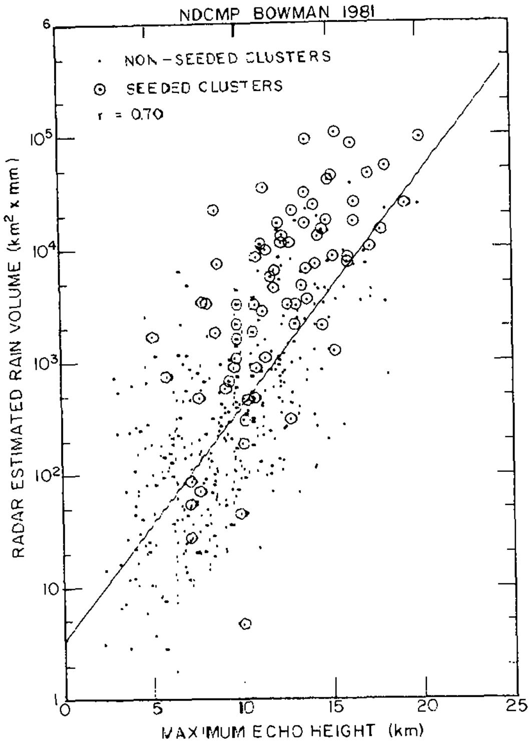

Fig. 5: Plot of radar-estimated rain volume vs. maximum echo height for 75 seeded clusters and 508 non-seeded clusters. Only half of the non-seeded data points are plotted on the graph. The mean maximum echo height is 9.9 km; it is 12.1 km for the seeded sample and 9.5 km for the non-seeded clusters.

3.4.2 Rain volume vs. area-time integral relationships. Doneaud et al. (1981) developed a method to estimate rain volumes using an area-time integral (ATI). In comparisons between average radar echo areas and radar-estimated rainfall using Project Cloud Catcher data, Dennis et al. (1974) used cube-root transformations of the variables and found a correlation $r = 0.98$. The correlation between the ATI and radar-estimated rain volume (RERV) using the 1981 NDCMP data in a log-log plot is also 0.98 (Smith et al., 1983). The logarithmic standard error of estimate is about 0.16, suggesting +45% to -31%, or one sigma, accuracy of the rain volume estimates.

Figure 6 shows a plot of a sample of the 1981 NDCMP data from Bowman. The selection bias is again evident, with points for seeded clusters concentrated toward the upper part of the graph. These results indicate another way in which seeding could enhance rainfall through dynamic effects. If the seeding could increase the echo area coverage, the echo duration, or both, the strong rain volume-ATI correlation suggests that increased rainfall would result.

3.4.3 Further searches for seeding effects. A more extended analysis for seeding effects is based on comparisons of storms in two classifications: a) seeded vs. non-seeded; and b) in-target vs. out-of-target.

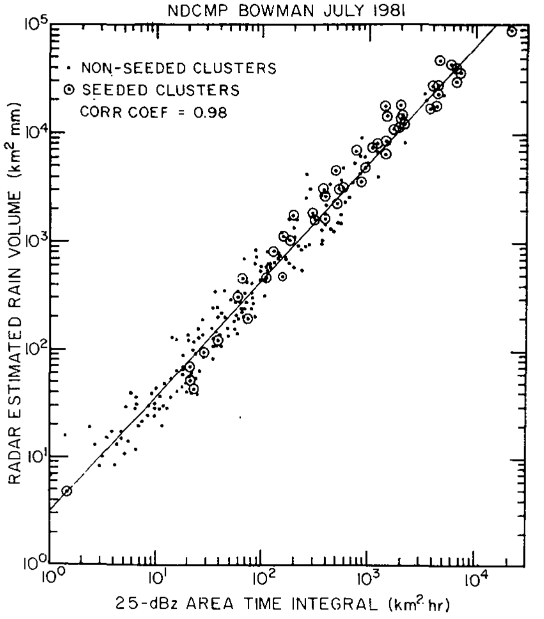

Fig. 6: Scatter plot of the echo cluster rain volumes vs. the 25-dBz area-time integrals, for the July 1981 Bowman radar data. Points are shown for all the seeded clusters, but only every other non-seeded cluster.

Seventy-five seeded clusters were identified in the 1981 data set and comparisons between seeded and non-seeded clusters were made. Figure 7 shows the relative frequencies of radar estimated rain volumes for seeded and non-seeded clusters. A great difference between the two samples is apparent upon examination of the diagram. However, as discussed previously, this difference is attributed primarily to the selection made by the NDCMP project meteorologists responsible for directing the seeding operations. Because of that, most strong or potentially strong storms should fall in the "seeded" category. Examination of case studies helps to confirm the presence of this "selection bias." Any seeded versus non-seeded comparisons, therefore, must take into account the initial storm intensity (or potential). The only conclusion we can glean from Fig. 7 is that NDCMP operations are, indeed, carried out in the manner prescribed in the operations manual, which gives first priority to seeding the strongest storms for hail suppression.

