The Persistence of Seeding Effects in a Winter Orographic Cloud Seeded with Silver Iodide Burned in Acetone

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ABSTRACT

A single case-study of a winter orographic cloud over the central Sierra Nevada is presented in which the effects of aerial seeding with silver iodide, an AgI NH_4I NH_4ClO_4 mixture burned in acetone, were observed to persist for over 90 min after seeding and 100 km downwind of the seedline. A research aircraft was able to locate and track the line source of AgI using an ice nucleus counter. High ice crystal concentrations due to seeding were not apparent until more than one hour after seeding. This may have been partially due to the high natural concentrations of ice, but post-mission analysis revealed that most sampling passes during the first hour following seeding were made below the AgI seeded volume. Ice nucleus measurements confirmed sampling of the seedline from 1–1.5 h after seeding, with associated increases in ice crystal concentrations. The effectiveness of the seeding material in the field was higher than laboratory measurements would suggest.

1. Introduction

Since the discoveries of Schaefer (1946) and Vonnegut (1947) a number of experiments have focused on determining the physical effects of cloud seeding. One approach has been to measure directly the effects with instrumented aircraft, radar, and detailed surface measurements (Leonov and Perelet 1967; Leskov 1974; Weickman 1974; Hobbs 1975; Super and Heimbach 1988; Super and Boe 1988). The research conducted during the Sierra Cooperative Pilot Project (SCPP) is a continuation of this effort (Reynolds and Dennis 1986). This paper deals specifically with identifying and tracking seeding material in a wintertime, fairly shallow, stratiform cloud over the central Sierra Nevada with the use of a research aircraft during the final year of the SCPP. It complements earlier studies over the central Sierra Nevada (Stewart and Marwitz 1982; Deshler et al. 1990) in which cloud seeding was done from aircraft using primarily either dry ice or droppable pyrotechnic flares containing AgI. These two droppable seeding agents were used during the SCPP because, according to clear air tests over a lake, they would produce a vertical curtain of ice crystals that extended 700 m below the seeder aircraft. Such an effect was expected to be more easily found and tracked with a research aircraft than a line source of AgI burned in acetone; however, the success rate for detecting seeding effects with these materials was low, even with the research aircraft (Deshler et al. 1990). This led, in the final year of the project, to the experimental use of AgI released as a line source.

The problems encountered from seeding with 20 g AgI flares or dry ice, and the low success rates, as well as the advantages of seeding by burning AgI in acetone have been described by Deshler et al. (1990). Measurements in a cloud chamber indicate that an AgI NH_4I NH_4ClO_4 mixture will produce 10^{13} nuclei g^{-1} of AgI at $-6°C$ and 6×10^{14} nuclei g^{-1} at $-10°C$ (DeMott et al. 1983). There is little increase in activity at temperatures below $-10°C$. With activities this high this mixture may produce detectable levels of ice crystals in clouds as warm as $-6°C$. Also the AgI is useful as a tracer since it can be measured with an ice nucleus counter. This paper presents one case study using AgI NH_4I NH_4ClO_4 that demonstrates the activity of this seeding material and the capability of a research aircraft to find and track a line source of AgI.

2. Instrumentation

The research aircraft, a Beechcraft Super King Air 200T operated by the University of Wyoming, carried a full complement of instrumentation for cloud physics research (Cooper et al. 1984). Instruments on the aircraft measured altitude, indicated turbulence, position, temperature, dewpoint, and winds. The aircraft also carried Johnson–Williams (JW) and CSIRO liquid water meters, a Rosemount icing rate meter, an inertial navigation system, an ice nucleus counter, a Particle Measuring System (PMS) Forward Scattering Spec-

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trometer Probe (FSSP) in the 3–45 μm range with 3 μm resolution, and the following PMS Optical Array Probes: 1D-C operated in the range 12.5–187.5 μm with 12.5 μm resolution, 2D-C in the 25–800 μm range with 25 μm resolution, and 2D-P in the 200–6400 μm range with 200 μm resolution (Knollenberg 1981). The research aircraft was capable of measuring the evolution of a packet of ice crystals as it drifted downwind. By integrating true airspeed and heading, the computer on the aircraft could direct the pilot to make repeated penetrations of a point drifting with the wind (Cooper and Lawson 1984; Huggins and Rodi 1985).

The ice nucleus counter on the aircraft was developed by the National Center for Atmospheric Research (Langer 1973) and is essentially a small cloud chamber where ice nuclei (IN) can activate and the resultant ice crystals can grow to a detectable size. For the SCPP the temperature of the cloud chamber was held at $-20°$C and air was sampled at a rate of 10.0 L min^{-1}. Although the instrument easily senses high concentrations of IN there are delays in the response and relaxation time of the instrument. Empirical tests of the counter indicated a 25–40 s delay between intake of IN and registration of the particles, while it frequently took up to 3 min for the chamber to be purged of IN sampled in a seedline. The 25–40 s delay measured here is consistent with tests reported by Super et al. (1988). Ice nuclei concentrations are also difficult to quantify because of a loss of nucleants and ice particles to the inside walls of the chamber. Langer (1973) estimates a 10% counting efficiency, but Sackiw et al. (1984) reports only a 1% counting efficiency. These counting efficiencies are not incorporated into the IN concentrations presented here. Thus the IN concentrations may be low by a factor of 10 to 100; however, the IN measurements represent activity at the chamber temperature, $-20°$C, and will be less at warmer temperatures, perhaps up to a factor of 100 at temperatures as warm as $-6°$C.

During the SCPP a variety of remote sensing and surface measurements were also available. A 5-cm weather radar was located at Sheridan (SHR) near the base of the Sierra Nevada. Rawinsonde stations were located at SHR and Kingvale (KGV), near the crest of the barrier. Telemetered precipitation gauges with a resolution of 0.1 mm in 5 min (Price and Rilling 1987) were distributed throughout the target area. Intensive surface and remote sensing observations were collected at KGV with a microwave radiometer (Heggli and Rauber 1988), vertically pointing Ka band radar, a 2D-C particle sensor, and a high resolution precipitation gauge.

