Snowfall from a Heavily Seeded Cloud

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ABSTRACT

Few documented cases exist to demonstrate that highly convective supercooled clouds *can* be completely glaciated or overseeded. By "overseeding" we imply a sufficient concentration of ice nuclei to accommodate all the water generated in the updraft and to consume rapidly the existing cloud liquid water. One such case is herein presented that describes the ground variations in snow crystal type, size and concentration as a seeded cloud passed by. During this period, snow crystal concentrations increased by approximately two orders of magnitude, and, within the limits of accuracy of the experiment, showed a one-to-one correspondence with the concentration of silver iodide released. Snowflake aggregates were dominant and individual crystals comprising the aggregates averaged only 200 μ, in general agreement with model predictions. Riming of crystals was significantly reduced, with thick plates and solid columns indicative of a "dry" environment replacing the original rimed dendrites. It was evident that heavy seeding, while limiting the riming and size of individual crystals, amplified the snowflake aggregation mechanism.

1. Introduction

During November and December of 1968 and 1969, lake-effect snowstorms were experimentally seeded in attempts either to augment or to redistribute precipitation to the lee of Lake Erie in western New York State. Redistribution to prevent snow from falling on a given area, the more populated coastal regions, essentially requires a change in the terminal velocity of the snow particles. A slower velocity would allow the snow to advect farther inland before reaching the ground. It was believed that slower velocities could be achieved by inhibiting riming and producing more numerous but smaller crystals if sufficient ice nuclei were added to the cloud. Thus, by heavily seeding a cloud, the snow might overshoot the normal precipitation region. Aircraft seeding and radar operations were conducted by ESSA, the Cornell Aeronautical Laboratory and the Pennsylvania State University, while the State University of New York was concerned with detecting any resultant perturbations in snowfall characteristics at the ground. A lake storm of 7 December 1968 was heavily seeded with silver iodide from the ESSA-directed Cornell Aeronautical Laboratory aircraft to test the snowfall redistribution concept. Pyrotechnic flares[1] totalling 2400 gm of AgI were burned just below cloud base. The snow crystals from the lake storm were replicated at a ground station (Charlotte Center), 28 km downwind from the initial seeding point, before, during and after the time the seeded cloud passed over. Fig. 1 depicts the seeding geometry involved and the relevant cloud and ambient conditions that prevailed. As shown, the 100-gm AgI flares were burned on four 22-km seeding tracks over a period of 27 min.

Formvar replicas of falling crystals were made on 25×65 mm glass slides exposed in a horizontal position from 5–30 sec, depending on the snow concentration. Care was exercised to prevent contamination of the samples by blowing snow, although it may have occurred on a few occasions. Exposure times were varied to get a representative sample and yet minimize the overlap of crystals and aggregates. Bulk snow samples were collected for subsequent neutron activation analysis of iodine.

2. Analysis

The concentration of airborne snow particles may be computed using the sedimentation equation

$$N_c = \sum_{i=1}^{j} n_i \times 10^3/(A v_i t), \tag{1}$$

where N_c is the individual crystal concentration in the air, n_i the number of crystals in the sample with terminal velocity v_i (cm sec^{-1}), A the slide sample area (cm^2), and t the exposure time (sec). The product Av_it represents the volume from which the particles fell in time t. In similar fashion the concentration of snowflake aggregates, best considered separately, is

$$N_a = \sum_{a=1}^{k} n_a \times 10^3/(A v_a t), \tag{2}$$

where the subscript a refers to the values for each

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[1] Type 1004, Olin Corp. Energy Systems Div., East Alton, Ill.