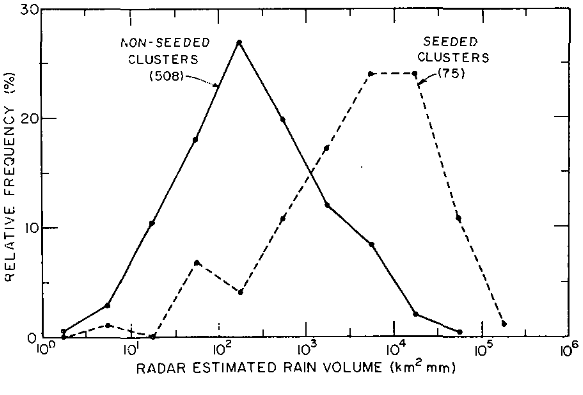

Fig. 7: Comparison of frequency distributions of the radar-estimated rain volumes for seeded and non-seeded echo clusters, for the 1981 Bowman data.

For a second comparison, the clusters were classified in the in-target category or the out-of-target category. In this data classification, we initially assume that all in-target storms are subject to appropriate treatment in this operational project. If this assumption were valid, we would have a reasonable data set on which to apply target-control statistical comparisons (assuming, of course, that seeding in the target would not, or did not, influence rain production outside the target area). If the assumption is not valid, the main effect will be to dilute the apparent effects of seeding in any in-vs.-out-of-target comparison.

A relative frequency diagram (Fig. 8) compares the radar estimated rain volumes (RERV) of the in-target versus the out-of-target clusters. Examination of Fig. 8 reveals that this comparison still favors in-target clusters over out-of-target clusters in the amount of radar estimated rain. Indeed, a simple non-parametric rank test shows that the probability of the null hypothesis (H_0: There exists no difference in the relative rain amounts for in-target and out-of-target clusters) being valid is less than 0.001. Therefore, we can accept the alternative hypothesis (H_a: The in-target clusters are stochastically larger rain producers than the out-of-target clusters).

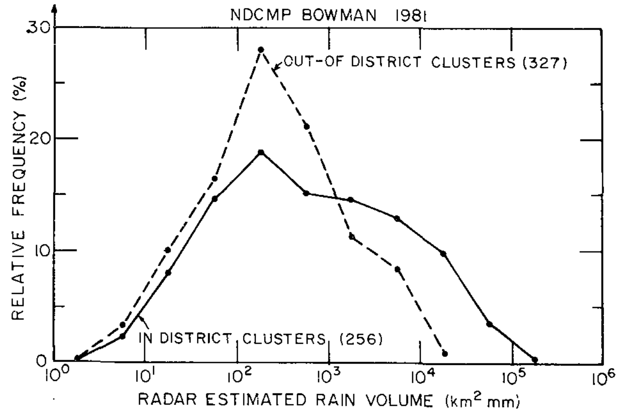

Fig. 8: Comparison of frequency distributions of radar-estimated rain volumes for in-district and out-of-district echo clusters, for the 1981 Bowman data.

There exists some radar beam spreading with range which may influence these estimates of rain volumes. Echoes for the seeded and in-target categories are, on the average, closer to the radar than those for the non-seeded and out-of-target categories. A decrease of observed maximum radar reflectivity factors is noted with increasing range, and a second contributing factor is the decrease in radar sensitivity with range. Nevertheless, the second analysis scheme comparing in-target with out-of-target echoes shows more promise than the first technique in helping to detect potential cloud seeding effects on an operational project.

3.4.4 First echo study. Six days of 1981 data were selected for examination for first radar echoes. Although several early radar echoes were identified, difficulty in identifying first echoes was encountered due to the 10 to 12-min scan interval. One day's data (14 Jun 81) with 15 first echoes showed an average height of 3.5 km MSL (ranging from 2.3 to 4.6 km) at an average temperature of -4C. This was a cold, wet, early-season day and probably not representative of typical NDCMP conditions. The first-echo times were furnished to the University of North Dakota to be used in conjunction with their cloud physics aircraft data.

The data-gathering procedure was significantly improved during 1982 to reduce the scan interval to 6 minutes or less. Plans call for comparisons between temperatures (and heights) of first echoes and seeding treatment. Other northern High Plains studies have shown that first radar echoes appear at higher temperatures in clouds seeded at cloud base, as compared to natural clouds (Dennis and Koscielski, 1972; Koscielski and Dennis, 1976).

4. SUMMARY

The primary goal of this study is to develop evaluation techniques that can be applied to operational weather modification projects. The study includes the development of climatological information aimed at assessing the potential for seeding opportunities; application of a steady-state, one-dimensional, numerical cloud model to regional soundings to assist in predicting dynamic seeding potential; and assessing the operational effectiveness of the actual seeding operations. We have illustrated ways in which digital weather radar data can be used to assist in the overall evaluation of operational projects. These include comparisons of characteristics of cell clusters in and out of the target area and of seeded versus non-seeded cluster characteristics.

To date, the technique development has been limited to evaluation of seeding effects on rainfall. These studies have been exploratory in nature. Various bias effects, such as the NDCMP seeding selection criteria and the variable distance of the clusters from the radar, make it difficult to draw definite conclusions. However, the preliminary results summarized here show favorable tendencies in the radar estimated rainfall comparisons made. Monte Carlo techniques may be used in attempts to overcome some of the bias effects identified in the seed/non-seed comparisons presented herein.

The development of evaluation techniques under the federal-state cooperative program is scheduled to continue. Increased emphasis is being placed on microphysical investigations, including studies of first echoes and aircraft observations. For future seasons, the suggestion of Changnon et al. (1979) to randomize among different seeding techniques during operational projects is being considered. Attempts to develop techniques to evaluate seeding effects on hail using the radar data should also be pursued.

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