The seeder aircraft, a Cessna Aero Commander, burned the $\mathrm{AgI\ NH_4I\ NH_4ClO_4}$ in acetone in a pressurized stainless steel container (Carly-type generator) mounted on the fuselage. The AgI was released at a rate of 0.4 g km^{-1} by burning a 3 percent by weight solution of $\mathrm{AgI\ NH_4I\ NH_4ClO_4}$ with the ammonium perchlorate at a 30 mole ratio. This solution was chosen since tests indicated it would produce approximately 10^{13} nuclei g^{-1} at $-6°$C (DeMott et al. 1983). With this activity a rough calculation of the ice crystal concentration (ICC) resulting from seeding can be made. Assuming that the AgI disperses at 1.0 m s^{-1} horizontally and 0.1 m s^{-1} vertically for winter orographic clouds (Hill 1980), and that 80 percent of the IN have activated (DeMott et al. 1983), the ICC would be approximately 40 L^{-1} after 10 min. However, if as DeMott et al. (1983) suggest, contact nucleation is the primary nucleation mechanism for $\mathrm{AgI\ NH_4I}$, then this estimate is too high. If the rate at which IN are scavenged by cloud droplets is included (Slinn 1971), and 100 cm^{-3} of 5 μm radius cloud drops are assumed, instead of the 2000 to 4000 cm^{-3} in the cloud chamber where the material was tested, the expected ICC would be 1.0 L^{-1} after 10 min. If this is the case, increases in ICC due to seeding would be difficult to separate from the background. On the other hand, Finnegan and Pitter (1987) presented evidence indicating that AgI may cause nucleation by condensation freezing when the AgI acetone solution is burned, due to the large amount of water vapor produced. If this occurs then the earlier estimate of 40 L^{-1} is more appropriate. Finnegan and Pitter point out that oxidation of 1 g of acetone produces 0.93 g of water. With this estimate the seeding generator on the aircraft was producing 1.2 g s^{-1} of water, similar to the water production rate during the ground seeding experiments described by Finnegan and Pitter.

3. Case Study

a. *Cloud structure and organization*

On 22 December 1986 at 1200 (all times expressed in UTC) a short-wave trough moved rapidly from the northwest into a split in the upper-level flow over Utah. In the next 12 hours the wave weakened and moved onshore with the main energy to the north of California. The surface front associated with this wave was in the northwest corner of California at 1200. This weak front was observed to pass SHR after 1500 and KGV at 1700 and preceded most of the precipitation associated with it. Liquid water above 0.5 mm, with peaks to over 1.0 mm, were measured with the radiometer at KGV from 1430–1630, but the liquid water diminished to 0.1 mm as the front passed and precipitation began. In the postfrontal air mass a well-defined orographic cloud developed with tops near 5.0 km, $-15°$C, and cloud base near 1.4 km, 0°C. Precipitation began at KGV at 1700, just after frontal passage and continued at over 4 mm h^{-1} until 1900. Light and intermittent precipitation, 0.5 to 1.0 mm h^{-1}, and liquid water near 0.1 mm were then observed until 0400 on 23 December 1986, with the liquid water persisting until 0700.