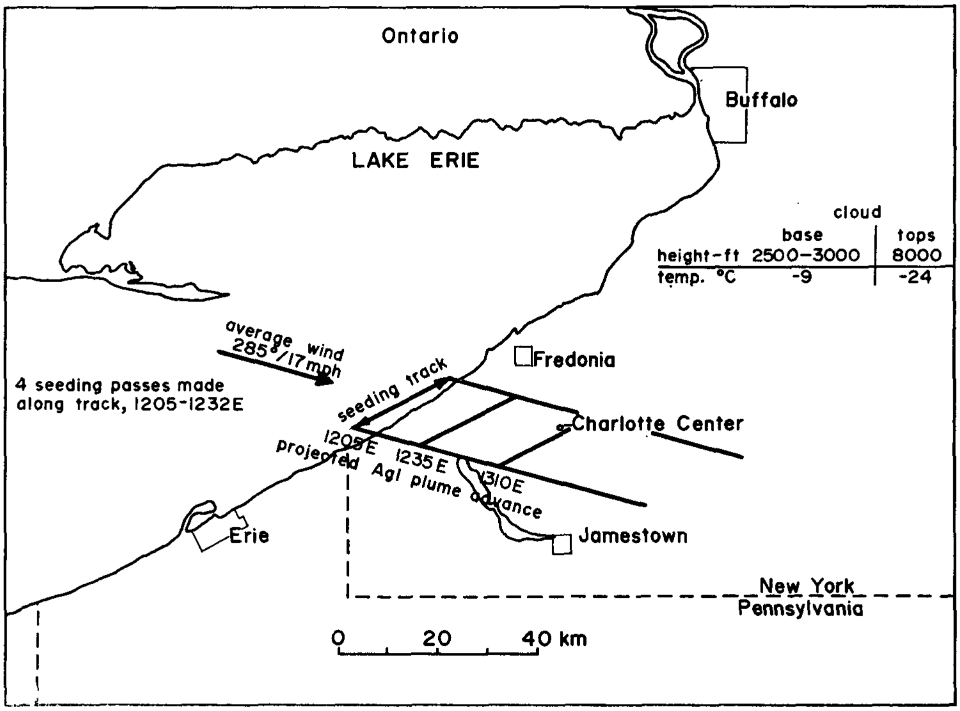

FIG. 1. Conditions during the seeding experiment of 7 December 1968.

aggregate. The total snow particle concentration is thus the sum of individual crystals plus the crystals comprising the aggregates.

The snow crystal replicas on a 12-cm^2 area of each sampling slide were analyzed with a stereo-zoom microscope and were classified according to the system of Magono and Lee (1966). The sizes were measured on a logarithmic scale (base $2^{\frac{1}{2}}$) using a Porton eyepiece reticle. The terminal velocities of individual crystals were determined from the data of Nakaya (1954), Todd (1964), and Bashkirova and Pershina (1964), or were estimated based on a comparison of their size, shape and density with crystals of known velocity. The error in this latter estimation would not exceed a factor of 2. The

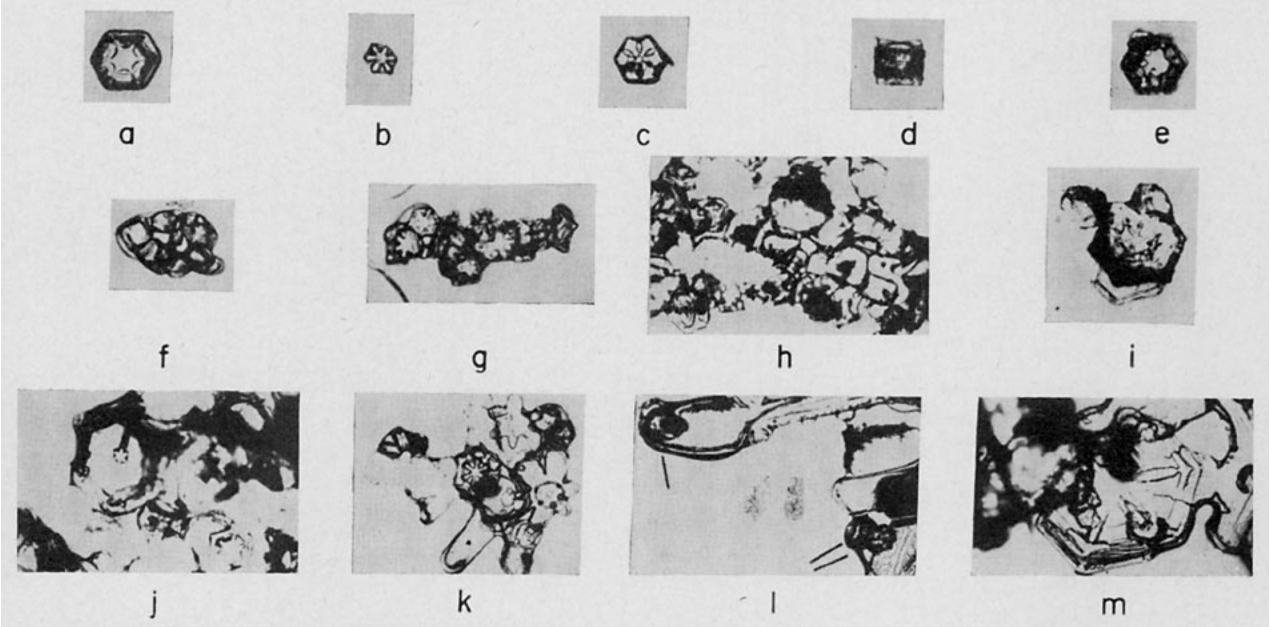

FIG. 2. Photographs of snow crystals falling from 1315 to 1411 EST on 7 December 1968 while the seeded cloud was overhead. Scale for all photographs: 1 cm = 300 μ.

