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SEEDING SUMMERTIME CONVECTIVE CLOUDS TO INCREASE BLACK HILLS RAINFALL[1]

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Abstract. Data from two Reclamation-sponsored randomized cloud seeding experiments near the Black Hills of South Dakota are combined with data on size distributions of showers to estimate the potential for modifying summertime precipitation. The analysis suggests that increases amounting to roughly 12 percent of the natural precipitation are possible through a combination of microphysical and dynamic effects. Convective clouds around 6 km deep are judged to be the most promising targets for seeding to increase summer rainfall.

1. INTRODUCTION

From 1963 through 1972 the South Dakota School of Mines and Technology (School of Mines) conducted a series of cloud seeding experiments in the western Dakotas to test effects of seeding upon rainfall from summertime convective clouds. Almost all of the experiments were conducted as a part of the Bureau of Reclamation's Project Skywater.

The most important of the School of Mines projects near the Black Hills were the Rapid Project and Project Cloud Catcher. Both projects dealt with summertime convective clouds near the eastern edge of the Black Hills. The purpose of this paper is to combine findings from the Rapid Project of 1966 to 1968 (Dennis and Koscielski, 1969) and Project Cloud Catcher I of 1969 and 1970 (Dennis et al., 1975a) with previously published information on size distributions of convective showers in order to assess the potential impact of seeding convective clouds upon total summer rainfall over and near the Black Hills.

2. CLOUD CATCHER: AN EXPERIMENT ON INDIVIDUAL CLOUDS AND CLOUD CLUSTERS

2.1 Experimental Design

Cloud Catcher was directed from a radar site about 10 km east of Rapid City. It was one of the first cloud-seeding experiments to use an on-line computer for recording and preliminary processing of radar data (Boardman and Smith, 1974). It used a single, moving target area to test the effects of seeding on isolated convective clouds or cloud clusters. Quoting from Dennis et al. (1975a), "Distinct clusters of cumulus clouds, well away from other showers, with updrafts of at least 2 $m \cdot s^{-1}$ below cloud base and cloud top temperatures less than -10°C were selected as test cases. The existence of a radar echo did not prevent the selection of a cluster of growing clouds as a test case."

By definition, each test case lasted 1 hour, which is about twice the lifetime of a typical convective cell in a multicell thunderstorm. The principal response variable was the radar-estimated rainfall (RER), which was determined from X-band radar data recorded by the on-line computer. No corrections for attenuation were attempted. For data logging purposes, the area around the radar site was laid off in squares 10 nautical miles on a side. A test case normally occupied two squares at one time, and all echoes in the designated squares were considered to be part of the test case.

In 1969 and 1970, a three-way randomization was used, with the choices being no-seed, salt seed, and silver iodide seed. All seeding was done from an aircraft operating in updrafts below cloud base. Attention was concentrated on updrafts under new cloud towers adjacent to existing showers.

Salt seeding was accomplished by releasing up to 50 kg of powdered sodium chloride during the first 30 minutes of each test case. Seeding of a silver iodide case was accomplished by burning flares, each containing 120 g of silver iodide, one at a time in place in wing-mounted racks. A flare burned for about 5 minutes, and up to 6 flares were used

[1]Based on an oral presentation at the Conference on the Science and Technology of Cloud Seeding in the Black Hills, Rapid City, South Dakota, October 16-17, 1989.

on a test case if the updrafts lasted long enough. There was no attempt to overseed the clouds to produce dramatic dynamic responses.

Eighty Cloud Catcher cases were recorded in 1969 and 1970, with 33 of them being no-seed cases, 18 silver iodide cases, and 29 salt cases. The relative lack of silver iodide cases can be attributed in part to the lack of sufficiently powerful blocking in the randomization scheme. In 1970 the random decision for the first test case of each day was applied to subsequent cases on that day, if any. This arrangement, which was intended to reduce possibilities of contamination, had the unfortunate effect of aggravating the imbalance among the three classes of test cases.

