EVALUATION OF ECHO CORE RESPONSES IN THE 1989 ILLINOIS EXPLORATORY CLOUD SEEDING EXPERIMENT USING A SEEDABILITY INDEX

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Abstract. Evaluation of individual echo core responses to silver iodide seeding in the 1989 exploratory cloud seeding experiment in Illinois is the focus of this paper. The analysis was based on a seeding suitability index defined in terms of 20 predictor variables chosen to represent either in-cloud, echo core, or synoptic/meso-scale conditions that might be suspected of being desirable based on the dynamic seeding hypthesis that was developed for Illinois. Two applications of the seedability index are reported; one for a subgroup of clouds with a high level of seedability index, and the other for a subgroup of clouds with a low level of seedability index. Reduction in sample size by creation of these subgroups, along with other factors such as the analysis being based on data from a single summer, precludes arriving at statistically significant conclusions about seeding effects on individual echo cores. However, examination of the data suggests that if AgI seeding had any initial effect on echo behavior that it may have been negative for cores with high seedability index and positive for cores with lower seedability index. The possibility that the initial reaction of individual echo cores may have been contrary to that expected according to the dynamic seeding hypothesis suggests that the initial steps of the seeding hypothesis, at least as it applies to Illinois, needs reconsideration. An alternative rationale for the initial effect of AgI seeding on echo core behavior is offered which is based on the recognition that it may not be possible to perfectly target seeding material to updraft regions, as is required in dynamic seeding, when the echo cores are characterized by a multi-updraft structure. Caution is expressed about the extent to which these results reflect on those reported for other experiments designed around the dynamic seeding hypothesis because of certain differences between the operational procedures followed during the 1989 Illinois experiment and those traditionally followed.

1. INTRODUCTION

Use of a seedability index to pick out initial silver iodide (AgI) seeding effects on the behavior of individual echo cores in the exploratory cloud seeding experiments that were conducted in Illinois during the summer of 1989 is focused upon in this paper. The experimental design, facilities, randomization scheme, flight procedures, and cloud selection criteria have been reported elsewhere along with a few preliminary results (Czys et al. 1992). A detailed account of the experimental design and operational procedures has been given in Changnon et al. (1989). One of the important preliminary findings presented in Czys et al. (1992) was that the population of sand- and AgI-treated clouds, randomly selected during the experiment, were statistically different (at first echo and treatment) in many physical respects that might be suspected of governing future cloud growth. Thus, despite the fact that the randomization scheme produced numerical and temporal balance between the number of echo cores and experimental units treated with AgI and those treated with sand, the problem of the "bad draw" would have to be satisfactorily overcome before any comparisons of sand- and AgI-treated echo core responses could be made to reveal useful information about potential seeding effects.

In Czys et al. (1992) a seedability index (SI) derived from the physical rationale of the dynamic seeding hypothesis for Illinois was introduced and used to show that there was probably a temporal shift in "suitability" for seeding throughout the course of the exploratory field experiment, and that even pairs of experimental units could produce clouds with considerable differences in their suitability for seeding. Utilization of the seedability index to form subgroups of clouds with a similar level of seedability index to account for the bad draw, and thus permit comparison of sand- and AgI-treated echo core response to reveal potential seeding effects are described in this paper. This presentation begins with a description of how the seedability index was developed, and how specific values of the SI were determined. The presentation continues by pointing out possible seeding effects for subgroups of echo cores with "high" and "low" values of SI. The paper concludes with a physical explanation for the possible seeding effects assuming that the response differences between AgI and sand-treated cores did not happen by chance and a cautionary note about relating these results to results from other cloud seeding experiments designed around the dynamic seeding hypothesis.

2. DEVELOPMENT OF THE INDEX

Seedability criteria were chosen after careful consideration of the most relevant physical conditions believed to be needed to exist during the initial phases of the dynamic seeding hypothesis that was derived for Illinois (Westcott and Ackerman 1985, Ackerman et al. 1985, Ackerman and Westcott 1986). Relevance was defined on the basis of physical principles, information from past cloud modification research (Rosenfeld and Woodley 1989, Smith, et al. 1986, Woodley and Sax 1976, Simpson and Dennis 1974, and Woodley 1970), and Illinois findings on the internal structure and development of cumulus congestus clouds (Czys 1991, Westcott 1990, Politovich and Reinking 1987, Ackerman 1986, Ackerman and Westcott 1986, and Ackerman, et al. 1978). Some of the variables that compose the seedability index were chosen to characterize in-cloud kinematic and microphysical features at the time of treatment that might be suitable for dynamic seeding (updraft size and velocity, buoyancy, amount of supercooled liquid water, and frozen condensate). Others were chosen to characterize early cloud behavior (radar measured height defined by the 10 dBZ contour, growth rates, reflectivity changes, and echo age at treatment). Mesoscale atmospheric variables, such as convective condensation level and instability parameters, which are relevant to summer cloud development and behavior, were also selected. Other variables defined seeding dosages, as well as potential measurement uncertainties associated with radar.

A total of 20 variables were selected to constitute the seedability index (SI), and these are listed in Table 1. Again, based on past findings, "thresholds" were established for each criterion listed in Table 1, indicating the level, depending on the criterion, at which a negative or positive suitability was represented. These thresholds are also listed in Table 1.

Broadest updraft diameter, its mean vertical wind, and the percentage of cloud with updraft (numbers 1-3) were chosen as indicators of the organization of a cloud's vertical circulation. The reasoning was that narrow clouds, clouds with many small updrafts, or clouds with weak updrafts had circulations that were poorly organized; therefore they would not respond too favorably to dynamic seeding. Net buoyancy of the broadest updraft (4) was chosen because if a cloud was either too negatively or too positively buoyant, the forces acting on these clouds might be too large to be appreciably modified. Potential buoyancy enhancement (5), calculated according to the method of Orville and Hubbard (1973), was chosen as an indicator of the potential invigoration from latent heat release due to seeding.

Table 1. Variables and Thresholds Limits Defining the Seedability Index.

Number	Variable Name	Threshold
1	Up_Dia	$x \geq 1000$ m
2	Mean_VW	$2 < x < 8$ m s^{-1}
3	%_Updraft	$x \geq 33\%$
4	NBuoy	$-2 \leq x \leq +2$ °C
5	Buoy_Enh	$x \geq 0.45$ °C
6	LWCd	$x \geq 0.1$ g m^{-3}
7	SWC_frac	$x \leq 40\%$
8	FECPt	$x < 15$ min.
9	range	$30 \leq x \leq 90$ km
10	CPMxZ	$x > 20$ dBZ
11	a_cdp	$-0.02 < x < +0.02$ km min^{-2}
12	CPFEdZ/dt	$x \geq 0.0$ dBZ min^{-1}
13	CPmndia	$x \geq 1.0$ km
14	CPHMxZ	$1 > x \geq 1.5$ km
15	tccl	$x > 14$°C
16	pb	$x \geq 3$°C
17	L	$x \leq 0$
18	Ri	$x \geq 11$
19	Dosage 1	$1.5 \leq x \leq 3.5$ flares km^{-1}

The presence of supercooled drizzle and raindrops in the main (broadest) updraft (6), and the absence of ice, expressed as the fraction of the total condensate that was frozen (7), were chosen because they are required according to the dynamic seeding hypothesis for release of latent heat (Lamb et al. 1981), and beneficial loading of the updraft. Past research has shown that it is possible for a cloud to occasionally develop "ultra-high" ice particle concentrations very early in the evolution of precipitation (see for example, Hobbs 1969, Hobbs and Rangno 1985, Rangno and Hobbs 1990, Mossop 1970, Mossop 1985a, Mossop 1985b, and Hallett et al. 1978). This is an unwanted condition for seeding, because the desired effect is to produce ice from supercooled water.

The time from first echo to treatment (8) was selected to include the effect of cloud age on seedability. Old clouds may have well-developed ice concentrations, or they may be past the stage where seeding can be effective. Although not directly related to the dynamic seeding hypothesis, the distance of the echo from the radar (9) was included to limit measurement errors related to spreading of the radar beam.

Maximum reflectivity at the time of treatment (10) and rate of change of maximum reflectivity from first echo to treatment (12) were chosen as indicators of the level of activity of rain production processes. Clouds with similar maximum reflectivity at treatment (10) can be considered to have initiated precipitation-size particles with the same intensity; and clouds with similar change in reflectivity from first echo to treatment (12) can be considered to have evolved the precipitation population at the same rate. Hence, these clouds potentially can reach final maximum reflectivity at about the same time and at about the same maximum level. Hence, differences in maximum reflectivity might be due to seeding.

