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Microphysical Effects of Seeding Wintertime Stratiform Clouds Near the Sierra Nevada Mountains

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ABSTRACT

The microphysical consequences of seeding stratiform clouds near the Sierra Nevada Mountains are examined. Airborne seeding was conducted with droppable AgI flares released every 250 m and with dry ice pellets released at a rate of 0.1 g m^{-1} into the clouds having widespread liquid water contents ~0.1 g m^{-3}. The Wyoming King Air penetrated the AgI curtains for ~1 h after seeding. The CO_2 ice crystal curtain could not be determined beyond ~10 min because of natural cloud glaciation. Precipitation sized particles grew mainly by diffusion, and particle size spectra at particular levels below cloud top reached and maintained equilibrium shapes as a consequence of particles falling from higher levels.

1. Introduction

The main goal of the Sierra Cooperative Pilot Project (SCPP) is to develop weather modification techniques for increasing precipitation in the American River Basin area of the Sierra Nevada Mountains. In support of this goal, a number of seeding experiments have been conducted within storms during the 1978–79 and 1979–80 field seasons of the SCPP. These experiments have utilized CO_2 pellets and droppable AgI flares as seeding agents in a variety of cloud conditions. Cloud types have ranged from stratiform characterized by low liquid water contents to convective clouds generally having higher liquid water contents and either few or many ice particles.

With the advent of Particle Measuring System probes, a number of articles have recently appeared in the literature concerning the detailed microphysical effects of seeding. The articles by Strapp *et al.* (1979), Hobbs, and Politovich (1980), Marwitz and Stewart (1981) and English and Marwitz (1981) are recent examples of such studies. These papers all focused on the effects of seeding convective clouds characterized by substantial supercooled liquid water and precipitation being ultimately produced by accretional growth processes. Either AgI nuclei or CO_2 pellets were used in the experiments.

The objective of this contribution is to discuss the microphysical effects associated with seeding stratiform clouds. Characteristics of these clouds were low but widespread liquid water and an absence of convection. Precipitation development in such clouds would typically result from diffusional and aggregational ice growth rather than by accretional growth. Overall features of such clouds and the effects of seeding them may be similar to some Great Lakes winter storms (Weickmann, 1973) and to the stratus clouds examined in the 1940's (Havens *et al.*, 1981).

Results from two experimental days with initially low ice crystal concentrations have been chosen for presentation. Flares were used on both days; CO_2 pellets were used on one of the days as well. These three experiments were chosen for presentation because seeding effects were documented more extensively than during the other 16 experiments within stratus clouds.

2. Seeding operations

The principle platforms in the seeding experiments were the Wyoming King Air aircraft and the Aero-Systems Aero Commander aircraft. The King Air was used to measure the effects of seeding; the Aero Commander was used to seed the clouds.

Seeding operations were similar in all the experiments. The King Air was flown through the clouds until significant supercooled liquid water was encountered. The Aero Commander crew was then instructed to seed along a line ~15–20 km long at right angles to the wind direction and through the region containing significant liquid water. Depending upon the day's seeding operation, either a particular

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TABLE 1. Mean values of parameters during penetrations of ice crystal curtain of 2 February 1980 (AgI).

Times (GMT)	Δt (min)	Temperature (°C)	IT (cm$^{2/3}$ s^{-1})	JW-LWC (g m^{-3})	FSP-LW (g m^{-3})	Concentration (cm^{-3})	$\bar{D}$ (μm)	1D-C (L^{-1})	2D-C (L^{-1})	2D-P (L^{-1})
192000–192022	−16	−11.0	2.0	0.06	0.05	58	11	1	0	0
194408–194415	8	−12.2	2.3	0.02	0.02	20	11	124	160	8.8
195054–195113	15	−12.0	2.2	0.02	0.03	38	10	36	35	8.1
195450–195535	19	−12.0	2.6	0.02	0.02	22	12	34	26	5.0
200006–200055	24	−11.9	2.5	0.00	0.01	11	14	39	23	5.5
200515–200604	30	−12.0	1.9	0.00	0.01	20	8	20	18	3.0
201036–	35	−11.9	2.3	0.00	0.01	14	14	35	25	4.9

