EVALUATION OF THE SOUTH DAKOTA WEATHER MODIFICATION PROGRAM

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ABSTRACT

Evaluation of the past four years of the state sponsored South Dakota weather modification program was performed through the use of computer gridded monthly rainfall data, daily precipitation data, and crop-hail insurance data. Results indicate that over the four years of seeding the seeded counties received, overall, 6.7% more rainfall than would have been expected based on unseeded county precipitation. Rank testing with 31 years of gridded historical data give a significance level of 1.5% to the results. Analysis of daily rainfall data shows both a 5.4% increase in rainfall frequency and a 2.8% increase in rainfall intensity in the seeded counties. In addition to the rainfall results, crop-hail insurance data shows that the seeded counties received less hail damage than the unseeded counties with significance at the 3.4% level. It is postulated that the high significance levels of the findings are a result of the great number of clouds treated and the large size of the regions participating in the program.

I BACKGROUND AND INTRODUCTION

Efforts toward development of weather modification in the State of South Dakota resulted in the initiation of a working, state supported program during the summer of 1972. The program was carried out cooperatively between the state and voluntarily participating counties during the summers of 1972, 1973, 1974 and 1975. The primary goal of the program was to provide an economic benefit to the people of the state by applying weather modification technology to augment rainfall and suppress hail during the May-August crop growing season. This strong emphasis on the production of an economic benefit, and the acceptance of preceding research results as strongly favoring possible benefit from an applied program, led to the formation of an operational, non-randomized program in the state. As such, emphasis was directed to application, rather than evaluation, of the technology.

The South Dakota Division of Weather Modification early recognized its responsibility to assess its ability to accomplish the program objectives. The non-randomized nature of the program, however, precluded application of statistical techniques similar to those used in much of the research behind its foundation. Evaluation attempts thus focused on comparison of rainfall or hail damage in participating counties (target area) and non-participating counties (control area) in light of their historical climatic relationships.

The first evaluation report of the program (Williams et al., 1973) described a relatively small scale target/control analysis of rainfall centered about the Gregory County area of south central South Dakota. The results suggested a 21% areal rainfall increase in light of the historical target/control relationship. A larger scale target/control evaluation of crop-hail insurance data indicated a 30% hail suppression effect during the first year of the program.

The 1973 operational season ushered in an "Area-of-Effect" evaluation technique. Essentially, the area-of-effect is a plume shaped target area constructed downwind (on the basis of winds aloft) of a seeding material release point. The area-of-effect serves as a small scale target area; a control area of similar size is constructed upwind according to an objective procedure. Fourty-four test cases in 1973 indicated an average rainfall increase of 18-22% from individual showers or shower systems (Donnan, 1973).

Evaluations were expanded following the 1974 season to include a new technique: the South Dakota Gridpoint Analysis. The gridpoint analysis evolved by overlaying a rectangular grid field on hand drawn percent-of-normal precipitation maps of South Dakota for the 1972, 1973, and 1974 operational seasons. Percent-of-normal rainfall at each grid point was tediously interpolated (calibrated eyeball technique) from the percent of normal countours. Seed/no-seed county target/control analyses of the gridded data indicated rainfall increases of 10.5%, 4.8%, and 8.5% in the 1972, 1973, and 1974 target counties respectively (Schock, et al., 1975). Expanded target/control analyses of ungridded monthly rainfall data for 1972, 1973, and 1974 pointed to an overall seasonal rainfall increase of 7% in the target areas. A refined area-of-effect analysis for 1974 suggested an average 35% rainfall increase from 98 test case showers. Target/control comparisons of crop-hail insurance data indicated damage reductions of about 55%, 21%, and 18% in 1972, 1973, and 1974 respectively.

At this point it appears that seeding increases rainfall from individual showers by about 20-30% with a net precipitation increase of 7-10% over a large area. Hail suppression seeding seems to reduce crop-hail damage by about 20-50%. The area-of-effect analysis however has been subjected to legitimate criticism on the basis that it may contain an unavoidable bias due to the seeding selection process.