Mean echo-core diameter (13) was selected as another indicator of the organization of cloud circulation, and the height of the maximum reflectivity at the time of treatment (14) was chosen to lower the SI if a cloud was raining out at treatment. (Note, a zero height in our sample indicates that an echo core did not exist at treatment. Therefore, the threshold for variable 14 was set to not lower the SI if CPHMxZ was either greater than 1.5 km or if it was equal to zero because an echo core with zero CPHMxZ could not be raining out at treatment.) The acceleration of the cloud top at treatment time (11), defined by the 10-dBZ contour, was chosen because rapid acceleration of growth or decline of the echo top may not be overcome by seeding.

To establish similarity in the meteorological conditions for the development of deep convective clouds, the temperature of the convective condensation level (15) was chosen as an indicator of cloud base height; potential buoyancy (16) was selected as an indicator of the strength of mesoscale vertical motion; a coalescence activity index was developed to provide an indication of the suitability of the mesoscale environment for the production of clouds with "warm" rain processes (17); and Bulk Richardson number (18) was selected as an indicator of an echo core's vertical tilt, because the Bulk Richardson number is the ratio of Convective Potential Available Energy (CAPE) to the density weighted vertical shear of the horizontal wind. Hence, on days when CAPE is relatively large compared to the horizontal shear, echo cores can be expected to exhibit little vertical shear, while the echo cores should be strongly tilted if CAPE is relatively small compared to the horizontal shear.

Finally, two criteria relating to dosage were included to account for responses that may be related to the amount of seeding material released: Dosage 1 (19) was defined to indicate the rate of seeding material released in the updraft, and Dosage 2 (20) refers to the percentage of the flares that were released in the updraft.

Table 2 summarizes the individual seedability index criteria for each of the 71 clouds treated in 1989. Cloud sequence numbers (first column) range from 1 to 71. Sequence 1 was the first large cloud treated during the experiment, and sequence 71 was the last. Individual clouds are identified in the second column. The first three or four characters indicate the month and date, the next four the experimental unit number, and the last four the echo-core number for the experimental unit. The treatment material is listed in the third column (S = sand and A = AgI).

Each column thereafter lists a seedability criterion shown in the same order as in Table 1. A dot in Table 2 indicates that seedability criterion was met according to the threshold levels given in Table 1. A number in Table 2 indicates that a specific criterion was *not* met, and the actual value has been provided to indicate its difference from the threshold value. The notation of "NA" in Table 2 indicates that a certain parameter was not computable, either because of an instrument failure, or because a computational method could not be applied to determine the criterion. For example, if vertical wind in a cloud could not be measured, parameters such as net buoyancy, buoyancy enhancement, liquid water content, and fraction of solid water content could not be computed. Also note in Table 2, the large number of NA notations listed for LWC_d (liquid water in the drizzle and raindrop size distribution). Data for this criterion are limited because the 2D C probe did not function properly, particularly for clouds 1 through 8.

Clouds 10 and 11 had no updrafts. That is, the instrumentation operated properly, but the cloud was composed of all downdraft or didn't have a region with at least one meter per second (m s^{-1}) of upward moving air for 3 continuous seconds. This occurred because flares were released according to our treatment strategy even in weak updraft situations. These clouds were assigned a zero updraft diameter and a zero percent updraft. Furthermore, because calculations of variables like net buoyancy, buoyancy enhancement, and liquid water content depend on the existence of an updraft, these values could not be computed. Hence, NAs appear when no updraft measurements were available.

In the analysis using seedability criteria, 19 of the 71 clouds had to be eliminated from consideration because of a lack of data on the critical variables. Seven of the clouds had no updraft data. One other cloud had no updraft data and did not produce an echo. Four more clouds had no updraft data and no 2D image data. Three more clouds never produced an echo, and another four had no 2D image data. After these exemptions, a sample of 52 clouds remained; 24 that were treated with AgI and 28 with sand.

3. DETERMINATION OF SI RATINGS

The seedability index was computed only for the sample of 52 clouds with all available criteria information, with the exception of cloud-top acceleration (a_cdp). The number of times each cloud met each criterion was summed, and then the percentage of the total possible 20 was computed for each cloud. In the event that a value for cloud-top acceleration could not be computed, the seedability index was calculated on the basis of 19 criteria. These percentages were used as an index, indicating each individual cloud's suitability for seeding. Thus, any two or more clouds could be considered similarly suitable for seeding, even though individual criteria may not exactly

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Table 2. Summary of Individual Seedability Index Criteria Outcomes

