The Disposition of Silver Released from Soviet OBLAKO Rockets in Precipitation during the Hail Suppression Experiment Grossversuch IV. Part II: Case Studies of Seeded Cells

J. P. LACAUX

Université de Clermont II, 653 Lannemezan, France

J. A. WARBURTON

Desert Research Institute, University of Nevada System, Reno, Nevada 89506

J. FOURNET-FAYARD

Université de Clermont II, 653 Lannemezan, France

P. WALDTEUFEL

Meteorologie Nationale (EERM), 92106 Boulogne Billancourt

(Manuscript received 11 August 1984, in final form 11 April 1985)

ABSTRACT

This paper describes analyses of data collected from four seeded storms during the 1978 summer program of Grossversuch IV in Switzerland. The storms all met the Soviet criteria for hail-forming potential and were seeded with Soviet-type OBLAKO rockets.

A seeding "quality" was estimated in each of the cases by observing the internal structure of the storm cells with C, S and X-band radar, and the trajectory, time of residence and dispersion of the AgI aerosols in the seeded clouds with radar and chemical techniques. The notion of "seeding coverage" is presented as the ratio of the surface area of precipitation in which the seeding chemical is found at the ground to the surface area of the rainfall (using the 40 dBZ radar reflectivity contour near the ground).

The study of two cells on 30 June 1978 shows that the seeding coverages were small (7% and 25%) and that estimated residence times for AgI in those portions of the cloud colder than −5°C were too short to allow for significant ice phase modification. The other two cells, seeded 11 and 14 July 1978 had seeding coverages of 100% and AgI residence times, in cloud colder than −5°C, of 500–700 seconds, which should be adequate for modification of the water–ice balance in these clouds.

Positive correlations exist between precipitation intensity and seeding chemical concentration when the seeding aerosol has a long residence time in cloud colder than −5°C (11 July case). This is not so when the AgI aerosols are scavenged in a short time interval as occurred in the two case studies of 30 June.

The hail suppression plan for the Grossversuch IV experiment was shaped in accordance with the Moldavian hail suppression organization. The seeding criteria attempts to guarantee that the seeding time always occurs at the same stage of development of a growing storm. This criterion is based on six 3-cm radar parameters in the RHI mode and by a radiosonde. These parameters are cloud top height, height of maximum reflectivity, the temperatures at these heights, the ratio of cold to warm parts of cloud and the maximum reflectivity. If the hail probability is determined to be greater than 50%, the maximum reflectivity Z_m is $\geqslant 45$ dBZ, and $Z_{\max}$ has a height above or at the freezing level, then seeding is carried out.

Although the Soviet criteria were met for seeding purposes in all cases described here, the results show that the *reflectivity structure* of the storms is also very important and should be allowed to play a prominent role in assessing where and when the seeding agent should be injected, if at all, in attempting to suppress hail growth.

1. Introduction

The research program Grossversuch IV aimed to make a statistical evaluation of the Soviet method of hail suppression; it operated between 1977 and 1981 in the NAPF district of Switzerland (Fig. 1). The estimate of any suppression effect is based on a statistical study of the kinetic energy of the hail measured by hail-gauges and by a calibrated S-band radar for the days of deep convection. The decision to seed or not is randomized (Federer *et al.*, 1979).

Although there is currently a move away from the "accumulation zone" concept, the Grossversuch program of suppression was based on the original Soviet concept of hail formation related to an accumulation or Big Drop Zone (BDZ) occurring at the top of the updraft region. The BDZ might be observable by radar as a high reflectivity zone.

Six radar parameters were used, together with information from radiosondes. The original Moldavian criteria for seeding was a probability of hail occurring $P > 30$–50%, the height of the maximum reflectivity $H_{ZM} + 1\text{ km} \geqslant H_0$ the height of the freezing level, and $Z_m > 34$ dBZ. The probability P was determined using an empirical relationship amongst these various parameters. The Grossversuch IV seeding criterion is slightly different, having been adjusted to the local climatology after discussions with Soviet scientists. This

© 1985 American Meteorological Society

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

modified criterion requires the probability $P > 50\%$, the maximum reflectivity $Z_m \geqslant 45$ dBZ, and the height of Z_m at or above the freezing level, $H_{ZM} \geqslant H_0$.

When these conditions were satisfied, AgI ice nuclei would be introduced with one large rocket or four small rockets every five minutes along the front side of a moving radar echo with the parachute release and consequent massive vertical seeding at the edge of the region of high echo intensity ($Z_m - 10$ dBZ). If the radar echo is stationary the vertical release is to be made inside the ($Z_m - 10$ dBZ) region.

The characteristics of the OBLAKO rocket are given in Table 1.

The primary objectives of the present study in 1977 and 1978 were to estimate the trajectories, residence times and dispersion of the AgI aerosol as functions of storm structure based on radar reflectivity data and silver analysis of precipitation from the seeded clouds.

The temporal and three-dimensional measurements of the reflectivity structure were made by the Ronsard radar system (Nutten *et al.*, 1979) using two meteorological C-band radars located at Seengen and Grossdietwill, and the S- and X-band radars located at Emmen (see Fig. 1). A network of time sequential automatic samplers, numbered 1–15, (Fig. 1) were used (Lacaux and Warburton, 1980) to collect the precipitation; four vehicles, directed by radar personnel, were also used for manual collections of precipitation. These sites are labeled H, J, K and L throughout the paper.

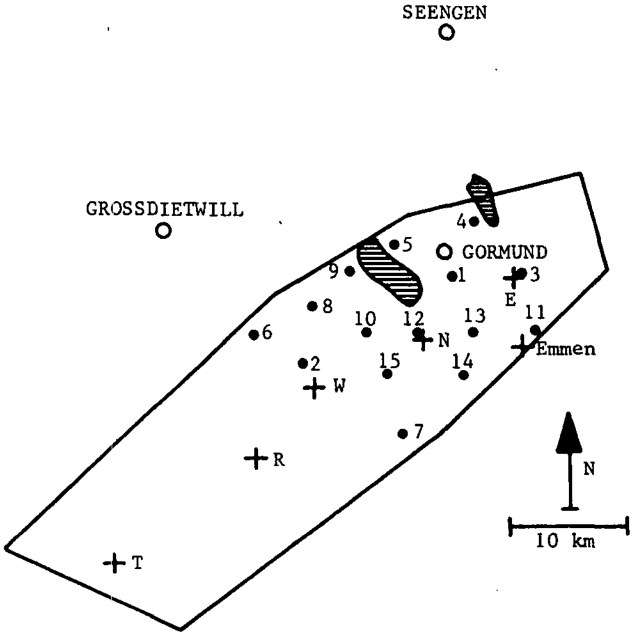

FIG. 1. Experimental area of Grossversuch IV. Ronsard C-band radars at Grossdietwill and Seengen; X- and S-Band radars at Emmen; Gormund radiosonde station; firing stations for OBLAKO rockets. E—Eschenbach; N—Neuenkirch; W—Wolhusen; R—Romoos; T—Trubschachen. Precipitation sampling sites 1-15. The stippled areas are lakes.

TABLE 1. Characteristics of OBLAKO rocket and AgI aerosol.

Characteristic	Value
OBLAKO rocket	
Caliber	125 mm
Weight	34 ± 0.5 kg
Length	2150 mm
Weight of the pyrotechnic charge	5.2 kg
Seeding materials	84 gr AgI
Maximum altitude	8.5 km
Maximum range	12.7 km
Maximum speed	475 m s^{-1}
Duration of AgI release	40 s
AgI aerosol	
Average diameter	0.03 μm
Number of active nuclei per gram of AgI at	
−5°C	6×10^{11}
−10°C	8×10^{12}
−15°C	3×10^{13}
−20°C	10^{14}

Earlier attempts have been made to include "seeding quality" as a means of stratifying seeding effects. For example, Foote *et al.*, (1979), for the National Hail Research Experiment and Federer *et al.*, (1979) for Grossversuch IV, have defined "seeding coverage" by comparing the amounts of seeding aerosol released, with some previously-prescribed amount. By contrast, this paper attempts to provide a quantitative estimate of "seeding quality" using the seeding agent as a tracer for targeting the effect in the manner outlined by Browning and Atlas (1977) and previously used by Linkletter and Warburton (1977) and Warburton *et al.*, (1982). This approach was possible in Grossversuch IV because the average number of rockets used to seed a cell is small, a well-adapted network of sequential precipitation samplers was available and several excellent radar systems were able to make detailed studies of reflectivities in the seeded clouds.

Results obtained from four seeded storms on 30 June, 11 July and 14 July 1978 are presented here. All times used are local (GMT + 1 hour).

2. Study of 30 June 1978 (two cases)

From 1430 radars observed a series of cells with growing periods of about 10 minutes followed by mature phases of 20–50 min. Their average motion was from 235° at 25 km h^{-1}. The 35 dBZ radar echo dimensions were 5–10 km in the horizontal plane; the vertical extent, determined by the 10 dBZ contour, rarely went above 7.0 km (−25°C). Convective activity weakened and cells were no longer identifiable after 1830.