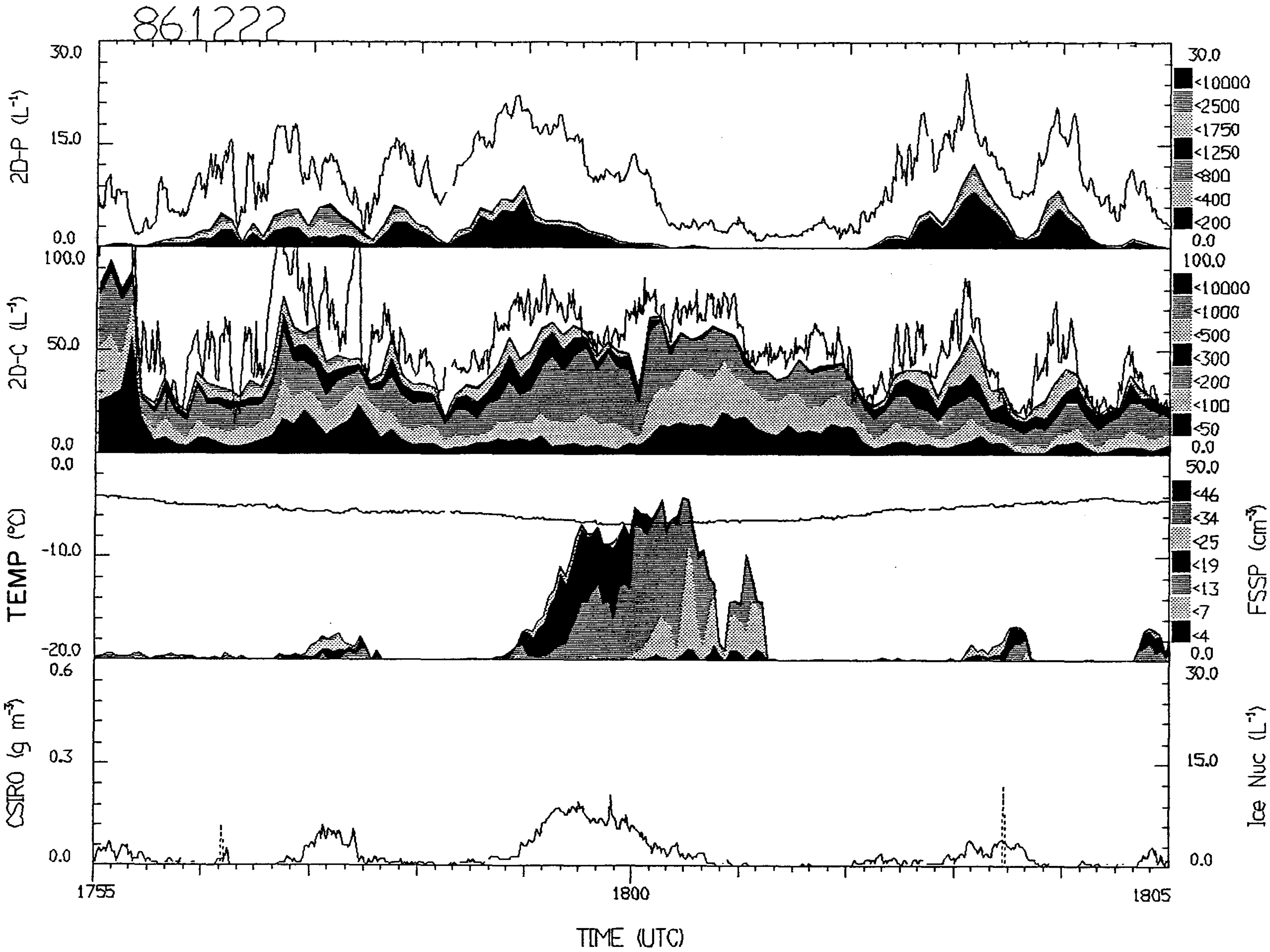

FIG. 1. Measurements by the research aircraft at the seedline prior to seeding. Both the uncorrected and corrected particle concentrations are shown for the 2D-C and 2D-P. The uncorrected concentration is the solid line above the shaded region and represents the concentration of all images sensed by the probe. The FSSP and corrected 2D-C and 2D-P concentrations are presented as a cumulative size distribution. The top of each shaded region represents the concentration of all particles ⩽ to the size (μm) indicated by the gray scale at the right. In the bottom panel liquid water content is given by the solid solid, and ice nucleus concentrations by the dashed line.

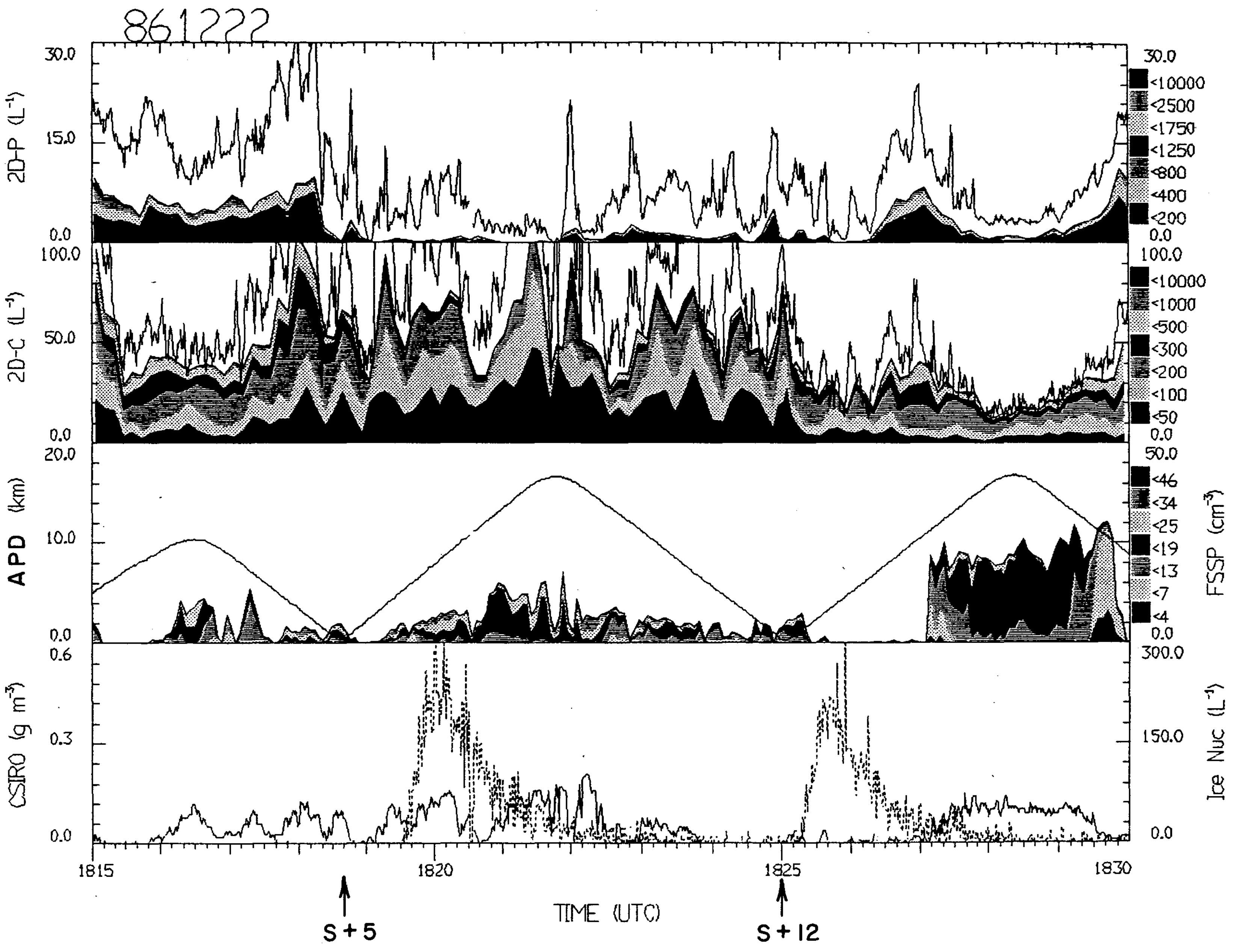

FIG. 2. Measurements, as in Fig. 1, by the research aircraft, a) 1815–1830, b) 1830–1845, while following the seedline out to 29 min. APD represents the distance of the aircraft from the air parcel being tracked. Seedline interception points and the age (min) of that point in the seedline are shown at the bottom. Note that in a) the scale for ice nucleus concentrations is increased from 0–30 to 0–300 L^{-1}.