Number	CLD_ID	Treat	UP_Dia	Mean VW	% Updraft	NBuoy	Buoy Enh	LWCd	% SWC	FECPt	range	CPMxZ	a_cdp	CPFE dZ/dt	CPmnd ia	CPHM xZ	tcd	pb	L	Ri	U_flrs/ U_km	%_in_ Up	SI
1	519bEU02EC01	S	.	.	.	NA	NA	NA	NA	.	98	.	.	.	.	.	13.2	0.8	.	0.2	4.124	.	NA
2	519bEU02EC04	S	.	9.41	.	NA	NA	NA	NA	.	.	.	-0.0476	.	.	.	13.2	0.8	.	0.2	.	.	NA
3	519bEU02EC05	S	.	8.92	.	NA	NA	NA	NA	.	.	.	.	.	.	.	13.2	0.8	.	0.2	.	.	NA
4	519bEU02EC03	S	763.9	.	.	NA	NA	NA	NA	.	92	.	.	.	.	.	13.2	0.8	.	0.2	6.411	.	NA
5	601EU05EC01	A	NA	NA	NA	NA	NA	NA	NA	.	.	.	NA	.	.	.	.	.	1.7	.	NA	NA	NA
6	601EU05EC02	A	NA	NA	NA	NA	NA	NA	NA	.	.	.	0.0748	.	.	.	.	.	1.7	.	NA	NA	NA
7	601EU05EC03	A	NA	NA	NA	NA	NA	NA	NA	15.83	.	.	.	.	.	.	.	.	1.7	.	NA	NA	NA
8	601EU05EC04	A	NA	NA	NA	NA	NA	NA	NA	.	.	.	.	.	.	.	.	.	1.7	.	NA	NA	NA
9	623aEU11EC01	A	.	.	.	.	.	0.0015	.	.	.	16	.	.	.	.	.	.	1.4	.	.	.	85
10	623aEU11EC02	A	0	0	0	NA	NA	NA	NA	.	.	.	.	.	.	.	.	.	1.4	.	0	0	NA
11	623aEU11EC04	A	0	0	0	NA	NA	NA	NA	.	.	.	-0.0203	.	.	.	.	.	1.4	.	0	0	NA
12	623aEU11EC05	A	.	1.76	.	-2.56	0.43	0.0427	.	.	.	.	.	.	.	.	.	.	1.4	.	.	.	75
13	623aEU11EC06	A	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	1.4	.	.	.	90
14	623aEU11EC07	A	0	0	0	NA	NA	NA	NA	.	.	.	.	.	.	.	.	.	1.4	.	0	0	NA
15	623aEU11EC08	A	253.1	1.62	26.09	-2.9	.	0.0025	.	.	.	.	.	.	.	1.2	.	.	1.4	.	.	25	60
16	623bEU13EC08	S	.	15.28	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1.4	.	.	.	90
17	623bEU13EC09	S	.	.	.	.	.	.	.	.	.	.	-0.0237	.	.	.	.	.	1.4	.	.	.	90
18	623bEU13EC10	S	.	14.28	.	.	.	0.0749	.	.	.	.	.	.	.	.	.	.	1.4	.	.	.	85
19	623bEU13EC11	S	.	10.02	.	.	.	0	.	.	.	14.24	NA	.	.	.	.	.	1.4	.	4.76	.	74
20	623bEU13EC12	S	.	13.9	.	.	.	0	.	.	.	0	NA	.	0	.	.	.	1.4	.	0.543	.	68
21	623bEU13EC13	S	.	.	.	-4.14	.	0.0021	.	.	.	.	.	.	.	.	.	.	1.4	.	1.45	.	80
22	623bEU13EC14	S	.	14.6	.	-3.07	.	0.0003	.	.	.	.	.	.	.	.	.	.	1.4	.	.	.	80
23	708EU17EC01	S	.	.	.	.	.	0	.	.	.	0	.	.	0	.	13.8	.	9	.	.	.	75
24	708EU17EC02	S	950.4	.	.	-5.41	.	0	.	.	.	.	.	.	.	.	13.8	.	9	.	.	.	75
25	708EU17EC03	S	.	.	.	.	.	0	.	.	.	0	.	.	0	.	13.8	.	9	.	0.807	40	65
26	708EU17EC05	S	.	.	.	.	0.39	0	.	.	.	0	.	.	0	.	13.8	.	9	.	.	.	70
27	708EU17EC06	S	.	.	.	.	.	0	.	.	.	.	.	.	.	.	13.8	.	9	.	0.865	.	80
28	708EU18EC07	A	884	1.7	27.03	.	.	.	0.5189	.	.	.	.	.	.	.	13.8	.	9	.	0	0	60
29	708EU18EC09	A	0	0	0	NA	NA	NA	NA	.	.	12.8	NA	.	.	.	13.8	.	9	.	0	0	NA
30	708EU18EC11	A	.	.	.	.	0.41	0	.	.	.	0	NA	-2.9807	0	.	13.8	.	9	.	.	.	63
31	708EU18EC13	A	968.6	.	26.92	.	0.39	0	.	.	.	0	NA	.	0	.	13.8	.	9	.	.	.	58
32	708EU18EC14	A	616.8	.	.	-3.74	.	0	.	.	.	19.24	NA	.	.	.	13.8	.	9	.	0.953	.	63
33	708EU18EC15	A	.	10.4	.	3.17	0.29	0.0498	.	.	.	.	NA	.	.	.	13.8	.	9	.	.	.	68
34	708EU18EC12	A	0	0	0	NA	NA	NA	NA	NA	.	0	NA	NA	0	.	13.8	.	9	.	0	0	NA
35	711EU19EC02	A	.	13.32	.	.	.	0.0005	.	.	104	.	.	-0.875	.	.	.	.	3.4	.	.	.	75
36	711EU19EC03	A	0	0	0	NA	NA	NA	NA	.	95	.	.	.	.	.	.	.	3.4	.	0	0	NA
37	711EU19EC06	A	.	12.88	.	.	0.43	0	.	.	103	16.68	NA	.	.	.	.	.	3.4	.	.	.	68
38	711EU19EC09	A	.	.	.	-2.55	0.41	0	.	.	91	0	.	.	0	.	.	.	3.4	.	.	.	65
39	711EU19EC04	A	864	.	.	-4.39	.	0.009	.	NA	103	0	NA	NA	0	.	.	.	3.4	.	0.615	25	NA
40	711EU19EC05	A	420.8	.	32	-3.67	.	0.0028	.	NA	106	0	NA	NA	0	.	.	.	3.4	.	.	.	NA
41	711EU19EC08	A	.	.	.	-3.27	.	0.0008	.	NA	104	0	NA	NA	0	.	.	.	3.4	.	.	.	NA
42	719aEU20EC01	S	.	11.27	.	.	.	.	.	.	95	.	.	.	.	.	.	2.3	.	.	.	.	85
43	719aEU20EC02	S	.	.	.	-18.32	.	.	0.9679	16.35	102	.	.	.	.	.	.	2.3	.	.	3.597	.	70
44	719aEU20EC03	S	.	.	.	.	.	.	0.5117	.	102	.	.	.	.	1.1	.	2.3	.	.	.	.	80
45	723EU22EC02	A	486.1	.	20.69	.	.	0.0965	.	.	112	.	.	.	.	.	.	.	.	.	4.135	33.33	70
46	723EU22EC04	A	.	.	.	.	.	.	0.4767	15.02	107	.	.	.	.	.	.	.	.	.	4.262	.	80
47	723EU22EC05	A	937	.	.	-2.28	.	0	.	.	99	.	.	.	.	.	.	.	.	.	.	.	80
48	723EU22EC08	A	.	.	.	-3.15	.	.	.	.	105	.	.	.	.	.	.	.	.	.	.	.	90
49	723EU22EC09	A	407.9	1.9	6.94	-2.25	.	.	.	.	100	.	.	.	.	.	.	.	.	.	.	20	70
50	723EU22EC10	A	NA	NA	NA	NA	NA	NA	NA	.	109	.	.	.	.	.	.	.	.	.	NA	NA	NA
51	723EU22EC11	A	0	0	0	NA	NA	NA	NA	.	103	.	.	.	.	.	.	.	.	.	0	0	NA
52	723EU22EC14	A	589	.	30.43	-3.33	.	0.0048	.	.	101	.	.	.	.	.	.	.	.	.	3.511	33.33	65
53	723EU22EC01	A	.	.	.	.	.	.	0.4036	.	110	.	.	.	.	.	.	.	.	.	.	.	90
54	723EU22EC03	A	.	.	.	.	.	0.0179	.	.	109	.	.	.	.	.	.	.	.	.	.	.	90
55	724EU23EC07	S	.	.	.	2.47	.	.	0.8497	17.67	.	.	.	.	.	.	.	.	.	.	1.1	.	80
56	724EU23EC08	S	.	.	.	3.51	.	.	0.9536	24.4	.	.	.	.	.	.	.	.	.	.	0.62	25	75
57	724EU23EC09	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1.318	28.57	90
58	724EU23EC11	S	.	.	.	.	.	0.0853	.	.	.	.	.	.	.	.	.	.	.	.	1.332	.	90
59	724EU23EC06	S	.	.	.	-2.68	.	.	.	.	.	.	NA	-1.2614	.	.	.	.	.	.	.	.	89
60	725EU24EC01	S	517.6	.	.	.	.	0.0028	.	.	102	.	.	.	.	.	.	.	.	.	4.691	.	80
61	725EU24EC03	S	.	.	.	.	.	0.0696	.	53.18	94	.	.	.	.	1.1	.	.	.	.	1.204	.	75
62	725EU24EC04	S	.	.	.	.	.	.	0.6296	.	91	.	.	.	.	.	.	.	.	.	.	.	90
63	725EU24EC05	S	.	.	.	.	.	.	0.7126	18.02	.	.	.	.	.	1.2	.	.	.	.	1.397	.	80
64	725EU24EC06	S	.	.	.	.	.	0.0824	.	15.75	.	.	.	.	.	1.4	.	.	.	.	.	.	85
65	725EU24EC07	S	275.3	.	.	.	.	0.0065	.	.	.	.	.	.	.	.	.	.	.	.	3.711	.	85
66	725EU24EC08	S	448	.	17.86	.	.	.	0.6386	.	98	.	.	.	.	.	.	.	.	.	.	33.33	75
67	725EU24EC09	S	.	.	.	.	.	.	.	.	98	.	.	-0.2333	.	.	.	.	.	.	.	.	90
68	725EU25EC10	A	380.6	.	11.43	.	.	0	.	.	.	0	NA	-4.5568	0	.	.	.	.	.	.	.	68
69	725EU25EC11	A	.	.	.	.	.	0.0029	0.7719	.	.	.	.	.	.	.	.	.	.	.	.	.	90
70	725EU25EC12	A	.	.	.	.	.	0.0203	0.9076	17.27	.	.	.	.	.	1	.	.	.	.	0.621	.	75
71	725EU25ECc3	A	.	.	.	.	.	0	0.6417	22.93	.	.	.	.	.	.	.	.	.	.	1.34	.	80

correspond. The resulting values for the 52 clouds, plotted in the sequence that they were treated, appear in Fig. 1.

This "temporal" plotting of an empirically derived seedability index reveals two interesting features. First, there is a downward trend of the index for experimental units declared from May to early July (clouds 1-41), while the experimental units declared at the end of July (clouds 42-71) varied around a constant level, at least for the criteria selected and the threshold values established. This SI trend indicates the potential inadequacy of visual and real-time in-cloud selection criteria to ensure selection of "similarly seedable" clouds.

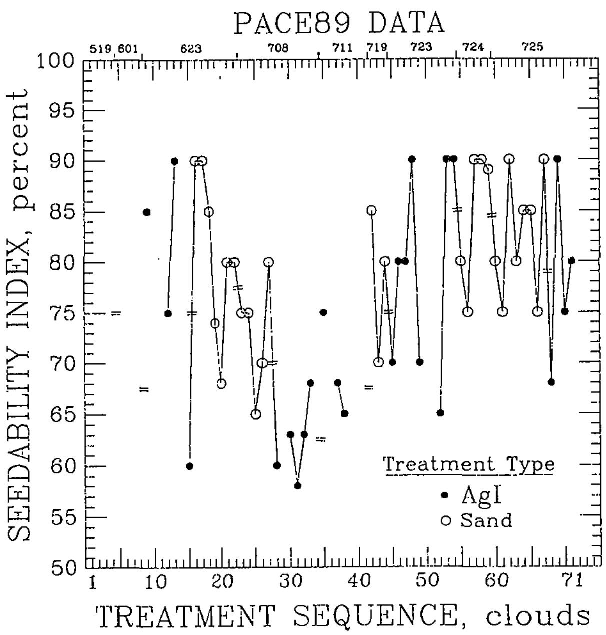

Figure 1. Temporal Variation of the Seedability Index. Values of the index are not joined by a solid line if an intervening value was missing. The beginning of values for experimental units are indicated by two short horizontal lines across the solid line joining intervening values.