2.2 Effects of Seeding on Individual Clouds

The radar data from Cloud Catcher showed that cloud seeding with either silver iodide or salt can stimulate precipitation in cumulus congestus clouds. "First echoes" from new precipitation shafts in clouds seeded with either silver iodide or powdered salt appeared closer to cloud base than first echoes in unseeded clouds (Dennis and Koscielski, 1972). The average height of first echoes above cloud base was 3.4, 2.1, and 1.6 km for the no-seed, silver iodide, and salt cases, respectively. This result is evidence that seeding speeded the formation of precipitation in the clouds studied, as is the fact that clouds greater than 2 km deep generally precipitated after seeding with either silver iodide or salt, whereas unseeded clouds did not precipitate until they reached about 4 km depth.

Dennis et al. (1975a) presented a statistical analysis of the Cloud Catcher test cases of 1969 and 1970. In particular, they studied RER as a function of cloud depth (CDP), which was defined as the highest radar echo top recorded in the test case minus the height of the cloud base. They obtained straight-line relationships by plotting the cube root of RER against CDP. Figure 1, which is patterned after their figure 4, has been replotted using data from table A.2 of Dennis et al. (1974).

Dennis et al. (1975a) found the equation of the regression line for the no-seed Cloud Catcher cases to be:

$$(\text{RER})^{1/3} = -4.02 + 1.43(\text{CDP}) \qquad (1)$$

where RER is in kilotons[2] and CDP is in kilometers.

Dennis et al. (1975a) found an indication that rainfall from salt cases exceeded that from no-seed cases of the same depth, but the statistical significance of this result was somewhat weak, with the p-value for the test for differences in adjusted means being 0.06. [The test for differences in adjusted means allowed for the fact that the distributions of CDP varied for the three classes of test cases. CDP averaged 6.5 km for the no-seed cases, 5.2 km for the silver iodide cases, and 5.8 km for the salt cases.]

RER for the silver iodide cases exceeded that from no-seed cases of the same depth. (It should be noted that, on figure 1, the values of CDP for the silver iodide cases are those actually observed, rather than the values that would have been observed had the clouds been left unseeded.) The difference in adjusted means was statistically significant, with the p-value being 0.01 under the assumption that all test cases were independent. Although the significance is weakened by the fact that in 1970 all cases occurring on one day received the same treatment, this is a surprisingly positive result to emerge from only two seasons of experimentation. It is assumed, for the purposes of the exercise presented in this paper, that real differences exist between the no-seed and silver iodide cases.

Dennis et al. (1975a) derived the following regression equation for the Cloud Catcher silver iodide cases:

$$(\text{RER})^{1/3} = -2.62 + 1.44(\text{CDP}) \qquad (2)$$

where the units are as in (1). The difference in the intercepts of (1) and (2) is 1.40, which is very close to the change associated with a 1-km difference in CDP. That is, the value of RER for a silver iodide case approximates that for a no-seed case with CDP 1 km greater.

Table 1 has been prepared to provide additional insight into the implications of (1) and (2), particularly when combined with information to be presented below on the frequency distributions of shower sizes. Application of (1) and (2) leads to columns 3 and 5 of table 1,

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[2]A metric ton is the mass of 1 m^3 of water. A kiloton is equivalent to 10^3 m^3.

respectively. Comparison of columns 3 and 5 indicates that rainfall from clouds of any given depth up to 10 km is increased by silver iodide seeding as practiced in Cloud Catcher. Expressed as a percentage of the expected or no-seed rainfall, the calculated effect decreases from small to large clouds; expressed in terms of rain volume, it continues to increase.

It is unlikely that the linear relationship between $(RER)^{1/3}$ and CDP for silver iodide cases shown in figure 1 extends to clouds with depths as great as 11 or 12 km. Uncertainties about inferences based on regression lines are greatest when one deals with the extremes of the size range, rather than the mid-range, and extrapolation is considered undesirable. The situation is made worse in this case by the fact that the largest value of CDP among the silver iodide cases was just 10.1 km. In view of indications from some cloud modeling studies (Orville, 1984, p.54) that silver iodide seeding of large storms can reduce their precipitation efficiency, and the lack of silver iodide cases with CDP exceeding 10 km in the Cloud Catcher sample, we can not draw any conclusions about the effects of silver iodide seeding on such clouds. It is for this reason that the entries in column 5 of table 1 end at CDP equal to 10 km.

