ORGANIC ICE NUCLEI FIELD TESTS: SOUTH DAKOTA AND LEADVILLE COOPERATIVE PROJECTS, SUMMER, 1975

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1. INTRODUCTION

Organic ice nucleants offer the prospect of effective and ecologically safe cloud seeding materials at much lower cost than silver iodide. We have been developing practical ice nuclei generators for three selected organic nucleants: 1,5-dihydroxynaphthalene (DN), phloroglucinol (PG), and metaldyhyde (MA). In the summer of 1975, we participated in two separate field experiments to investigate the effectiveness of DN for cumulus seeding. Both experiments used the airborne jet-mixing organic smoke generator described by Fukuta et al.(1975). The first experiment, denoted "Special Organic Field Tests" (SOFT) was carried out in June and July in Butte and Meade counties in South Dakota, just north and east of the Black Hills. It was a randomized experiment using radar, visual and photographic observations to detect seeding effects. The second experiment, extending from mid-July to early August, was headquartered in Leadville, Colorado. Seeding and tracer materials were released at cloud base and the NCAR sailplane "Explorer" gathered quantitative data on ice nuclei, ice crystal, and tracer concentrations in a small number of seeded clouds. We describe the SOFT experiment in some detail here, and then give preliminary results from the Leadville experiment.

2. SOFT EXPERIMENT

In August, 1974, in cooperation with the Division of Weather Modification, South Dakota Department of Natural Resources (SDDWM), we carried out an exploratory cloud seeding program to test the effectiveness of DN for cumulus seeding (Fukuta, et al., 1975). The approach was to seed any growing cumuli in the area around Rapid City, South Dakota, to see if a seeding effect could be detected. This experiment was very successful; every time a cloud with an appreciable supercooled liquid water content was seeded, visual evidence of cloud glaciation and virga development was obtained. No systematic attempt was made to select and observe control (unseeded) clouds, however. The 1975 experiment was undertaken to supply this information. An objective procedure for choosing test clouds was set up, and the decision to seed or not seed was made after a test case was chosen, by opening a sealed envelope containing a random seeding instruction. The same seeding generator, mounted on a Piper Aztec airplane, was used in both 1974 and 1975, and seeding in both experiments was done by penetrating clouds at the $-5^{o}C$ level. The design and operation of the generator are described by Fukuta, et al. (1975).

The experimental design is described in the next section. The SDDWM carried out an operational program of cloud seeding for rain increase and hail suppression in over 40 of the 65 counties in the state of South Dakota. In western South Dakota, the counties of Custer, Pennington, and Lawrence (covering most of the Black Hills region) participated in the operational program, so that experimental seeding was prohibited in these counties. The SOFT experiment was carried out in Butte and Mead counties, which lie just north and northeast of the Black Hills, since these counties did not participate in the operational program. The SOFT experiment used the SDDWM radar located near the town of Newell in Meade county, and a Piper Aztec seeding aircraft based at Rapid City airport. The Denver Research Institute field team consisted of a project director stationed at the radar site and seeding generator operator-observer, stationed at Rapid City on board the seeding aircraft. Since the SDDWM operational program needs carried top priority at all times, any SOFT experiments were cancelled whenever the facilities were needed for the SDDWM program. In particular, the heavy demands on the radar during hail suppression operations precluded SOFT operations at such times.

a. Experimental Design

The 1975 SOFT program in South Dakota was planned as a randomized cumulus seeding experiment with radar as the primary observational tool. The design for the experiment itself and the plan for evaluation of results were as follows.

Seeding Design:

Growing cumuli were seeded by penetration at the -5°C level. The seeding aircraft chose a suitable cloud (the criteria for the choice are described below), and photographed it before penetration. Just prior to penetration, a sealed envelope was opened to determine whether the cloud was to be seeded or not. After first penetration, the aircraft executed a 180° turn, thus enabling a second penetration in the opposite direction, but approximately along the same path as the first. After the second penetration, the aircraft returned to the vicinity from which the first photograph was taken, and took successive photos at about 5-minute intervals until 30 minutes had elapsed from the start of the first penetration. This constituted one test case. These steps were followed whether the cloud was seeded or not.

