A Numerical Experiment on the Spatial Distribution of Cloud Seeding Nuclei[1]

George H. Milly,[2] John T. Ball, and David B. Spiegler

The Travelers Research Center, Inc., Hartford, Conn.

(Manuscript received 1 July 1968, in revised form 27 September 1968)

ABSTRACT

An examination is made of the hypothesis that the inconclusive or marginal effects of many cloud seeding operations are due, at least in part, to an inhomogeneous distribution of freezing nuclei resulting in great ranges of concentration and extensive areas of overseeding and underseeding over the target region. Distributions of silver iodide nucleus concentrations arising from ground based generators were computed using a Gaussian plume diffusion model. Meteorological conditions and the number, locations, and yield of ground based generators were varied in a series of numerical experiments which bracketed conditions typical of many cloud seeding operations. The results indicated that effective seeding concentrations of nuclei can be achieved over a significant portion of the target area only by carefully considering initial atmospheric conditions as they affect nucleus diffusion and activity, and by accordingly designing and deploying the system of silver iodide generators.

1. Introduction

A great variety of cloud seeding experiments and commercial operations have been undertaken following the pioneering work of Schaefer (1946) and others. The majority of these field experiments have used silver iodide to generate artificial nuclei. The conflicting and frequently inconclusive results that were obtained have been summarized (National Academy of Sciences, 1959, 1966).

The research reported here was performed to test the hypotheses that:

1) In many cases, seeding operations from ground-based silver iodide generators produce nonhomogeneous spatial distributions of artificial nuclei, characterized by a very large range in concentration that result in only a small portion of the operational target area being exposed to near-optimum concentration levels, while over most of the area extensive overseeding or underseeding takes place; and 2) it is possible to achieve near-optimum concentrations of artificial nuclei (under varying meteorological conditions) over most of the target area through appropriate design and deployment of the sources.

Thus, the general objective of this study was to examine computed distributions of artificial nuclei produced by silver iodide generators of various capacities for a) sensitivity to meteorological conditions, at least in so far as the model used permits their inclusion, b) variations in concentrations, particularly as a function of the number and location of generators, and c) prevalence of areas where either underseeding or overseeding could occur.

2. Cloud seeding and diffusion experiments

a. Cloud seeding experiments

Most previous cloud seeding experiments or commercial operations have been evaluated by noting the rainfall measured at selected sites in the target area and comparing these with measurements at sites in a control area. Both "positive" and "negative" results have been obtained for both randomized and nonrandomized seeding experiments. Because the question of the effectiveness of cloud seeding is extremely complex, it is useful to list some of the factors and variables involved.

1) Source type, strength and location of sources. In many field operations and experiments the separation between ground-based silver iodide generators has been 10 km or more and relatively few generators were used. An example of more liberal use of ground-based generators is given by de Pena *et al.* (1963) in which 100 generators were used with typical spacings of 3–5 km. Typical rates of burning have been in the range of 5–30 gm of silver iodide being consumed per hour. Steele (1966) has designed a prototype generator with a predicted capacity of 336 gm hr^{-1}.

2) Variability of background nuclei. Previous measurement studies, such as one conducted by Schaefer (1954), have indicated a variability in the number of natural nuclei present.

3) Most efficient or "optimum" distribution of condensation nuclei for initiating and maintaining significant precipitation. In a personal communication, Schaefer (1966) indicated that between 100 and 200 nuclei per liter appear to be most efficient for initiating the cloud growth and precipitation process. The optimum concentration probably varies with level (and

---

[1] This work was supported under a research agreement with the Travelers Corporation.

[2] Present affiliation: GEOMET, Inc., Rockville, Md.

hence, temperature) and also with varying stability and horizontal and vertical motion.

4) Decay rate. Previous field studies such as one conducted by Smith *et al.* (1958) have indicated that the effectiveness of silver iodide may decrease by a factor of 1000 in two hours of daylight.

