"REVIEWED"

SEEDING RESULTS FAVOR SMALL CLOUDS IN CHINA, SOUTH DAKOTA, AND YUGOSLAVIA

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Abstract. A comparison of four cloud seeding projects on three continents indicates that smaller clouds may give much greater percentage increases in rainfall than do larger ones in weather modification efforts. Project Cloud Catcher, a randomized single-cloud project in South Dakota 1969-1970 (Dennis et al., 1975) is compared here to a randomized two-area project in Fugian province, China, 1975, 1977, 1981 (Yeh et al., 1982). Also compared are rainfall results from two non-randomized, hail suppression efforts in South Dakota, 1972-1976 (Pellett et al., 1977) and in Serbia, Yugoslavia, 1970-1979 (Curič, 1981).

1. RESULTS FROM TWO RAIN SIMULATION RESEARCH PROJECTS

In Cloud Catcher, updrafts were seeded near cloud base with either salt or AgI. Figure 1 shows seed (AgI and salt) and no-seed regression lines relating radar estimated rain volumes to cloud depths. The seed line lies above the no-seed line suggesting greater rainfall production from a seeded cloud when compared to a no-seed cloud of the same depth. In view of the cube-root scale on the ordinate, the percentage differences in rainfall between the seed and no-seed cases are much larger for the smaller clouds.

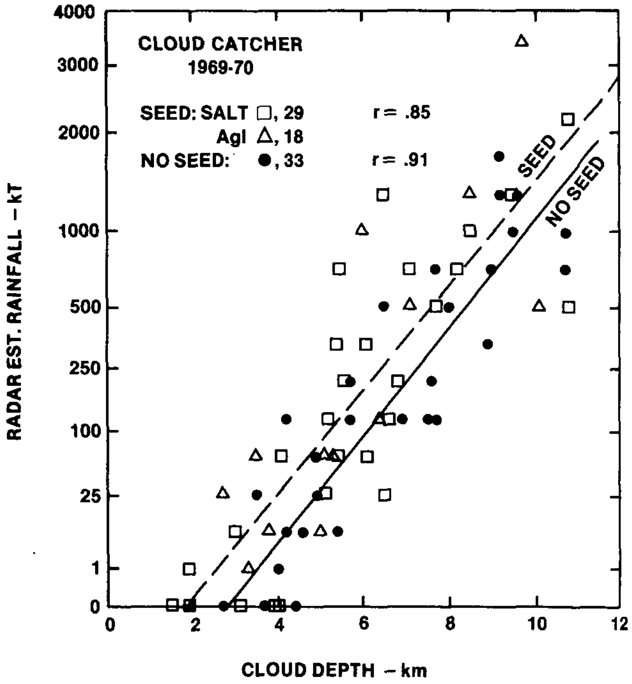

Figure 1. Scatter plot of cube root of radar estimated rainfall (RER) vs. cloud depth (CDP) for 1969-1970 Cloud Catcher cases. [Adapted from Fig. 4, Dennis et al., 1975].

No-seed line (solid): $RER^{1/3} = -4.02 + 1.43$ CDP
Seed line (dashed): $RER^{1/3} = -2.63 + 1.39$ CDP

Figures 2a and 2b, reproduced from Yeh et al. (1982) show fourth roots of areal precipitation in target and control areas and the seed and no-seed target-control regression lines for the cumuliform and total cloud stratification schemes, respectively (additional stratifications are included in the original paper). For larger rainfall events, smaller percentage increases in rain seem due to seeding.

Estimated percentage differences in rainfall are shown as a function of cloud depth for the Cloud Catcher project and the fourth root of rainfall for the China project in Fig. 3; the enhancement due to seeding is indicated by a solid line for Cloud Catcher and by dashed lines for China. It is well known that taller clouds produce more rainfall, and the scales are chosen to elucidate the possibility that similar seeding effects occur in the convective clouds of both regions.

Of interest is the "comparability" of these projects halfway around the world from one another. Smaller, weaker clouds, and/or cloud systems respond with greater percentage increases, whereas larger, stronger clouds show lesser effects. These results strengthen the development of seedability criteria for operational cloud seeding projects such as the North Dakota Cloud Modification Project (NDWMB, 1980). In North Dakota, seeding for rainfall enhancement is aimed primarily at moderate-sized clouds/cloud systems (cloud depths less than 30,000 ft or 9 km).