The second important finding revealed in Fig. 1 relates to clouds 23-34, all treated on one day, July 8, when a pair of experimental units was obtained. Comparison of the sand- and the AgI-treated echo core values of the seedability index reveals considerable difference in the seedability of the two experimental units. The clouds in the initial unit on this day received sand treatments, and the seedability index shows that these clouds may have been more suitable for seeding than those of the second experimental unit, which was treated with AgI. These two experimental units were separated in space by roughly 50 km and in time by less than 40 minutes. This example of potential storm differences in nearby experimental units that were not separated by different mesoscale or synoptic features, further demonstrates the problem of obtaining comparable samples even within storm periods. It is also worth noting that clouds 60-71, which occurred on July 25, showed no appreciable difference in seedability. These unaccountable likenesses and differences demonstrate one aspect of the great difficulty that natural variability imposes in evaluating cloud seeding experimentation.

4. APPLICATION OF THE SEEDABILITY INDEX

The seedability index was used as a mechanism to create subgroups of clouds that show similarity at the time of seeding, thus providing a valid basis for comparison of responses. For example, this analysis could set a threshold of 90 percent on the seedability index, and then compare the properties of the sand-treated and AgI-treated echo cores at the time of seeding. If the comparisons show no differences in initial cloud characteristics, then comparison of AgI- and sand-treated cloud responses might reveal valid seeding effects if sample sizes are large enough. Thus, any differences discerned in responses might be attributed to the seeding material, assuming that sand truly has no effect on cloud dynamics, and that AgI has an effect at least somewhat consistent with the dynamic seeding hypothesis under testing.

Analyses were performed using SI levels of 90, 80, 70, 60, and 50 percent. *The 1989 PACE Data Book* (Czys et al. 1993) summarizes the results for each of these SI filter levels. Furthermore, clouds with low seedability indexes were also analyzed as a check against biases introduced by the subjective selection of the seedability criteria and thresholds.

Tables 3 and 4 summarize the number of sand- and AgI-treated clouds that met the varying seedability index levels. All 52 clouds met at least 50 percent of the criteria (Table 3). Note that the sample sizes begin to diverge at the 70 percent level. Values in these tables show that there were fewer AgI-treated than sand-treated clouds which had high levels of the SI. This occurred in spite of the randomization scheme. From the standpoint of clouds with low SI, Table 4 shows that only two sand-treated clouds met fewer than 70 percent of the seedability criteria, while ten AgI-treated clouds met less than 70 percent of the criteria, again implying that fewer suitable clouds may have been treated with AgI.

Table 3. Seedability of the Sand and AgI Treated Clouds Expressed in Number of Clouds

Treatment	Number of Clouds Meeting ≥ X% of the SI					
	≥ 50	≥ 60	≥ 70	≥ 80	≥ 90	100
Sand	28	28	26	18	6	0
AgI	24	23	14	9	5	0

Table 4. Non-Seedability of the Sand and AgI Treated Clouds Expressed in Number of Clouds

Treatment	Number of Clouds Meeting < X% of the SI					
	< 50	< 60	< 70	< 80	< 90	100
Sand	0	0	2	10	22	28
AgI	0	1	10	15	19	24

5. KEY FINDINGS

Key results are presented for the most suitable clouds, defined as those with SI ≥ 70 percent; and for less suitable clouds, defined as those with SI < 80 percent. These two subgroups were selected for analysis because they provide a fairly large sample of clouds for each SI filter level chosen. In general, the major findings for clouds in both subgroups are not contradicted by similar analyses at other SI percentages. The data for these analyses are in the *The 1989 PACE Data Book* (Czys et al. 1993).

5.1. Analysis of Clouds with High Seedability Index

Means, standard deviations, sample sizes, and significant levels of the key predictor variables for the clouds that met 70 percent or more of the seedability criteria appear in Table 5. The values of the key predictor variables for the 40 clouds with SI ≥ 70 percent (Table 5) were compared with those for all 67 clouds (Table 6). Comparison revealed that the clouds with SI ≥ 70 percent produced a subgroup of AgI-treated clouds with properties similar to the sand-treated clouds at the time of treatment:

1. Their mean diameters (CPmndia) were greater than the diameters of the sample of all other AgI-treated clouds that had echoes.
2. They were taller, on average, than all other AgI-treated clouds at the time of treatment by nearly 1 km, as indicated by CPHtp10.
3. They had maximum reflectivities (CPMxZ) about 8 dBZ higher at the time of treatment than all other AgI-treated clouds that echoed.
4. They had maximum area weighted reflectivities or maximum brightnesses (CPMxB) about 3 dBZ greater at the time of treatment than all other AgI-treated clouds that echoed.
5. They had areas (CPA10) about 8 km^2 larger at the time of treatment than all other AgI-treated clouds that echoed.
6. Their time from first echo to treatment (FECPt) was longer, on average, than for all other AgI-treated clouds that echoed.
7. There was very little difference in net buoyancy (NBuoy) between them and all other clouds; this was also true for buoyancy enhancement (Buoy_Enh).
8. On average, the mean vertical wind (Mean_VW) was higher for them than for all clouds that echoed.
9. Their fraction of total condensate that was ice (SWC_frac) was greater than the fraction of ice, on average, for all clouds that echoed.
10. Their potential buoyancy (pb) was, on average, lower than that of all clouds that echoed.
11. Their temperature of convective condensation level (tccl) was about the same as that of all clouds that echoed.
12. Their bulk Richardson numbers (Ri) were lower than those of all other clouds that echoed.

A similar comparison of the sand-treated clouds with SI ≥ 70 percent to all sand-treated clouds that echoed showed very little difference between the two samples. Hence, the net effect of using the seedability index as a filter was to obtain sub samples of AgI- and sand-treated clouds that were very similar at the time of treatment, but at the expense of reduced sample size. This provided for a valid comparison of seeding responses.

Results in Table 5 show that none of the predictor variables were significantly different. In contrast, Table 6 shows that 9 of the 13 predictor variables for sand- and AgI-treated clouds were significantly different for either the *t*-test, the Wilcoxon test, or both. It should be noted that in testing 13 variables, approximately 10 to 15 percent can be expected to be significantly different from one another by chance. Hence, at least one or possibly two predictor variables should be statistically different from one another by chance. Therefore, with no significant differences shown in Table 5, the sand- and AgI-treated clouds can be considered to be virtually identical at the time of treatment; any differences discerned in the response variables could be cautiously attributed to the treatment, considering the small sample size.

Table 7 lists key response variables for clouds that met ≥ 70 percent of the seedability criteria. Only one response variable showed a significant difference between the AgI and sand treatments: maximum height of the 10 dBZ contour (MaxH10). Again, it should be noted that one response variable may be found to be statistically significant by chance. Hence, to the extent that this significant difference did not happen by chance, the response data suggest that the AgI-treated clouds may not have grown as tall as the sand-treated echo cores. Evidence of no other effects on parameters such as area, reflectivity, or brightness, whether from either the time of treatment or from the time of first echo to maximum could be found in the data for clouds with SI ≥ 70 percent. Examination of similar responses for clouds with SI ≥ 50 to 90 percent can be made in *The 1989 PACE Data Book* (Czys et al. 1993). These analyses also support the conclusion that if AgI had any appreciable effect on cloud growth, it was a negative effect on maximum height. This conclusion is clearly opposite from that expected according to the dynamic seeding hypothesis.

Figure 2 was constructed using data for clouds with SI ≥ 70 percent, following methods that are similar to those presented in Rosenfeld and Woodley (1989). The figure was created from echoes that were tracked 3 dimensionally from first echo until they either merged and were no longer distinguishable as an individual entity, or until they

Table 5. Population Statistics of Predictor Variables for Clouds with SI ≥ 70% (N = 40).