2.3 Consideration of Dynamic Effects

The Cloud Catcher radar data indicated that the additional rainfall associated with clouds of a given depth was *not due to increases in peak* rainfall intensity, but rather to additions in space or time, or both, of additional precipitating areas similar to the natural showers (Dennis et al., 1975a). In other words, the showers responded to seeding by becoming more numerous, increasing in horizontal extent, lasting longer, or some combination of all three responses. Such a result could be produced by microphysical effects alone, but it is judged more likely to represent some

Table 1. - Relative abundance of clouds, rainfall per case, and total contribution to convective rainfall, all as functions of cloud depth, for no-seed and silver iodide cases

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2	48.4	0.00	0	0.02	<1	1.4	70
3	22.8	0.02	<1	4.9	110	17	390
4	12.0	4.9	60	31	370	64	770
5	6.8	31	210	96	650	160	1090
6	4.0	95	380	220	880	330	1320
7	2.4	210	500	420	1010	580	1390
8	1.5	410	620	700	1050	930	1400
9	0.93	690	640	1100	1020	1400	1300
10	0.59	1100	650	1600	940	-	940
11	0.38	1600	610	-	610	-	610
12	0.24	2300	550	-	550	-	550
	100		4220		7190		9830

(1) Cloud depth (CDP) in kilometers.
(2) Relative number of cases for $\alpha = 0.35\ km^{-1}$, normalized to 100.
(3) Rainfall $(10^3 \cdot m^3)$ per no-seed case.
(4) Contribution to total convective rainfall (arbitrary units) from all clouds expected with CDP in range indicated.
(5) Rainfall $(10^3 \cdot m^3)$ per silver iodide case according to Eq. (2), assuming no change in CDP due to seeding.
(6) Contribution to total convective rainfall (arbitrary units) from all clouds expected with CDP in range indicated, assuming all clouds seeded with silver iodide and no change in CDP due to seeding.
(7) Rainfall $(10^3 \cdot m^3)$ per silver iodide case according to Eq. (2), assuming an increase in CDP of 600 m due to seeding. In this case, the CDP shown in column 1 refers to the cloud left unseeded. The observed clouds would be 600 m taller.
(8) Contribution to total convective rainfall (arbitrary units) from all clouds expected with (unseeded) CDP in range indicated, assuming all clouds seeded with silver iodide and an increase of 600 m in CDP due to seeding for all values of CDP up to 9 km.

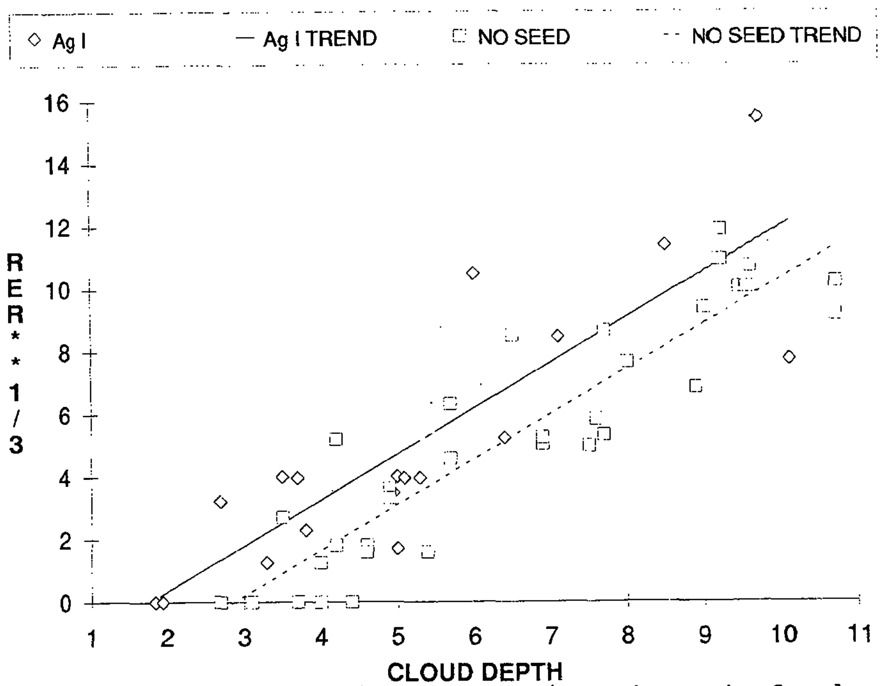

Figure 1. - Scatter diagram comparing cube root of radar-estimated rainfall (RER) to cloud depth (CDP) for no-seed and silver iodide cases of Project Cloud Catcher in 1969-70.

dynamic effects as well, perhaps an intensification of secondary cloud towers around the major precipitation cells.

