DIFFUSION OF GROUND-GENERATED SILVER IODIDE TO CUMULUS CLOUD FORMATION LEVELS

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INTRODUCTION AND PROBLEM DEFINITION

During the past three decades, most experimental convective cloud seeding programs have relied exclusively on aircraft for delivery of ice nuclei to the clouds. However, some commercial operators have made extensive use of ground-based generators intending to accomplish the same objective. Use of aircraft as a delivery system has a definite advantage from an experimental point of view because a controlled amount of seeding material can be introduced into a specific cloud. This is not the case with ground-released material and, in fact, considerable skepticism exists as to whether ground-released ice nuclei routinely become entrained in actively growing cumulus clouds in sufficient quantities and at the correct time to produce a positive seeding effect. Relatively few measurement programs have attempted to document the transport and diffusion of ground-released silver iodide (AgI) from non-mountainous terrain during summer. A survey of pertinent literature can be found in Super and McPartland (1973).

The high cost of aircraft seeding operations is a disadvantage for operational seeding programs. It is probable that a considerable cost saving could be achieved if ground generators were shown to be capable of supplying clouds with sufficient (but not excessive) ice nuclei at the right time and location to achieve desired seeding effects.

The uncertainties surrounding use of ground-based generators for cumulus seeding focus on two separate but interrelated problem areas. First, there appears to be reasonable doubt among scientists in the field whether ground-released seeding material will usually diffuse to sufficient heights to become entrained in growing cumulus clouds. This problem area is the focus of this paper. Second, a substantial body of scientific information exists which indicates that AgI crystals, and smoke produced by burning silver iodide-sodium iodide complexes in acetone solutions, are subject to rapid deactivation of ice-nucleating ability as a result of exposure to sunlight (Super and McPartland, 1973). Field investigations of this problem (Super et al., 1975) were made concurrently with the diffusion measurements presented here. The results indicated that for the silver iodide-ammonium iodide in acetone complex used, the decay rate was no more than a factor of two per hour and may have even been non-existent.

Exploratory field experiments were conducted near Rapelje, Montana, (latitude 45° 58', longitude 109° 15') during July and August of 1972. This location was chosen largely because the terrain was typical of much of Montana's high plains, having relatively little relief.

The purpose of the program was to investigate the persistence, as active ice nuclei, and diffusion (especially in the vertical), of the $AgI-NH_4I$-acetone seeding agent. No attempt was made to achieve any given concentration of AgI at any particular location in the clouds that formed. Rather, the limited field program had the goal of determining whether ground-released AgI reached cumulus clouds in significant concentrations.

Modified Skyfire-type generators, developed at Montana State University, produced the seeding agent. The calibration of these generators, as reported by Garvey (1975), indicates a production rate (at-20^oC) of from 4×10^{14} nuclei min^{-1} at natural draft to 1×10^{16} nuclei min^{-1} at maximum wind tunnel fan speed for the approximate 30 g AgI hr^{-1} consumption rate used.

The ice-nucleus (IN) concentrations were measured effective at -20^oC, using an airborne NCAR-type acoustical ice-nucleus counter (Langer, 1973). Natural or background IN concentrations measured upwind and far cross-wind of the AgI generators were never greater than 5 ℓ^{-1}, and generally did not exceed 1 ℓ^{-1}. The acoustical counter measurements within the AgI plume were usually greater than 10 ℓ^{-1} and often greater than 100 ℓ^{-1}. Background In concentrations were, therefore, ignored for measurements within the AgI plume which were assumed to represent AgI only.

To illustrate the results of these experiments, measurements are presented from two periods when small cumulus clouds were actively growing within the research area. Silver iodide was also detected near cloud base on four other occasions; and, in fact, during all measurement periods when convective clouds were present. This included the single occasion when a moderate-sized thunderstorm passed over the seeding generators. Limited measurements suggested that the AgI was being entrained into the inflow regions of this thunderstorm. A complete treatment of all data can be found in Super and McPartland, 1973.

Experiment of 1 August 1972. Widespread cumulus cloud development was observed to be occurring over the research area early in the afternoon. Wind conditions, as measured by surface instruments and pibals, were consistent throughout the flight period. The near-surface wind was NW and light to moderate; westerly winds generally prevailed at higher altitudes. Air temperatures obtained during the flight indicated that a dry-adiabatic lapse rate existed from near surface (1250 m - all elevations above sea level) to 3960 m, which was the highest level of measurement. Cloud-base temperatures were about 4^oC.