5) Terrain. Some of the more successful seeding experiments have been conducted in areas where orographic effects make a significant contribution to the vertical motion field.

6) Preferred meteorological conditions. It has been suggested that clouds with tops between -6 and -15C are most suitable for seeding with silver iodide. Temperatures <-4C are required for nucleation to occur. Meso- or microscale variations in stability and vertical motion will strongly affect the cloud and droplet growth. MacCready and Baughman (1968) conclude from measurement studies that silver iodide is an effective ice nucleus for temperatures as warm as -7C.

7) Precipitation mechanism. The usefulness of silver iodide is contingent on the assumption that the sublimation-coalescence process and resultant ice nuclei play an important role in initiating the precipitation process.

b. Atmospheric diffusion experiments and mathematical diffusion models

Numerous experimental programs dealing with the diffusion of aerosols in the atmosphere have shown that dispersion over relatively short distances can be described reasonably well by a simple Gaussian plume model.[3]

Diffusion on a larger scale (up to 100 mi) has been investigated by Braham *et al.* (1952), Crozier and Seely (1955) and Pasquill (1955). Analysis of the data from these experiments appears to indicate that the crosswind distribution at these distances is satisfactorily represented by a Gaussian form.

Only limited data are available on vertical diffusion. Crozier and Seely (1955) noted that there was a tendency toward a uniform vertical distribution over a large portion of the depth of a plume and attributed it to vigorous mixing.

In discussing large-scale diffusion Pasquill (1962) concludes that "For horizontal spreads and also vertical spreads in regions clear of the ground or stable layers, the shape of the distribution of material from a maintained source is, on the average, a close approximation to Gaussian form." He qualifies the statement by adding that individual cases may show "considerable irregularities and distortion from the simple form."

It was therefore decided to proceed with the computation of distributions of silver iodide concentrations, using a Gaussian plume diffusion model, but recognizing that there are instances where the actual distributions could vary markedly from the Gaussian form.

c. Characteristics of the model employed

The Gaussian diffusion model used contained parameter values as developed by Milly (1958) and is represented by

$$\chi=\left(\frac{Q}{2\pi u\sigma_y\sigma_z}\right)\exp\left[\frac{-y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right]\right\},\qquad(2.1)$$

where

$$\sigma_y=3.41\left(\frac{x}{100}\right)^\alpha,\quad \sigma_z=1.35\left(\frac{x}{20}\right)^\beta,$$

and χ is concentration (m^{-3}), Q release rate (min^{-1}), σ_y, σ_z crosswind and vertical plume standard deviations, α, β atmospheric stability dependent parameters, u mean wind speed ($\mathrm{m\,min}^{-1}$), x, y, z downwind, crosswind and vertical distances (m), and h release height (m). Constants for the model were determined empirically.

The meteorological parameters that are allowed to vary in the model are the mean wind speed; the low level stability (defined as the difference in temperature between 0.5 and 4 m above the ground, represented in the computations by the values assigned to α and β, as empirically correlated with the temperature gradient; and the lapse rate of temperature (in an indirect manner by computing the concentration of silver iodide at different levels in the vertical).[4]

The model has the following limiting assumptions:

1) Flat terrain.

2) The mean wind speed (or direction) is invariant with height.

3) Large scale stability (vertical motions) is not specifically accounted for, although the low level stability is related to the large scale stability.

4) While a Gaussian crosswind distribution is well supported by observations of time mean concentrations, the evidence is less strong for instantaneous profiles. Instantaneous source parameters have been used, although the generator produces a continuous emission, since we are concerned with the instantaneous field in a Lagrangian sense; thus, the relative diffusion has been calculated about a meandering cloud axis. This reflects our desire to follow the main body of air being affected by the seeding activity.

---

[3] Atmospheric diffusion experiments have been so numerous over the years that there is a very large volume of literature on the subject. A book by Pasquill (1962) summarizes the literature and contains a significant percentage of the references.