The analysis to this point has taken no account of possible increases in CDP, the depth of the tallest precipitation echo in each test case. An increase in CDP due to seeding would shift a point on figure 1 corresponding to a seeded cloud some distance to the right. Analysis of the Cloud Catcher radar and aircraft data with the aid of cloud models showed no increases in CDP associated with salt seeding, but suggested increases in CDP due to silver iodide seeding, with maximum cloud top in a test case rising, on average, by perhaps 600 m (Dennis et al., 1975a). The model analysis showed no skill in assigning increases in CDP to particular days; however, the increases must vary from day to day, or even from cloud to cloud, depending on the ambient conditions. Any changes in rainfall associated with changes in CDP would be in addition to those indicated in column 5 of table 1. Column 7 of table 1 provides an estimate of the total rainfall increases produced by the combination of increases in CDP (a possible dynamic effect) and changes in the relationship between RER and CDP (probably a combination of dynamic and microphysical effects). The numbers in column 7 were obtained by adding 600 m to CDP and applying (2); it would be the enhanced cloud tops that would actually be observed rather than the no-seed values as shown. Comparison of columns 5 and 7 shows that the additional impact of a 600-m increase in cloud height upon rainfall would be comparable to that revealed by the regression analysis.

We repeat, for emphasis, that the increases in CDP would not be uniform. Cloud model runs using North Dakota Pilot Project data (Dennis et al., 1975b) suggest that the increases in cloud height are greatest for clouds with (unseeded) top temperatures in the range from -10 to -30°C, that is, to clouds with CDP from 2 to 6 or 7 km, and nonexistent for most cases with CDP greater than 10 km (Smith et al., 1986). Because of the many uncertainties, there are no entries in column 7 for clouds whose depth is 10 km or greater.

2.4 Potential Effects of Seeding Assemblages of Convective Clouds

In order to determine the potential impact upon Black Hills summer rainfall of seeding all available convective clouds, it is necessary to develop some statistics regarding the size distributions of natural clouds and the contributions of the different size categories to the natural rainfall. For this purpose, it is not sufficient to look at the size distribution of the Cloud Catcher cases, because many factors influenced their selection, including location with respect to the radar, visibility below cloud base, and a need to develop a statistical base by sampling clouds rather uniformly distributed along the size range from cumulus congestus to moderate thundershowers.

Numerous studies have shown that small convective clouds greatly outnumber large ones. For example, Dennis and Fernald (1963) found that the radii of radar echoes from showers in many parts of the world follow an exponential distribution. Miller et al. (1975) fitted exponential distributions to the diameters of echoes in the North Dakota Pilot Project radar data from 1972 to determine the parameter α in

$$N = N_0 \exp(-\alpha D) \qquad (3)$$

where N is the number of shower echoes with diameters between D and (D+dD), N_0 is a constant reflecting the number of showers in the space-time domain studied, and the parameter α characterizes the size distribution. They found α for the entire data set to be about 0.35 km^{-1}, in good agreement with Dennis and Fernald (1963). As the height of a convective cloud tends to approximate its diameter (e.g., Miller et al., 1975), we assume that the exponential relationship with a similar value for α holds for CDP.

Equation (3) was derived from hourly snapshot views. As there is a positive correlation between echo size and echo lifetime, a large shower has a greater chance of showing up in such a census than does a smaller one. Miller et al. (1975) studied a supplementary sample of 479 echoes, from which echoes that were obviously multi-cellular were excluded; they found a roughly linear relationship between echo diameter and echo lifetime (r = 0.65). Therefore, in order to make table 1 reflect more closely the size distribution of all echoes that form, exist, and dissipate, as opposed to the size distribution observed at a given moment, we have modified (3) as follows:

$$N' = N_0 D^{-1} \exp(-\alpha D) \qquad (4)$$

There is a further complication in that the snapshot views must catch some undefined fraction of the echoes in their growing or dissipating stages, thereby leading to underestimates of their maximum size. No satisfactory method of adjustment for this second-order complication has been devised. Therefore no allowance is made for it in the calculations that follow. It is considered a minor factor compared to the other uncertainties in the analysis. All results should be interpreted as indicating only general trends, rather than as exact calculations of the possible rainfall increases.