seeding agent was chosen or the agent was selected on a random basis by the crew in the seeding aircraft and was consequently known only to them. The seeding modes were AgI (1–20 g flare released every 250 m), CO_2 pellets (0.1 g m^{-1}), or a placebo. The flares burn while falling for ~1 km; the pellets fall at least to the 0°C level. After the seeding operation, the King Air was flown upwind–downwind through the seeding curtain to measure the evolution of seeding effects.

The King Air was equipped with a full compliment of cloud physics probes. These included a Forward Scattering Spectrometer Probe (FSSP) operated in the range 2–30 μm intervals, an OAP 2D-C (see Knollenberg, 1976) in the range 25–800 μm with 25 μm intervals, an OAP 2D-P in the range 200–6400 μm with 200 μm intervals, and an OAP 1D-C for the range 12.5–187.5 μm with 12.5 μm intervals. A JW liquid water probe was the principal device for measuring liquid water content. A decelerator was included to capture ice crystals on an oil-coated glass slide for later microscopic analysis. Ice nuclei were measured with an NCAR ice nucleus counter operating at −20°C.

3. 2 February 1980 experiment

a. *Sounding information and seeding logistics*

Stratiform clouds were present on 2 February 1980 as the King Air was launched. The ascent sounding from McClellan AFB showed that a thin stratus deck existed between 550 and 510 mb and that the atmosphere was quite dry below this ~500 m thick layer. The atmosphere was stable below 550 mb and neutral above. The stratus deck existed within a layer of strong wind shear (0.017 s^{-1}).

AgI flares were released in the stratiform cloud at an altitude of 5.6 km (510 mb and −15°C). Seeding lasted for 3 min so that a curtain ~15 km long was produced. Interceptions of the seeding curtain were made by the King Air at an altitude of 5.1 km (−12°C) and parallel to the wind for the first 35 min after seeding.

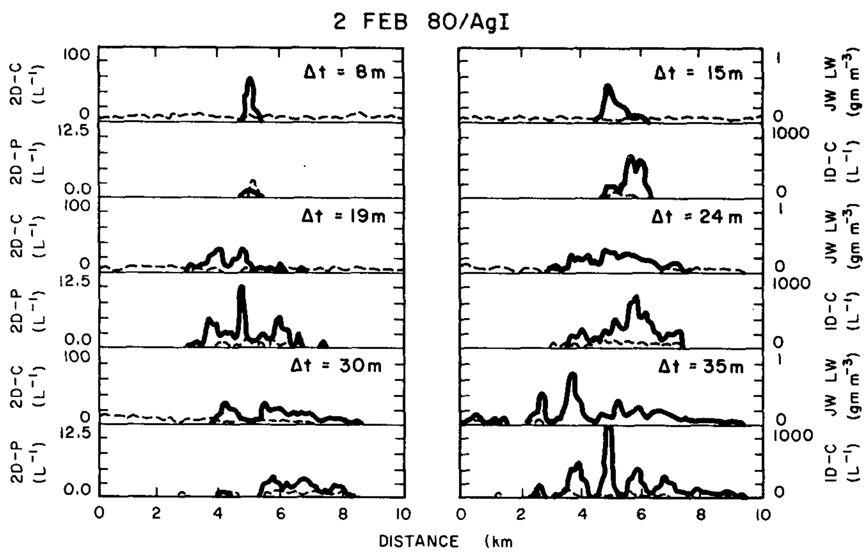

FIG. 1. Analog traces of several microphysical quantities at different times after seeding on 2 February 1980. The upwind edge is on the left in all cases. The lines in the various panels represent the following parameters: upper panel and solid line = 2D-C concentrations; upper panel and dashed line = JW-LW content; lower panel and solid line = 2D-P concentrations; lower panel and dashed line = 1D-C concentrations.