The criteria for an operational day were as follows:

1. Forecast called for towering Cu between 8 and 30 k ft (2.44-9.14 km) in depth (cloud base to cloud top) during daylight hours, in Butte and Meade counties.

2. No SOFT operations to be carried out if:

   a. 500 mb temperature colder than -15°C
   b. Newell radar not operational
   c. Hail suppression activities in progress in the district
   d. Operations deemed hazardous by aircraft pilot, SOFT personnel, or SDDWM operations manager.

3. The criteria for a suitable test cloud were as follows:

   a. Cloud top temperature -8°C or colder
   b. Cloud diamter 1 statute mile or greater
   c. Cloud depth 8 kft (2.44 km) or greater
   d. Cloud has hard, unglaciated "cauliflower" top.

The radar was equipped with a digital data acquisition system to automate the gathering of quantitiative radar data (echo intensity, azimuth, elevation, and range). Procedures for use of this equipment were worked out prior to the start of operations. However, problems with the radar and, especially, the echo processor persisted through much of the summer. The radar and echo processor functioned simultaneously on only two days, 22 and 23 June, which were also the two days when 9 test cases were obtained. The echo processor was inoperative for the remainder of the experiment. In view of the effort required to process this small sample of radar data, compared with its potential value, it was decided not to use the digital radar data for evaluation of the experiment.

Evaluation design:

Radar was intended as the primary observational tool. Supplementary data were to be derived from visual and photographic observations of test clouds. A time-lapse movie camera was opearated at the radar site for photographic coverage to supplement the airborne still photographs.

Test case duration was set at 30 minutes. In the initial design, only clouds with no radar echo were to be selected, and any cloud developing a radar echo sooner than 5 minutes after declaration of a test case was to be eliminated from the data sample, since seeding effects should not appear on radar in times less than this. Primary radar data for evaluation was to be the time of first echo appearance, maximum echo intensity vs time, and maximum echo height and area, in order of importance. Supplementary data were to be visual and photographic observations of glaciation at cloud tops, vertical development, and virga formation.

b. Results

The weather:

The weather in western South Dakota, and Butte and Meade counties in particular, was almost uniformly unsuitable for a cumulus seeding experiment during the months of June and July, 1975. Only 15 test cases were obtained in the randomized experiment, and 9 of those occurred on two consecutive days in late June. The early season was characterized by very cold weather, with only stratiform clouds or a very few large storms in the area. Development of moderate-sized Cu was inhibited on many days by very strong shear in the middle troposphere. Occasionally, large severe Cb formed in this period. Thereafter, a large persistent 500 mb high moved over the central United States and conditions were mostly dry and stable. (The two days with 9 test cases marked, approximately, the transition between these two weather patterns.) The weather during the remainder of the experimental period was predominantly fair and dry. For the most part, suitable clouds for the SOFT experiment were rare over the entire Black Hills area, and not just in Butte and Meade counties.

The clouds:

The clouds that were selected for test cases were, at best, only marginally satisfactory for seeding tests, especially in the first half of the experiment. In fact, the persistently unfavorable weather led us to bend the criteria for test case selection on most days, to get any test cases at all. Of the 15 test clouds in the randomized experiment, three were clearly less than 8000 ft (2.44 km) deep and four were barely that deep, at best; five clouds definitely had radar echoes at the time of selection and two more may have had echoes; and nine clouds were listed as being fairly dry inside, from observations of the rate of aircraft icing during penetrations. On 22 June, five test cases were obtained. However, the aircraft observations for that day persistently reported cloud base heights increasing with time and very ragged-looking cloud bases, indicating a decrease in the moisture supply with time and entrainment of dry air even at cloud base. Also, time-lapse movies showed that the lifetimes of growing towers were severly limited by shear at cloud top level. None of these five clouds was thus ideally suitable for seeding tests.