Variable	Mean Sand	Mean AgI	Standard Deviation Sand	Standard Deviation AgI	Sample Size Sand	Sample Size AgI	P-Values *t*	P-Values *W*
CPmndia	4.8	4.4	2.1	2.3	26	14	0.65	0.16
CPHtp10	7.5	7.6	2.6	1.9	26	14	0.98	0.42
CPMxZ	44.3	41.7	17.3	14.2	26	14	0.77	0.45
CPMxB	23.1	22.1	8.7	5.8	26	14	0.80	0.32
CPA10	34.3	33.1	22.6	38.3	26	14	0.88	0.27
FECPt	9.5	8.3	11.8	7.3	26	14	0.69	0.88
NBuoy	-1.3	-1.2	3.9	1.2	26	14	0.95	0.24
Buoy_Enh	0.5	0.5	0.0	0.0	26	14	0.23	0.23
Mean_VW	6.3	4.7	3.8	3.0	26	14	0.53	0.32
SWC_frac	0.2	0.3	0.3	0.3	26	14	0.86	0.75
pb	4.4	4.2	1.8	1.1	26	14	0.82	0.74
tccl	16.9	16.8	1.8	1.2	26	14	0.94	0.88
Ri	71.3	78.9	21.9	32.9	26	14	0.64	0.91

p ≤ 5%	p ≤ 10%	p > 10%

Table 6. Population Statistics for All Clouds with Radar Data (N = 67).

Predictor Variable	Mean Sand	Mean AgI	Standard Deviation Sand	Standard Deviation AgI	Sample Size Sand	Sample Size AgI	P-Values *t*	P-Values *W*
CPmndia	4.8	3.5	2.5	2.3	32	35	0.04	0.02
CPHtp10	7.1	6.1	3.1	2.8	32	35	0.03	0.01
CPMxZ	43.2	33.9	19.7	17.9	32	35	0.07	0.02
CPMxB	22.4	18.25	10.0	8.6	32	35	0.11	0.02
CPA10	38.2	23.5	29.5	28.7	32	35	0.07	0.03
FECPt	8.8	6.0	11.1	6.2	32	35	0.15	0.28
NBuoy	-1.3	-1.2	3.8	1.6	28	24	0.97	0.20
Buoy_Enh	0.5	0.5	0.1	0.1	28	24	0.06	0.06
Mean_VW	6.6	4.0	3.8	3.6	32	30	0.23	0.15
SWC_frac	0.2	0.2	0.3	0.3	28	24	0.75	0.94
pb	4.1	5.4	2.1	1.8	32	35	0.09	0.02
tccl	16.3	16.4	2.1	1.6	32	35	0.90	0.83
Ri	62.1	81.1	31.0	38.9	32	35	0.42	0.75

p ≤ 5%	p ≤ 10%	p > 10%

Table 7. Population Statistics of Response Variables for Clouds with SI ≥ 70% (N = 40).

Variable	Mean Sand	Mean AgI	Standard Deviation Sand	Standard Deviation AgI	Sample Size Sand	Sample Size AgI	P-Values *t*	P-Values *W*
MaxH10	10.8	8.6	2.7	2.0	26	14	0.08	0.09
MaxA10	80.2	65.6	61.2	55.6	26	14	0.25	0.27
MaxZ	52.6	52.1	13.5	12.2	26	14	0.98	0.88
MaxB	27.7	28.2	6.4	6.5	26	14	0.84	0.72
MXCPdH10	2.5	0.7	2.7	1.5	26	14	0.25	0.20
MXCPdA10	37.0	26.9	57.5	46.0	26	14	0.49	0.75
MXCPdZ	5.0	6.6	12.2	12.8	26	14	0.81	0.86
MXCPdB	2.7	3.3	6.2	7.0	26	14	0.88	0.79
CPMXtMxA	9.5	8.3	14.1	7.7	26	14	0.82	0.44
FEMXtMxA	19.0	16.6	11.1	9.2	26	14	0.44	0.34

p ≤ 5%	p ≤ 10%	p > 10%

dissipated. Of the 67 echo cores that were tracked, 7 dissipated without merging. Five of these echo cores were treated with AgI and 2 treated with sand. Of the 60 echo cores whose tracking was terminated because of merger, 30 received an AgI treatment and 30 received sand.

In Fig. 2a, mean echo-core height was computed for only those echo cores that existed at each interpolated observation time relative to the time of treatment, indicated by the vertical dashed line at time zero. Hence, sample size, given by the numbers above and along the abscissa of the figure for either AgI- or sand-treated clouds, changes with time. Thus, in the top diagram of Fig. 2, the AgI-treated echoes observed at 9 minutes prior to treatment are not necessarily the same AgI-treated echoes observed 24 minutes after treatment. Because Fig. 2a allows only for comparison of echoes that were in existence at the observation time, mean values were recomputed using the entire sample of clouds at each interpolated observation time, and this is shown in Fig. 2b. In this case, a zero height was used for every observation time at which no echo core existed.

Examination of both plots of Fig. 2 reveals two important features. First, both methods of computing mean maximum height reveal that for a period of time after treatment the sand-treated clouds were taller than the AgI-treated clouds. Figure 2a suggests that this difference is greater than one standard measurement error $\left(\frac{\sigma}{\sqrt{n}}\right)$ by 2 to 3 km, for a duration of approximately 30 minutes, beginning at about the time of treatment. The difference between the mean maximum heights of the sand- and AgI-treated clouds is much less dramatic when computed on the basis of a constant sample size (Fig. 2b). However, Fig. 2b suggests that there may have been a short period of time (~12 minutes) when the mean maximum height of the sand-treated clouds exceeded that of the AgI-treated clouds, by one standard measurement error.

In Fig. 2a differences that might be due to seeding are obscured somewhat because the growth trend, both for the sand- and AgI-treated clouds, appears to be nothing more than an extension of expected echo-top behavior beginning almost 21 minutes prior to treatment. However, this conclusion is not supported by Fig. 2b which indicates that the mean maximum echo-core tops for both the AgI- and sand-treated clouds begin to diverge from each other possibly as soon as 3 minutes after treatment. Therefore, evidence that AgI treatment had any effect on mean maximum echo core height is extremely weak. To the extent that AgI treatment may have had an effect, it may have been negative and opposite to that expected according to the dynamic seeding hypothesis.

Figure 3 shows composite diagrams for mean maximum echo-core areas. As can be seen in Fig. 3a, mean area growth rates overlap one another beginning almost as early as 21 minutes prior to treatment, and they continue to be similar until about 12 minutes after treatment. After that time the AgI-treated echo cores suddenly decline in mean

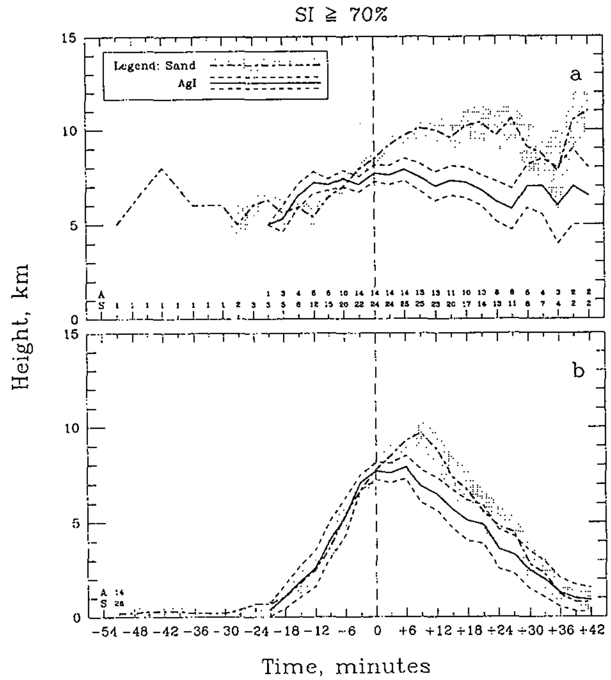

Figure 2. Variation with Time of Maximum Echo Top Height for Sand- and AgI- Treated Echoes With SI ≥ 70% in Existence at Each Interpolated Volume Scan (a) and all Treated Echoes (b).

area, separating the means by more than one standard error. However, mean areas computed on the basis of the entire sample of clouds (Fig. 3b) do not show a dramatic difference. Thus, although the "snap-shot" of response variables that is offered in Table 7 did not suggest an effect on area, Fig. 3a and Fig. 3b provide some indication that there may also have been a negative effect on echo core area. This finding is also inconsistent with that expected from the dynamic seeding hypothesis.

Figure 4 shows mean maximum reflectivity with time before and after treatment. While Fig. 4b gives no indication of a seeding effect on reflectivity, Fig. 4a shows faint evidence that there may have been a reduction in reflectivity which roughly corresponds to the time that Fig. 3a suggests a reduction in area. However, the decrease in reflectivity at about 21 minutes after treatment occurs only briefly adding to the uncertainty with which a firm conclusion can be drawn.