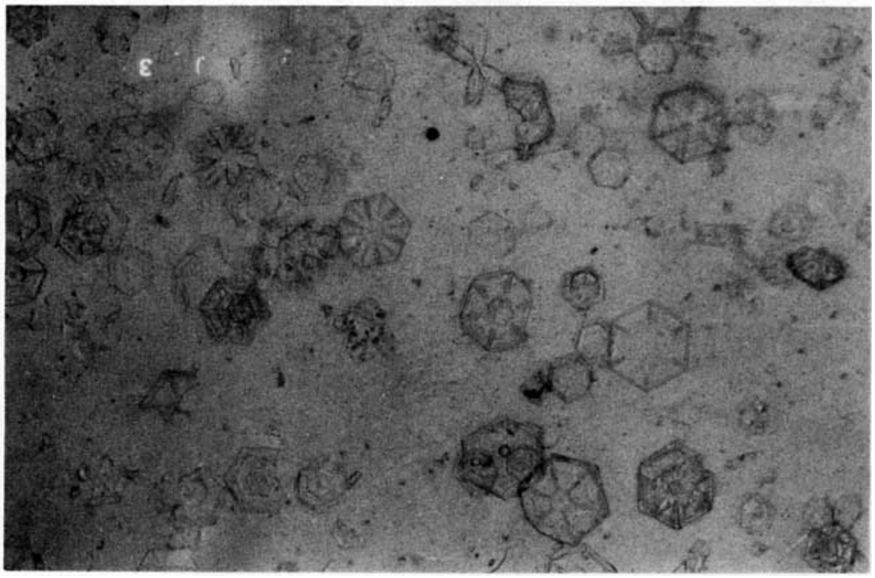

FIG. 2. Photograph taken of ice crystals collected on an oil-covered slide at 19 min after seeding on 2 February 1980. The height of this photograph is equivalent to ~4 mm.

b. *Observations within the seeding curtain*

Table 1 and Fig. 1 show the evolution of a number of parameters observed during the ice crystal curtain penetrations. Ice nuclei were observed on each of the penetrations in typical concentrations of 1–5 L^{-1}. Background ice particle concentrations were low (<1 L^{-1}), so that seeding effects stood out dramatically even though liquid water contents were low

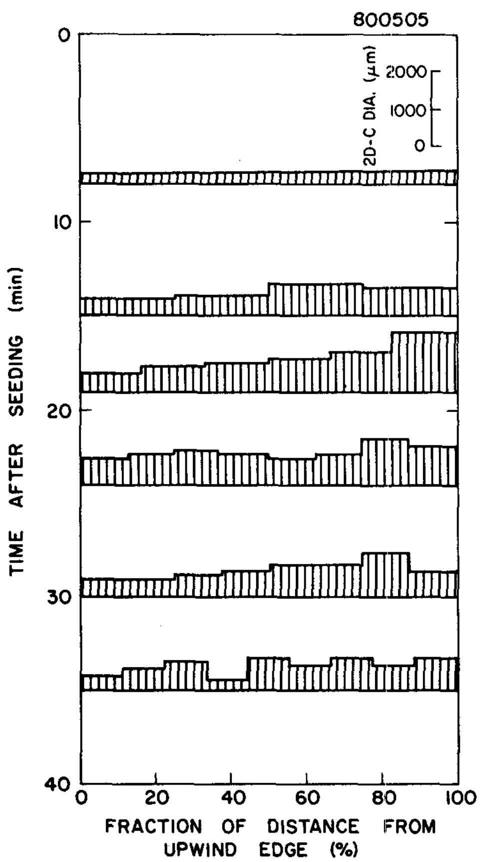

FIG. 3. Maximum observed particle size as a function of location within the curtain and time after seeding on 2 February 1980.