Precipitation began in the network at 1417, and 132 samples of precipitation were collected; (maximum intensity observed 120 mm h^{-1}). A dozen small zones of

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

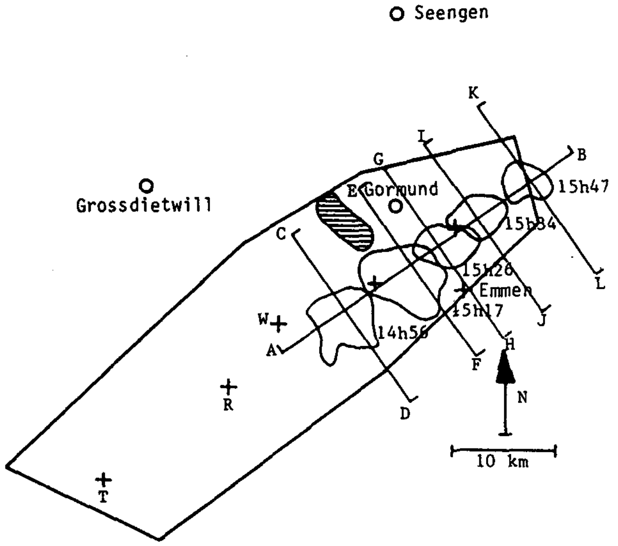

FIG. 2. Movement of cell G: 35 dB*Z* contour at 3.5 km altitude. AB, CD, EF projections of the vertical sections shown in Fig. 3.

hail (maximum diameter 0.9 cm) were observed by the hail-pad network.

On 30 June, a seeded day, 10 OBLAKO rockets were used. Cell G (see nomenclature of Projekt Grossversuch IV, 1978) was seeded by three and Cell N by five of these rockets. The following analysis relates to these two cells.

a. Study of cell G

Figures 2 and 3 show the motion and vertical sections of reflectivity structure of cell G from 1456 to 1547. This cell originated (within the project area) around 1450. The lines AB delineate the locations of scans parallel to the direction of the cell's motion and lines CD, EF, GH, . . . , etc., of scans perpendicular to its motion.

There is good agreement between the locations of higher radar reflectivity and precipitation at the ground. For example, the location of the 30 dB*Z* contour at 1456 corresponded to precipitation first reaching the ground at Collector number 6 (see Fig. 4) at 1505. Rainfall from this cell was collected at five sites. Figure 4 shows the movement with time from site 6 to site 14. Two manual collectors were operated at site L.

The vertical sections AB and CD in Fig. 3 at 1456 show the existence of a precipitation "pocket" outlined by the 30 dB*Z* contour between the altitudes of 2.5 and 5 km above ground, and which contained zones of higher reflectivities (40–45 dB*Z*) which changed significantly with time and often extended to the ground.

The radar and precipitation data shows that this unicellular storm had a mature phase lasting about 30

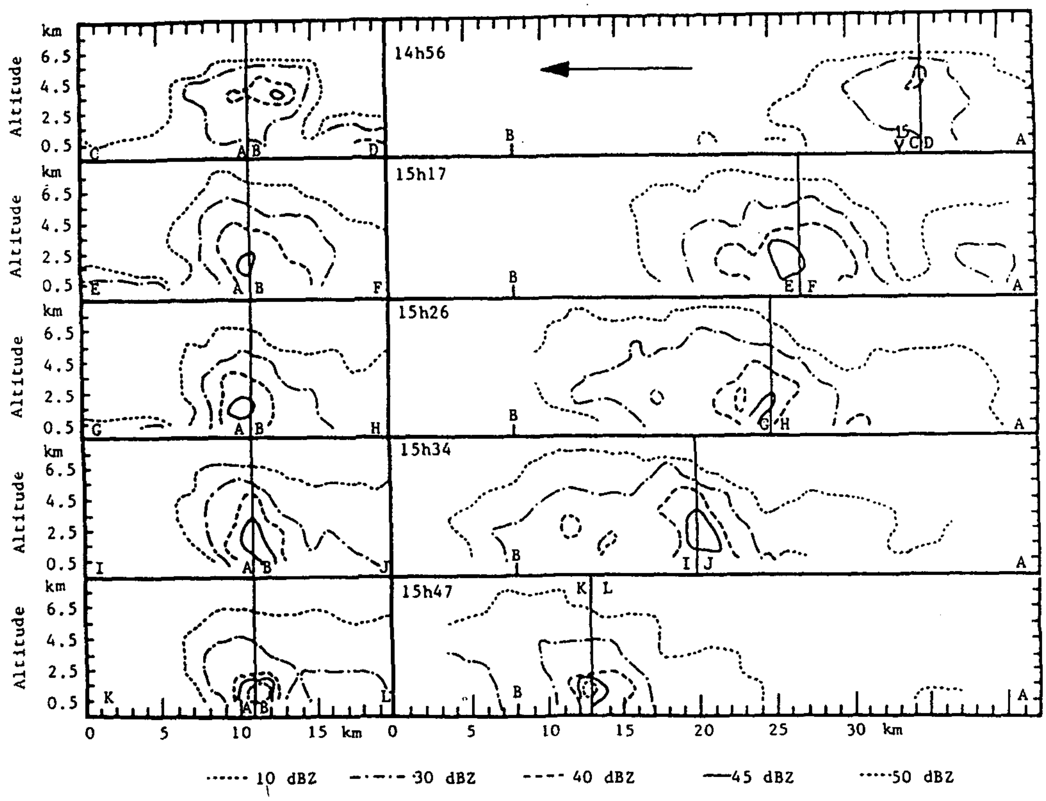

FIG. 3. Vertical sections of reflectivities parallel (right) and perpendicular (left) to the direction of motion of cell G; 10 dB*Z* dashed; 30 dB*Z* dot-dashed; 40 dB*Z* long dashed; 45 dB*Z* solid; 50 dB*Z* dotted.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

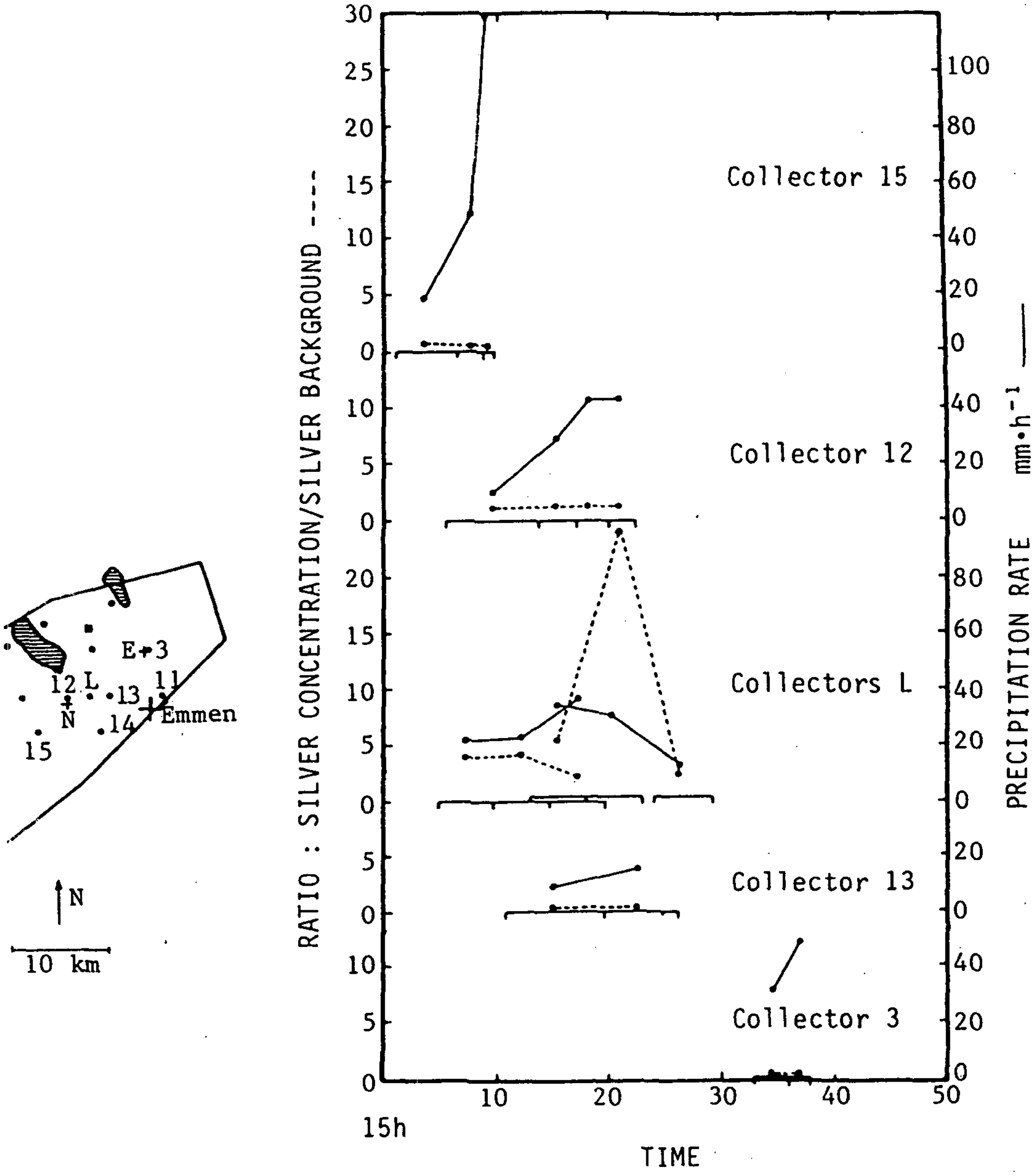

FIG. 4. Silver content (dashed line) of G cell precipitation ([Ag]/background) and precipitation rate (solid line) (mm h^{-1}) as functions of time, 30 June.

min, during which it produced significant precipitation. It maintained a fairly steady reflectivity structure with vertical development up to 7.1 km (temperature −26°C). Around 1510, it developed a well-defined column of precipitation, identified by the 40 dB*Z* contour, inside of which was a smaller column of 45 dB*Z* reflectivity having cross sectional area about 3 km^2 and maximum elevation 3.1 km (temperature −5°C).