All five AgI ground generators had been ignited in mid-morning and operated reliably from then until after the measurement period. From calibration tests at the Colorado State University cloud simulation laboratory, it is estimated that the total AgI source strength was about 2×10^{16} nuclei min^{-1}.

During the portion of the flight discussed here, vigorous cloud development was observed throughout the area. A general mixture of updrafts and downdrafts existed beneath the cloud bases, with maximum values of about 2 to 3 m sec^{-1}. Vertical velocity estimates were made from the aircraft rate-of-climb indicator while the aircraft was flown at constant attitude and power settings. The instrument utilized was not an instantaneous response type, resulting in some blurring and undermeasurement of the vertical velocity field, particularly in the case of updrafts and downdrafts of limited horizontal extent.

A single length measurement was obtained for each cloud by noting the indicated air speed (later converted to true air speed) and time under or within cloud. For purposes of presentation in Fig. 1, each length was assumed to represent the diameter of a circular cloud. The numbers inside each cloud are the ice-nucleus concentrations, measured at -20^{o}C, averaged over the cloud length.

Figure 1a shows ice-nucleus concentrations measured within 100 m of several cloud bases and the concentration along a particular flight path which defines the horizontal extent of the plume near cloud base at that downwind distance. Examination of Fig. 1a indicates that clouds growing above the AgI plume were considerably enriched in ice-nucleus content, particularly in the region close to the generator network. The degree of enrichment declined with increasing downwind distance as would be expected because of plume dilution.

Figure 1a also shows that clouds in the vicinity of the flight path made at 3500 m, approximately 15 km downwind of the generator network, contained ice-nucleus concentrations similar to that found between clouds. This suggests that entrainment of nuclei in updraft cores extending to lower, more nuclei-rich levels was not appreciable. Rather, significant addition of artificial nuclei to the growing clouds was occurring due to widespread diffusion of the nucleating agent to cloud-base levels. Later in the afternoon when clouds began to dissipate and downdrafts dominated, nuclei transport into the clouds was observed to be effectively blocked.

<u>Experiment of 3 August 1972</u>. During the afternoon of 3 August, 23 individual small cumulus clouds were penetrated for ice-nucleus measurements. Surface wind directions were quite variable, ranging from E to WSW during the experiment. Pibal observations indicated that upper winds were also light and variable. Observations of cloud shadows on the ground from the aircraft indicated that clouds were almost stationary.

Temperature measurements made during the flight indicate that the lapse rate was superadiabatic near the surface, then dry-adiabatic to 2130 m, and slightly stable from 2130 to 3050 m. An inversion was present between 3050 and 3140 m, overlain by a dry adiabatic lapse rate up to at least 3350 m, the highest level flown.

All five AgI generators were ignited by approximately 1300 MDT and operated reliably throughout the duration of the experiment. Due to the light surface winds, total AgI source strength is estimated at about 4 x 10^{15} nuclei min^{-1}, or approximately one-fifth of 1 August 1972.

The first portion of the sampling flight was expended in attempts to locate a clearly defined plume. However, the AgI was found to be widely distributed over the entire area at elevations up to and exceeding that of cloud bases.

Cloud-base elevations ranged from 2380 to 2530 m. The higher cloud bases were generally associated with higher terrain, so that the distances from cloud base to ground level were almost uniform. Temperatures at cloud base were about 7^{o}C. Cloud tops were also rather uniform, averaging approximately 3200 m. Updrafts of 2 to 3 m sec^{-1} were frequently encountered within the clouds.

Measurements of ice-nucleus concentrations were made within all clouds that formed within approximately 25 km of the generators. Penetrations were made at elevations ranging from 2770 to 3110 m, with most entries below 2960 m. Results presented in Fig. 1b indicate that the clouds sampled contained ice-nucleus concentrations ranging from 10 to over 800 ℓ^{-1}, effective at -20^{o}C. The profile along the flight path about 4 km west of the generator line shows that the ice-nucleus concentration close to cloud base elevation ranged from about 100 to over 1250 nuclei ℓ^{-1}. This profile in an average of four individual passes made along the same flight line at 2350 m during the period ½ to 2 hours before the initiation of in-cloud measurement. These passes revealed considerable differences in locations of peak nucleus concentrations, indicating that core areas of the plume were shifting erratically with the variable wind. It is thus not surprising that nucleus concentrations in the clouds along the flight path did not always correspond closely to the concentrations shown in the averaged plume.