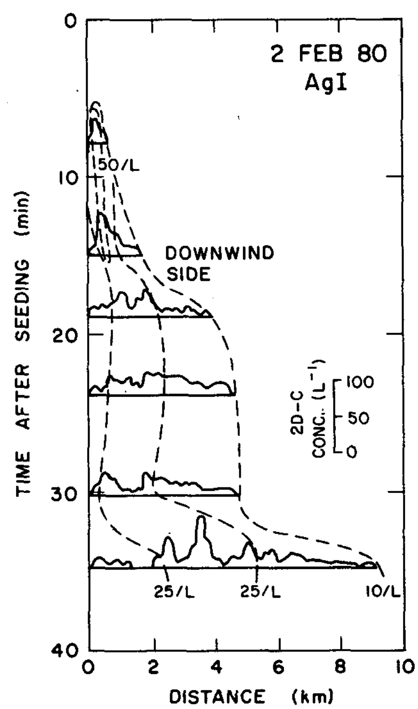

FIG. 4. Evolution of the ice crystal concentration as a function of time after seeding and location within the curtain on 2 February 1980. The upwind edge of the curtain is on the left in all cases. Contours of 2D-C derived concentration were drawn closest to the edge of the curtain at which those particular concentrations occurred.

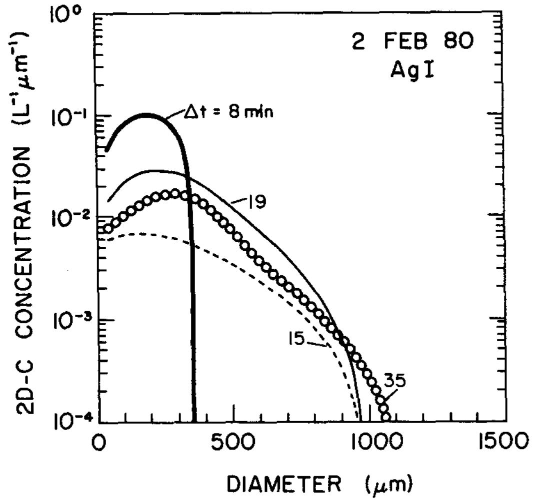

FIG. 5. Ice crystal size spectra, as derived from 2D-C data, averaged across the width of the curtain at four times after seeding.

(~0.05 g m^{-3}) but fairly continuous. Indicated turbulence values (~1.5 $cm^{2/3}$ s^{-1}) were also low. The first three passes at 8, 15 and 19 min after seeding indicated that the mean liquid water had been depleted to 0.02 g m^{-3} from the pretreatment value of 0.05 g m^{-3} and thereafter the liquid water was near zero in the ice crystal curtain. The 1D-C concentration was high during the first pass after seeding (124 L^{-1}) with concentrations ~35 L^{-1} during the other passes. The 2D-C concentration was very high during the first pass after seeding (160 L^{-1}) whereas it was 20–30 L^{-1} during the other passes.

Fig. 2 shows an ice crystal slide taken during the interception of the curtain 19 min after seeding. Since most of the crystals were thin plates with some branching, they originated at temperatures near −13°C. The largest plates were ~500 μm in diameter, and there were few frozen droplets on the crystals. Similar observations were made from slides obtained at later times.

The 2D images across the curtain illustrate another feature of the ice crystal characteristics within the seeding curtain. The maximum particle size of ~1 mm consistently was observed at the downwind edge of curtain (Fig. 3). Such a size sorting was predicted by Stewart and Marwitz (1982) as a consequence of ice particle trajectories within a sheared environment.