[4] Silver iodide as a nucleating agent has the property of varying nucleation activity at different temperatures. It does not possess any nucleating capability above about -4C, but the number of active particles of AgI increases rapidly at temperatures below -4C to about -15C, then more slowly below -15C. Thus, the lower the temperature below -4C, the higher the effective strength of the source.

TABLE 1. Number and locations of generators used for numerical experiments.

Number of generators	Crosswind and downwind location, x,y (km)
1	0,10
6	0,5; 0,10; 0,15; 10,5; 10,10; 10,15
8	0,5; 0,10; 0,15; 5,7.5; 5,12.5; 10,5; 10,10; 10,15
12	0,6; 0,9; 0,12; 0,15; 5,6; 5,9; 5,12; 5,15; 10,6; 10,9; 10,12; 10,15

3. Results of numerical experiments with the diffusion model

Experiments with the diffusion model were designed to obtain information regarding the effects of varying the number and location of the ground-based silver iodide generators, the output capabilities of the generators, the vertical temperature structures, the low-level stability, and the decay of silver iodide particles due to daylight.

The area used for the experiments was defined by a grid 20 km wide and 40 km long with intersections every 200 m in the y direction (crosswind) and 400 meters in the x (downwind) direction. A constant mean wind speed used for all diffusion calculations was 10 mph (268 m min^{-1}).

a. *Number and location of silver iodide generators: Effects on distributions of AgI nuclei when varied*

To test the sensitivity of the nuclei distributions over the grid, the number and configurations of generators listed in Table 1 were used for the computations with the diffusion model.

TABLE 2. Numerical experiments illustrating effect of varying number and location of generators.

Experiment no.	1C	2C	3C	4C
Sampling level (m)	1500	1500	1500	1500
Temperature at sampling level (°C)	−12	−12	−12	−12
Effective source strength (nuclei gm^{-1} AgI)	5×10^{13}	5×10^{13}	5×10^{13}	5×10^{13}
Rate of AgI output (gm hr^{-1})	30	30	30	30
Number of generators	6	8	12	1
$\Delta T = T_2 - T_1$ (°F)*	−1	−1	−1	−1
α, β	1.2	1.2	1.2	1.2
Decay	0	0	0	0
Peak concentration from one generator (nuclei liter^{-1})	51	51	51	51
Distance downwind (km)	4.7	4.7	4.7	4.7
Nuclei liter^{-1}	Percentage of area covered			
1–9.9				
10–49.9	20.7	38.7	45.4**	2.6
50–99.9	0.4	0.6	4.7	0
100–199.9	0	0	0	0
200–399.9	0	0	0	0
400–699.9	0	0	0	0

* T_1, temperature 0.5 m above the ground; T_2, temperature 4 m above the ground.

** Indicated percentage is for that within the grid only; concentrations in the range extend beyond the 20- by 40-km grid.