The significance of the results could not be tested using these approaches. It was apparent to the division staff that more meaningful results could only be obtained by detailed analysis of long term precipitation records over a large area. To this end, the process of compiling NWS precipitation records for South Dakota and the six surrounding states on magnetic tape (from National Climatic Center master tapes) was accelerated. Data compilation was completed in the fall of 1975 and computer analysis began immediately. The Institute of Atmospheric Sciences assumed the task of studying the hail suppression efforts (Miller et al., 1975).

II ANALYSIS OF GRIDDED MONTHLY RAINFALL DATA

A. Data

The objective was to use all available National Weather Service 1941-1975 monthly precipitation data for South Dakota and bordering stations in the six surrounding states. Figure 1 shows the nearly 300 NWS stations which have reported, at one time or another, since 1941. Two important problems may arise when working with masses of precipitation data on a state-wide scale:

1. The station periods of record vary, causing seasonal averages from one year to another to include some variance due to shifts in reporting points.

2. The stations are not evenly distributed, causing problems in large area averaging.

A common means of reducing these problems is to select for analysis only those stations having continuous periods of record and representing a relatively uniform geographical distribution. Appropriate estimations may be used to fill in short record gaps. The price paid is a loss of valuable data and perhaps criticism for employing only "selected" stations in the analysis.

Computerized gridding permits all data to be used in the analysis without concern for moderate shifts in station density or periods of record. The gridding interpolation process is totally objective throughout the grid field.

B. The Grid Analysis Program

The core of the computer program came from "An Operationally Oriented Small Scale 500 mb Analysis Program" by Glahn and Hollenbaugh (1969), modified by Dr. Dennis Baker at the University of Michigan. Further extensive revision was required to adapt the program to the peculiarities of precipitation statistics.

The analysis area is covered by a 43 x 27 point grid field with gridpoints spaced 10 statute miles (scale) apart. The grid field completely covers South Dakota and extends about 20 miles into surrounding states as shown in Figure 2. The 20 mile extension is necessary to push boundary problems outside the state. Each reporting station must be located within the grid field and its location information paired with all its precipitation records.

Initially a "first guess" grid field is generated from the raw data. This is accomplished by each gridpoint taking on the precipitation value of its nearest reporting station. Each first guess grid value is then smoothed as a function of its initial value, its four surrounding neighbors, and a smoothing coefficient. The smoothed first guess grid field then enters the basic analysis routine.