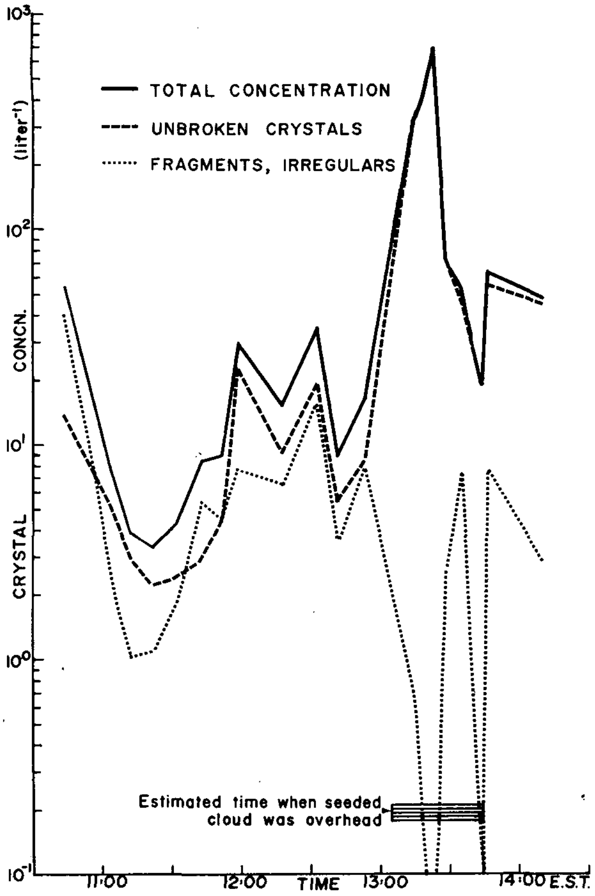

Fig. 3. Snow crystal concentrations.

terminal velocities of aggregates were determined mainly from the measured data of Magono and Nakamura (1965) and the following snowflake velocity expressions derived by Jiusto and Holroyd (1970):

$$\left.\begin{aligned} v_a &= 123\, r_a^{0.2} \text{ (for dendritic aggregates)} \\ v_a &= 178\, r_a^{0.2} \text{ (for plate and column aggregates)} \end{aligned}\right\}, \tag{3}$$

where v_a is the snowflake fall velocity (cm sec^{-1}) and r_a is flake radius (cm).

3. Discussion of observations

The snow crystal analysis showed that the natural crystals falling during the observation period prior to seeding were mostly dendritic with some other planar forms present. This indicated that snow was falling from clouds with abundant liquid water content. From 1315 to 1347 (all times Eastern Standard), when the seeded plume should have been influencing the ground station, the crystals consisted mostly of skeleton plates, solid thick plates and solid columns. These crystals indicated an environment very near ice saturation. By 1411, when the plume had passed, broad branch and some dendritic crystals were dominant, reflecting a return to a water-saturated cloud.

Photographs of selected crystals and aggregates falling at and after 1315 are shown in Fig. 2. The columnar forms illustrated by the skeleton plates of photos a, b, c, and the columns of photos d and e were very small, with diameters $\sim 200\ \mu$. Yet in the interior of these small crystals the design is highly detailed. Cold-chamber work by Schaefer and Cheng (1968) indicates that minutely designed crystals form on AgI and PbI nuclei; natural crystals of the same size generally lack this design. The presence of such crystals from 1315 to 1411 adds to a body of evidence that they came from the cloud seeded with AgI.

Small crystals with low terminal velocities of $\sim$25–30 cm sec^{-1} were produced by seeding as was expected. However, most of these crystals came to the ground in aggregates having estimated velocities of $\sim$100 cm sec^{-1}. Such aggregates are shown in photos f, g and h; while the former two show the individual crystals and AgI pattern well, aggregate h was more typical. These more-dense columnar aggregates fall faster than dendritic aggregates, as suggested by Eqs. (3).

The passage of the seeded cloud was followed by a gradual return to natural crystals. During the transition period, the lower concentrations of AgI nuclei and increasing cloud humidity produced the larger plate