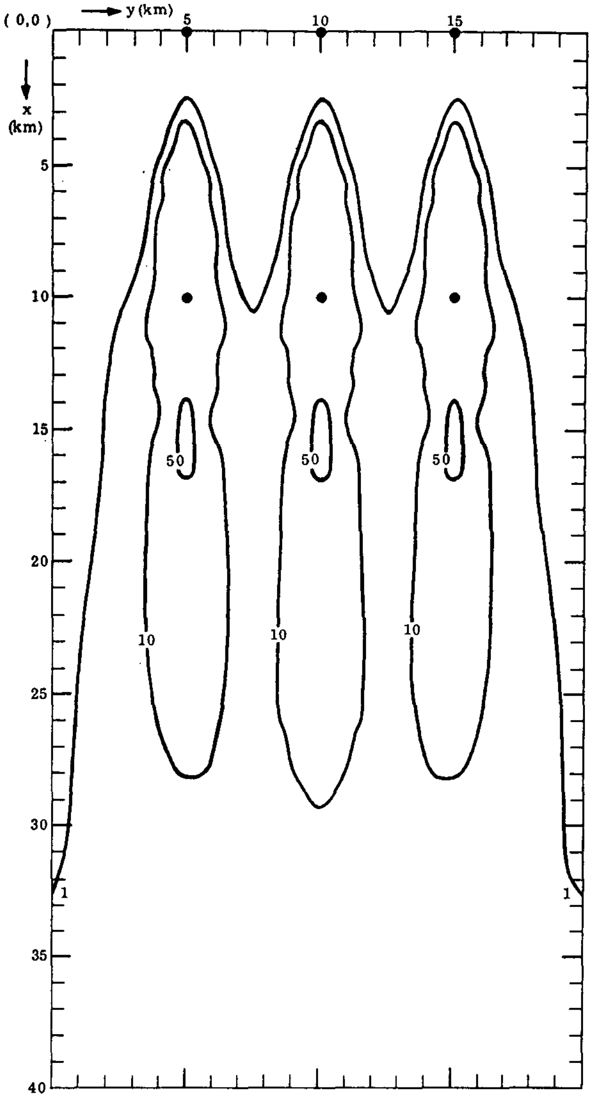

FIG. 1. Distribution of concentrations of silver iodide nuclei (nuclei liter^{-1}) obtained in experiment 1C. The locations of the ground based generators are shown by a large dot.

The level at which the distributions were computed was 1500 m, with the temperature assumed to be −12C (typical of cold season temperatures in middle latitudes at this level). Table 2 lists other pertinent input to the computations and presents the results in terms of maximum concentrations per liter and percentage of area covered by desirable and marginally desirable concentrations.

It is immediately obvious from examination of the results that one generator whose output is 30 gm AgI hr^{-1} is not nearly adequate to produce concentrations of AgI nuclei in the range considered desirable for growth of the cloud-precipitation process (i.e., 100–200 liter^{-1}). Yet, the literature indicates that the generator spacing for some previous field experiments was often of the order of 10–15 mi (16–24 km) (National Academy of Sciences, 1966). Thus, one generator for the area used in the numerical experiments is consistent with the spacing of generators in field seeding experiments.

Using six generators through the area results in nearly an order of magnitude increase in per cent area covered by concentrations of 10–49 nuclei liter^{-1}. Fig. 1 shows generator locations and the nuclei distributions. When two additional generator sources are strategically placed (a total of 8 generators), the area covered by concentrations of 10–49 liter^{-1} nearly doubles (Fig. 2).

Twelve sources only increased the area of 10–49 nuclei liter^{-1} concentrations by 6.7% (from 38.7–45.4%). However, the 45.4% value in Table 2 represents the percentage area within the 20- by 40-km grid; the distribution shows that concentrations of 10–49 nuclei liter^{-1} at distances farther downwind than 40 km would exhibit a higher per cent increase in that range for a larger area than given by our grid.