These characteristics indicate that cell G would not satisfy the Soviet definition for strong hail formation (zone of accumulation of liquid between −15 and −30°C). However, it did meet the Soviet reflectivity requirement for seeding to occur, but this reflectivity came from intense precipitation at low elevations and warmer temperatures (1.5–3.5 km and 0 to −5°C) as shown in Figs. 3 and 4 rather than from a high elevation accumulation zone (−15 to −30°C).

1) SEEDING OF CELL G

Cell G was seeded with three OBLAKO rockets (N9, E18 and E20). The horizontal projections of the seeding tracks of the three rockets and the 45 dB*Z* contours of reflectivity at the times of rocket release, are given in

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

Fig. 5. The trajectories of N9, E18 and E20 in relation to the vertical sections of reflectivity in the firing plane are shown in Fig. 6. Mean altitudes of AgI release for the three rockets were 3.3, 3.1 and 3.7 km respectively. Corresponding temperatures at these heights were −5, −4.5 and −7°C.

At the launch time of N9 (1509), the cell was already in a mature phase and precipitating; see Figs. 5 and 6 which show a column of precipitation (45 dB*Z* contour) extending from 5.5 km to the ground. The N9 rocket trajectory is located in this column showing that seeding did not occur in a strong updraft region below a high reflectivity zone. It appears that the strong reflectivity zone selected as a dB*Z* target was simply a portion of the precipitation zone.

The trajectories of E18 and E20 (Fig. 6) are also entirely within the 40 dB*Z* reflectivity zone extending to the ground between 1519 and 1543.

2) AgI AEROSOL DIFFUSION IN CELL G—SILVER CONTENT OF PRECIPITATION

Figure 4 gives the precipitation rate and the ratio of the silver concentration to the average silver background as functions of the collection time. This background is 0.6×10^{-11} g ml^{-1} ($\sigma = 0.5 \times 10^{-11}$ g ml^{-1}). For details see Lacaux and Warburton (1980).

The ratio exceeded unity at sites 6, 8 and L, but if we use the maximum observed value of natural silver as the background criterion, (3.3×10^{-11} g ml^{-1}), the ratio exceeds unity only at site L between 1518 and 1523.

Figure 4 also shows that in this case, this ratio is independent of precipitation intensity.

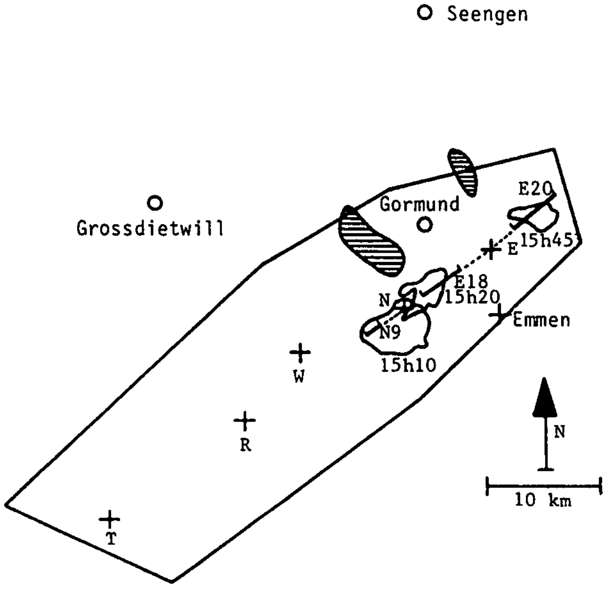

FIG. 5. Horizontal outline of cell G: 45 dBZ (solid) and 50 dBZ dotted contours during the OBLAKO N9, E18 and E20 seedings.

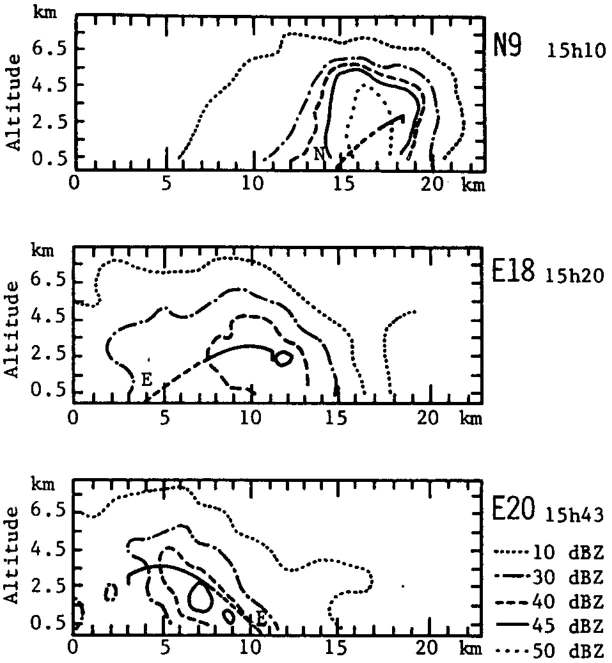

FIG. 6. N9, E18, E20 rockets trajectories in relation to vertical sections of reflectivities in the firing plane, 30 June. Solid line of trajectory is AgI release portion.

3) RESIDENCE TIME OF AgI PARTICLES IN CELL G

The residence time is defined as the time difference between AgI aerosol release and the time of peak silver value in the precipitation. The release time is determined by adding half the time the rocket emitted AgI (22 seconds) to the launch time. The time of occurrence of peak silver at collection site L is 1520.5. Table 2 lists the *measured* residence times for the N9, E18 and E20 launchings.

The residence time can also be *calculated* by estimating the time needed for the precipitation to fall from the altitude where the rocket emitted half of the AgI aerosol. This can be done using either reflectivity–fall velocity relationships or from precipitation rate measurements at the ground. For example, the precipitation rate measured at site L (31.4 mm h^{-1}) yields a mean drop size of 1.6 mm, (using the Marshall-Palmer drop size distributions for intensities between 1 and 35 mm h^{-1}). The average fall speed of 1.66-mm diameter rain drops between 600 mb and the ground is 6.3 m s^{-1} (Beard and Pruppacher, 1969). The average calculated residence times for each rocket are also in Table 2. The differences (ΔT) between measured and calculated times show that only N9 (ΔT positive) could have contributed to the silver observed at site L. Furthermore, the motion of G and the trajectories of E18 and E20 (Fig. 5) indicate that those rockets have not influenced the silver content of precipitation at site L. Even though the evidence indicates that the seeding

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

TABLE 2. Measured and calculated residence times of AgI aerosols.

OBLAKO	Average time of seeding	Corresponding altitude (km/ground)	Time of peak Ag value	Residence time measured (sec)	Residence time calculated (sec)	Measured minus calculated time ΔT (sec)
			Cell G			
N9	1509:22	3.3	1520:30	668	524	144
E18	1519:22	3.1	1520:30	68	492	<0
E20	1543:22	3.7	1520:30	<0	587	<0
			Cell N			
(i) Period 1759–1808						
T22	1711:22	3.0	1803:30	3128	667	2461
W14	1744:22	3.6	1803:30	1148	800	348
(ii) Period 1825–1830						
T22	1711:22	3.0	1827:30	4568	667	3901
W14	1744:22	3.6	1827:30	2588	800	1788
W15	1809:22	3.0	1827:30	968	667	301

aerosol entered a precipitation zone, we have assumed that half of the 144 sec (ΔT for N9) was available for transport of the seeding aerosol to higher elevations in updraft equal to the average 6.3 m s^{-1} needed to suspend 1.66 mm diameter drops. If this were the case, the altitude attained would be 3.7 km where the temperature was −7°C. This indicates that about <1% of the AgI particles reaching that elevation could serve as ice nucleants (see Table 1).

4) SILVER IODIDE BUDGET AND SEEDING DISPERSION

Since silver was observed only at one sampling site, we have assumed (i) that the precipitation aerosol was confined within a circle of 2.5 km diameter (network spacing), and (ii) that the observed silver to background ratio (24.2) is constant in the 2.6 mm of precipitation collected between 1518 and 1523 at site L. From this we calculate that 4 grams of AgI were precipitated out, or 5% of the quantity released by N9. The ratio of surface area of precipitation (characterized by the 40 d*BZ* contour between 1520 and 1547) to the surface area over which the silver was detected, yields a "seeding coverage" of 7%.

In summary, cell G fulfilled the Soviet criteria for seeding for hail suppression, and the cell was seeded between 3.1 and 3.7 km altitude with 250 g of AgI. The dispersion and residence time of the seeding aerosol in the cell show that there was little opportunity for the AgI to affect the ice phase processes in the cloud. The high reflectivity regions were due to precipitation zones reaching from 5.5 km altitude to the ground and not to accumulation zones (dBZs).

b. Cell N, 30 June 1978

Figure 7 shows the successive locations of cell N derived from radar data from Grossdietwill. Details of vertical structure, using sections along and orthogonal to the direction of motion are shown in Fig. 8. There is good agreement between the passage of higher radar reflectivity zones and the appearance of precipitation at the ground (see Figs. 8 and 10). For example, collector 2 (for location see Fig. 1), measured 5.4 mm of water (maximum rate 51.4 mm h^{-1}) between 1813 and 1815.