The evolution of the ice crystal curtain, as denoted by 2D-C concentrations, is elucidated in Fig. 4. One can see a relatively steady increase in width of the curtain with time, although the periods between 15 and 19 min and between 30 and 35 min were characterized by the largest increase in width. The width of the curtain enclosed by concentrations in excess of 25 L^{-1} remained relatively constant with time and only increased appreciably at 35 min when concen-

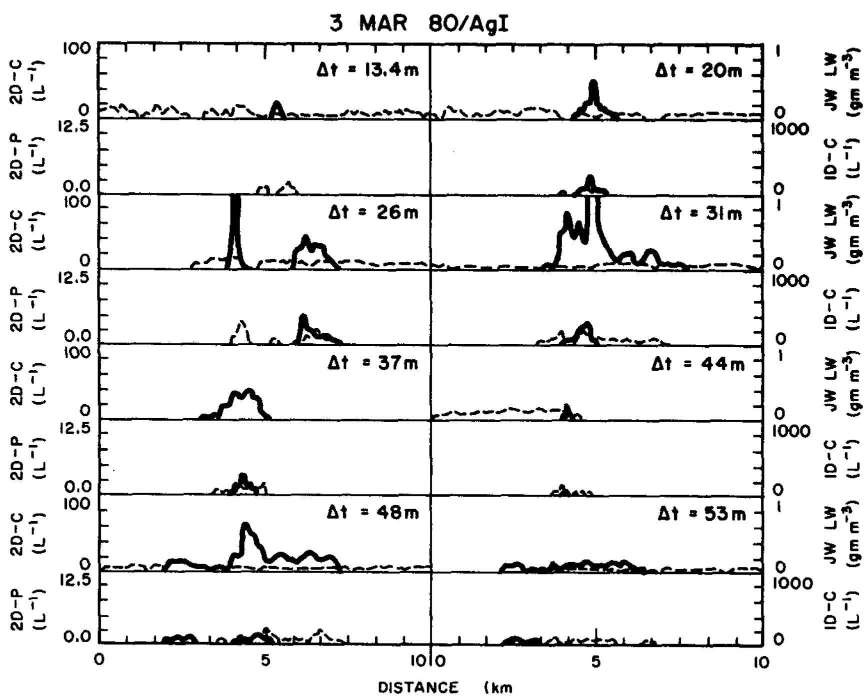

FIG. 6. Analog traces of several microphysical quantities at different times after seeding with AgI on 3 March 1980. The upwind edge is on the left in all cases. The lines in the various panels represent the following parameters: upper panel and solid line = 2D-C concentrations, upper panel and dashed line = JW-LW content; lower panel and solid line = 2D-P concentrations; and lower panel and dashed line = 1D-C concentrations.

TABLE 2. Mean values of parameters during penetrations of ice crystal curtains of 3 March 1980 (AgI).

Times (GMT)	Δt (min)	Temperature (°C)	IT ($cm^{2/3}\,s^{-1}$)	JW-LW ($g\,m^{-3}$)	FSP-LW ($g\,m^{-3}$)	Concentration (cm^{-3})	$\bar{D}$ (μm)	1D-C (L^{-1})	2D-C (L^{-1})	2D-P (L^{-1})
173410–173510	−4	−7.7	1.1	0.05	0.16	64	13	0	0	0
175154–175210	13.4	−5.4	1.0	0.03	0.13	35	12	8	3	0
175750–175840	20	−5.5	0.9	0.06	0.23	75	16	15	8	1.4
180354–180445	26	−5.6	1.1	0.05	0.22	76	16	37	25	2.5
180942–181035	31	−5.8	1.3	0.03	0.12	59	15	37	40	3.7
181455–181540	37	−3.6	1.2	0.0	0.0	—	—	27	14	2.0
182010–182105	44	−7.7	1.3	0.07	0.23	69	14	9	2	0.1
182603–182715	48	−5.6	1.3	0.02	0.02	28	10	46	19	2.7
183130–183235	53	−6.0	1.1	0.0	0.01	19	13	20	7	0.8
183430–183535	57	−5.8	1.3	0.01	0.01	25	9	15	6	0.6

trations became highly variable. Concentrations in excess of 50 L^{-1} were only observed at 15 and 35 min after seeding. Peak concentrations at all times tended to occur near the upwind edge of the curtain. This observation was also predicted by Stewart and Marwitz (1982).