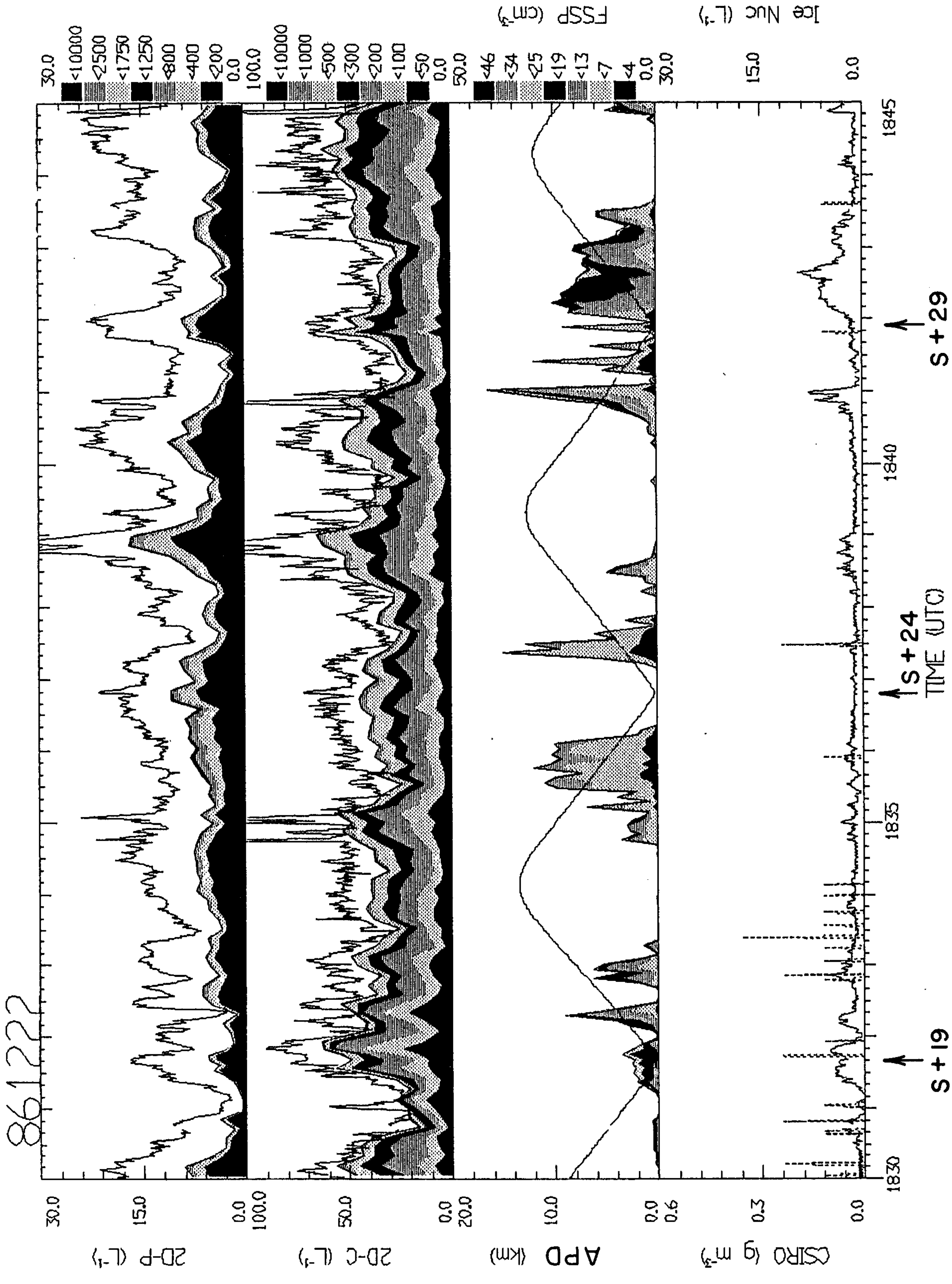

FIG. 2. (*Continued*)

Based on research aircraft measurements during the experiment, 1700–2000, the orographic cloud consisted of ice, 30–100 L^{-1} on the 2D-C, 6–20 L^{-1} on the 2D-P, and almost no liquid water in the FSSP size range. FSSP concentrations, when they existed, were <40 cm^{-3}, with droplets predominantly between 7 and 19 μm diameter. Images from the 2D-C and 2D-P indicated that the ice was primarily small graupel and needles. Analysis of the 2D-C, and comparison of the CSIRO and JW liquid water meters, indicated the possibility of many regions of large drops, 100–200 μm (Rauber and Heggli 1988). At times water drops dominated the particle concentrations sensed by the 2D-C and 2D-P, still only low concentrations of drops 7–19 μm were recorded by the FSSP. Needles, or spikes protruding out of frozen drops were often seen in the 2D-C images in regions of large drops.

b. *Treatment*

A seeding experiment was conducted as a test of the effectiveness of AgI NH_4I NH_4ClO_4 at −6°C. The seeding location was chosen based on measurements by the research aircraft, Fig. 1, which showed a region of liquid water of 0.05 g m^{-3} at 10 km west of SHR. This was nearly the only region of liquid water observed during the ascent sounding and descent along the barrier by the research aircraft.

From 1810 to 1818 the seeder aircraft released AgI NH_4I NH_4ClO_4 at 0.4 g km^{-1} along one 40-km-long seedline. The seedline was 10 km west of SHR and oriented nearly north–south, although average winds were from 235°. The seeder aircraft then left the area while the research aircraft tracked the seedline for 1.5 h making perpendicular passes through the seedline.

c. *Results of seeding*

Measurements by the research aircraft at the seeding location 10 min prior to seeding showed 2D-C concentrations of 50 L^{-1}. After the seeding material was dispensed the research aircraft made 16 penetrations of the seedline. The air parcel tracking capability of the aircraft was used for the first 11 penetrations. The average advection of an air parcel for these penetrations was 242° at 18 m s^{-1}. This average advection was used to determine the seedline age during each penetration by the research aircraft. These ages are shown at the bottom of Fig. 2 which displays the research aircraft measurements during the first five penetrations. The first penetration occurred 5 min and the last penetration 92 min after seeding. A strong signal on the IN counter confirmed seedline interception for the first two penetrations at 5 and 12 min after seeding, Fig. 2a. On the third and fourth penetrations, 19 and 24 min, however, only a few IN were detected, Fig. 2b. Recall that the IN concentrations are calculated based only on the sampling rate and the number of IN counted, and that there is a 25–40 s delay between intake of nuclei and detection. Also, because of the long residence time of nuclei in the chamber and the stochastic nature of ice crystal development, several minutes are required for the instrument to decay to background after sampling a high concentration of IN. This explains the long tail after sampling of IN at 181930 and at 182520.