After 20 July, it was obvious that the sample of randomized test cases would be too small to permit statistically significant conclusions to be drawn. As a result, it was decided to discontinue the randomized experiment and to seed any and all suitable clouds for the duration of the experiment, relying on radar and photographic data to monitor other clouds in the area. Only two more clouds, designated special test cases (STC), were seeded in the last 10 days of July. Another test cloud was selected by N. Fukuta for deliberate seeding on 7 July, and is designated FTC. Thus the total data sample consists of 18 clouds, of which 11 were seeded and 7 unseeded.

Data and analysis:

The data for the 15 randomized test cases and the three special test cases are tabulated in Table 1. The data fall into four categories:

Identification - date, time, case number

Seeding control - seeded or unseeded, penetration temperature and altitude

Initial cloud properties - Base height and temperature, depth, penetration times, maximum updrafts (and downdrafts), radar echo, liquid water content

Description of subsequent cloud behavior

A qualitative inspection of the data in Table 1 shows that many of the clouds in this sample, small as it is, did not meet the criteria set forth initially in the design for the experiment and its evaluation. There is no clear indication of the seeding effects originally expected. The data also suggest, however, that the clouds chosen at random for seeding were initially less virgorous than the unseeded clouds.

Due to the small sample size and the poor clouds in the sample, no statistically significant seeding effect, either positive or negative, was detectable. Pronounced vertical development was observed for two unseeded test clouds (cases 9 and 11) and two seeded clouds (13 and 15). Only two clouds, both unseeded (cases 5 and 11) developed a radar echo during the 30-minute test period. The data clearly show that the seeded clouds as a group were less vigorous at the time of penetration. Fig. 1 shows histograms of aircraft penetration times in 10-second class intervals, for the total data sample and separately for seeded and unseeded cases. It is clear from this figure that the seeded sample contained a disproportionately large fraction of clouds with small penetration times, and none with very large penetration times. The Wilcoxon two-sample rank test shows that the probability of obtaining such different distributions by chance is less than 7%. Updraft velocity data show the same effect. Thus we may have been unfortunate in the randomized selection of seeded test cases. The real problems, however, are the small size of the data sample and the poor quality of clouds as a whole.

Although the conditions of the statistical experiment originally set forth were not met, some seeding effects are apparent in radar data and the supplementary photographic data for several of the seeded test cases. Fig. 2 shows the variation of maximum radar echo intensity for three seeded test cases (cases 1, 13, and 15), one unseeded test case (case 9), and three unseeded clouds which were not part of the series of test cases. The common feature of the seeded test cases in this figure is the appearance of abrupt increases in peak echo intensity in the period 10-20 minutes after first penetration. Test case 1 was particularly interesting. On this day, which was relatively cold (500 mb temperature $-20^{\circ}C$), numerous small clouds were glaciating naturally and giving weak radar echoes and light virga. The test cloud, however, showed a sudden brief spurt of vertical growth in the first 10 min after seeding; thereafter, the entire body of the cloud near and below the penetration level glaciated completely and snowed out in the form of a heavy column of virga. Simultaneously, the radar echo increased by 12 dbz, after which both cloud and echo rapidly disappeared. Cases 13 and 15 also showed similar pulses in echo intensity shortly after seeding. These clouds were seeded during the growing phase. It should be noted that on these two days, no other clouds grew at all in the area; the seeded clouds dominated the sky. The one unseeded test case (case 9) which exhibited very rapid vertical growth and echo intensification remained near that level for some time. The other three unseeded clouds in Fig. 2, studied on the day following test case 15, did not show the pulsations in echo intensity that characterized these seeded clouds.

Because of their eventual size and intensity, cases 13 and 15 produced rain, and 15 was later seeded for hail suppression by SDDWM. Test case 1 and STC-1 and -2 clearly glaciated and produced virga from the seeded area between 10 and 20 minutes after seeding. Every other seeded cloud dissipated very rapidly after seeding; the aircraft penetration data and photographic records show that almost all these clouds had passed the growth stage and were already in the process of dissipating at the time of seeding.