2. RAINFALL EFFECTS ASSOCIATED WITH OPERATIONAL HAIL SUPPRESSION

Rainfall in South Dakota during the State project, 1972-1976, was evaluated by Pellett et al. (1977); (see also Leblang and Pellett, 1976). The State supported operational project had goals of reducing hail damage and enhancing rainfall, with hail suppression operations having priority. Seeding in South Dakota was primarily by AgI released into updraft regions from aircraft flying below cloud base. Comparison of target-control (T/C) ratio developed for the historical period 1941-1970 and the seeding years T/C ratios indicated rainfall enhancements as shown in Table 1.

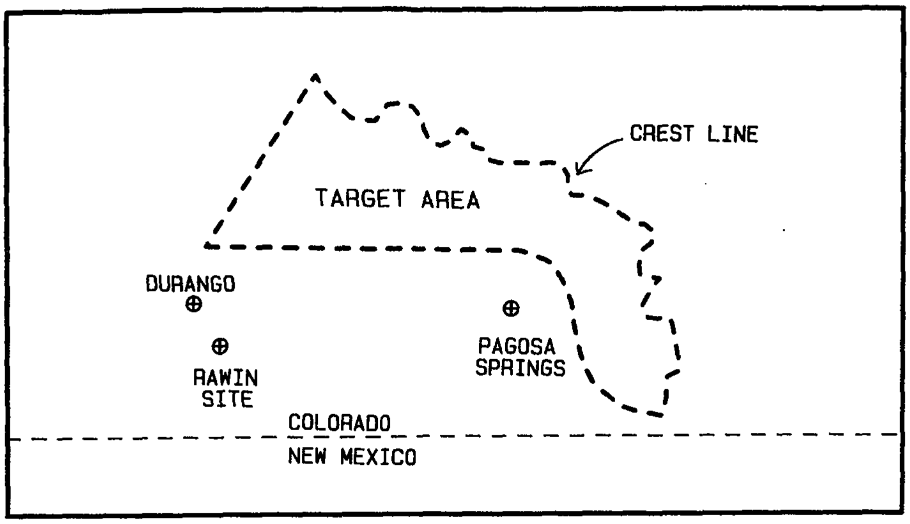

Fig. 1 COLORADO RIVER BASIN PILOT PROJECT AREA

Table 1 **Ratios of seeded to not seeded precipitation in three-hour blocks for unstable cases.**

Precipitation Group	Hours before (-) or after (+) Tropas (trough passage)						
	+9	+6	+3	0	-3	-6	-9
Wrn upwind flank	1.09	.79	.33	1.08	1.33	1.32	1.75
Wolf Creek Pass	1.15	.81	.62	.78	.85	2.26	1.37
Downwind flank	.73	.76	.65	.65	1.38	1.79	1.60

To test this hypothesis, the entire sample, without reference to position with respect to tropas, was divided into two groups. In one the top of the positive area shown on the upwind sounding (found associated with convection tops over the barrier) was higher than the cloud top calculated to exist over the barrier by lifting the top of the main deck, using the Durango upwind sounding. This will be referred to as the "emergent" case. In the second the reverse was true. This will be referred to as the "embedded case". However, it is not the same as the "embedded band" precipitation echo type employed in the Sierra Cooperative Pilot Project. The cases employed were subject to the various exclusions used by Shaffer, but in addition the base of convection, as determined from the sounding, had to lie below the crest level so as to insure entrainment of the ground generator plumes into convection.

Results of this division (Table 2) show that the Wolf Creek group of precipitation stations experienced a low ratio of seeded to not seeded precipitation in the emergent case. The rankings of the precipitation values for the seeded and not-seeded samples were compared using the Mann-Whitney U test. This indicated that the probability of a null effect was .008 for Wolf Creek pass. The other groups do not appear to be adversely affected. In the embedded case all groups show a positive ratio, with a probability of .073 in the downwind flank group. It should be mentioned that the crest group used in Shaffer's article included stations covering a larger area than used in this analysis.