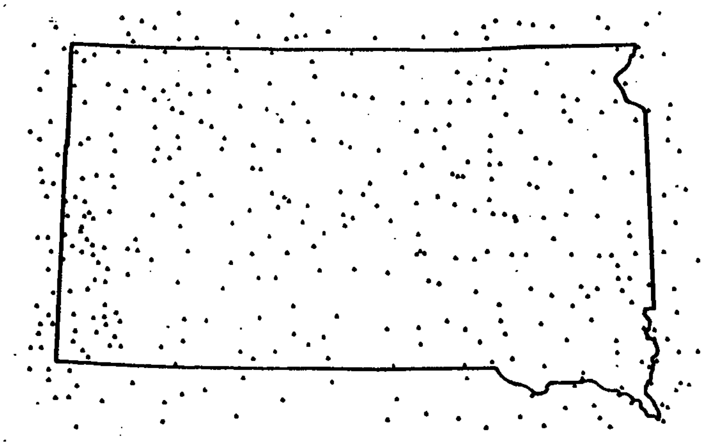


Figure 1. NWS Raingage Stations

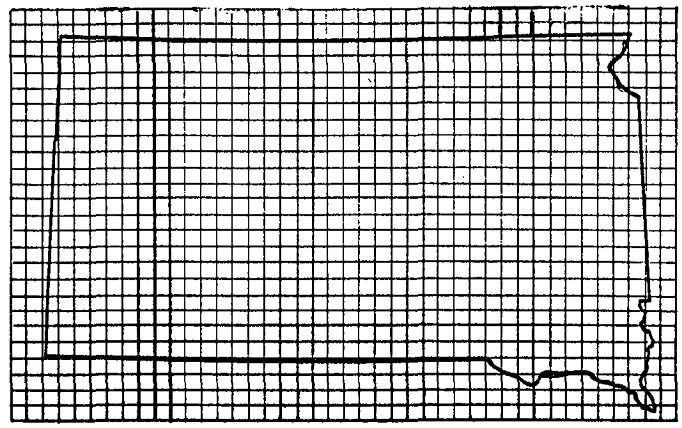


Figure 2. South Dakota Grid Field

A biquadratic interpolation from the first guess grid field to each observing station is performed. The difference between the interpolated and actual value at each station, termed the correction factor, is in fact a measure of how well the grid field conforms to the raw data. Employing a distance weighting function, the next step of the program averages all the correction factors within a 30 mile range of each gridpoint. The accuracy of the first guess grid field is then improved as each gridpoint's value is adjusted by its correction factor average. With the completion of this step, the cycle repeats, this time with the newly adjusted grid field replacing the first guess grid field.

The cycle is run three times, reducing the mean grid field error to .04". In the strictest sense this value is not an error; it is a measure of how much the field deviates from a biquadratic interpolation scheme.

C. <u>Results</u>

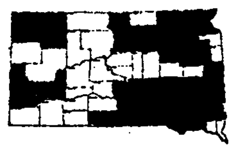
The gridpoint analysis was performed for each month, May through August, for the years, 1941-1975. The data base included every official NWS cooperative climatic station monthly precipitation record for South Dakota and bordering portions of the six surrounding states. More than 29,000 monthly precipitation records were used to produce 162,540 gridded precipitation values. The gridded values served as input to a target/control analysis.

The target/control analysis compares the mean seasonal (May-August) rainfall in the participating counties (target) to the mean seasonal rainfall in the non-participating counties (control). Since counties participate on a voluntary basis, we have no control over the selection of target and control counties. The county commissions make this decision.

The target and control means were calculated by taking the average of all the gridpoint seasonal precipitation totals in each of the two regions. Anticipating a natural climatic difference between target and control, the analysis was performed on the historical non-seeded years, 1941-1971, in addition to the four years of the seeding program, 1972-1975.

Table 1 summarizes the results. Ratios of target to control rainfall were computed for each year 1941-1971, based on each of the four operational seeding year configurations. The maps heading each column show the actual breakdown between participating and non-participating counties. Natural climatic target/control ratios were computed by averaging the 1941-1971 historical ratios corresponding to each configuration. Note that in all four target/control configurations, the target historically received slightly more precipitation than the control. The climatic advantage the participating counties enjoy is likely due to their concentration in the eastern and Black Hills portions of the state where summertime precipitation is naturally greater.

TABLE 1
Seed/no seed county seasonal rainfall ratios and seed years rank statistics