3. LEADVILLE EXPERIMENT

Field tests of the airborne jet-mixing organic smoke generator were carried out near Leadville, Colorado, from 17 July through 8 August 1975. The project was undertaken in cooperation with the National Center for Atmospheric Research (NCAR), Colorado State University, and Atmospherics Incorporated, under the sponsorship of the National Hail Research Experiment (NHRE). The objective was to obtain quantitative data on the effectiveness of the organic ice nuclei generator by using the NCAR sailplane "Explorer" to make simultaneous in-cloud measurements of ice nuclei, ice crystals, and a tracer material released along with the seeding material.

Test cases were obtained on three days: 22 July, and 4 and 5 August. The cloud seeded on 22 July was quite small, and the organic smoke generator was found to be operating improperly at the time of this experiment. On 4 August a seeding experiment was conducted near Buena Vista. The duration of seeding was about 15 minutes, with a pilot estimate of at least 5 minutes spent in the cloud updraft. The tow plane pilot reported significant dissipation of the cloud in the seeded area. The sailplane made two ascents in cloud, but may have been in another cell, since the sailplane pilot noted no cloud dissipation. A higher than normal ice nucleus count was observed, uniformly distributed throughout the sampling period. The uniform concentration distribution suggests that these may have been natural nuclei, since pronounced variations would be expected as the sailplane intersected a seeded plume.

The final test case on 5 August has been more extensively studied, due to the large numbers of ice crystals observed by the cloud particle camera on the sailplane. This was the best test case from Leadville project. Cloud base (at -10°C) and cloud top were 20.5 and 23.5 kft (6.25 and 7.16 km) at the start of seeding. The organic seeding generator was operated for 13 minutes, with at least 10 minutes spent in the updraft. The sailplane reached 25.5 kft (7.77 km) during the experiment, revealing considerable cloud growth. Color photographs taken from the two plane showed glaciation at cloud top. Precipitation was observed about 15 minutes after the start of seeding from both the seeding aircraft and tow plane.

Data from the cloud particle camera and ice nucleus collector for this case are shown in Fig. 3. The abscissa is time, while the ordinate indicates relative estimated concentrations of ice nuclei and ice crystals. The two curves show trends only, and are not corrected for the sampling volumes of the two instruments. Nevertheless, the correlation between ice nuclei and ice crystal concentrations is clear. Further analysis performed at NCAR indicates a reasonable correlation with the time of seeding when the sailplane altitude and updraft velocity measurements are taken into account.

4. SUMMARY AND CONCLUSION

Although the number of test cases in each of the experiments was considerably smaller than we would have liked (or expected), the results of the 1975 summer field programs indicate that 1,5-dihydroxynaphthalene is an effective weather modification agent. Presently, our Cloud Physics Laboratory at the Denver Research Institute is developing an improved jet-mixing organic smoke generator and a supersonic-nozzle organic ice nuclei generator that will enable seeding with much higher numbers of ice nuclei. We expect these generators to be ready for field testing in the summer of 1976.

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5. REFERENCE

Fukuta, N., J. A. Armstrong, and A. Gorove, 1975: A new airborne organic ice nuclei generator and its tests in summertime cumuli. J. Weather Modif., 7, 17-30.