Fig. 5 contains ice crystal size spectra, as measured by the 2D-C probe, averaged across the width of the detectable curtain during the first four passes after seeding. An approximate equilibrium in the size distribution was reached near 15 min and persisted through 35 min.

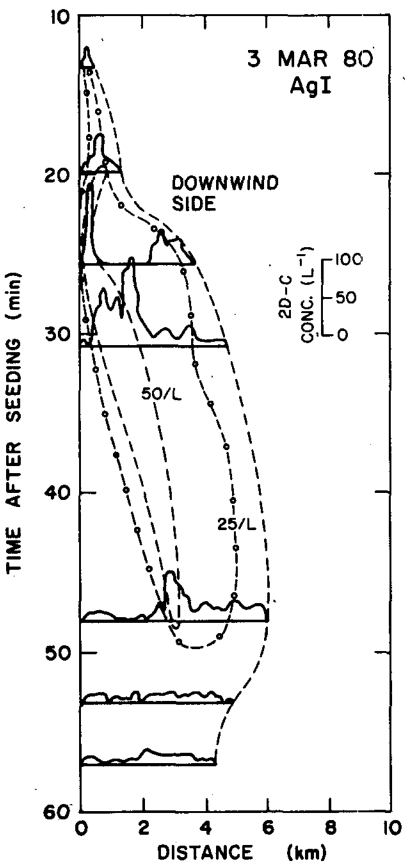

FIG. 7. Evolution of the ice crystal concentration as a function of time after seeding and location within the curtain on 3 March 1980. Contours of 2D-C derived concentrations were drawn closest to the edge of the curtain at which those particular concentrations occurred.

4. 3 March 1980 experiments

a. Sounding information and seeding logistics

Stratiform clouds were also present on 3 March 1980. Because a dual-wavelength radiometer (Snider *et al.*, 1980) was registering significant liquid water in the cloud, the King Air was launched for a possible seeding mission. After finding liquid water contents up to 0.2 $g\,m^{-3}$ in the cloud, the King Air crew instructed the seeding aircraft crew to conduct a randomized seeding experiment.

The ascent sounding on takeoff from McClellan AFB revealed a relatively moist atmosphere that was saturated from 820 to 750 mb (1.8–2.5 km). The atmosphere was essentially neutral through this stratiform cloud deck. Even though the wind speeds were light, the directional wind shear produced a shear of 0.005 s^{-1} through the stratus deck.

The seeding aircraft was flown for about 25 km near 3.1 km (−7°C) during the seeding experiments. This was essentially at cloud top. The stratus cloud tops in the vicinity of the seeding experiment were 0.6 km higher than the heights indicated from the takeoff sounding. Passes made with the King Air were mainly at 2.8 km (−5.5°C) or 300 m below the top of the seeding curtain.

b. Observations within the AgI seeding curtain

The seeding curtain produced by AgI was penetrated nine times by the King Air within 57 min of seeding. AgI nuclei, as measured by the NCAR ice nuclei counter, were observed in concentrations of ~1-5 L^{-1} in each of these penetrations.

Table 2 and Fig. 6 illustrate the evolution of the seeding signature observed during the ice crystal curtain penetrations. A number of observations can be

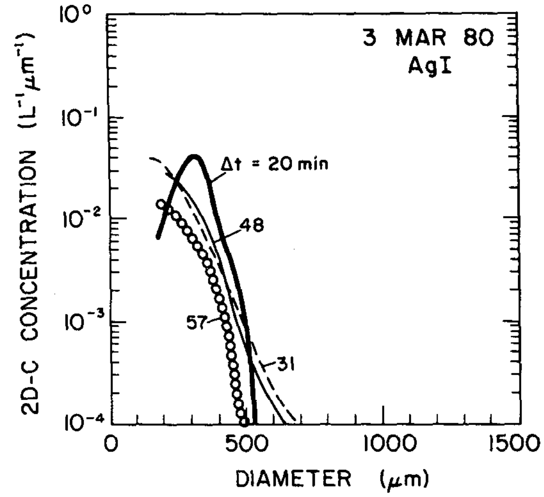

FIG. 8. Ice crystal size spectra, as derived from 2D-C data, averaged across the width of the curtain at four times after seeding.