Column 2 of table 1, which shows the relative frequency of clouds of different sizes, was obtained by applying (4) with the parameter α set at 0.35 km^{-1} and normalizing so that the total number of clouds considered came out to 100. This is a truncated distribution. Ignoring clouds with CDP exceeding 12.5 km is of little consequence as far as number of clouds is concerned, although such clouds may be significant in terms of total rainfall. On the other hand, there are many clouds with CDP less than 2 km. Dennis and Fernald (1963) quoted work by earlier authors showing that the exponential distribution they observed for radar echoes from isolated showers extends down-scale to the visual dimensions of small cumulus clouds. However, we can ignore such clouds in the present case because they do not produce any precipitation whether seeded or unseeded.

The numbers in column 4 of table 1 are the products of the corresponding numbers in columns 2 and 3. They show the relative contributions of clouds of different sizes to the total natural convective rainfall over the Black Hills, and peak for CDP around 10 km. As the bases of summertime convective clouds near the Black Hills are, on average, very close to 3 km above sea level, the 10 km value corresponds to large storms with cloud tops about 13 km above sea level. This number agrees with the common perception that much Black Hills summer rain falls from large thunderstorms.

The entries in column 6 of table 1 for all values of CDP up to 10 km were obtained by multiplying the corresponding numbers in columns 2 and 5, and represent the expected rainfall from silver iodide seeded showers according to (2) and (4). On the assumption that seeding would not be done on clouds more than 10 km deep or, if it were done, would have no effect, the entries of column 4 for such clouds are repeated in column 6.

A comparison of columns 4 and 6 ignores the possibility of increases in CDP but suggests, nevertheless, that silver iodide seeding can increase the total rainfall from isolated summertime convective clouds by a factor of roughly 1.7. It is instructive to consider where the predicted increases come from; this can be seen in figure 2, which shows the rainfall contributions as a function of CDP for both no-seed and silver iodide cases, as well as in table 1. Small clouds are numerous and respond well to seeding (percentage-wise), but they produce very little rain whether seeded or not, so the impact of seeding them is not great. On the other hand, large clouds are scarce and the effect of seeding (percentage-wise) drops off as one moves to large clouds. The contribution to the additional rainfall peaks for CDP between 6 and 7 km. Clouds in this size range are significantly smaller than the ones that produce the bulk of the natural rainfall.

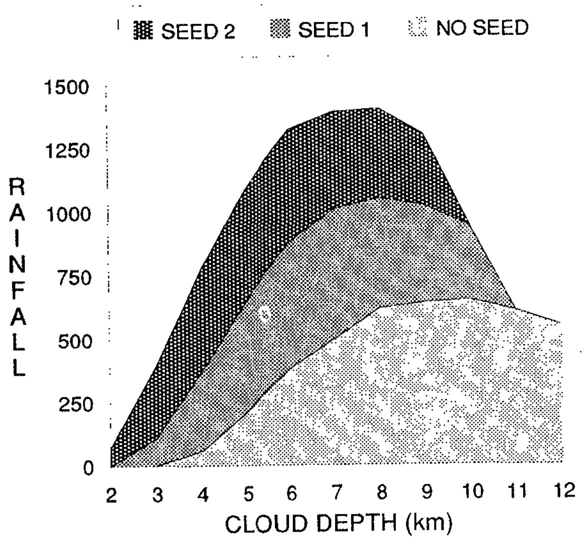

Figure 2. - Contributions to total shower rainfall from clouds of different depths under assumptions of no seeding, silver iodide seeding without changes in cloud depth (Seed 1), and silver iodide seeding with 600-m increases in cloud depth for clouds with depth less than 10 km (Seed 2).

The entries in column 8 of table 1 for all values of CDP up to 9 km are the products of the corresponding numbers in columns 2 and 7. They account for the possibility of increases in CDP of 600 m as a dynamic response to silver iodide seeding. On the assumption that there would be no increases in maximum height for clouds with CDP of 10 km or greater (Smith et al., 1986), the entries of column 6 are repeated in column 8 for these large clouds. The differences between columns 4 and 8 of table 1 (see also fig. 2) suggest a 2.3-fold increase in total shower rainfall through a combination of microphysical effects, with the maximum contribution coming from clouds or cloud clusters with values of CDP around 6 km.