Table 1. Summary of field data for organic ice nuclei cloud seeding experiment

Date	Time	Test Case No.	*	Cloud Base Temp/ Alt ($^\circ$C/kft)	Pen. Temp/ Alt ($^\circ$C/kft)	Est. Cloud Depth (kft)	Pen. Times (sec)	Up-drafts (ft/sec)	Down-drafts (ft/sec)	Est. IWC	Radar Echo Before	Radar Echo After	Remarks
6/11	1252	1	S	0° 9	-5° 12	6	35 30	900 400	-800 -	Lt.	yes	yes	Echo intensified after 10 min. Glaciated at and below penetration level, bottom precipitated out as virga leaving flat stratus cloud at top
6/19	1608	2	S	4° 10	-5° 14	5	15 0	0	- -	Lt.	no	no	Cloud dissipated after first penetration, disappeared
6/22	1456	3	N	8° 7.3	-8° -15.5	8.5	72.5 59.5	200 200	-500 -500	Lt.	no	no	No visible glaciation, cloud appearance changed little for 19 min, then cloud dissipated by 24 min.
6/22	1525	4	N	- 10.5	-8° 15.5	8	26.5 16	0 0	- -	V.Lt.	no	no	Poor cloud, ragged bottom, bottom part of cloud dissipated within 10 min.
6/22	1608	5	N	10° 8.3	-4° 13.5	8	63.5 85.7	1200 1250	- -	Lt-Mod.	no	yes	Cloud top rose rapidly, glaciation visible, radar echo by 9 min, but tower then collapsed and dissipated by 15 min.
6/22	1644	6	S	- -	-4° 13.5	8	29 30	200 200	- -	Lt.	no	no	Very poor cloud, breaking up at time of second penetration, indistinguishable from surrounding clouds by 10 min.
6/22	1709	7	N	- -	-4° 14	10	62.8 69.4	1800 1800	- -	Lt-Mod.	yes	yes	Strong towers rising and shearing off toward the east, virga observed below sheared-off layer.
6/23	1509	8	S	10° 8.5	-5° 14.5	7	64.7 120.8	1100 1100	- -	Lt.+	no	no	Very poor cloud, bottom dissipated leaving flat stratus-like layer after 8 min.
6/23	1537	9	N	-	-5° 14.5	9	190 255	600 1000	-700 -2000	Lt.+ graupel	?	yes	Two growing towers penetrated; one glaciated and dissipated, the other grew to large intense Cb.
6/23	1620	10	S	- 12	-5° 14.5	9	75 60	1000 1000	- -	Lt.	no	no	Seeded tower overpowered in 6 min by neighboring tower (which grew tall), dissipated. Ground visible through ragged cloud base on second penetration.
6/23	1636	11	N	- 12	-5° 14.5	10	45 65	1000 1000	- -	Lt.	no	yes	Cloud grew to same height as cases 9 and 10; no visible difference in appearance.
7/7	1745	12	N	11° 9	-5° 17	8	171.2 197.5	500 1000	-1900 -2600	Lt., graupel	?	?	Broad round-topped cloud; top in penetrated region dropped by 13 min, entire cloud dissipated in 19 min.
7/15	1653	13	S	8° 12.5	-5° 17.5	10	68 60	1500 2000	- -	Lt., graupel	yes	yes	Cloud sheared to north. *Cloud growth visible from south* (from aircraft); strongly glaciated overhang on north. Only cloud that grew this day.
7/16	1629	14	S	9° 11.5	-5° 17.5	8.5	45 35	0 0	- -	Dry	yes	yes	Cloud top separated from base just prior to penetration, dissipated by 7 min.
7/20	1622	15	S	6° 11.5	-5° 17.5	9-10	115 120	1800 1700	-1500 -2000	Lt-Mod.	yes	yes	Very vigorous cloud, only one in the entire area which grew this day; seeded for hail suppression later.
7/7	1816	FTC	S	-	-5° 16	8	60 20	0 0	- -	Lt., graupel	?	?	Cloud base ragged, cloud mostly gone by second penetration, completely dissipated by 8 min.
7/21	1636	STC-1	S	6° 12	-5° 17.5	8	80 82	1300 800	-700 -1000	Lt.+, graupel	?	?	Tops in seeded area fell in 12 min, virga below seeded area in 16 min. (also from other nearby clouds), everything glaciated by 21 min.
7/29	1739	STC-2	S	2° 14	-5° 17.5	8	59 62	400 500	- -1000	Lt.	no	no	Top in seeded area dropped in 9 min, seeded region glaciated by 11 min, virga observed by 20 min.