2. DISCUSSION

In the embedded case, constituting 72% of the unstable sample, positive effects of seeding seem to be indicated. In the emergent case the crest zone shows an adverse effect with a seed/no seed precipitation ratio of 0.55. The region of adverse effect appears at about the same place in the synoptic sequence that has been chosen by Cooper and Marwitz (1980) in their analysis of aerial observations over the San Juan Mountains as a region favorable

Table 2 **Group precipitation (mm/3 hr) statistics for embedded and emergent convection.**

State of Instability	Item	Precipitation Group Wm. Upwind Flank	Wolf Creek Pass	Downwind Flank	No. of cases
	S precip	1.36	2.47	1.43	63
Embedded	NS precip	.95	2.05	.98	53
	Ratio	1.43	1.20	1.46*	
				Total	116
	S precip	1.70	1.53	1.60	22
Emergent	NS precip	1.71	2.80	1.54	24
	Ratio	.99	.55**	1.04	
				Total	46

* Probability = .073 for two tail Mann-Witney U test.
** Probability = .008 for two tail Mann-Witney U test.

for seeding from ground generators. The generalized criteria developed by Vardiman and Moore (1978) suggest that with a greater depth of convective instability, such as would occur in this region, the odds for a favorable response to seeding diminishes. This supports the author's analysis.

From the viewpoint of a purely microphysical effect of seeding, it is difficult to identify a reason why seeding effects in the mergent cases would be radically different from seeding effects in the embedded cases. One possible reason would be that in the emergent cases there are more high tops than in the embedded cases, thus leading to excessive nucleation and therefore to overseeding. As a test of this idea, all the cases with a positive thermodynamic area exceeding 200 mb in depth were examined and a table (Table 3) similar to Table 2 constructed. In the Wolf Creek Pass group the same adverse effect appears in the emergent case and again, the embedded cases do not show this effect. Therefore, a purely microphysical explanation is ruled out.

There is an argument for relative seeding losses in the emergent case due to dynamic effects. In presenting this argument we first refer to Weinstein's (1972) analysis of numerous soundings by means of a one-dimensional convection model, in which he showed that the effect of a dynamically produced (by seeding) rise in convection top could be associated with precipitation loss, as well as a gain. In the former case, the loss resulted from the reduction in time for growth of the particles due to the stronger updraft, even though the top was raised and total condensation increased. His analysis showed that the model did predict this outcome on a substantial fraction of the soundings he analyzed. A logical extension of this thesis is that the adverse effect on precipitation would be more pronounced in emergent convection due to the entrainment of relatively dry air at higher levels. Also, a factor not considered by Weinstein is the possibility of some evaporation of ice particles ejected from convection tops in their passage through dry air to the lower orographic cloud deck.

In the embedded case, although seeding growth time would be reduced due to dynamic effects, precipitation could be increased simply because of the added growth of the ice particles as they fell through a greater depth of cloud.

On the basis of this argument, an adverse dynamic seeding effect in the CRBPP in connection with the seeding of convection having a potential for emergence is quite likely. It might be argued that seeding with ground based generators would not provide an adequate concentration of nuclei to produce such a dynamic effect. However, this argument fails to consider that the nuclei concentrations were adequate to glaciate the available liquid water, which was small in comparison to that found in summer convection, but which is just as large in proportion to the size of the convection systems involved.

This conceptual model for adverse dynamic effects of seeding cannot safely be extended to very large convective systems, or to banded mesoscale systems, both of which generate their own embedding cloud mass. Nor can it be extended to convection under a limiting stable layer where tops cannot rise into the drier upper region. Since it appears

Table 3 Group precipitation (mm/3 hr) statistics for embedded and emergent convection for cases with positive area deeper than 200 mb.

State of Instability	Item	Wm. Upwind Flank	Wolf Creek Pass	Downwind Flank	No. of cases
	S precip	2.29	2.86	2.13	11
Embedded	NS precip	1.72	3.13	1.80	11
	Ratio	1.33	.91	1.18	
				Total	22
	S precip	2.01	1.33	1.73	14
Emergent	NS precip	1.99	2.98	1.73	20
	Ratio	1.01	.45	1.00	
				Total	34

* Probability = .003 for two tail Mann-Whitney U test.

at the crest only, the effect is keyed to a time period of about 100 minutes from the average nucleant source in an average wind flow.

The relatively low frequency of occurrence of conditions favoring such an adverse seeding effect under convective conditions in the winter orographic setting can cause this effect to be easily lost in analyzing a sample that includes all convective cases. In the much larger fraction of cases (embedded) that appear to have a positive reponse to seeding, the response quite likely is also dynamic in character. Therefore, future seeding experiments should be designed to detect dynamic responses to seeding, including enhancement of vertical circulation as well as direct effects on precipitation, even though the intent of the seeding is to produce only a microphysical effect.

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