County Configurations Seeded Unseeded					
Average Rainfall Season (May-Aug)		1972 Configuration Seed/no seed Ratio	1973 Configuration Seed/no seed Ratio	1974 Configuration Seed/no seed Ratio	1975 Configuration Seed/no seed Ratio
U	1941	0.930	0.971	0.972	0.975
N	1942	0.987	1.076	1.096	1.031
S	1943	0.986	1.108	1.180	1.136
E	1944	1.204	1.197	1.239	1.219
E	1945	1.085	1.162	1.180	1.166
D	1946	1.010	0.970	0.944	0.961
E	1947	1.131	1.023	1.014	1.032
D	1948	1.048	1.069	1.051	1.047
	1949	0.994	1.194	1.231	1.131
Y	1950	1.067	1.194	1.234	1.200
E	1951	1.093	1.108	1.153	1.149
A	1952	1.123	1.036	1.025	1.068
R	1953	0.939	1.124	1.187	1.177
S	1954	1.195	1.154	1.177	1.182
	1955	0.928	1.053	1.059	1.067
	1956	0.922	1.101	1.119	1.124
	1957	0.993	1.042	1.028	1.007
	1958	1.025	0.997	0.988	0.991
	1959	1.130	1.118	1.153	1.149
	1960	1.071	1.189	1.213	1.187
	1961	1.104	1.193	1.189	1.178
	1962	1.157	1.170	1.177	1.176
	1963	0.973	1.158	1.147	1.094
	1964	1.004	1.042	1.027	1.010
	1965	1.159	1.101	1.100	1.086
	1966	0.927	1.106	1.178	1.176
	1967	1.061	0.998	0.974	1.022
	1968	0.969	0.963	0.958	0.981
	1969	1.048	1.118	1.157	1.151
	1970	1.041	1.075	1.120	1.106
	1971	0.991	1.182	1.206	1.167
Natural Climatic Ratios (1941-71 Mean)		1.042	1.097	1.112	1.101
Seed Year Ratios		1.157 (1972)	1.139 (1973)	1.208 (1974)	1.1400 (1975)
Seed Year Ranks		4th of 32 (1972)	11th of 32 (1973)	5th of 32 (1974)	14th of 32 (1975)

It should be noted that statewide seasonal (May-August) precipitation was 118% of normal (1941-1970) during 1972, 69% during 1973, 72% during 1974, and 86% during 1975. However, the seed counties fared better overall percent-of-normal wise than did the no-seed counties each year of the program.

In each of the four program years, the seed year target/control ratio exceeded the natural climatic ratio. In other words, the participating counties overall received more rainfall than would have been expected on the basis of non-participating county rainfall. The suggested amount of additional rainfall, found from the ratio of the seed year target/control ratio to the natural climatic ratio is itemized below -

YEAR	AVERAGE RAIN INCREASE
1972	11.0%
1973	3.8%
1974	8.6%
1975	3.5%
1972-1975	6.7%

To determine the significance of the results, a rank test was applied to the data appearing in Table 1. Each seed year target/control ratio was ranked with the 31 historical ratios appearing in the same column. The seed year ranks appear in the last row of Table 1. Note that all four years of the weather modification program rank in the upper half. The probability of one year ranking 4th or better, one year 5th or better, one year 11th or better and one year 14th or better, by chance without preference to order of occurrence, is only 1.47%.*

One of the factors adding to the high degree of significance found in the South Dakota results is the very strong correlation between target and control rainfall during the 31 historical years. Linear regression analysis yields correlation coefficients between target and control rainfall in each of the four configurations exceeding .91, which for 31 pairs indicates a less than 1% probability that the correlation was due to random sampling fluctuations. The use of control rainfall as a predictor of target rainfall

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* The solution to this probability problem, although simple at first glance, is actually quite complex due to the difficulty of eliminating redundant permutations. The probability equation derived by Dr. J. N. Srivastava of the Colorado State University Statistics Department is:

$$P = 24abcd + 12abc^2 + 12ab^2d + 12\,ab^2c + 4ab^3 + 12a^2cd + 6a^2c^2 + 12a^2bd + 12a^2bc + 6a^2b^2 + 4a^3d + 4a^3c + 4a^3b + a^4$$

where a = 4/32, b = 1/32, c = 6/32, d = 3/32 and P is the probability of equalling or bettering the ranks by chance.

is well justified. The most probable explanations for this high degree of correlation lie in the very large areas of both target and control (each in excess of 15,000 square miles) and their similarity of summertime precipitation regimes.

III ANALYSIS OF DAILY RAINFALL DATA

South Dakota daily rainfall records were studied to determine how the seed year rainfall might have been affected through changes in frequency of rainfall events, magnitude of rainfall events, or both. For simplicity, only counties with a consistent history of participation or non-participation in the first three program years were included in the daily rainfall study.