Profiles along flight paths which extended through several clouds at noted penetration altitudes are presented in Figs. 1c and 1d. These indicated that ice-nucleus concentrations as measured within the clouds again closely corresponded to the concentrations between the clouds. It thus appears that any cloud forming within the broad AgI plume contained an ice-nucleus concentration similar to that of the surrounding air. Transport of nuclei from lower levels in updraft cores did not appear to be significant, and augmentation of cloud ice-nucleus concentrations was again apparently a result of widespread diffusion from the ground to cloud levels.

DISCUSSION AND CONCLUSIONS

The exploratory AgI tracing program discussed herein has shown that vertical diffusion, during summer afternoons in central Montana, was often sufficient to transport AgI into small cumulus clouds based 1.5 to 2.5 km above ground within a few to several kilometers of the ground-based generators. On one occasion, it appeared that AgI was entrained into a thunderstorm. The transport of nuclei from lower levels in the updraft cores of cumulus clouds was generally limited. Rather, a widespread vertical dispersion of the AgI plume took place. Clouds forming within or just above the plume entrained the seeding material.

In addition, as previously reported (Super et al., 1975), the nucleating ability of the silver iodide-ammonium iodide in acetone seeding agent was quite persistent in sunlight.

An implication of these findings is that the seeding of summer cumulus clouds with ground-based generators may be possible under certain conditions. However, no selectivity in treatment is currently possible using the method. All clouds developing in the treated area would receive additional nuclei regardless of their size or stage of development. The amount they would receive would depend upon several factors including their position down-wind and cross-wind of the generators, and their distance above the generators, since the AgI plume concentration would usually vary considerably in all three dimensions.

An additional implication is that the seeding agent may be active far downwind of the intended target area. This latter implication is true for both airborne and ground-based seeding with the type of AgI used in this study. However, it is assumed that airborne cloud-based seeding would usually result in a much larger proportion of ice nuclei being utilized over the intended area.

It is certainly not recommended that ground-based seeding for summer weather modification operations or experiments be justified on the basis of the admittedly limited work presented. Considerable further work should first be accomplished, incorporating diffusion modeling and turbulence measurements as well as airborne tracking of the seeding material.