1) SEEDING OF CELL N

Three OBLAKO rockets (T22, W14, W15) effectively entered the storm cell; the mean altitudes of release were 3.0, 3.6 and 3.0 km respectively, where the

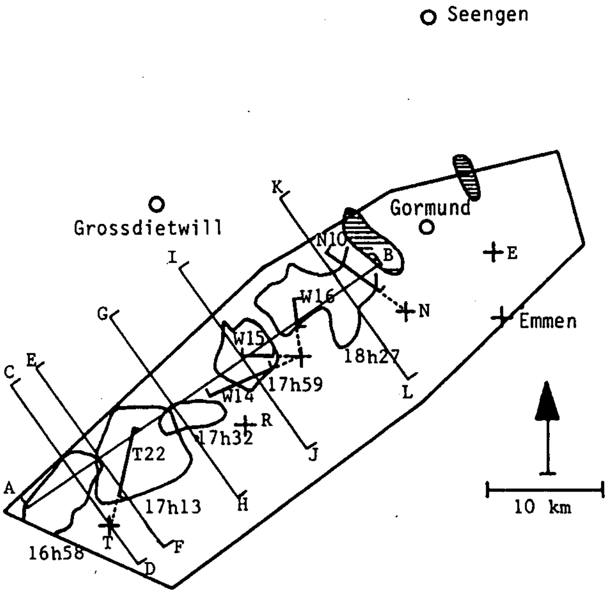

FIG. 7. Trajectory of cell N 35 dBZ contour at 3.5 km altitude. Also horizontal tracks of various OBLAKO rockets, 30 June. AB, CD, EF projections of the vertical sections shown in Fig. 8.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

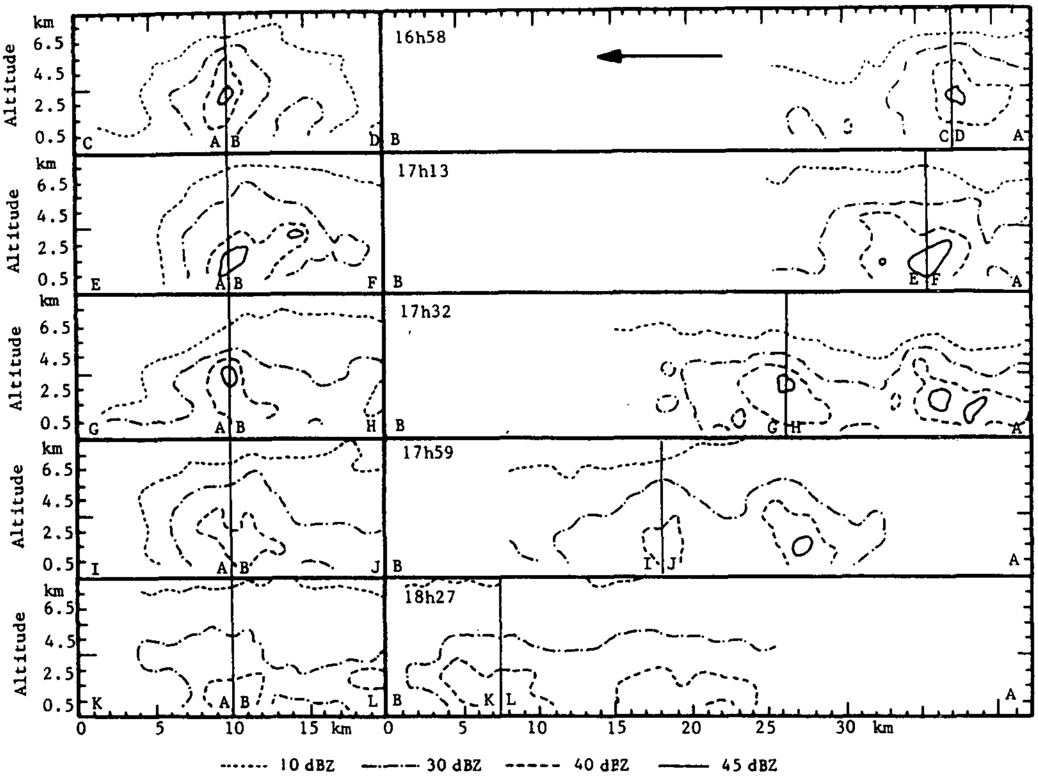

FIG. 8. Vertical sections of reflectivities parallel (right) and perpendicular (left) to the direction of movement of the N cell: 10 dBZ dashed; 30 dBZ dot-dashed; 40 dBZ long dashed; 45 dBZ solid; 30 June.

temperatures were −4.0°C, −6.5°C and −4.0°C; the horizontal projections of the trajectories are shown in Fig. 7 and the seeding details are in Table 2(b). The radar RHIs in the planes of the three rocket trajectories are given in Fig. 9.

Two-thirds of T22 is within the 40 dBZ and one-third in the 30 dBZ region at the front of the cell. Four-fifths of W14 is in the 30 dBZ region at the front of the cell, with one-fifth in the 40 dBZ region. Most of W15 is in the 40 dBZ and a small amount in the 30 dBZ region of the cell.

2) AgI AEROSOL DIFFUSION IN CELL N

As shown in Fig. 10, there were two periods (1759–1808 and 1825–1830) when the silver content of the precipitation was significantly above background (16 times and 61 times respectively). For this case the ratio of silver content to background was, as for cell G, independent of precipitation rate.

Using the same procedures as before, the measured and calculated residence times of AgI in the regions of cloud colder than −5°C were determined (Table 2) for the period 1759–1808. The measured time for T22 AgI is greater than 52 min, which should allow for significant dispersion in the front part of the cell (Fig. 9). We would therefore have expected collectors 2, 4, 5 and L to receive (as did collector K) some of the silver in their precipitation. Because this did not happen we have concluded (perhaps without complete justification) that T22 did not contribute to the silver content

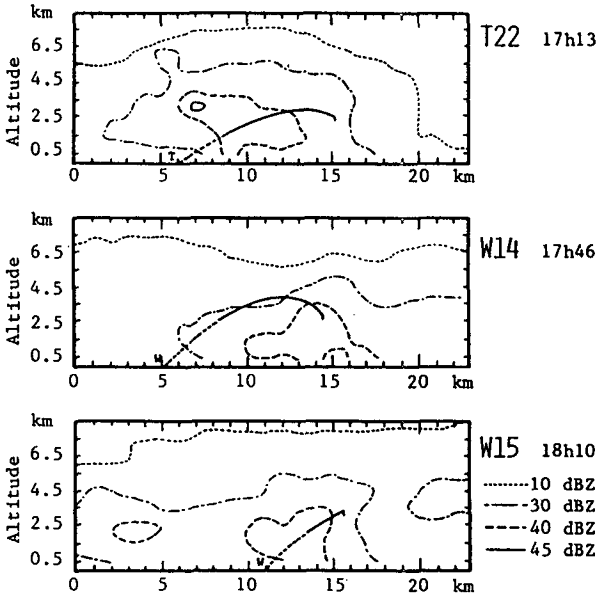

FIG. 9. T22, W14 and W15 rockets trajectories in relation to vertical section of reflectivities in the firing plane, 30 June.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