Twenty-six National Weather Service (NWS) rainfall reporting stations in South Dakota were designated "seed" stations. They fall within the "always seeded" counties in Figure 3. All of these counties were seeded each year, 1972-1974. Twenty-four NWS stations were designated "no-seed" stations. They fall within the "always unseeded" counties. These counties were unseeded each year, 1972-1974. The other South Dakota stations were not used in the analysis because their daily rainfall records do not cover the 1941-1974 period, they fall in counties which were "in and out" of the seeding program, or their 1941-1974 records are not available in the Division of Weather Modification tape library. Data for 1975 was not available on magnetic tape and therefore not included in this study.

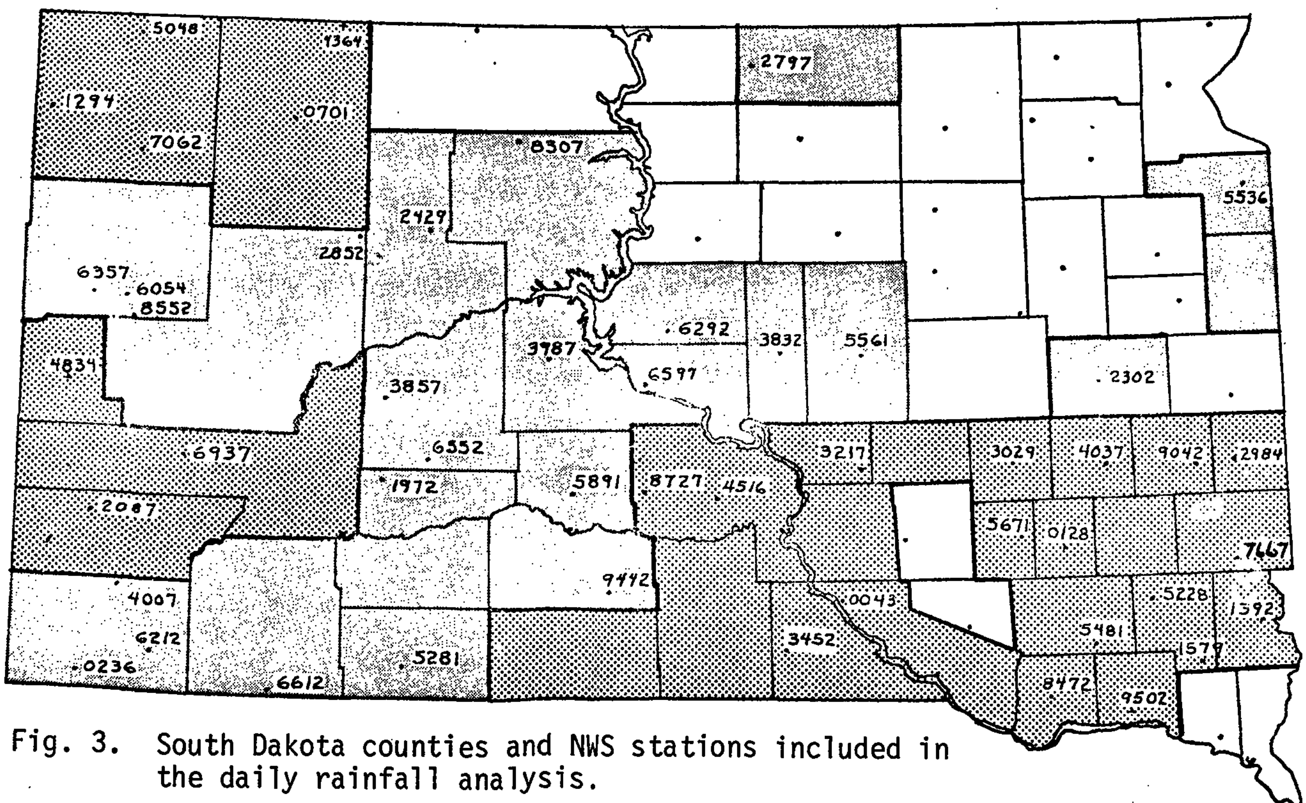

Fig. 3. South Dakota counties and NWS stations included in the daily rainfall analysis.