made from the data. First, the seeding was conducted within relatively small but widespread liquid water of <0.2 g m^{-3} and low indicated turbulence values (1.5 $cm^{2/3}$ s^{-1}). Some liquid water existed within the seeding curtain at all penetration times except 37 min. Second, very small ice crystals, measured by the 1D-C probe, were continuously present within the seeding curtain. In other words, small and presumably new particles were continually present within the curtain. Third, the largest mean ice crystal concentrations, as measured by the 2D probes, were observed 31 min after seeding.

Ice crystal characteristics were deduced from ice crystal photographs and the 2D images. Most of the crystals were regular and thick columns. The largest crystal sizes were ~500 μm and maximum sizes were not a function of location within the curtain.

The evolution of the ice crystal curtain is illustrated in Fig. 7. The peak concentrations (~100 L^{-1}) were observed at 26 and 31 min after seeding, and there was a tendency at these two times for the peak concentrations to occur near the upwind edge of the curtain. Concentrations as high as 50 L^{-1} were still observed at 48 min after seeding.

As in the 2 February 1980 seeding experiment, ice crystal size spectra evolved into a relatively steady-state profile (Fig. 8). In this case, the distribution was relatively independent of time after the penetration at 19 min. Maximum ice crystal sizes were ~500 μm.

c. *Observations within the dry ice seeding curtain*

The curtain produced by CO_2 was penetrated a number of times but a well-defined ice crystal curtain was only detected during the first two passes. On later passes it was impossible to tell whether penetrations were through the curtain or through ice produced naturally within the cloud. Since these two penetrations were made at 4 and 8.5 min after seeding, and the penetrations through the AgI seeded curtain was ⩾19 min after seeding, it was not possible to directly compare seeding effects from the two agents.

Table 3 contains the mean values of a number of parameters observed during the ice crystal curtain penetration. The mean values are also included for pass No. 3 (at 14 min) based on the extrapolated position and intersection of the curtain. Fig. 9 contains analog traces of microphysical characteristics encountered during the first two penetrations. The sharp spikes in the 2D-C and 1D-C concentrations correspond to the seeding curtain and the widespread regions of lower concentrations are attributable to natural cloud processes. As with the AgI experiment, seeding was conducted within a region of the cloud characterized by low (<0.15 g m^{-3}) but widespread liquid water and low indicated turbulence (~1.5 $cm^{2/3}$ s^{-1}). The typical 1D-C and 2D-C concentrations were nearly constant at 100 and 30 L^{-1}, respectively.

5. Discussion of seeding observations

Persistent seeding effects were produced in stratus clouds on two days by AgI curtains. Liquid water contents in the clouds were <0.2 g m^{-3}. Since the ice crystal curtain initiated by dry ice could not be followed very long, it was not clear whether a persistent effect was produced by this seeding agent.

The two AgI curtains exhibited two important similarities. First, some ice nuclei, as measured by the NCAR ice nucleus counter, were detected during each penetration. This important observation means

TABLE 3. Average values of parameters during penetrations of ice crystal curtains of 3 March 1980 from CO_2 seeding.

Times (GMT)	Δt (min)	Temperature (°C)	IT ($cm^{2/3}$ s^{-1})	JW-LW (g m^{-3})	FSP-LW (g m^{-3})	Concentration (cm^{-3})	$\bar{D}$ (μm)	1D-C (L^{-1})	2D-C (L^{-1})	2D-P (L^{-1})
185100–185200	−8	−7.7	1.4	0.04	0.21	60	17	7	2	0.4
190358–190406	4	−7.3	1.6	0.02	0.09	53	13	100	25	0.0
190830–190341	8.5	−7.2	1.3	0.04	0.14	52	15	79	36	0.4
191406–	14	−5.4	1.4	0.03	0.16	56	12	100	32	6.8