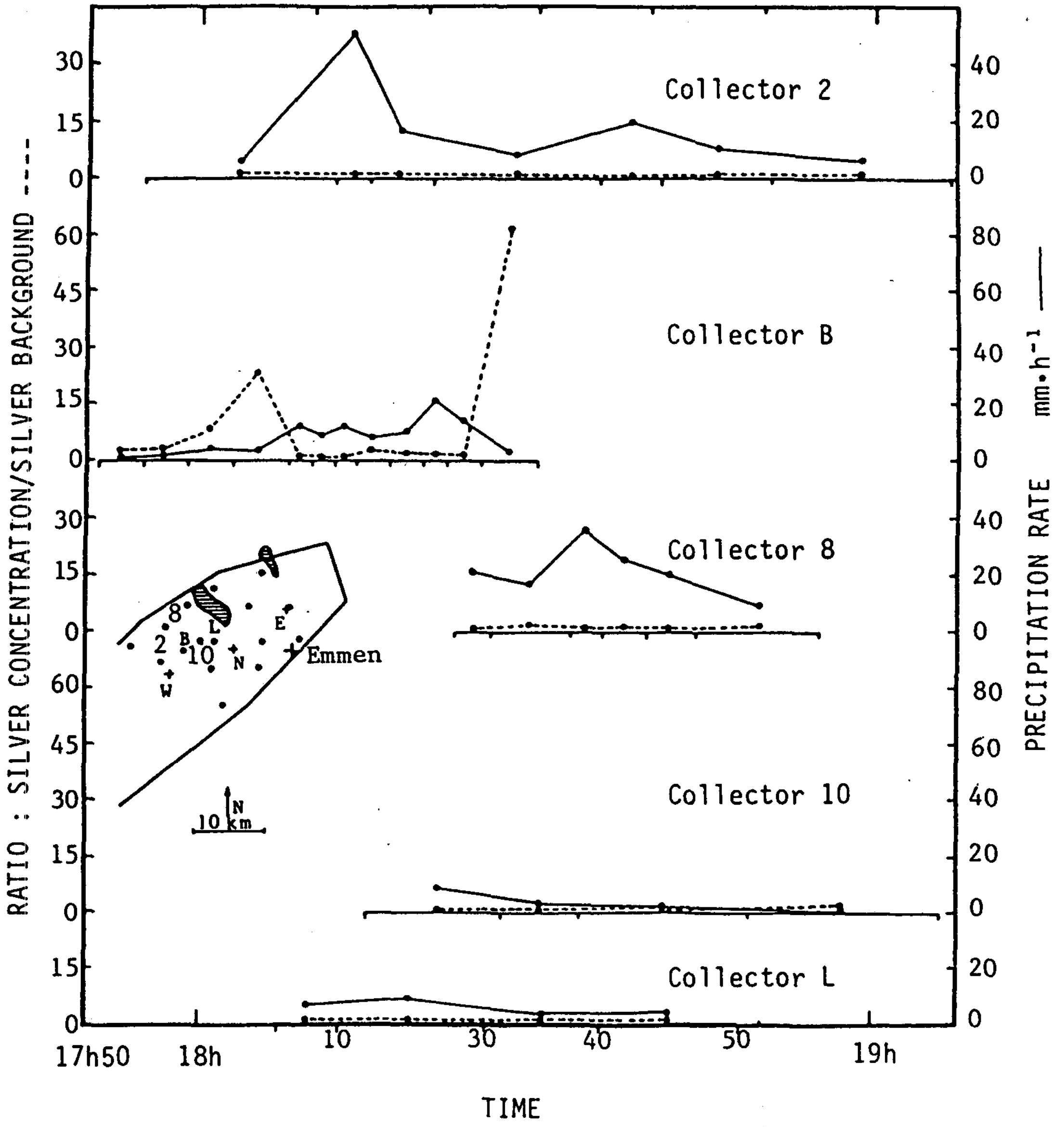

FIG. 10. Silver content (dashed line) of N cell precipitation ([Ag]/background) and precipitation rate (solid line) (mm h^{-1}) as functions of time, 30 June.

of the precipitation collected during this period. If rocket W14 produced the observed effects, and if half of the time (ΔT = 348 seconds) was available to carry AgI particles to higher elevations with average velocity 4.5 m s^{-1} (necessary to suspend 1 mm drops), the altitude reached would be 4.4 km where the temperature was −13°C. This would allow about <10% of the AgI particles reaching that elevation to behave as ice nuclei.

For the second period of silver detection (1825–1830) the measured and calculated times of residence are also shown in Table 2. The value of ΔT for W15 is estimated as 301 seconds, which implies that the lowest temperature reached by the AgI particles from this source would allow less than 5% of them to become active as ice nuclei. The high ΔT values for T22 and W14 released earlier lead to high dispersion diameters which should cause silver to appear in other adjacent samplers. Since this was not observed, it is concluded that W15 was the only contributor to the silver at site K between 1825 and 1830.

3) SILVER IODIDE BUDGET AND SEEDING DISPERSION

Seeding silver was detected only at site K. If the AgI in precipitation is confined to a 2 km radius circle at the ground, then 1.5 g of AgI for period (i) and 3 g of AgI for period (ii) were precipitated in the network. Using the same definition as for cell G, the seeding coverage for cell N was 25%.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

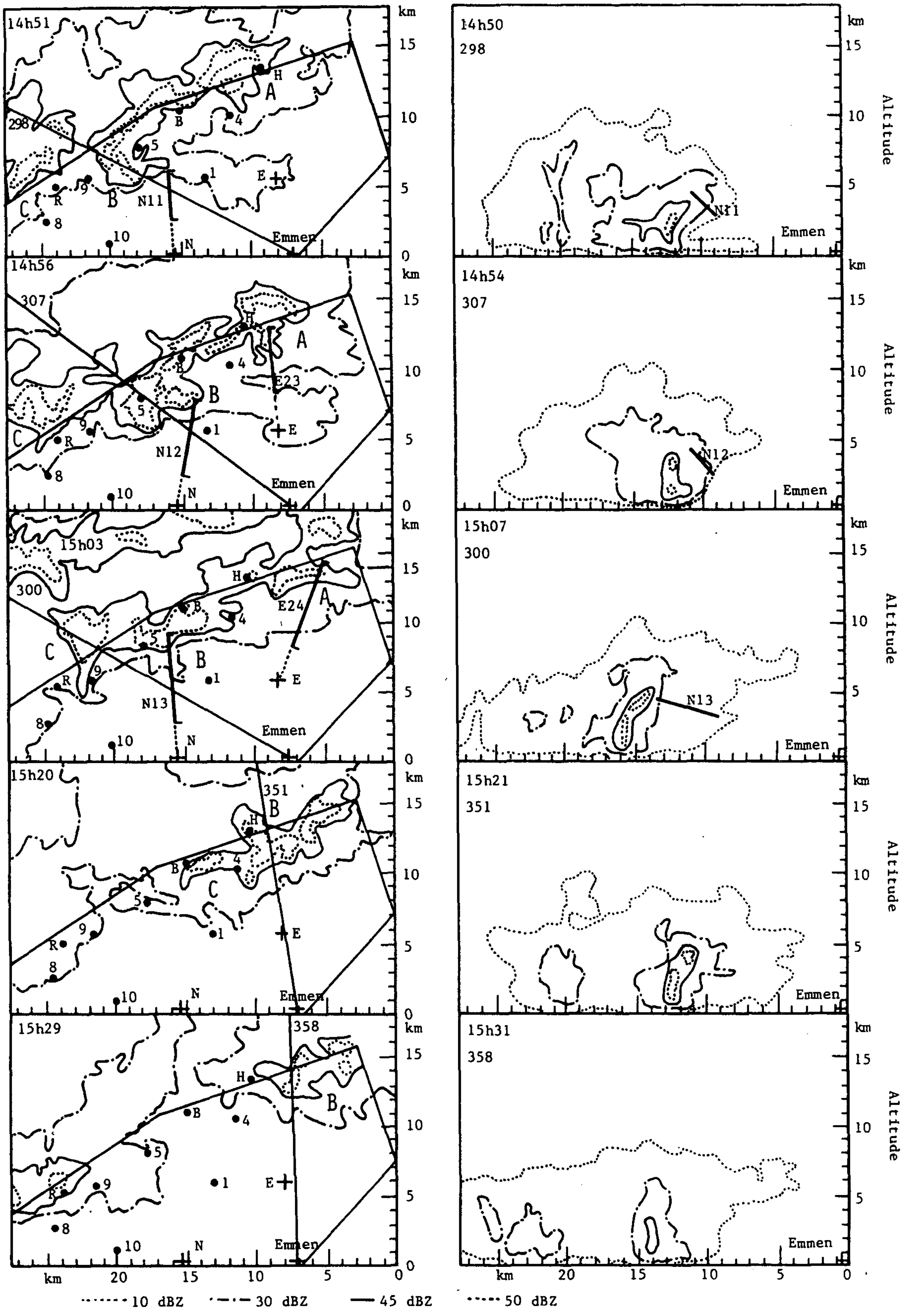

FIG. 11. Horizontal sections of reflectivities at an altitude of 1.3 km of cells A, B and C with the rocket trajectories projections. 11 July (from Emmen S- and X-band radars). Vertical sections of cells A, B and C with the rocket trajectories projections, 11 July (from Emmen S- and X-band radars).