In summary, the Cloud Catcher results, combined with some modeling studies and data on size distributions of shower echoes, indicate that silver iodide seeding could increase total rainfall from isolated convective clouds or cloud clusters near the Black Hills by a factor somewhere between 1.5 and 2.5, with much of the increase coming from moderate shower clouds or small thunderstorms with tops from 7 to 10 km above sea level.

In order to draw conclusions about the impact of seeding isolated convective clouds upon total summer rainfall near the Black Hills, one requires information on the contribution that isolated convective systems make to that rainfall. It is also necessary to consider the possibility that seeding one convective cloud might suppress rainfall from other clouds in the vicinity through dynamic effects (e.g., Simpson and Dennis, 1974). Some information about both of these points can be drawn from the results of the Rapid Project although, as we shall see, some questions remained unanswered following its completion.

3. THE RAPID PROJECT: AN EXPERIMENT ON AREA RAINFALL

3.1 Experimental Design

The Rapid Project of 1966-68 has been described by Dennis and Koscielski (1969). It used a randomized crossover design, with two pairs of target areas laid out east of the Black Hills, one pair for days with southwest flow and one pair for days with northwest flow. This arrangement minimized cross-target contamination. Each target area encompassed about 2500 km^2.

Days were classified in advance as southwest-flow or northwest-flow days. They were also classified according to the synoptic situation into four types, of which the most important were shower days and storm days. Shower days and storm days had the same requirements regarding precipitable water and upper winds as determined from the Rapid City rawinsonde. Storm days were characterized by forcing by large-scale weather systems, as evidenced by positive vorticity advection at the 500-mb level; they normally produced substantial rainfall, often from squall lines. Shower days were characterized by absence of positive vorticity advection at the 500-mb level; they normally produced only isolated showers, which were often limited to the Black Hills.

The static seeding approach was followed. Ice crystal formation was induced in supercooled cumulus clouds for microphysical effects, with the principal effect sought being an increase in precipitation efficiency. The experimenters were aware that dynamic effects might be produced too, but dynamic effects were not deliberately sought. The seeding rate was kept low to reduce the possibility of overseeding. Several seeding agents were used. By far the most common treatment was the release of silver iodide from an acetone generator on an aircraft flying in updrafts below cloud base. Sodium iodide was used as the solubilizing agent. Only one generator was used at a time, with the release rate being approximately 300 $g \cdot h^{-1}$.

Seeding directions were radioed to the pilot from the radar station east of Rapid City. The objective was to treat all promising cumulus congestus and towering cumulus clouds that were over or approaching the seed target area. Seeding was sometimes suspended when the only target clouds available were large, heavily glaciated cumulonimbus clouds.

3.2 Results

The Rapid Project included 98 operational days, of which 27 were shower days and 50 were storm days. A more extensive breakdown is given in table 2.

The Rapid Project was evaluated on the basis of observations at a network of almost 100 rain gauges. Under the randomized crossover design, there was a seed target area and a no-seed target area each operational day. The rain gauge data (table 2) show that the seed target received more rain than the no-seed target on shower days, but less rain on storm days. Statistical analyses by Chang (1976) showed that the differences on shower days were likely real, with the p-values being 0.01 and 0.09 for southwesterly flow and northwesterly flow days respectively. However, the p-values for the storm days, 0.35 and 0.61 for southwesterly flow and northwesterly flow days respectively, were too large to support any conclusions about effects of seeding on those days.

If one assumes that the differences in rainfall patterns on north-seed and south-seed days represent rainfall increases in the seed target rather than suppression effects in the unseeded target, the Rapid Project results foreshadowed those obtained later on Cloud Catcher. That is, the most promising clouds to be seeded for potential rainfall increases are cumulus congestus and towering cumulus, and the rainfall increases obtainable on days when such clouds predominate are very large, when expressed as a percentage of the natural rainfall on those days. Adding up the numbers in table 2 for shower days pertaining to seed and no-seed targets yields totals of 4.87 and 1.73, respectively. The ratio of those two numbers is 2.8, which agrees surprisingly well with the estimate of 2.3 obtained from the Cloud Catcher data. One can hypothesize that the Cloud Catcher cases correspond to the shower days of the Rapid Project, and that the storms on the Rapid Project storm days are samples of a different type of phenomenon, which is completely outside of the shower size distributions expressed by (3) and (4). While further study might enable one to improve on this assumption, it is not possible to be more precise at this time.