No IN were measured on the next seven penetrations, 29–61 min after seeding. Particle concentrations near the seedline during these penetrations were high, and although increases in particle concentration were observed at the expected seedline interception times, they were not different from increases observed away from these locations. Examination of the 2D-C and 2D-P images indicated that the particles were a mixture of small particles, possibly water drops (1825), graupel, needles and frozen drops with protruding needles or spikes (183637), Fig. 3. Decreases in the FSSP droplet concentration and a shift of the droplet distribution to smaller sizes at the seedline interception times at 24 and 29 min indicate that evaporation was occurring there; suggesting a higher depletion rate of water in the seedline compared to surrounding regions. CSIRO liquid water concentrations also decreased between 19 and 24 min; however, based on the ice nucleus measurements, the research aircraft was not sampling the seedline after the penetration at 12 min.

After the eighth penetration the crew on the research aircraft decided to climb to attempt to intercept again the line of IN. As the aircraft ascended ice particle concentrations decreased. Definite increases in ICC were then observed simultaneously with seedline penetrations at 55 and 61 min (not shown). These penetrations were at temperatures < −8°C. Because the aircraft had climbed into higher winds its tracking information was invalid; however, clear signals on the ice nucleus counter confirmed seedline penetration for the last five passes, 64–92 min, Fig. 4. Increases in particle concentration were also observed during these five penetrations at temperatures between −9 and −12.6°C. Note that IN concentrations in the seedline had decreased from a peak near 300 L^{-1} soon after seeding to a peak near 30 L^{-1}. Still considering the efficiency of the IN counter to be between 1 and 10% a significant number of nuclei were still available. In Fig. 4 the time of seedline interception is based on the peaks observed in ICC. In 3 of the 5 penetrations shown, the point indicated precedes the increase in IN by the delay time of the IN counter, 25–40 s, while in the penetrations at 64 and 77 min the 25–40 s delay indicates that IN were sensed on the edge of the ice crystal plume. In all five penetrations shown, the IN and ICC increase nearly simultaneously, providing reasonable evidence that the increases in ICC are the result of seeding. For these penetrations the advection speed of the seedline increased from 18 to 20 m s^{-1}. After the penetration at 92 min the seedline was near the crest and the downwind edge of cloud. Given the age of the seedline and the width of the ice crystal plume, the overall dispersion rate was calculated to be 1.3 m s^{-1}.

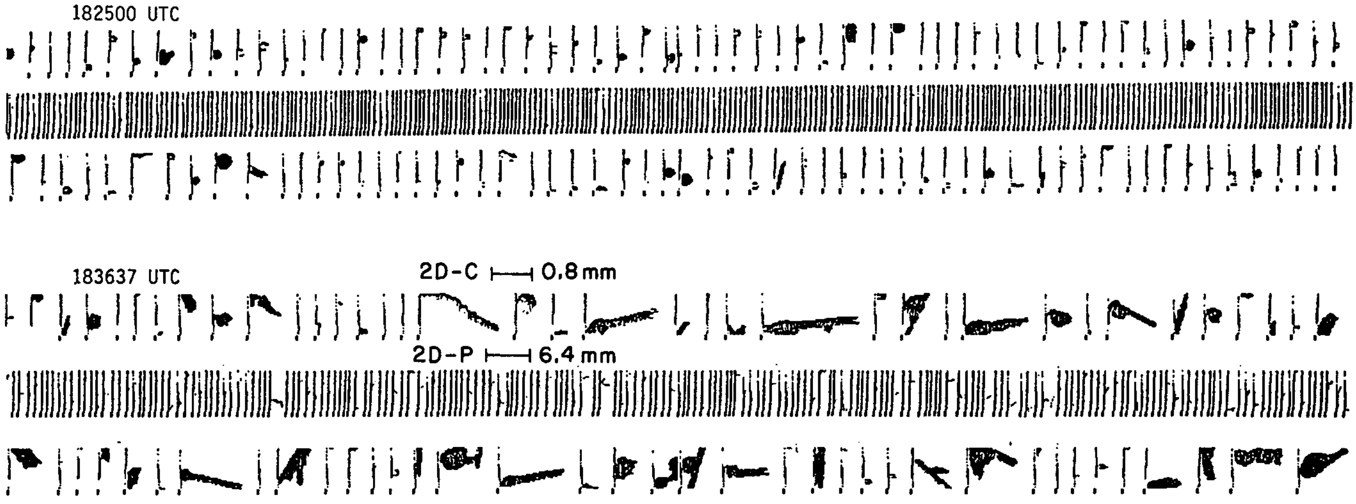

FIG. 3. Images from the 2D-C and 2D-P showing water drops and frozen drops with protruding needles. The center row of images in each set is from the 2D-P.

Images indicated that the particles in the seedline were primarily graupel and plates, while outside the seeded plume branched crystals and aggregates were observed. Within the seedline the crystal habits are consistent with nucleation and growth at temperatures between −8 and −12°C, where thick columns and plates are expected (Magono and Lee 1966). These compact crystal-types rime efficiently and graupel could easily result (Heymsfield 1986). In contrast, outside the seedline branched crystals and aggregates were observed, which are consistent with nucleation and growth near the top of the cloud, −15°C.

The cloud conditions and ice crystal types observed during these final penetrations are not similar to cases when ice multiplication was observed during the SCPP (Deshler et al. 1990), and it is unlikely that an ice multiplication mechanism would confine itself to the seedline. The increases in ICC observed during the seedline penetrations shown in Fig. 4 are also not believed to result from aircraft-produced ice particles (APIPS). During the SCPP several specific experiments were conducted to test for APIPS from the seeder aircraft and no evidence was found (Gordon and Marwitz 1986), although in other experiments the research aircraft was found to cause APIPS in 2 out of 37 penetrations (Marwitz et al. 1986). During the first 11 penetrations of the seedline on this day the research aircraft made repeated penetrations of a point drifting with the wind. If the aircraft was producing ice particles they should have been observed during these penetrations since the aircraft repeatedly returned to the same point, yet no unusual increases in ICC were observed until the last 2 of these 11 penetrations when the aircraft had climbed. However, definite increases in ICC at the seedline were observed during the final five penetrations (all shown in Fig. 4), and these were made at different points along the line. The aircraft flew a "Z" pattern, advecting with the seedline, but moving from the center of the seedline to the north end. Thus these particles could not have been nucleated by the research aircraft.