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ICE NUCLEUS CONCENTRATIONS NEAR CLOUD BASE

1 August: 1325-1410 MDT

Average Cloud Base: 3570m

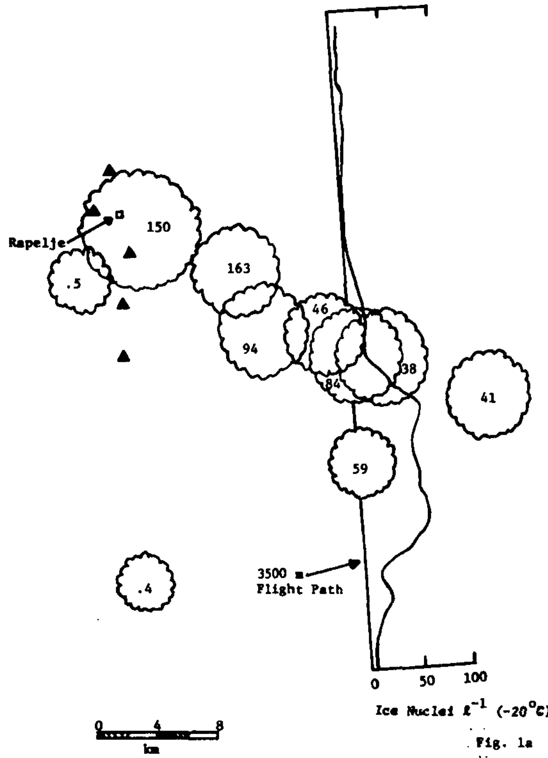

Fig. 1a

ICE NUCLEUS CONCENTRATIONS IN CLOUD

3 August: 1620-1754 MDT

Average Cloud Base: 1780m

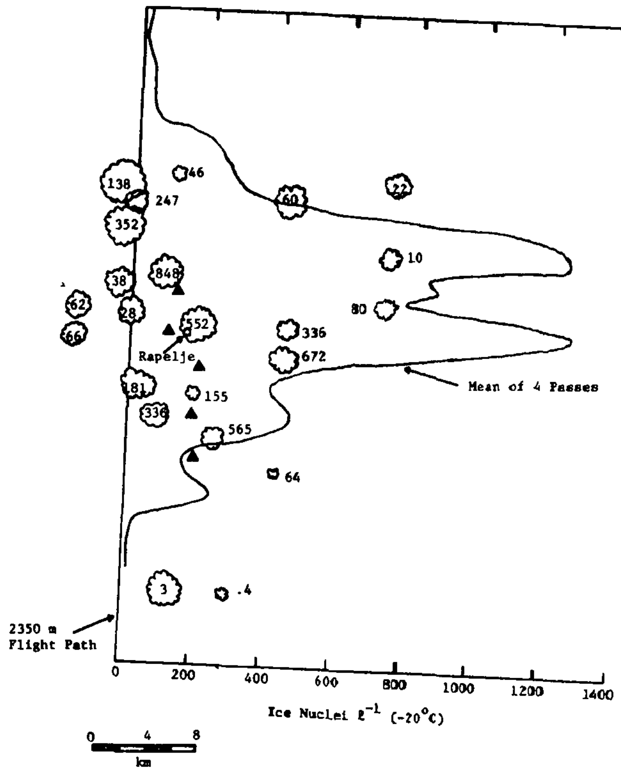

Fig. 1b

ICE NUCLEUS CONCENTRATIONS IN CLOUD

3 August: 1657-1706 MDT

Average Cloud Base: 2740m

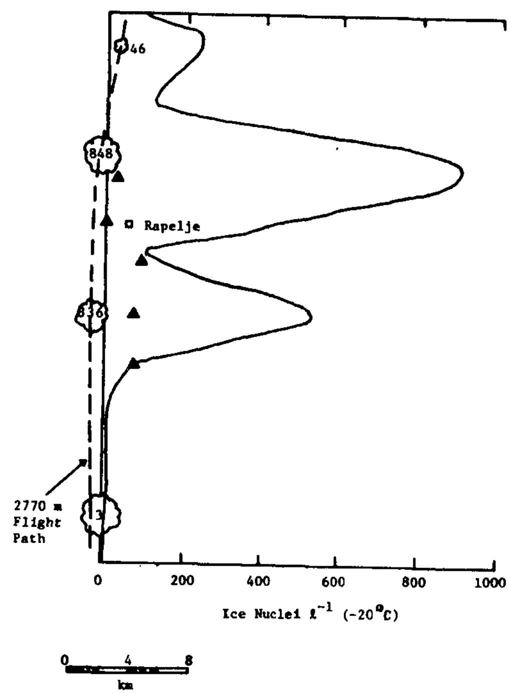

Fig. 1c

ICE NUCLEUS CONCENTRATIONS IN CLOUD

3 August: 1717-1722 MDT

Average Cloud Base: 2650m

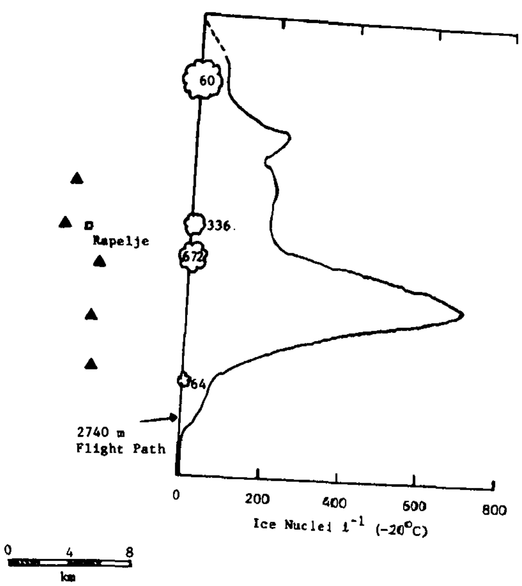

Fig. 1d

KEY:

Clouds shown by

Numbers inside clouds are the ice nucleus concentration, measured at -20°C, averaged along the flight path under or within each cloud.

AgI Generator = ▲