Table 2*. - Average rainfall (in mm) per gauge per operational day and seed/no-seed ratios in target areas for all days of given type on Rapid Project

(Number of days by category follows north-area entries)

	SW-flow	NW-flow
	Shower days	
North area, seed N	0.99 / 6	0.91 / 7
seed S	0.69 / 8	0.64 / 6
Seed/no-seed ratio	1.4	1.4
South area, seed S	1.83	1.14
seed N	0.30	0.10
Seed/no-seed ratio	6.0	11
	Storm days	
North area, seed N	2.18 /15	0.89 / 7
seed S	2.82 / 14	4.32 / 14
Seed/no-seed ratio	0.77	0.21
South area, seed S	2.36	1.37
seed N	2.97	3.18
Seed/no-seed ratio	0.79	0.43

* after Dennis and Koscielski, 1969

We turn next to the possible effects of seeding isolated convective clouds or cloud clusters upon total seasonal rainfall. The indicated effect is modest, in large part because of the scarcity of shower days. The Rapid Project, which was in the field 6 days a week from roughly June 1 to August 15 for 3 years, logged only 27 shower days. For an operational project, one should plan on about 10 days per season providing good seeding opportunities over a small, fixed target area.

The data in table 2 on numbers of shower and storm days and on average rainfall per operational day in the unseeded targets indicate that shower days contribute about 7 percent and storm days about 93 percent of the natural summer rainfall on the east side of the Black Hills. (Contributions from other types of days, which include frontal overrunning situations, are negligible after early June.) Combining the data in table 2 for seeded targets on shower days and unseeded targets on storm days, we find that the shower days now contribute some 16 percent of the total rainfall, which is increased thereby by about 12 percent.

The preceding calculations rest on the assumption that results of Cloud Catcher and the Rapid Project can be extrapolated to larger areas. In fact, interactions among the seeded clouds might complicate matters considerably. A seeding strategy for increasing rainfall can not be selected intelligently without having the target area clearly in mind. Consider, for example, the Rapid Project shower days with southwesterly flow (table 2). There is no doubt that, in both the north and south targets, rainfall was heaviest on days when the particular target was seeded. [We do not know what fraction of this favorable result was due to suppression effects in the no-seed target.] Therefore, if one wants more rain in the north target area, he should seed it; if one wants more rain in the south target area, he should seed it. However, if the objective is to maximize total rainfall over the two target areas, the recommended treatment would be to seed the south target always. Seeding the south target yielded an average rainfall across the two target areas of approximately 1.3 mm, compared to an average of only 0.65 mm when the north target was seeded.

Of course, the Rapid Project did not test the more obvious treatment for maximizing total rainfall, namely, seeding clouds in both target areas on the same day, whenever and wherever they appeared, nor, for that matter, did it test the option of not seeding at all. This exercise points out the need for clearly defined objectives in selecting a seeding strategy, as well as the ambiguities that arise in the interpretation of results from randomized crossover experiments when strong dynamic effects are present or suspected.

4. SUGGESTIONS FOR FUTURE RESEARCH

Cloud Catcher I left some unanswered questions about the effects of silver iodide seeding on convective clouds, particularly when the convective cells are clustered together. It provided evidence of significant rainfall increases due to silver iodide seeding of clouds of moderate size, but it did not make clear how the individual cells reacted to produce the apparent increases. These unanswered questions were to be addressed in Cloud Catcher II, which was in the field in 1971 and 1972. It used an S-band radar to avoid attenuation by precipitation, a floating target design, and quite sophisticated programming in the on-line computer which controlled the radar scans, logged and processed the radar data, and provided real-time graphic displays to the project meteorologist (Boardman and Smith, 1974). Unfortunately, seeding suspensions following the Black Hills flood of 1972 and program cuts in 1973 led to termination of Cloud Catcher II before its potential could be realized. Lingering questions on the part of the general public about whether or not cloud seeding contributed to the 1972 flood make it doubtful whether seeding of Black Hills summer clouds will be attempted again during this century. Nevertheless, this section considers what a new round of experiments might entail.