Figure 5 shows composite diagrams for mean maximum rain flux for echo cores that met ≥ 70 percent of the seedability criteria. These plots are the "noisiest" of the composite diagrams and of course calculation of rain flux is subject to large uncertainty, all of which adds to interpretation difficulty. However, the plots appear to indicate that both samples of echo cores had similar rain flux from approximately 18 minutes prior to treatment until about 15 minutes after treatment. After this time and corresponding to the decrease in mean echo-core area and reflectivity, rain fluxes for the sand-treated echoes become about one standard error greater than the AgI-treated echoes. This difference persists up to 33 to 42 minutes after treatment.

In summary, the evidence presented in Figs. 2 - 5 and in Table 7 does not provide a definitive conclusion about what effect, if any, that AgI treatment may initially have had on the individual echo cores with SI ≥ 70 percent. However, if there was any effect at all, the evidence seems to point toward some reduction of echo core:

1. height;
2. area;
3. reflectivity; and
4. rain flux.

All of which are contrary to that expected from the dynamic seeding hypothesis. Therefore, above all, these results warrant a reconsideration of the dynamic seeding hypothesis and call into question its applicability in Illinois.

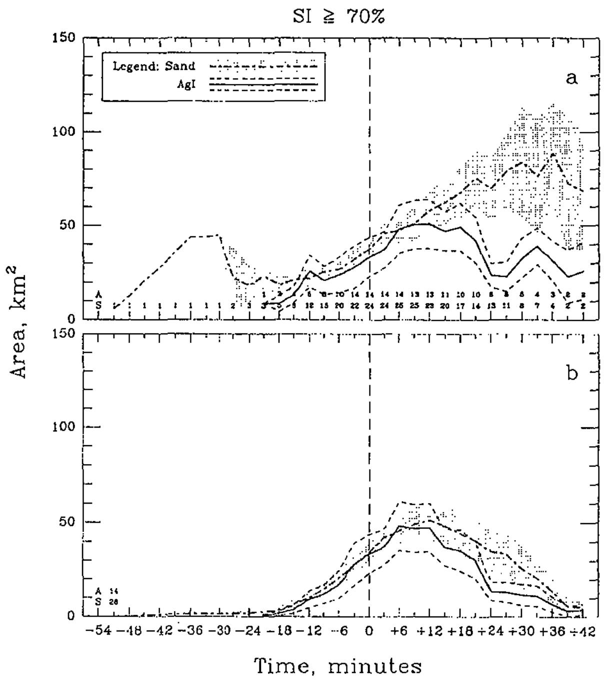

Figure 3. Variation with Time of Maximum Echo Area for Sand- and AgI- Treated Echoes With SI ≥ 70% in Existence at Each Interpolated Volume Scan (a) and all Treated Echoes (b)..

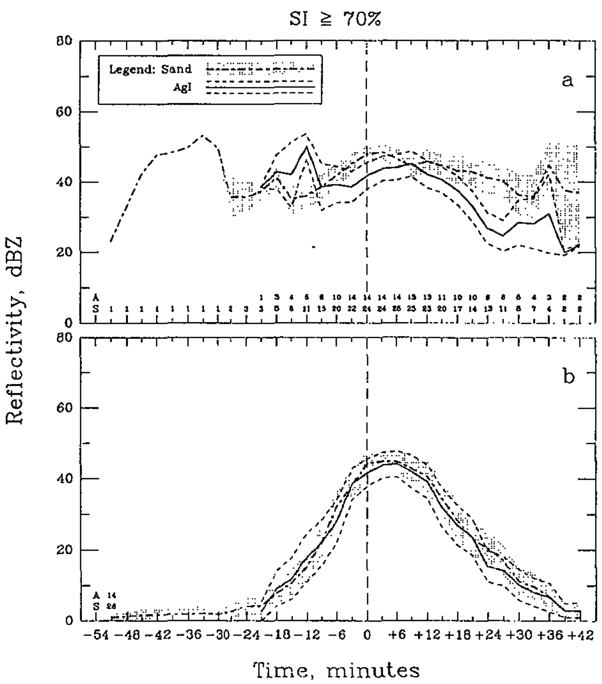

Figure 4. Variation with Time of Maximum Echo Reflectivity for Sand- and AgI- Treated Echoes With SI ≥ 70% in Existence at Each Interpolated Volume Scan (a) and all Treated Echoes (b).

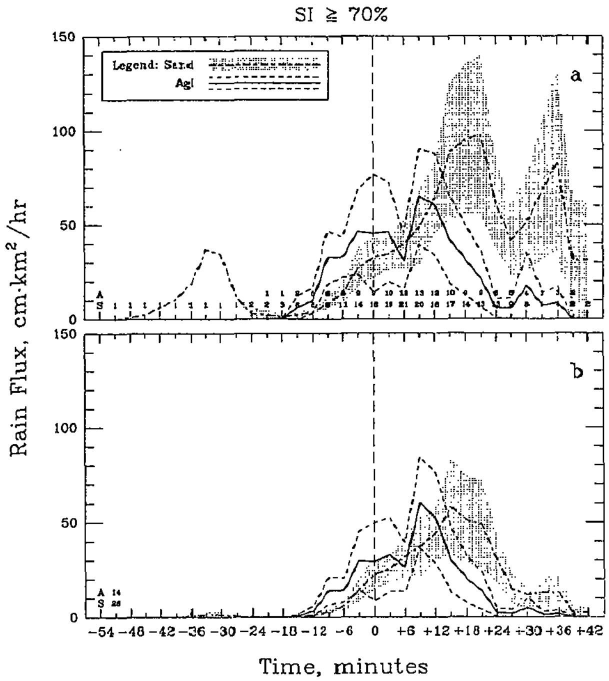

Figure 5. Variation with Time of Maximum Rain flux for Sand- and AgI- Treated Echoes With SI ≥ 70% in Existence at Each Interpolated Volume Scan (a) and all Sand- and AgI- Treated Echoes (b).

5.2 <u>Analysis of Clouds with Low Seedability Index</u>

Comparative analysis was also performed on clouds with relatively low seedability indexes; that is, clouds with SI < 80 percent. Key predictor variables for clouds with SI < 80 percent are listed in Table 8. The significance tests indicate that the subgroup of clouds with SI < 80 percent were similar at the time of treatment, noting that buoyancy enhancement (Buoy_Enh) had the highest significance levels. However, the mean and standard deviations for buoyancy enhancement are the same. Given the high likelihood of one significant difference in ten due to chance, the populations of sand- and AgI-treated clouds in this subgroup can be considered similar at treatment, thus allowing for comparison of response to discern seeding effects.

Table 9 lists key response variables for clouds with low SI. The only variable with a weakly significant difference is change in area from treatment time to maximum (MXCPdA10). This indicates that the AgI-treated clouds may have undergone a larger change in area than the sand-treated clouds. However, if we again apply the general rule that 10-15 percent of a sample of variables will show significant differences, this one weak significance level is insufficient for a strong claim for a seeding effect. Therefore, the results in Table 9 suggest that AgI may have had little or no initial effect on the echo cores with SI < 80 percent.

Figure 6 shows mean maximum heights for clouds with SI < 80 percent. In both panel "a" and "b", the two traces are intertwined, and the behavior after treatment appears to be nothing more than an extension of that expected from the trends prior to and around the time of treatment. Thus on average, AgI seeding likely had no effect on maximum echo-core height.

Figure 7 indicates that the sand-treated clouds generally had larger areas prior to the time of treatment, but from about 6 minutes after treatment their areas were generally smaller than the AgI-treated echo cores. However, the differences are barely more than one standard error, and in both the sand and AgI cases, trends after treatment do not appear to be different from that expected from trends in area prior to treatment.

Figure 8 shows mean maximum reflectivity for the sand- and AgI-treated echo cores prior to and after treatment. Fig. 8a shows that on average, the maximum

Table 8. Population statistics of predictor variables for clouds with SI < 80% (N = 25).