= Seed counties = No-seed counties

More than 197,000 station records were computer processed to obtain the fraction of station-days (a station-day is a 24 hour day at one station) during which rain fell (expressed as ratios F_S and F_{NS} in Table 2) and the mean rainfall per station-day rain event (I_S and I_{NS}). The ratios F_S/F_{NS} and I_S/I_{NS} describe the seed/no-seed county rainfall frequency and intensity respectively. The greater the ratio, the greater the seed counties beat the no-seed counties in terms of rainfall frequency or intensity. A ratio less than one favors the no-seed counties.

From the 1941-1970 historical record it is evident that the seed counties normally experience slightly more frequent rainfall events (9%) and slightly more intense rainfall events (5%) than do the no-seed counties.

TABLE 2

Rainfall frequency and intensity comparisons among seeded and unseeded counties during historical years 1941-1970 and seeded years 1972-1974

Block	Historical Years	SEEDED COUNTIES Frequency (F_S)	SEEDED COUNTIES Intensity (I_S)	UNSEEDED COUNTIES Frequency (F_{NS})	UNSEEDED COUNTIES Intensity (I_{NS})	SEEDED VS UNSEEDED RATIOS Frequency Ratio (F_S/F_{NS})	SEEDED VS UNSEEDED RATIOS Intensity Ratios (I_S/I_{NS})
1	1941-43	0.2989	0.3501	0.2762	0.3578	1.0822	0.9785
2	1944-46	0.3234	0.3743	0.2917	0.3263	1.1087	1.1471
3	1947-49	0.2713	0.3191	0.2498	0.3070	1.0861	1.0394
4	1950-52	0.3169	0.3087	0.2780	0.2804	1.1399	1.1009
5	1953-55	0.2773	0.3347	0.2584	0.3125	1.0577	1.0710
6	1956-58	0.3016	0.3050	0.3041	0.2953	0.9918	1.0328
7	1959-61	0.2803	0.3346	0.2278	0.3155	1.2305	1.0605
8	1962-64	0.3220	0.3552	0.3100	0.3286	1.0387	1.0809
9	1965-67	0.2963	0.3257	0.2755	0.3167	1.0755	1.0284
10	1968-70	0.2709	0.3235	0.2440	0.3318	1.1102	0.9750
					Historical Mean	1.0921	1.0515
	Seeded Years						
11	1972-74	0.2710	0.3215	0.2354	0.2974	1.1512	1.0810
					1972-74 Rank	2nd of 11	3rd of 11

Subscript 's' denotes seeded counties; subscript 'NS' denotes unseeded counties.

F = (actual station-day rainfall events) ÷ (number of possible station-day rainfall events)

I = mean rainfall (inches) per rainfall event

Yet, in the 1972-1974 seed years, the seed versus no-seed county differences were even more dramatic. The seeded counties experienced 15% more frequent rainfall events and 8% more rainfall per event than did the no-seed counties. When allowance is made for the climatic advantage the seed counties enjoy, the seed counties still come out ahead in the seed years...5.4% more frequent rainfall events and 2.8% more rainfall per event.

A rank test was employed to determine the probability of these being "chance" results. Table 2 shows that the seed years ranked second out of the 11 three year blocks of frequency ratios (1.1512 in 1972-1974 was beaten by 1.2305 in 1959-1961). The probability of this occurring by chance is

2/11 or 18%. The seed years ranked third out of the 11 three year blocks of intensity ratios. The probability of this occurring by chance is 27%. Though these are not statistically significant results, they suggest that increases in frequency and intensity of rainfall events play a role in the overall effect of cloud seeding on precipitation over a large area.