The seeding material was released in the upwind edge of an orographic cloud with radar reflectivities of 15–20 dBZ. Although there was evidence of ice generation near 5 km, and subsequent enhancement of reflectivity as the particles fell through the cloud, the echo region was generally below 5 km. The seedline remained with this same level of background echo throughout the 92 min of sampling and there were no changes in reflectivity that could be attributed to seeding. This is typical for this type of cloud. Deshler et al. (1990) found in similar experiments that only 4% of the clouds had a background echo low enough for the radar to be sensitive to seeding effects.

A schematic of the cloud and barrier in two dimensions is shown in Fig. 5. The seeding location, the *X*–*Z* location of the research aircraft during seedline penetrations, and the expected envelope of AgI IN, based on the detection of IN at 64 min and assuming a vertical dispersion of 0.1 m s^{-1}, are also shown. According to this calculation the research aircraft was generally below the IN for the first hour. Note that the ascent of the seeding material between 61 and 92 min, 0.2 m s^{-1}, parallels the slope of the barrier. Also shown in Fig. 5 are predictions for the trajectories of ice crystals nucleated after delays of 5, 15, 30 and 45 min, from a targeting model used by the SCPP (Rauber et al. 1988). Although for this case the direction of the model winds and the aircraft measured winds are in good agreement, the model winds are slower by 4 m s^{-1}. This causes the disagreement between the predicted seedline position and the aircraft determined seedline position at, for example, 60 min.

The model predictions of fallout give an average advection of seeding material to the surface of 233° at

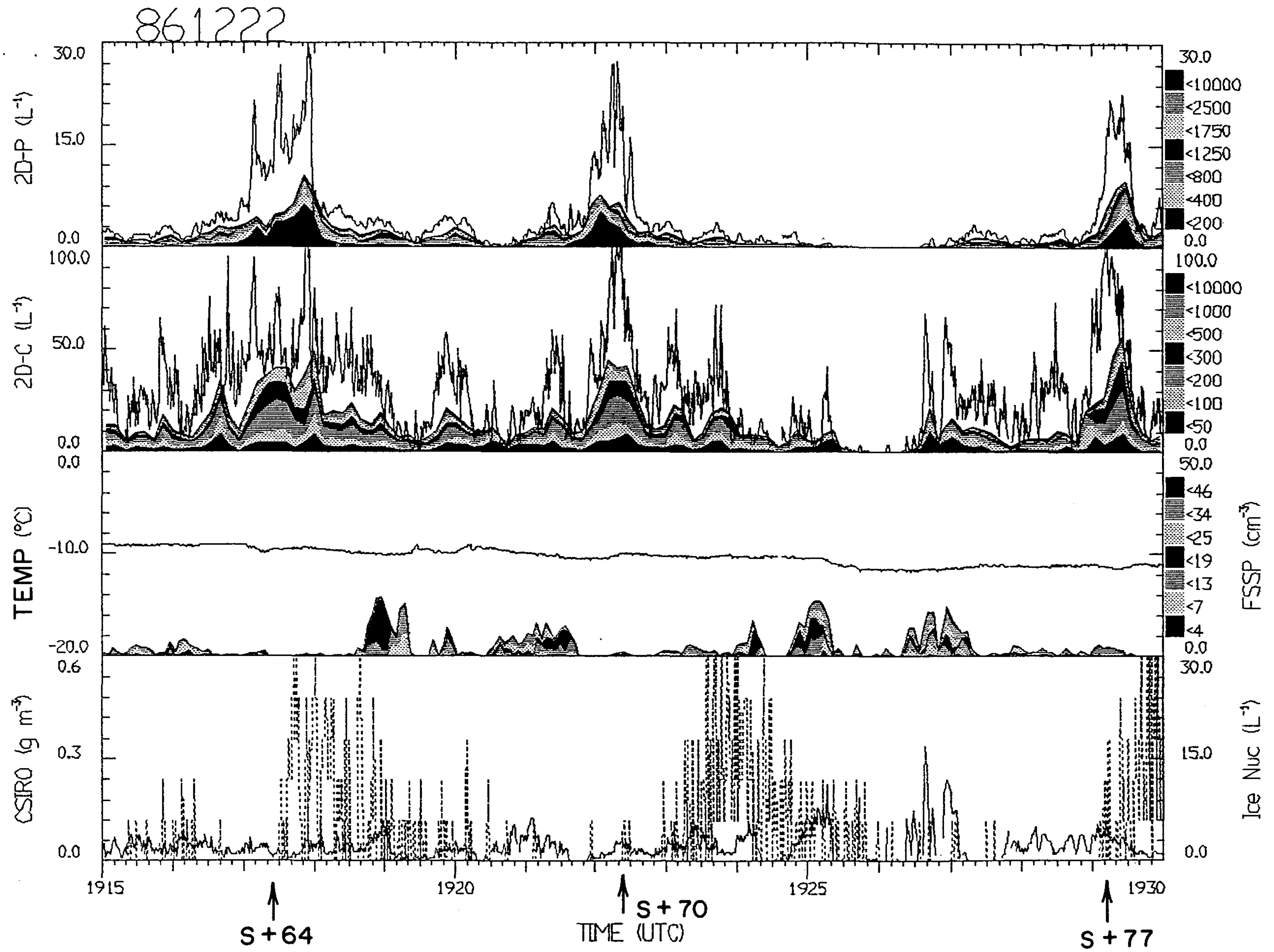

FIG. 4. Measurements, as in Fig. 1, by the research aircraft, a) 1915–1930, b) 1930–1945, while tracking the seedline between 64 and 92 min after seeding. Seedline interception points and seedline age (min) are shown at the bottom.