In assessing the status of seeding of convective clouds, it is of some value to compare the South Dakota results with those obtained subsequently in other places. Statistical analyses of the second Florida Area Cumulus Experiment (FACE-2) failed to prove the existence of rainfall increases for either the total target area or for the floating targets encompassing the cells selected for treatment (Woodley et al., 1983). Subsequently, Gagin et al. (1986) used computerized cell-tracking techniques in a detailed post-hoc study of convective cells within seeded and unseeded cloud systems on FACE-2. They found evidence suggestive of rainfall increases for clouds that were treated early in their lifetimes with more than 8 silver iodide flares. Their results for such cases were in good agreement with the estimates based on table 1, namely, that rainfall from a moderate shower cloud can be multiplied by a factor of 2 or 3 by silver iodide seeding. However, unlike Dennis et al.

(1975a), Gagin et al. (1986) found no difference in the relationships between cell height and other variables, including rainfall volume, for unseeded and silver iodide seeded cells. Therefore, they interpreted all of the apparent FACE seeding effect in terms of changes in cell height.

On the other hand, Rosenfeld and Woodley (1989) found for a seeding experiment in Texas a "large indicated effect of treatment on cell rain volume, despite the small indicated effect on maximum cell heights." It is interesting to note that the Texas result, which is only tentative due to the small number of cases analyzed to date, is in line with the Cloud Catcher seeding hypothesis, which stressed a combination of microphysical and dynamic effects, rather than the hypothesis in the Texas project design, which was patterned after FACE and considered increases in cell height as the principal, if not the sole, source of additional rainfall (Rosenfeld and Woodley, 1989).

Any future experiments near the Black Hills should be designed to shed light on these questions, as well as interactions between the clouds and the Black Hills themselves. Seeding clouds over the Black Hills to maximize precipitation requires consideration of wind, temperature, and moisture fields over the entire area. Kuo and Orville (1973) showed how the interactions between the Black Hills and the air streams passing over them set up preferred areas for cloud and shower formation. Because seeding influences cloud dynamics, one should not assume that seeding over one part of the Black Hills does not influence subsequent cloud developments elsewhere.

A unifying concept, which seems to bring together various pieces of evidence, is that rainfall increases are produced when seeding helps convective clouds merge into clusters, rather than continuing as single-cell showers (Dennis et al., 1976). Such organization promotes the precipitation efficiency of clouds. It also appears to increase the total amount of water vapor processed, which accounts for the great attention paid to cloud mergers in cloud seeding experiments in Florida and Texas (e.g., Simpson and Dennis, 1974; Rosenfeld and Woodley, 1989).

The apparent success of seeding on Rapid Project shower days has already been noted, as well as the lack of overall success on storm days. On Rapid Project storm days with southwesterly flow, there were indications of rainfall decreases at the edge of the Black Hills, but of substantial increases some 30 to 40 km northeastward, still within the target areas (Dennis et al., 1976). It appears that, for that particular situation, additional organization or clustering induced by seeding was still beneficial over the open prairie, but could not be produced (or was not beneficial) over the Black Hills themselves.

These inferences are only tentative, but suggest a possible strategy to be followed in any future field experiments. On shower days, only clouds supported by low level convergence induced by the Black Hills themselves have any chance of producing significant showers. Seeding would be directed at the most promising growing clouds, wherever they occurred. On storm days, as evidenced by positive vorticity advection (synoptic-scale forcing), systems over the Black Hills would organize with no help, and seeding there likely would have no effect. However, clouds forming in the less disturbed regions might be of a size (CDP around 4 to 6 km) that could be stimulated to further growth and organization. Evaluation should be on both a cell or cluster basis and an area-wide basis to study the larger scale effects.

Continued work with powerful numerical models, such as the new three-dimensional models developed by Clark and others (e.g., Smolarkiewicz et al., 1988), is required to sort out the various possible effects. In time, it should be possible to integrate detailed parameterizations of microphysical processes in individual clouds into three-dimensional mesoscale models capable of simulating air motions over and around the Black Hills. The output of such models would suggest additional seeding hypotheses, and might even provide statistical controls for seeding experiments. This would be an extremely important development, as it would provide to single-area experiments a degree of sensitivity now obtainable only with target-control or randomized crossover experiments. As we have seen, the interpretation of results from target-control or randomized crossover experiments is ambiguous when strong dynamic effects are present or suspected.

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