The combined effect of increased rainfall frequency (5.4%) and increased rainfall intensity (2.8%) suggests an overall increase in precipitation of about 8% over the target area. This is in line with the findings of the gridded monthly rainfall analysis.

IV ANALYSIS OF CROP-HAIL INSURANCE DATA

The hail suppression portion of the evaluation was performed by the Institute of Atmospheric Sciences (IAS), South Dakota School of Mines and Technology (Miller, et al., 1975). Their study used crop-hail insurance data compiled by the Crop Hail Insurance Actuarial Association (CHIAA) of Chicago. Approximately 5% of the crops in South Dakota are insured for hail damage, and most of the insurance is by firms participating in CHIAA.

The crop-hail insurance variable selected for use in this study was the loss-cost value. This is the ratio of damage paid out to the liability insured, which eliminates problems relating to changes in the amount of crop insured from year to year, the long term inflationary trend, and fluctuations in crop prices.

The analysis of the crop-hail insurance data was performed in a manner similar to the monthly rainfall analysis, the only exception being the direct use of the data without gridding. Target-control ratios of loss-cost values were calculated for 25 non-seeded historical years in addition to the seeded years 1972-1974. Data for 1975 was not available at the time of the study. As in the rainfall analysis, the historical year target and control areas were prescribed by the 1972, 1973 and 1974 seed/no seed county configurations. Results of the rank test are as follows:

a) 1972 ranked 1st of 25 years
b) 1973 ranked 14th of 25 years
c) 1974 ranked 12th of 25 years

The probability that, by chance one year would rank 1st, one year 14th or better and one year 12th or better, without preference to order of occurrence, is only 3.4%. This result clearly shows that the seeded counties fared better, crop-hail wise, in the seeded years than did the unseeded counties, even when account is made of the natural historical bias in favor of the seeded counties. Actual hail damage suppression is estimated at 25% - 50%.* Again it is believed that the high degree of significance in the results is due to the large region and the great number of storms seeded by the state sponsored program.

*Dennis, A. S., personal communication

V CONCLUSIONS

The results of these analyses attempt to shed light on three difficult questions that have challenged weather modification research:

1. Can the results of small area cloud seeding experiments be safely extrapolated to large areas?

2. What is the net effect of seeding large fields of cumuli?

3. Can a large scale seeding program accomplish the dual objectives of augmenting rainfall and suppressing hail?

The South Dakota statistics cannot answer the theoretical aspects of these questions; however, they strongly support the concept of rainfall augmentation over a large area through proper application of summertime cumulus seeding techniques developed and applied by researchers over much smaller areas. The net effect of rain augmentation seeding over South Dakota appears to be an increase in growing season rainfall of about 7% over what occurs in the absence of seeding. This falls short of the 10 or 15% limit suggested by Dennis et al., (1975a). The difference may lie in interactions among individual cells, operational limitations, juxtaposition of a hail suppression program, and/or precipitation regimes encountered during the past four years.

Analysis of daily rainfall records indicates a 5.4% increase in the frequency of rainfall events and a 2.8% increase in the average rainfall per event. These figures are proportionally similar to, but of less magnitude than, those resulting from analysis of the North Dakota Pilot Project (Dennis et al., 1975b). One may hypothesize that the higher frequency of station-day rainfall events in seed counties compared to no-seed counties evolved through shower initiation, spreading areal extent of showers, and/or increases in shower duration through seeding.

The latest South Dakota rainfall evaluations were based on all available NWS precipitation data without any attempt to segregate rain and hail operational days. Since positive results were found in both rainfall and hail analyses, concerns that the price of hail suppression is a net decrease in rainfall are alleviated.

It is interesting that a statewide weather modification program with primary emphasis on operations rather than research presents, under certain circumstances, an excellent opportunity to study weather modification effects. The large regions involved and the consistent treatment of clouds numbering into the hundreds in statewide programs help balance the wide variability of natural convective rainfall and specific cumulus seeding response; two problems which complicate most cumulus seeding evaluations.

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