* S = Seeded; N = Unseeded; seeding rate 0.375 gm DN/sec

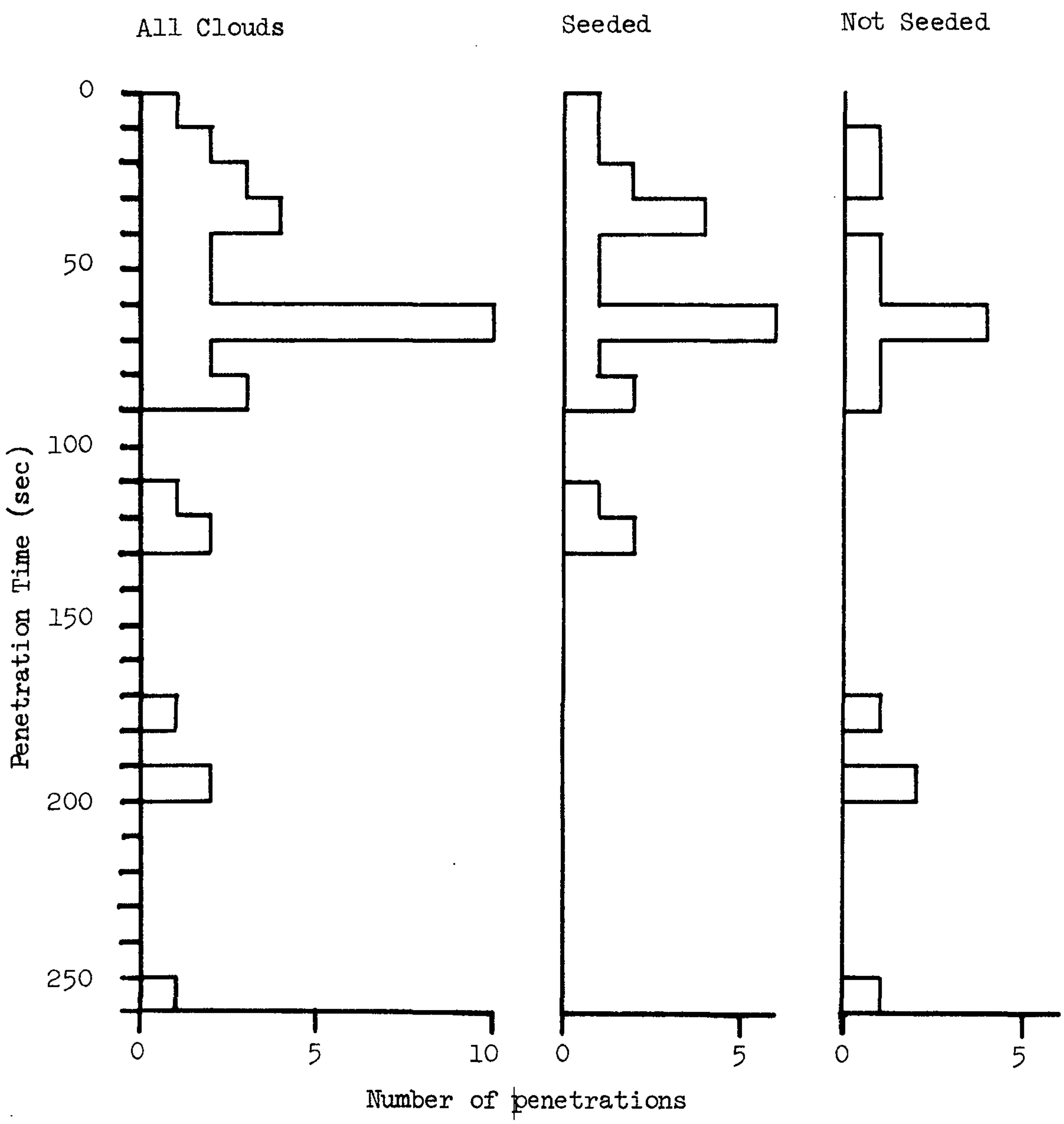

Fig. 1. Frequency distribution of penetration times for all clouds, and for seeded and unseeded clouds separately