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

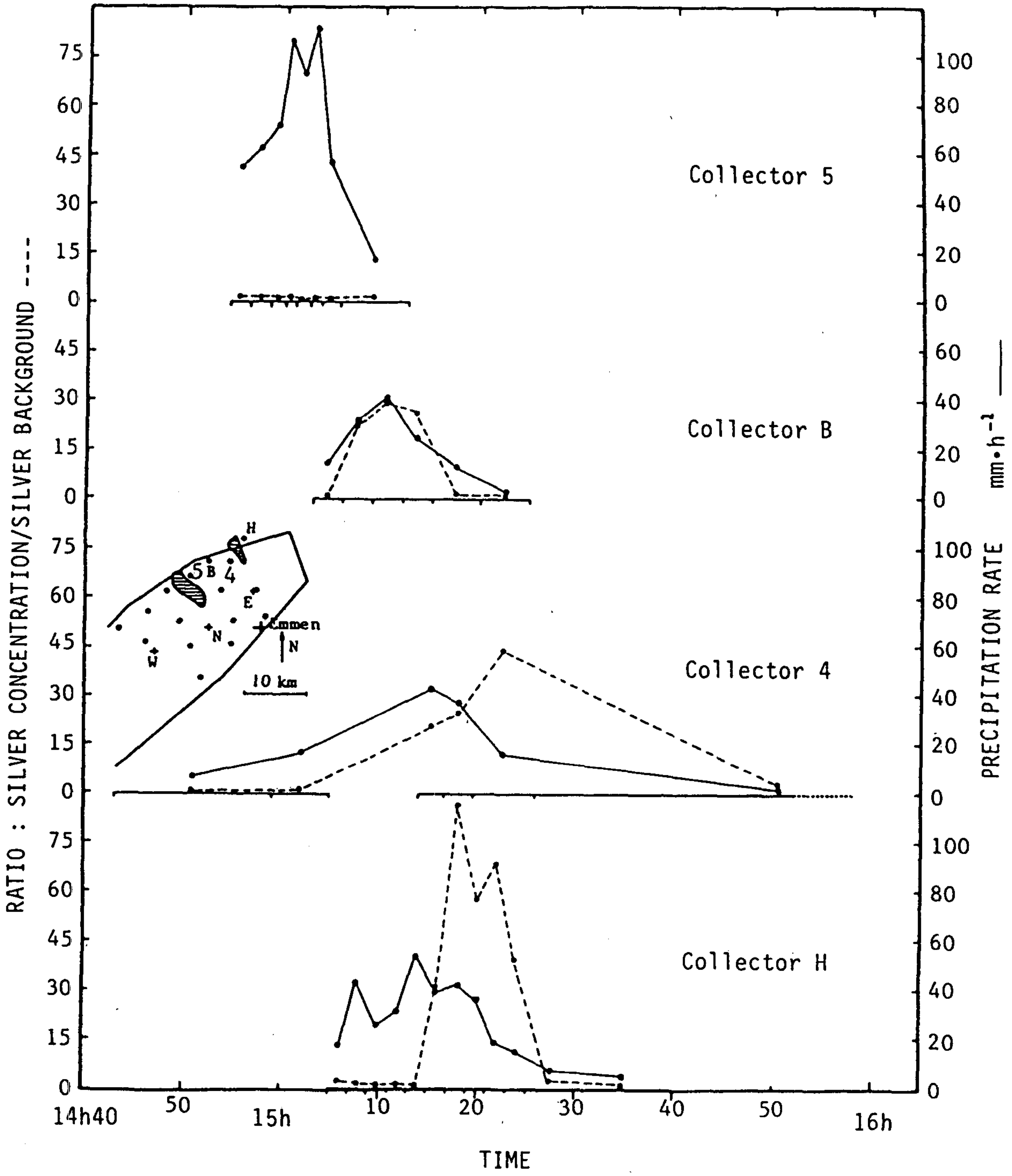

FIG. 12. Silver content (dashed line) of B cell precipitation ([Ag]/background) and precipitation rate (solid line) (mm h^{-1}) as functions of time, 11 July.

In summary, cell N had dynamic characteristics similar to cell G but of lesser amplitude. The Soviet criteria for seeding for the suppression of hail were fulfilled. The RHI reflectivity patterns indicate that the rockets were not fired into dBZs but into precipitating regions of high reflectivity (⩾40 dB*Z*) which extended from 4 km to the ground. The times of residence of seeding aerosol in the cold cloud regions were relatively short and the correspondingly small numbers of nuclei which might have been activated were probably insufficient for significant ice phase production effects to occur in such a large cloud volume.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

3. Case study for 11 July 1978

On this day the Emmen radar observed a line of squalls along a southwest–northeast line. A large number of precipitating cells moved toward the northeast. Several persistent cells grew at the right flank of the storm complex and moved along the wind directions at about two-thirds the wind speed. Figure 11a shows horizontal sections of three persistent cells (A, B, C) at an altitude of about 1.3 km. The corresponding vertical sections perpendicular to the cell's motion are given in Fig. 11b. The vertical sections indicate, on the right flank, the existence of a zone of weak echoes coupled with a column of strong reflectivity (45 dBZ contour) which originates about 5 km above ground. The vertical and horizontal reflectivity gradients seem to indicate that the right side of the storm corresponds to a region of ascending currents feeding cell B during the mature stage between 1450 and 1530 (Chisholm and Renick, 1972).

The precipitation network collected 143 samples. The maximum intensity was around 110 mm h^{-1} and several zones of hail (maximum diameter 0.9 cm) were observed.

a. Seeding of A, B, C cells

The Soviet seeding criteria were met and the randomized experiment gave a "seed" decision. Seeding was carried out with 10 OBLAKO rockets. Cell A was seeded by two rockets (E23, E24) at 3.6 and 3.8 km mean elevation (temperatures of −8.5 to −10°C).

Cell B was seeded with four (N11, N12, N13, E25) at 3.4, 3.6, 3.8 and 3.7 km height (temperatures of −7.5 to −10°C); and cell C by one rocket (N14) at 3.7 km elevation where the temperature was −9.5°C. Horizontal and vertical projections of their trajectories in relation to the radar sequences are also shown in Figs. 11a, b.

The three sequences in this figure show that the B cell seeding was remarkably repetitive with the N11, N12 and N13 trajectories almost entirely contained within a zone of weak echoes (10–30 dBZ) on the right flank, at heights of 3–4 km (temperature range −7.5 to −10°C). This is consistent with the aims of the Soviet seeding concept in which the weak echo region is related to updrafts which can carry the seeding agent into the higher reflectivity zone which is growing vertically in the cell core (e.g., vertical cross-section at 1507).

b. AgI aerosol diffusion—silver content of precipitation from cells A, B and C

The precipitation from cell A was sampled by collectors 13 and H between 1434 and 1507. All samples contained background concentrations. Sections at 1456 and 1503 of Fig. 11 show that the relative position and the times of the two rocket firings (E23, E24) make it impossible for the precipitation collected at these two sites to contain AgI from these rockets. In fact any seeded precipitation from this cell would have fallen outside the precipitation sampling network.

Cell C was sampled by four collectors, J, K, 7 and 10 *before* it was seeded by N14 at 1513. All seven samples have silver contents close to the background. There was no sampling of precipitation from this cell after the N14 seeding.

Twenty-nine samples of precipitation from cell B were collected at four sites. Figure 12 shows the ratios of silver concentration to background, and the precipitation intensities as functions of time. Silver was detected at three of the sites (J, 13 and H). Table 3 shows that almost exactly the same precipitation amounts occurred at all three sites, (5 mm water in 10 min). Figure 12 shows that the silver content of this precipitation is positively correlated with precipitation intensity.

1) RESIDENCE TIME OF AGI IN CELL B

Experimental and calculated estimates for residence times for each rocket are given in Table 4.

Since the ΔT values are negative for N14 and E25, we conclude that these rockets have not influenced the silver content of rain at sites J, 13 and H. The average of all positive ΔT values in Table 4 is 713 seconds (σ = 352 secs). If half of this time is available to carry the AgI upwards after release, we estimate it could have reached temperatures around −20°C where large numbers of AgI particles could become active ice nuclei.

2) SILVER IODIDE BUDGET AND SEEDING DISPERSION

For the precipitation contained within the 40 dBZ contour between 1506 (start of silver detection in precipitation) and 1535, the mean silver concentration for the three sites was 37.6 times background, while the average depth of rainfall containing silver was 5 mm. From this we calculate that about 120 grams of AgI was precipitated to the ground. This represents almost 50% of the quantity emitted by N11, N12 and N13. Since the area of the rainfall and the area where the

TABLE 3. Characteristics of the period of detection of silver in B cell precipitation.

Collector	Time period with silver	Water depth with silver (mm)	Ratio average Ag content to background
J	1506:00–1515:00	4.9	27
13	1514:00–1525:46	5.3	29.7
H	1515:00–1525:00	5.0	56.1

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

TABLE 4. Measured and calculated residence times of AgI particles in the B cell.

OBLAKO rocket number	Average time of seeding	Corresponding altitude km above ground	Time Ag at the ground	Time of residence measured (sec)	Calculated time of residence (sec)	ΔT (sec)
Collector J						
N11	1451:22	3.4	1510:30	1148	540	608
N12	1456:22	3.6	1510:30	848	571	277
N13	1503:22	3.8	1510:30	428	603	<0
N14	1513:22	3.7	1510:30	<0	587	<0
E25	1517:22	3.7	1510:30	<0	587	<0
Collector 13						
N11	1451:22	3.4	1519:53	1711	540	1171
N12	1456:22	3.6	1519:53	1411	571	840
N13	1503:22	3.8	1519:53	991	603	386
N14	1513:22	3.7	1519:53	391	587	<0
E25	1517:22	3.7	1519:53	<0	587	<0
Collector H						
N11	1451:22	3.4	1520:00	1718	540	1178
N12	1456:22	3.6	1520:00	1418	571	847
N13	1503:22	3.8	1520:00	998	603	395
N14	1513:22	3.7	1520:00	398	587	<0
E25	1517:22	3.7	1520:00	132	587	<0

silver was detected were practically equal, the seeding coverage of the B cell is close to 100%.

In summary, cells A, B, and C formed a multicellular unit with a persistent region of weak echoes coupled with a column of high reflectivity. At the time seeding commenced there was no precipitation reaching the ground from cell B, and the Soviet criteria for seeding had been met. Seeding did occur in the weak echo region and very possibly in the updraft zone. Although there was no high reflectivity BDZ above the seeding altitude, the overall Soviet concept was potentially in process. For this cell the spatial and temporal disper-

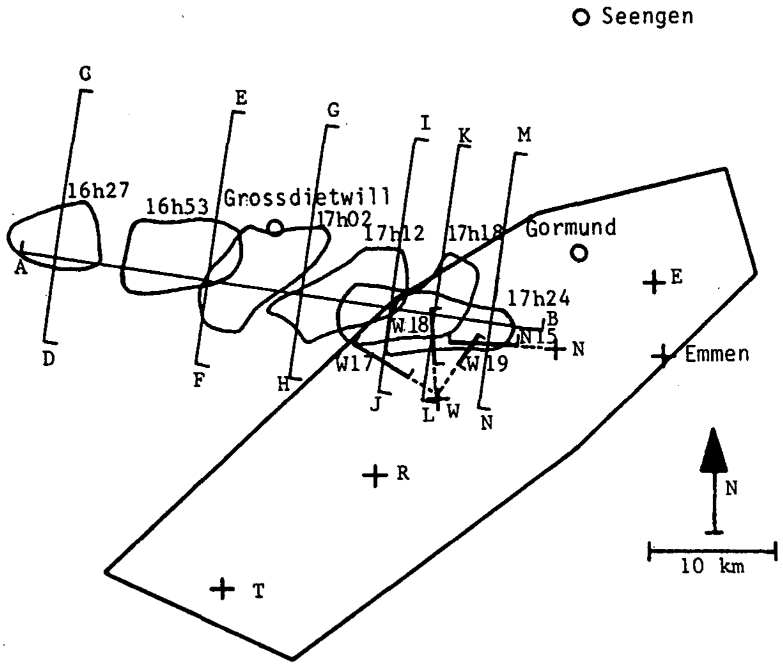

FIG. 13. Motion of cell B,C, 40 dBZ contour at 3.4 km above ground; also horizontal projections of OBLAKO rocket tracks, W17, W18, W19 and N15.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

sions of the AgI aerosol were very large, and the diffusion of the AgI and its time of residence in the cloud appear sufficient for possible ice phase modification. And we note that this set of circumstances leads to the observed positive correlations between precipitation intensity and silver content at the three sampling sites J, 13 and H.