	Mean		Standard Deviation		Sample Size		P-Values	
Variable	Sand	AgI	Sand	AgI	Sand	AgI	*t*	W
CPmndia	2.6	2.3	2.7	1.8	10	15	0.64	0.81
CPHtp10	4.8	5.0	4.2	3.3	10	15	0.89	0.50
CPMxZ	24.3	23.4	24.4	17.9	10	15	0.93	0.98
CPMxB	13.5	13.2	12.7	9.3	10	15	1.00	0.85
CPA10	18.3	10.5	23.5	12.4	10	15	0.28	0.78
FECPt	8.9	4.0	18.5	5.1	10	15	0.37	0.81
NBuoy	-2.5	-1.3	6.0	1.7	10	15	0.67	0.74
Buoy_Enh	0.5	0.5	0.1	0.1	10	15	0.14	0.14
Mean_VW	5.6	5.2	3.8	4.0	10	15	0.74	0.59
SWC_frac	0.3	0.1	0.4	0.3	10	15	0.33	0.81
pb	5.6	6.1	2.4	2.1	10	15	0.54	0.56
tccl	15.8	16.0	2.1	1.9	10	15	0.96	0.75
Ri	70.8	95.3	20.3	46.2	10	15	0.67	0.67

$p \leq 5\%$ | $p \leq 10\%$ | $p > 10\%$

Table 9. Population Statistics of Response Variables for Clouds with SI < 80% (N = 25).

	Mean		Standard Deviation		Sample Size		P-Values	
Variable	Sand	AgI	Sand	AgI	Sand	AgI	*t*	W
MaxH10	8.8	8.5	1.5	2.2	10	15	0.70	0.55
MaxA10	38.5	39.5	29.4	39.4	10	15	0.92	0.83
MaxZ	39.1	42.9	16.5	13.9	10	15	0.38	0.43
MaxB	21.6	23.6	7.7	7.4	10	15	0.38	0.56
MXCPdH10	0.7	0.0	0.8	3.3	10	15	0.55	0.58
MXCPdA10	2.8	27.8	25.1	39.2	10	15	0.05	0.26
MXCPdZ	9.3	10.9	17.6	22.9	10	15	0.85	0.75
MXCPdB	5.2	5.6	9.7	12.7	10	15	0.91	1.00
CPMXtMxA	3.2	8.8	15.2	7.2	10	15	0.36	0.56
FEMXtMxA	12.1	12.8	7.4	8.2	10	15	0.77	0.94

$p \leq 5\%$ | $p \leq 10\%$ | $p > 10\%$

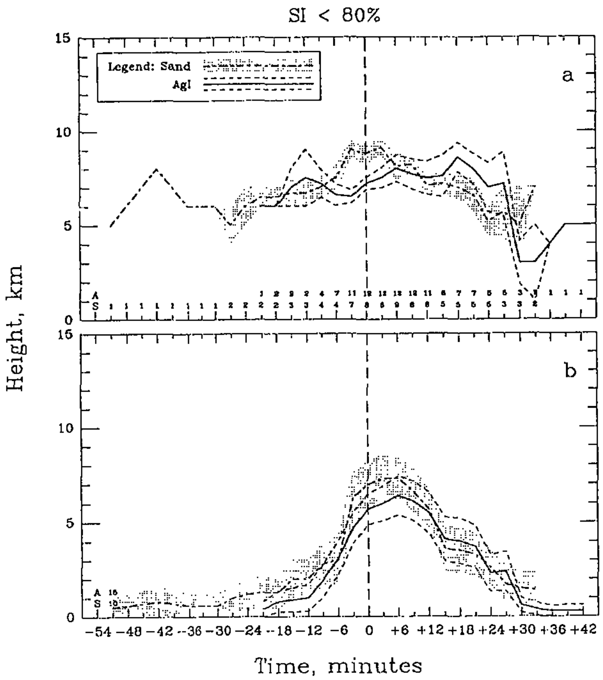

Figure 6. Variation with Time of Maximum Echo Top Height for Sand- and AgI- Treated Echoes With SI < 80% in Existence at Each Interpolated Volume Scan (a) and all Treated Echoes (b).

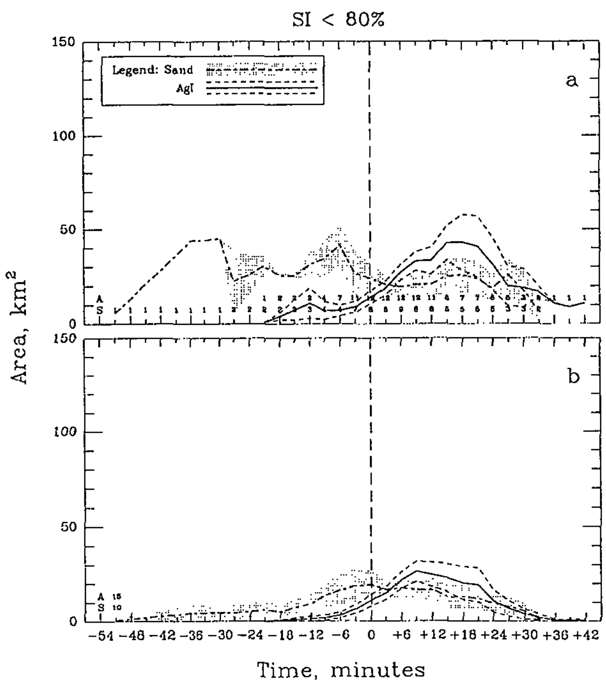

Figure 7. Variation with Time of Maximum Echo Area for Sand- and AgI- Treated Echoes With SI < 80% in Existence at Each Interpolated Volume Scan (a) and all Treated Echoes (b).

reflectivity for sand-treated clouds declined from approximately 12 minutes prior to treatment to about 30 minutes after treatment, while the mean maximum reflectivity of the AgI-treated echo cores follows an inverted parabolic curve such that reflectivities exceed those of the sand-treated cores for much of the time after treatment. However, as has previously been the case, the trends do not appear to be drastically different than expected from pre-treatment behavior.

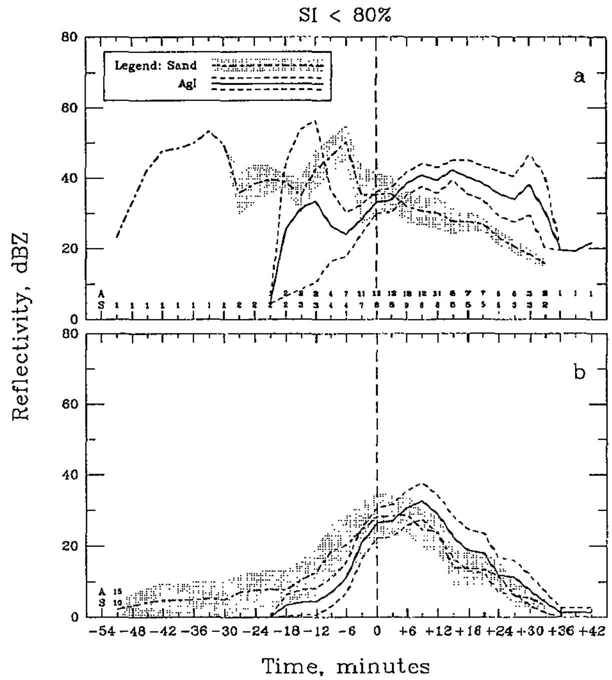

Figure 8. Variation with Time of Maximum Echo Reflectivity for Sand- and AgI- Treated Echoes With SI < 80% in Existence at Each Interpolated Volume Scan (a) and all Treated Echoes (b).

The diagrams for rain flux (Fig. 9) show little difference, on average, between the sand- and AgI-treated clouds. However, rain flux among the AgI-treated clouds continues for approximately 15 minutes after the values for the sand-treated clouds hover into zero, weakly suggesting that the AgI treated echo cores may have had a greater persistence of rain flux.

In summary, the evidence presented in Figs. 6 - 9 and in Table 9 again does not provide a definitive conclusion about the effect that AgI treatment may initially have had on the population of individual echo cores with SI < 80 percent. However, the evidence for "less suitable" echo cores seems to indicate positive seeding effects on:

1. area;
2. reflectivity; and
3. rain flux.

All of which are consistent with that expected from the dynamic seeding hypothesis, but yet unexpected for

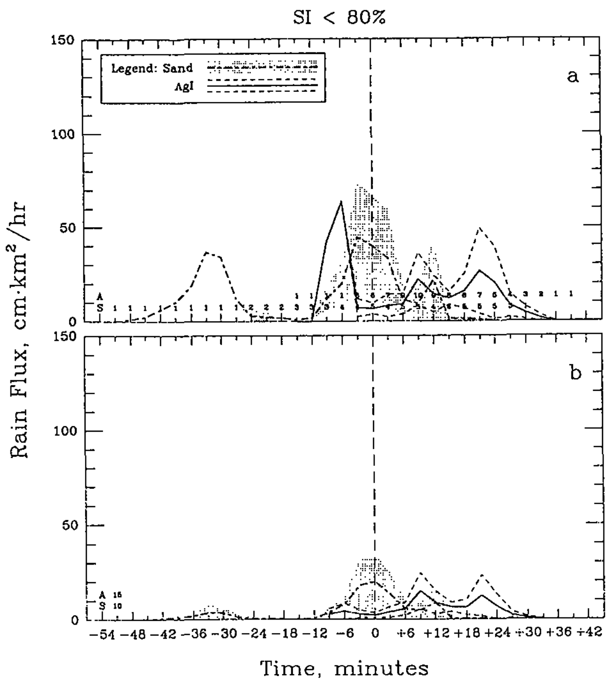

Figure 9. Variation with Time of Maximum Rain flux for Sand- and AgI- Treated Echoes With SI < 80% in Existence at Each Interpolated Volume Scan (a) and all Sand- and AgI- Treated Echoes (b).

echo cores with lower SI. Thus, to the extent that these results indicate a valid seeding signal, the dynamic seeding hypothesis for Illinois is further called into question.