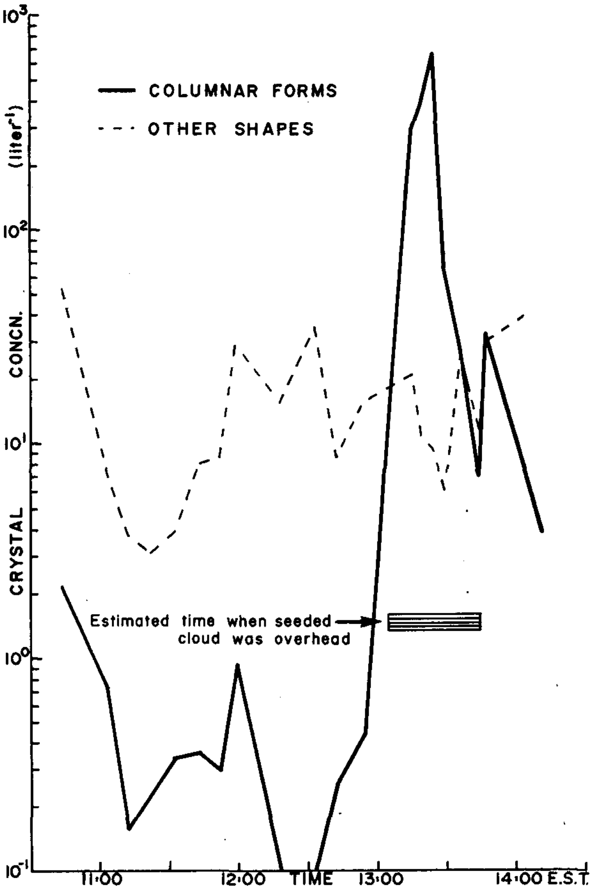

Fig. 4. Columnar snow crystal concentrations.

crystals of photos i and j. The very small crystals in the 1411 sample (photos k and l) were presumably seeding-induced and captured by aggregates of natural broad branches and by dendrites. Natural plates subsequently appeared, as shown in photo m; they too were highly designed, but their embryos, located in the crystal centers, were not.

Analysis of snow samples by Han (1969) revealed that snow falling from the seeded cloud had over ten times the amount of iodine as natural snow samples. Tipping buckets measurements of melted snow indicated a slight increase in precipitation rate during the time snow from the seeded cloud was falling, but the increase was not statistically significant.

The concentration of snow crystals, which provided the most telling seeding evidence, was calculated by the methods described above. The results are presented in Figs. 3 and 4. In Fig. 3 are plotted the unbroken crystal concentrations (dashed line), the concentration of fragments and irregulars (dotted line), and the total ice crystal concentration (thick line). Natural concentrations ranged from a few crystals per liter during the 1115 sunshine period to about 50 liter^{-1} during heavy snow showers. At 1315, when the seeded cloud arrived, the concentration jumped to over 700 liter^{-1} before returning to a more normal 50 liter^{-1}. (Such high concentrations definitely were not due to any contamination by blowing snow, as indicated by the reduced concentration of fragments.)

The seeding pulse may be seen more spectacularly in Fig. 4. Here the thick line indicates the concentration of columnar forms (columns, thick plates, skeleton plates), suggestive of drier cloud conditions, while the thin line indicates all other crystals. The latter shows no significant change during the time of the seeding pulse. The columnar concentration, however, increases from a natural background of less than 1 liter^{-1} to over 700 liter^{-1} at 1319. This nearly three orders of magnitude change clearly denoted the seeding effect.

Such high concentrations agreed well with the computed aircraft dispersal of AgI nuclei of at least several hundred per liter^{-1}. Also, the minute size ($\sim 200\,\mu$) of observed crystals is in general agreement with that predicted theoretically by the microphysics model (Jiusto, 1968; Jiusto and Schmitt, 1970) for extreme ice nucleus concentrations.

In all other experiments where the seeding amounted to ~ 10 nuclei liter^{-1} or less, snow showers were induced or amplified without a dramatic change in crystal size or type. Again, this tends to be compatible with model predictions.

4. Conclusions

The results of the 7 December 1968 experiment show that it is possible to modify crystal type and size in a natural cumulus cloud, and the cloud humidity, by seeding. The cloud humidity in this experiment was reduced from approximately water saturation to nearly ice saturation, as indicated by crystal type. The low humidity prevented the numerous crystals of the seeded cloud from growing large and initially limited their terminal fall velocities. The presence of AgI nuclei was confirmed by crystal patterns, by neutron activation analysis of the bulk snow, and by a near one-to-one correspondence between the amount of released AgI and the resultant measured concentrations of snow crystals. Crystal sizes, concentrations, and inferred cloud conditions agreed with model calculations of a heavily seeded cloud.

It was the objective of this experiment to make the snow advect farther inland than normal. Success was achieved in inhibiting riming by rapid glaciation of the cloud and in generating the slowly falling crystals, but they aggregated and came down faster than desired. These observations suggest that aggregation will be a limiting factor in the redistribution of lake storm snow by overseeding. A factor of 2–3 in fall velocity reduction in graupel situations (where fall velocities characteristically exceed 2 m sec^{-1}) and corresponding snowfall displacement would appear realistic, although more experiments are needed to verify this estimate.

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