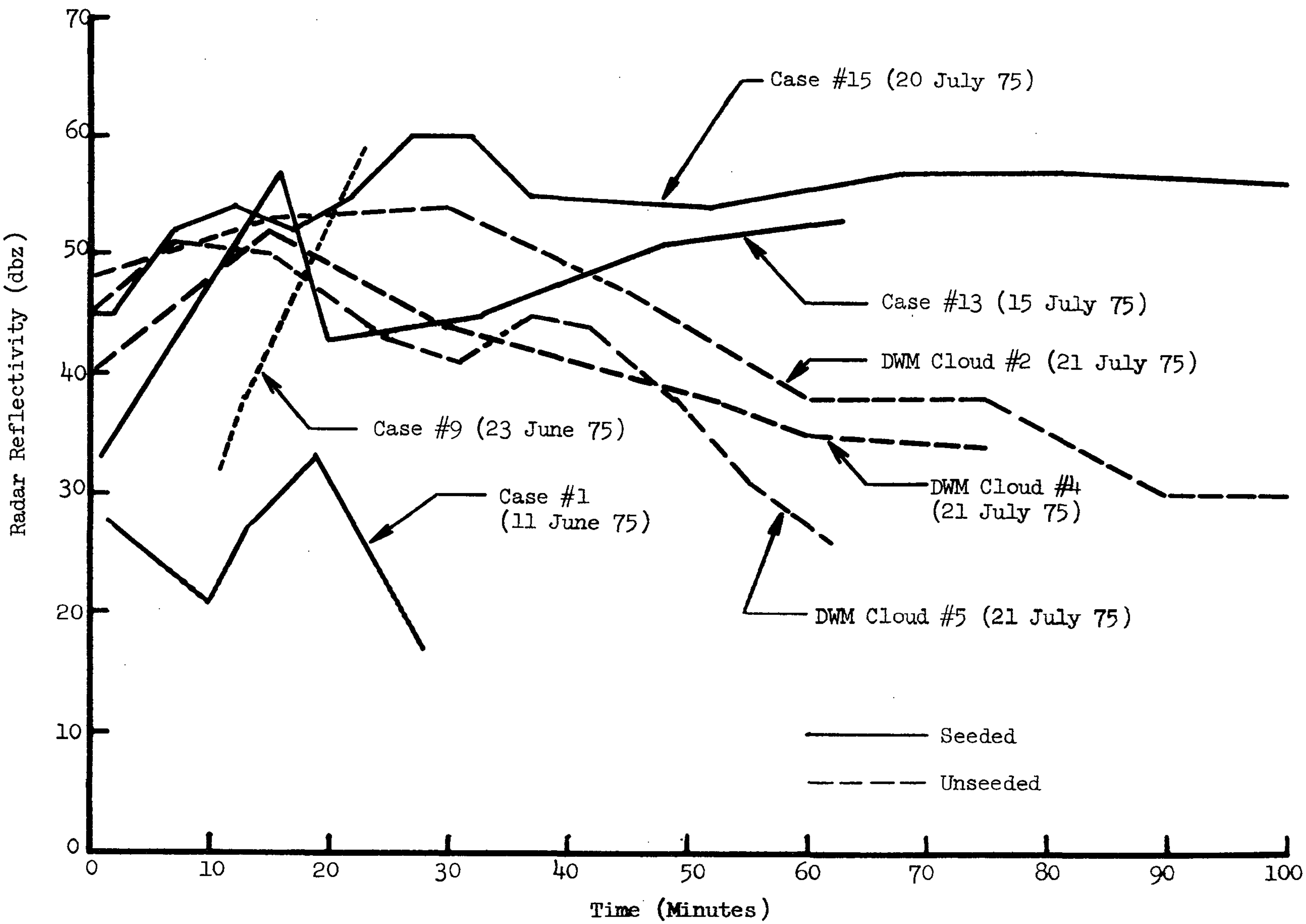

Fig. 2. Maximum radar echo intensity vs time for seeded and unseeded clouds

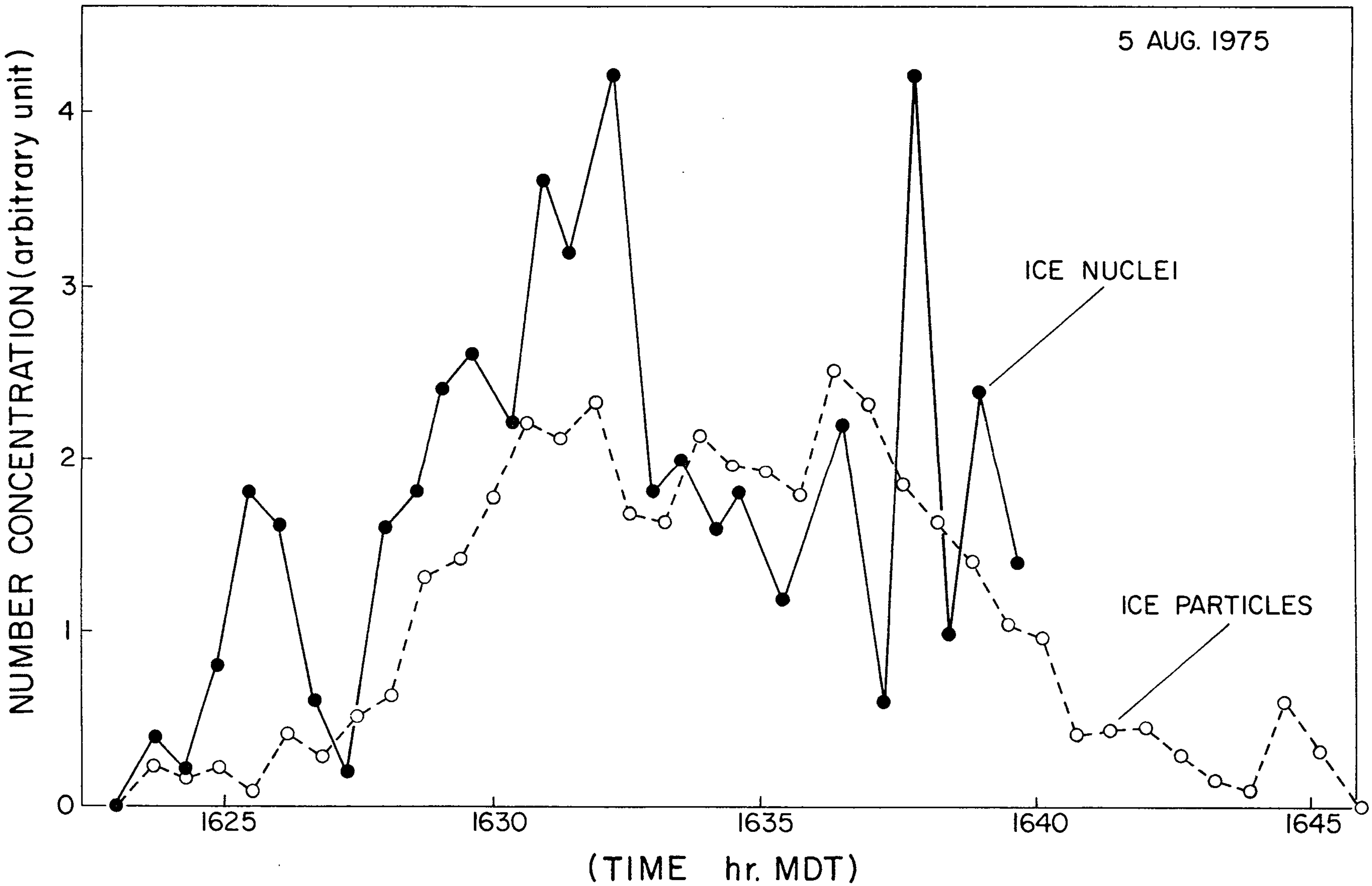

Fig. 3. Comparison between observed number of ice crystals and ice nuclei (-20°C) in a cumulus seeded with 1,5-dihydroxynaphthalene smoke in Leadville