6. DISCUSSION

This paper focused upon initial responses, those only up to about 30 minutes after treatment, of individual echoes to AgI seeding. It did *not* address the potential effect that AgI seeding may have on the echo system as a whole. Such effects may not be present until 30 minutes or more after AgI treatments (Rosenfeld and Woodley 1989). Furthermore, the 1989 echo core sample was initially small, and analysis by filtering according to the seedability index made the sample even smaller. This condition and the fact that the analysis was based on only a single summer's worth of data precludes statistical support for any conclusions.

The primary result from the seedability index analysis was that AgI seeding did not have a dramatic initial effect on the behavior of individual echo cores, at least for the radar based response variables chosen for their relevance to the Illinois dynamic seeding hypothesis. The analysis for echo cores with high seedability index (i.e., those which were perhaps better suited for dynamic seeding than those with low seedability index) gave some very limited indication of a general negative effect on individual echo core behavior in regard to growth stimulation, while evidence for echo cores with low seedability showed very limited indication of a general positive reaction. Both indications, if they reflect more than that related to natural variability, are contrary to that expected according to the dynamic seeding hypothesis for Illinois. These highly unexpected results from such a limited sample are cause for extreme caution before taking the next step toward interpretation within the context of physical processes, and rejection and/or revision of the initial steps of the seeding hypothesis for Illinois.

These results may also have limited implications for interpreting those from other dynamic seeding experiments because some of the operational procedures and selection criteria used during the 1989 Illinois experiment departed somewhat from those traditionally used. For example, in declaring experimental units used in the analysis reported herein, the cumulus congestus clouds growing as individuals or feeder cells must have shown vertical propagation of cloud top to heights easily through the -10°C level, surpassing an estimated 7.6 km usually by about 150 to 300 m min^{-1} (500 to 1000 ft min^{-1}). Thus, at the time any particular experimental unit was declared during the 1989 Illinois experiment, it was permissible to have at least one cloud with top greater than approximately 10 km residing within the experimental unit (Changnon et al. 1989). This condition has not been permissible in other dynamic seeding experiments such as that conducted in West Texas (Rosenfeld and Woodley 1989), but the extent to which this particular difference makes the Illinois experiment completely incomparable to other dynamic seeding experiments is uncertain.

There were several reasons that an experimental unit was allowed to be declared even if it may have had clouds taller than 10 km. First, it helped fulfill one of the main objectives of the exploratory experiment: to obtain the largest possible sample of treated clouds and experimental units. More importantly, for rain augmentation to have some practical benefit to agriculture, it would have to come from the "garden" variety rain systems that were the subject of 1989 Illinois experimentation, and not a few special and isolated cases that make only an inconsequential contribution to the summer rainfall needed by agriculture. Thus, more work is needed before we will be able to assess the true implications of the 1989 exploratory experiment in Illinois.

However, it may not be prudent to simply ignore the present evidence, particularly because of the strong implications that it has for future exploratory seeding in Illinois, if not also on other future convective cloud seeding experiments.

Perhaps some reexamination of the early steps of the dynamic seeding hypothesis for Illinois are in order. The multi-updraft structure of the Illinois echo cores (Czys 1991, Ackerman et al. 1978) made it impossible to perfectly target the seeding material. Thus, negative effect of AgI seeding on maximum echo top height in the echo core sample with relatively high SI could have occurred as a consequence of uneven latent heat releases that may increase cloud turbulence rather than strengthening and organizing the updraft (Gayet and Soulage 1992). The effect of enhanced turbulence would be to mix updraft regions into downdraft and vice versa. Consequently, AgI-treated cores should not grow to maximum heights that would be greater than the sand-treated cores. This argument aims at the need to properly target the seeding agent to the updraft regions, as has long been understood.

The seeding agent may also have had a profound effect on the entire size spectrum of supercooled droplets and drops. The supercooled cloud droplet population ($d < 100\ \mu m$) should not be selectively spared from interacting with the seeding agent because the concentration of supercooled cloud droplets is several orders of magnitude greater than that of drizzle and raindrops ($D \geq 100\ \mu m$), and cloud droplets must be in much closer thermoequilibrium with the environment than supercooled drizzle and raindrops. Following the discussion in Dennis (1980), estimates based on simple Brownian collection theory indicate that approximately 10,000 cloud droplets should capture an AgI particle in the same time it takes one raindrop to capture an AgI particle, assuming 1989 Illinois seeding rates and cloud droplet concentrations measured at the seeding level. This estimation does not take into account depletion of AgI particles by the direct production of artificial ice crystals from the vapor.

One component of the seeding effect based on these considerations is that broadening of the particle spectrum by coalescence and riming processes would be stunted to some extent because both of these processes depend on supercooled cloud droplets as a source for growth. Thus, processes that tend to move condensate into precipitation particle sizes would be restricted in the presence of enhanced latent heat release. However, the 1989 Illinois reflectivity data presented herein do not suggest any large differences between the AgI- and sand-treated echo cores as might be expected if the production of precipitation-size particles is suppressed. These are issues which should be resolved in future field programs to achieve a better theoretical and observational understanding about natural precipitation processes, and how they may be altered by AgI at the in-cloud, cloud, and meso scales.

7. CONCLUSIONS

The use of a seedability index to create subgroups of clouds with similar characteristics at the time of the treatment so that comparisons of responses could reveal a true seeding effect was reported. The seedability index was developed and used to create sub-groups of "suitable" and "unsuitable" clouds for dynamic seeding with nearly identical properties at the time of treatment, thereby overcoming the "bad draw." This allowed for comparison of responses to discern possible seeding effects. However, the inherent reduction in sample size along with other factors precluded obtaining conclusive evidence.

The primary finding from this analysis was that AgI treatment did not have a dramatic initial effect on the behavior of individual echo cores.

A detailed examination of the responses for "suitable" clouds (those with SI $\geq$70 percent) indicated that *if* AgI had any effect on cloud behavior it was to reduce maximum echo-top height. Composite diagrams showing average maximum echo-core height with time also suggested a negative effect of AgI on vertical cloud growth. Similar composite diagrams for area, reflectivity, and rain flux indicate that AgI-treated clouds may have had, on average, smaller areas, lower reflectivities, and smaller rain fluxes than sand-treated clouds. However, it remains uncertain whether these responses were the result of seeding or merely extensions of that expected from echo behavior before the time of treatment. These results are not generally sensitive to the SI filter level used, and are inconsistent with the dynamic seeding hypothesis that was developed for Illinois.

Responses of clouds with low seedability indexes (those with SI < 80 percent) showed no conclusive evidence that AgI affected cloud growth behavior in maximum height, area, reflectivity, or rain flux. Close examination of composite diagrams for average maximum height, area, and rain flux suggested that AgI may have had a positive effect on clouds that were "less suitable" for dynamic seeding. However, the extent to which this indicates a weak seeding signal cannot be totally separated from expectations based on the trend of cloud behavior prior to treatment.

In general, the effect of AgI on echo cores within approximately 30 minutes of treatment was unappreciable according to radar observations. Possible effects opposite to those expected from the dynamic seeding hypothesis were found for clouds with both high and low seedability indexes. This calls into question the validity of the initial steps of the dynamic seeding hypothesis for Illinois, and draws attention to the need to improve basic understanding of how natural cloud processes operate and interact at different atmospheric scales.

Speculation was made about one alternative view of how the seeding material may initially negatively affect echo core behavior. The role of the feeder cores may be to disperse the seeding material throughout a large echo core volume at the expense of vertical growth. One important implication of these findings is that future seeding experiments should note the potential extreme sensitivity of results to what and how measurements are taken, and that the multi-scaled nature of cumulonimbus systems be taken well into account.

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