4. Case study for 14 July 1978

Radars detected a series of cells moving through the experimental zone from west to east. Thirty-two samples of precipitation were collected. A maximum precipitation intensity around 56 mm h^{-1} and hailstones (maximum diameter 16 mm) were observed. This was a seed day in the randomized experiment.

Figure 13 shows cell B,C movement (40 dB*Z* contour at 3.4 km altitude) as 280° at 9 m s^{-1}. The rawinsonde at Gormund gave a wind of 275°/15 m s^{-1} at this altitude. The life span of B,C in the project area was 30 min (1715–1745).

The right side of Fig. 14 shows vertical sections parallel to the cell's direction of motion, and the left side,

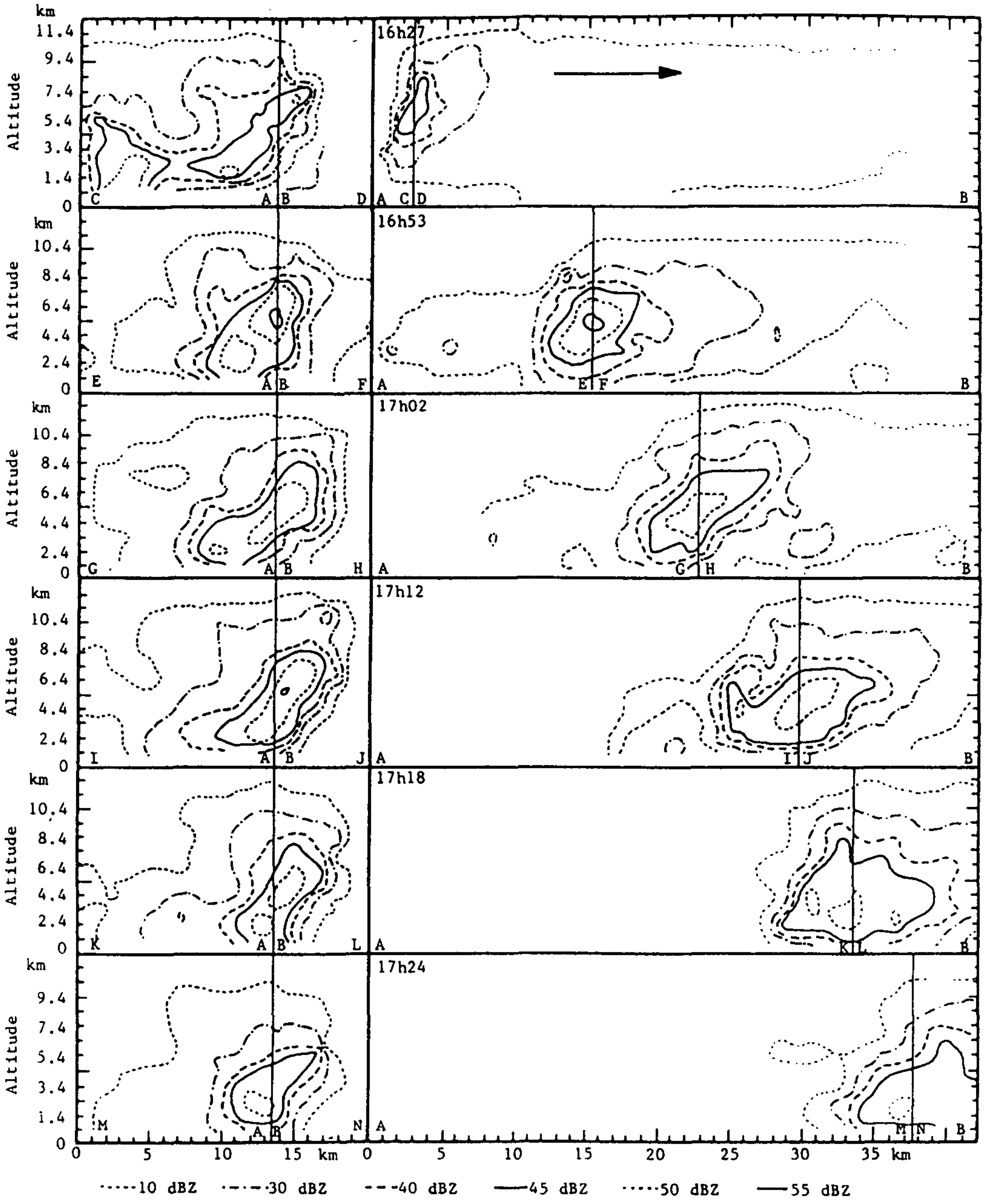

FIG. 14. Vertical sections of reflectivities of cell B,C parallel (right) and perpendicular (left) to the direction of motion.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

sections perpendicular to the motion. They show an inclined structure at the front right side of a zone of weak echoes (<30 dBZ) from 1627 until 1724, characteristic of the durable existence of an updraft (Browning and Foote, 1976). Reflectivity values reached 55 dBZ at 1627 and continued at the 50 dBZ level until 1724.

Details of precipitation samples collected are given in Table 5. The collectors measured successively decreasing intensity precipitation from the core of the cell.

a. Seeding of cell B,C

The Soviet criteria for seeding this cell were met and it was seeded with four OBLAKO rockets as it entered the project area. Rockets W17, W18, W19 and N15 seeded the cell at elevations of 3.2–3.5 km (temperature range from −3°C to −5°C). The horizontal projections of the rocket trajectories are shown in Fig. 13. The elapsed time between the first and last firing is eight minutes, representing a high seeding rate of 40 g min^{-1}. Figure 15 shows that W17 seeded the front of the cell on its right flank, W18 and W19 seeded almost entirely in the high reflectivity (40–45 dBZ) region, while about one-third of the release from rocket N15 seeded the front of the cell on the right flank while the other two-thirds seeded the zone of high reflectivity.

As Fig. 14 shows, the 10 dBZ and 30 dBZ contours slope upwards on the leading edges of the storm and, on the basis that the Soviet seeding technology aims to inject the aerosols in the updraft regions close to the reflectivity maximum zones, we conclude that W17 and part of N15 were well positioned *under* a high reflectivity zone of average altitude 5.5 km (temperature −18°C). However, the majority of the W18 and W19 releases were probably not well positioned *in* high reflectivity zones where temperatures were relatively warm and from which precipitation was already falling.

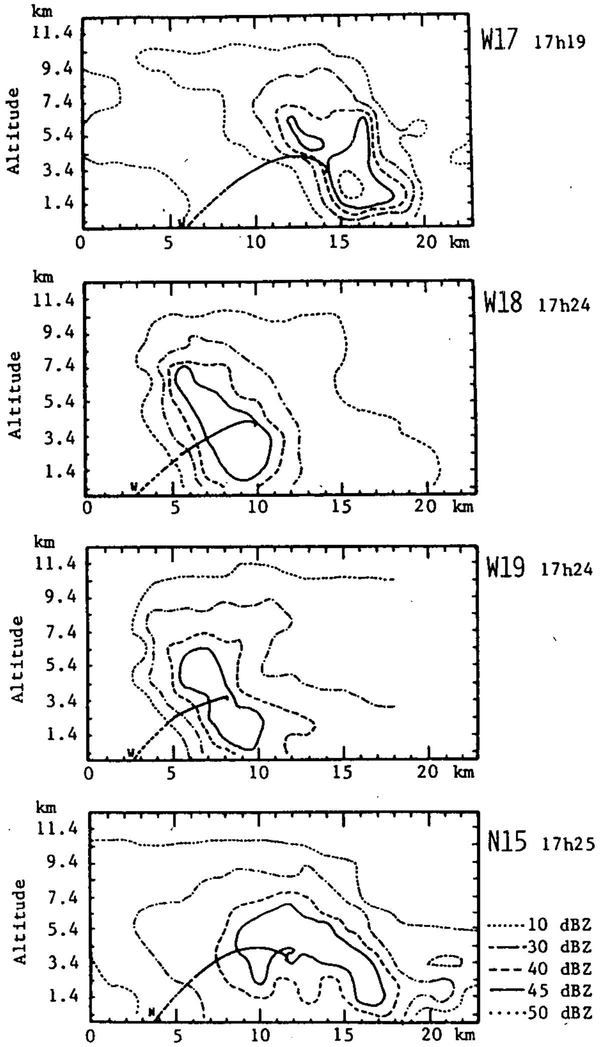

FIG. 15. W17, W18, W19, N15 rockets trajectories in relation to vertical section of reflectivities in the firing plane, 14 July.

b. AgI aerosol diffusion in cell B,C—silver content of precipitation

The measurements of silver for this cell are given in Table 5. Silver values above the background were observed at eight of the eleven sites. At site 15 the values were at the level of the highest observed background. The maximum value observed (site 15) was 23.3 times the background.