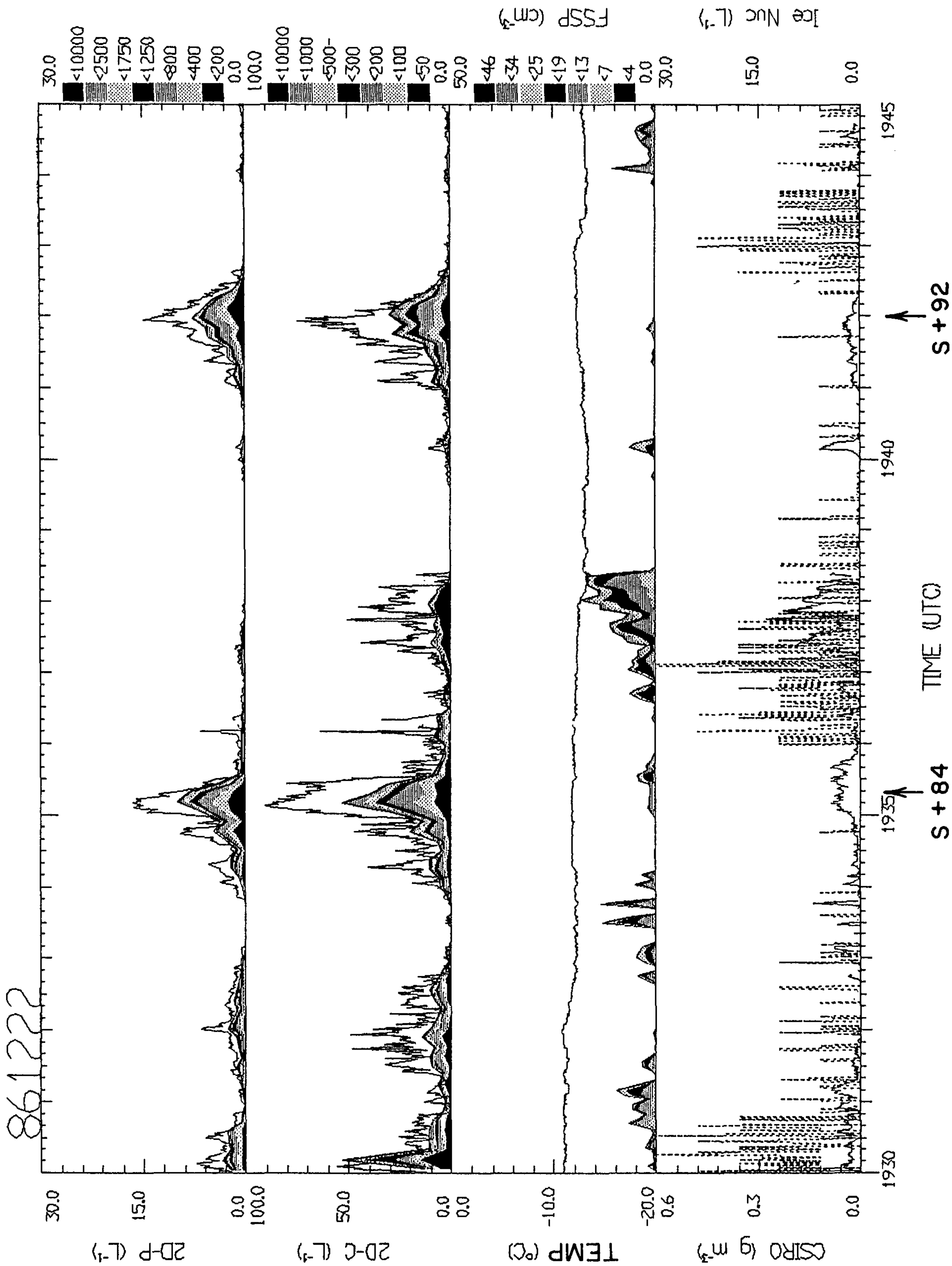

FIG. 4. (*Continued*)

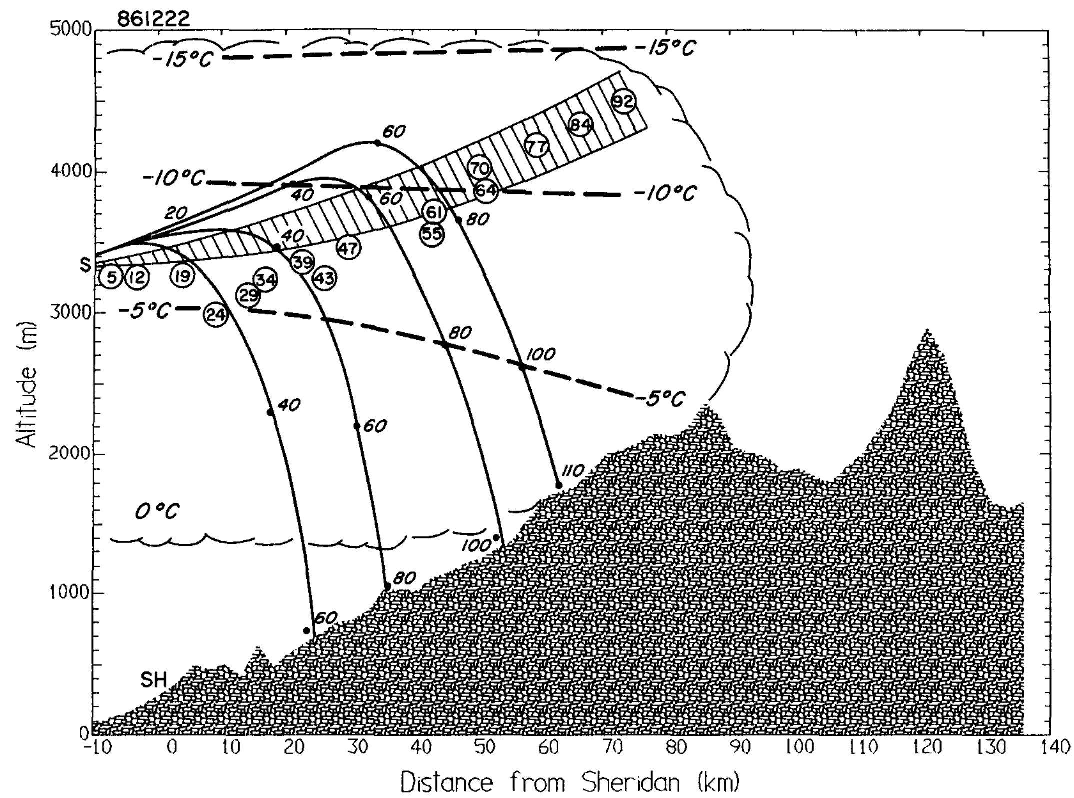

FIG. 5. Cross section of the cloud over the barrier showing temperature structure, seeding location (S), X–Z positions of aircraft penetrations of the seedline (circles containing the time in min after seeding), predicted envelope of ice nuclei assuming a vertical dispersion of 0.1 m s^{-1} (hatched area), and predictions of the trajectory model for ice crystals nucleated at 5, 15, 30 and 45 min after seeding. The numbers along the trajectories indicate time (min) after seeding. The barrier cross section shown is a generalized cross section and does not represent specifically the terrain along the seedline trajectory. Ice nuclei were measured by the aircraft during penetrations at 5, 12, and 64–92 min.