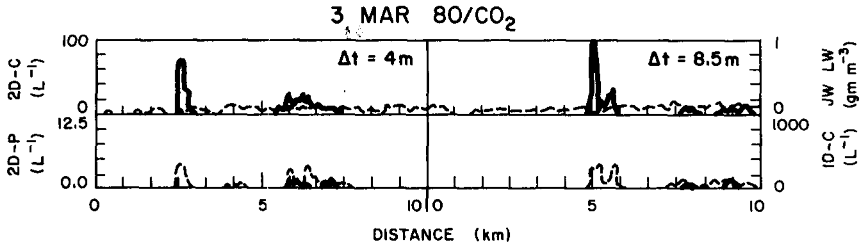

FIG. 9. Analog traces of several microphysical quantities at different times after seeding with CO_2 on 3 March 1980. The upwind edge is on the left in all cases. The lines in the various panels are as in Fig. 1.

that at least 30 min was available for ice nuclei to be active. Second, diffusional growth required 20–30 min to deplete the liquid water in the region of the curtains.

The AgI curtains did not broaden at the same rate. At all equivalent times after seeding, the curtain in the high shear case (2 February 1980) was wider than the curtain in the low shear case (3 March 1980). According to the predictions of Stewart and Marwitz (1982), this is consistent with shear effects.

The observed ice crystals were essentially unrimed, presumably because of the low liquid water contents. The size distributions of particles within each AgI curtain reached approximately equilibrium spectra within 20 min of seeding. This observation of equilibrium spectra is likely a consequence of sampling at a fixed distance below the top of an AgI seeding curtain in clouds where vertical air motions are small. If crystals were continually being nucleated over the depth of the curtains, an equilibrium size distribution would be expected as particles continually grew and fell through the observations level.

In summary, seeding experiments have been conducted in stratiform clouds with AgI flares and dry ice pellets. The AgI curtains persisted and evolved for ~1 h; due to natural cloud glaciation, the dry ice curtain persisted as an identifiable entity for ~10 min. Seeding such thin clouds with low liquid water content obviously cannot produce significant precipitation. However, seeding effects in thin stratus should be similar to seeding effects near the tops of more optimum clouds.

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REFERENCES

English, M., and J. D. Marwitz, 1981: A comparison of the effects from seeding cumulus clouds in Alberta with AgI and CO_2. *J. Appl. Meteor.*, **20**, 483–495.

Havens, B. S., J. E. Jiusto and B. Vonnegut, 1981: Early history of cloud seeding. *J. Wea. Mod.*, **13**, 14–88.

Hobbs, P. V., and M. K. Politovich, 1980: The structures of summer convective clouds in eastern Montana II. *J. Appl. Meteor.*, **19**, 664–675.

Knollenberg, R. G., 1976: Three new instruments for cloud physics measurements. *Preprints Int. Conf. Cloud Physics*, Boulder, Amer. Meteor. Soc., 554–561.

Marwitz, J. D., and R. E. Stewart, 1981: Some seeding signatures in Sierra storms. *J. Appl. Meteor.*, **20**, 1129–1144.

Snider, J. B., F. O. Guiraud and D. C. Hogg, 1980: Comparison of cloud liquid content measured by two independent ground based systems. *J. Appl. Meteor.*, **19**, 577–597.

Stewart, R. E., and J. D. Marwitz, 1982: The downwind spread of an initially vertical column of particles in a sheared environment. *J. Appl. Meteor.*, **21** (in press).

Strapp, J. W., H. G. Leighton and G. A. Isaac, 1979: A comparison of model calculations of ice crystal growth with observations following silver iodide seeding. *Atmos.-Ocean*, **3**, 234–252.

Weickmann, H. K., 1973: The modification of Great Lakes winter storms. NOAA Tech. Rep., ERL 265-APCL 36, 103 pp.