1) RESIDENCE TIMES OF AGI IN CELL B,C

Using the same procedure as before, there were 32 calculated and measured residence times. The mean of all ΔTs is 556 seconds (σ = 285 seconds). Using similar criteria as before regarding reflectivities drop sizes and precipitation intensities, we find that there is plenty of time available for AgI to reach the upper regions of strong reflectivity (average altitude 5.5 km) which, according to the Soviet concept is the hailstone embryo production zone. The temperature at this altitude was −18°C, which would allow a high percentage of the AgI particles to become active ice nuclei.

2) SILVER IODIDE BUDGET AND SEEDING DISPERSION

The data indicates that about 8 grams of AgI was precipitated out in the network. This is 2% of the AgI emitted by the four OBLAKO rockets.

The area of precipitation and the area where seeding silver was observed are equal, yielding a defined seeding coverage of 100%.

To summarize, the structure of cell B,C of 14 July shows the closest approach to the Soviet hailstorm model for all four cases studied. In particular we note the presence of a weak echo region possibly associated with the existence of strong updrafts, as well as pockets of high reflectivity at altitudes with temperatures around −20°C. The distribution of seeding silver on

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

TABLE 5. Rainfall data and silver content of precipitation from cell B, C.

Collector	Start of sampling	End of sampling	Water depth (mm)	Intensity (mm h^{-1})	Ag (10^{-11} g ml^{-1})	Ratio [Ag] content to background
4	1718:13	1722:33	1.4	20.2	0.8	1.3
	1722:23	1724:19	1.8	55.9	1.1	1.8
	1724:19	1727:06	2.0	43.1	1.0	1.7
	1727:06	—	1.4	—	1.0	1.7
5	1726:58	1736:21	2	12.8	0.9	1.5
	1736:21	1743*	0.2	1.4	2.6	4.3
L	1730:15	1744:30	0.1	0.4	3.9	6.5
11	1729:12	1746*	0.2	0.7	2.7	4.5
8	1728:52	1746*	1.5	5.6	4.4	7.3
Lo	1735:00	1739:40	0.7	9.0	0.4	0.7
	1736:10	1740:30	0.6	8.3	0.7	1.2
	1739:40	1743:00	0.2	3.0	4.9	8.2
12	1737:21	1751*	0.9	4.3	8.9	14.8
14	1737:34	1750*	0.3	1.4	4.2	7.0
15	1740:24	1757*	0.3	1.9	14.0	23.3

* Determined from radar analysis.

TABLE 6. Observations and estimations.

	30 June		11 July	14 July
	G cell	N cell	B cell	B,C, cell
A. Observations				
Characteristics of Cell				
Maximum reflectivity (dBZ)	53	50	55	61
Echo top altitude (km above ground)	7.1	8.3	9.3	11
Altitude of 0°C isotherm	2.4	2.4	2.5	2.8
Lifetime (min)	63	98	>46	81
Time in Grossversuch area (min)	54	98	46	32
Seeding				
Number of OBLAKO rockets	3	5	4	4
Precipitation				
Number of samples	25	24	29	17
Number of collectors	7	6	4	11
Maximum intensity (mm h^{-1}) observed	120	51.4	110.8	56
Maximum diameter of hailstones (mm)	9		9	16
Time of sampling (min)	37	44	>46	32
Silver content of precipitation:				
Ratio of maximum value—observed background	24	61.3	80	23.3
B. Estimations				
Seeding				
Fulfilled Soviet criteria	Yes	Yes	Yes	Yes
Quality (AgI dispersion in precipitation) %	7	25	100	100
Significant effect on ice phase	No	No	Yes	Yes
Silver iodide behavior				
Estimated surface (km^2) with Ag in precipitation	5	12.6	50	112
Highest attained altitude (km)	3.7	3.7	5.8	5.7 (W17)
Lowest attained temperature (°C)	−7	−7	−20.5	−20
Average time of residence in cloud < −5°C (sec)	144	162	713	556
% of silver recovered in network	4.8	4.0	49	2.3

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC

the ground and the residence times for the AgI are consistent with opportunities for modification of the ice phase of this cell.

5. Conclusions

In contrast to most experiments in weather modification where statistical analysis of precipitation measurements are used for estimating seeding effects, we have presented a set of results from four Grossversuch IV storms, employing three-dimensional, temporal radar measurements of convective cell structure, accurately known seeding rocket trajectories and the seeding chemical content of the precipitation. This strategy was first used by Linkletter and Warburton (1977) in the National Hail Research Experiment (NHRE).

The principal measured characteristics of the four storms studied are summarized in Table 6A. The estimated characteristics are given in Table 6B. From the latter we see that the Soviet criteria for seeding were fulfilled in all four cases. However, the estimated seeding qualities range from 7 to 100%, while the estimated residence times of seeding aerosols range from 150 seconds for the first two cells (G and N) to 500 and 700 seconds for the last two cells (B and B,C). The corresponding minimum temperatures attained by the seeding aerosols in the latter pair of cells are much lower (approximately −20°C) than for cells G and N (−7°C).

Although the Soviet criteria for seeding for hail suppression were met in all four cases and rocket injections of the clouds were made, our analyses show that because these criteria do not involve the detailed reflectivity structure and dynamic characteristics of the storms to be treated, problems can arise in the interpretation of seeding effects. For the two storms on 30 June the seeding aerosols were injected into high-reflectivity precipitation shafts which transported the seeding agent to the ground within a few minutes. Although the technology described here yielded 7 and 25% seeding qualities, the results show that an apparent effectiveness of seeding based on hail kinetic energy could be completely misleading. For these two 30 June case studies it was also found that the silver content of the precipitation was independent of the corresponding precipitation intensities. This is to be expected if the AgI aerosol was substantially scavenged by the precipitation (see Lacaux *et al.*, 1982).

For the two storms seeded on 11 and 14 July, the results are quite different. They indicate that the seeding aerosols did have time to affect the ice phase growth in the clouds, and the distributions of seeding agent in the precipitation corresponded to defined 100% seeding qualities. Hail was observed in both cases and it is not known whether suppression occurred or not. However, in the 11 July case the silver content of the precipitation is positively correlated with precipitation intensity. Similar positive correlations observed by Warburton *et al.* (1982) in the U.S. National Hail Research Experiment were interpreted as evidence of a positive seeding effect, and the same conclusion is drawn here.

Acknowledgments. We wish to thank C. R. Cornish, L. Buades and J. Segala for their assistance in conducting the field program in Switzerland. The staff of Grossversuch IV were very supportive of our work and we express our appreciation to them. Particular thanks go to S. Ribet and A. Anderson for their very carefully controlled analyses in the trace chemistry laboratories at Lannemezan and Reno. This research was supported by the Observatoire du Puy-de-Dome and the Delegation Generale a la Recherche Scientifique et Technique under Grant 78-7-2847, and also in part by the U.S. National Science Foundation under Grant ENV77-01600.

REFERENCES

Beard, K. V., and H. R. Pruppacher, 1969: A determination of the terminal velocity and drag of small water drops by means of a wind tunnel. *J. Atmos. Sci.*, **26,** 1066–1072.

Browning, K. A., and G. B. Foote, 1976: Airflow and hail growth in supercell storms and some implications for hail suppression. *Quart. J. Roy. Meteor. Soc.*, **102,** 499–533.

——, and D. Atlas, 1977: Some new approaches in hail suppression experiments. *J. Appl. Meteor.*, **16,** 327–332.

Chisholm, A. J., and J. H. Renick, 1972: The kinematics of multicell and supercell Alberta hailstorms, Alberta hail studies. Research Council of Alberta Hail Studies, Rep. No. 72-2, 24–31.

Federer, B., and Collaborators, 1979: Plan for the Swiss randomized hail suppression experiment. Design of Grossversuch IV, *Pure Appl. Geophys.*, **117,** 548–571.

Foote, G. B., C. G. Wade, J. C. Fankhauser, P. W. Summers, E. L. Crow and M. E. Solak, 1979: Results of a randomized hail suppression experimentation Northeast Colorado. Part VII: Seeding logistics and post hoc stratification by seeding coverage. *J. Appl. Meteor.*, **18,** 1601–1617.

Lacaux, J. P., and J. A. Warburton, 1980: The disposition of silver released from Soviet OBLAKO rockets in precipitation during the hail suppression experiment, Part I: Measurements of background and a preliminary seeding test. *J. Appl. Meteor.*, **19,** 771–778.

——, and ——, 1982: Precipitation scavenging of submicron particles released by rockets into convective clouds, *Fourth Int. Symp. on Scavenging, Dry Deposition and Resuspension,* Santa Monica, U.S. DOE, EPA; Amer. Meteor. Soc., 303–314.

Linkletter, G., and J. Warburton, 1977: An assessment of hail suppression technology based upon silver analysis. *J. Appl. Meteor.*, **16,** 1332–1348.

Nutten, B., and Collaborators, 1979: The Ronsard radars, versatile C-band dual facility. *IEEE Trans. Geos. Elec.*, **GE 17,** 281–288.

Projekt GROSSVERSUCH IV, 1978: E.T.H. Zurich, 234 pp.

Warburton, J. A., G. O. Linkletter and R. Stone, 1982: The use of trace chemistry to estimate seeding effects in the National Hail Research Experiment. *J. Appl. Meteor.*, **21,** 1089–1110.

Unauthenticated | Downloaded 03/23/23 04:28 AM UTC