12 m s^{-1}, indicating that ice crystals would begin reaching the surface after 60 min. With this advection the southern end of the seedline crossed three precipitation gauges, but passed to the north of the instrumented surface station, KGV. The duration of effects at the ground from this one seedline was estimated to be <10 min. For all three gauges intermittent precipitation of 1 mm h^{-1}, the minimum detectable signal, was observed during the time of seedline passage. Thus there was no indication in the surface data of seeding effects; however, the resolution of these gauges, 0.1 mm in 5 min, is likely too coarse to be sensitive to most seeding effects. From a survey of wintertime orographic seeding experiments Reynolds (1988) found precipitation increases expected from seeding to be on the order of 0.25 mm h^{-1}.

4. Summary and conclusions

One line of AgI NH_4I NH_4ClO_4 was released at −6°C in a stable post frontal stratiform cloud with natural particle concentrations in excess of 50 L^{-1} on the 2D-C. The research aircraft was able to track this seedline to the downwind edge of cloud, some 100 km and 92 min after seeding. During the first two penetrations of the seedline high concentrations of ice nuclei were measured, but increases in particle concentration on the 2D-C or 2D-P were difficult to separate from the background. This may be due in part to a slow nucleation rate. The seedline then apparently ascended above the research aircraft. No ice nuclei or increases in ice crystal concentration were detected on penetrations between 19 and 47 min, but based on the ice nucleus measurements the aircraft was not sampling the seedline. When the aircraft ascended, seeding material was again detected with the ice nucleus counter during penetrations between 64 and 92 min after seeding. The ascent of the seedline matched the slope of the barrier. Increases in particle concentrations at the seedline were clear at the higher altitudes where background concentrations had decreased to 10–20 L^{-1} on the 2D-C, and 2 L^{-1} on the 2D-P. Then increases to 30–40 L^{-1} on the 2D-C, and 6–9 L^{-1} on the 2D-P were observed at the seedline from 55 to 92 min after seeding in a cloud with droplet concentrations of <40 cm^{-3}. If CO_2 had been used instead of AgI, the effects of seeding would have been below the altitude of the research aircraft before natural particle concentrations had decreased to a level where the seeding effects could have been observed. Also, CO_2 may have been ineffective on this day considering the low liquid-water content observed at the seedline.

No effects from seeding were observed with radar; however, considering the intensity of natural echo, relative to echoes anticipated from seeding (Deshler et al. 1990), no radar seeding effects were anticipated. Similarly no seeding effects were observed with the surface instrumentation; however, the resolution of the precipitation gauges was above what may be expected from the passage of one seedline, and the seedline did not pass over the heavily instrumented surface station.

The final penetration of the seedline, 10 km from the downwind edge of cloud, Fig. 4b, still showed a significant concentration of ice nuclei, suggesting that seeding effects would be limited by the dimensions of the cloud and not by the amount of seeding material released. The unscavenged nuclei at the downwind edge of cloud will pass over the barrier. If they enter another cloud system they could be expected to contribute to the ice formation process in that cloud. Thus, these measurements lend credence to predictions of extra area effects from seeding with AgI (Brown et al. 1978).

Although the goal of documenting ice crystal nucleation at −6°C with AgI NH_4I NH_4ClO_4 was not met, this case presents an outstanding example of the ability to track seeding material for a long period of time. It also suggests that AgI NH_4I NH_4ClO_4 is an effective cloud seeding agent with properties in the field that meet or exceed those measured in the laboratory. Using the width of the ice crystal plume on the last penetration (7 km), the length of the seedline (40 km), and assuming the ice crystal curtain reached the surface 2.5 km below, the volume of cloud affected by seeding can be roughly calculated. The result is 7×10^{14} L. Sixteen grams of AgI were released, which according to DeMott et al. (1983) would give approximately 10^{16} nuclei active at −10°C, assuming all ice nuclei have activated. This amounts to an ice particle concentration of 14 L^{-1} from seeding in agreement with measurements at 92 min that show 10–20 L^{-1} in the seeded curtain. DeMott et al.'s measurements indicate that all ice nuclei in the cloud chamber activate within 20–30 min, while these field measurements indicate approximately 10% of the ice nuclei still available after 90 min. Given the 1–10% counting efficiency of the ice nucleus counter, the 30 L^{-1} shown in Fig. 4 may represent a relatively high concentration of ice nuclei. This difference in ice nucleus scavenging rate could be attributed to the lower droplet concentration in the natural cloud compared to the cloud chamber where droplet concentrations are higher by a factor of 100. The collection rate in the cloud chamber would be significantly faster because of the high droplet concentration. Considering the ice crystal concentrations observed and the ice nuclei still available these observations indicate that the activity of this AgI mixture meets or exceeds laboratory measurements. In particular they suggest that contact nucleation is not the primary mode of nucleation. If the above calculation is repeated, including a scavenging rate for the ice nuclei (Slinn 1971), the prediction is an ice crystal concentration of 5 L^{-1} after 90 min.

Based on these observations, AgI is active at temperatures > −10°C, which is necessary for seeding in the Sierra Nevada, and has several advantages over CO_2. For CO_2, liquid water is necessary at the time of seeding and all nucleation occurs instantaneously; for AgI, this is not the case. Seeding could even be done upwind of cloud to allow more time for the material to disperse, before the AgI nuclei encounter liquid water and become active (Hill 1980). Also, with AgI, nucleation will be spread out over a longer time, thus perhaps making better use of the liquid water available.

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