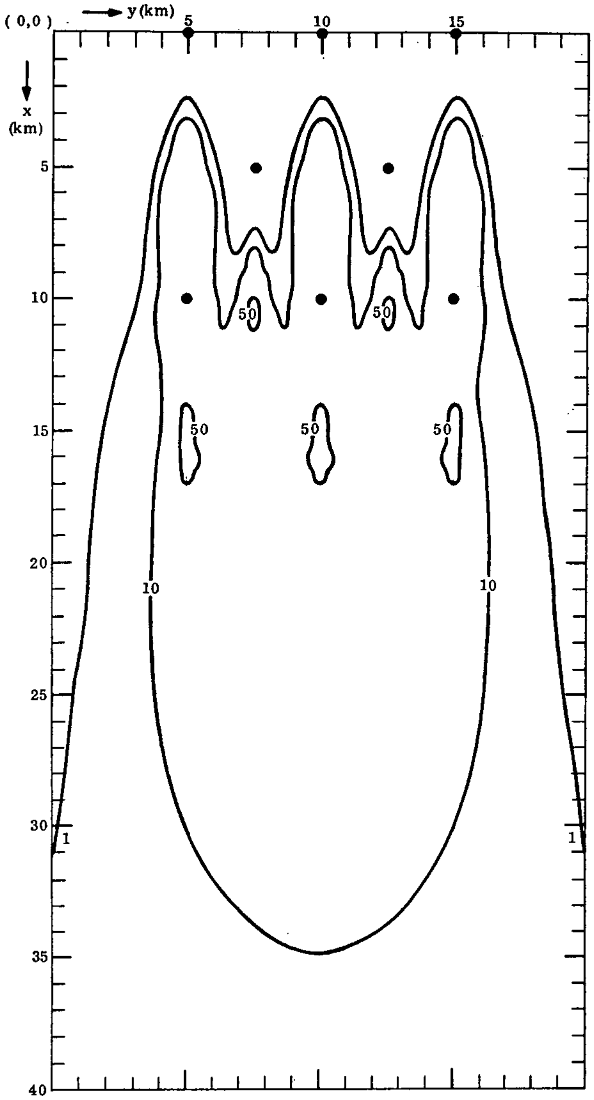

FIG. 2. Same as Fig. 1 except for experiment 2C.

TABLE 3. Comparison of results of varying generator capacity.

Experiment no.	1B	2B	1C	5C
Sampling level (m)	1000	1000	1500	1500
Temperature at sampling level (°C)	−9	−9	−12	−12
Effective source strength (nuclei gm^{-1} AgI)	5×10^{12}	5×10^{13}	5×10^{13}	5×10^{14}
Rate of output (gm hr^{-1})	30	300	30	300
Number of generators	6	6	6	6
$\Delta T=T_2-T_1$ (°F)*	−1	−1	−1	−1
α, β	1.2	1.2	1.2	1.2
Decay	0	0	0	0
Peak concentration from one generator (nuclei liter^{-1})	12	119	51	501
Distance downwind (km)	4.0	3.6	4.7	6.0
Nuclei liter^{-1}	Percentage of area covered			
1–9.9	22.7	52.3**	53.6**	
10–49.9	0.5	20.4	20.7	
50–99.9	0	2.3	0.4	30.1**
100–199.9	0	0	0	13.4
200–399.9	0	0	0	6.1
400–699.9	0	0	0	1.7

* T_1, temperature 0.5 m above the ground; T_2, temperature 4 m above the ground.

** Indicated percentage is for that within the grid only; concentrations in the range extend beyond the 20- by 40-km grid.

b. Capacity of the generator

The importance of the capacity of a generator, or the rate at which silver iodide may be burned, is graphically illustrated in the next two sets of paired experiments to be discussed. The descriptive information and results from the four experiments are summarized in Table 3. In these experiments we were less concerned with the homogeneity of concentrations than with the attainment of concentration levels that will efficiently initiate precipitation. The levels for which concentrations were computed were 1000 and 1500 m with temperatures of −9 and −12C, respectively. Six generators at (x,y) locations of (0,5), (0,10), (0,15), (10,5), (10,10) and (10,15) km were used. In Experiments 1B and 1C, 30 gm of silver iodide were consumed per hour, while in Experiments 2B and 5C the rate was increased to 300 gm hr^{-1} with the corresponding indicated increase in effective source strength.

It is immediately apparent from Table 3, for the meteorological conditions assumed, that the number and spacing of generators are not adequate if the consumption rate of silver iodide is limited to 30 gm hr^{-1}. Examination of the figures giving percentage of area covered shows at 1000 m that concentrations are entirely inadequate, while at 1500 meters, with a somewhat colder temperature, only about one-fifth of the area has concentrations >10 nuclei liter^{-1}. With an increase in consumption rate to 300 gm hr^{-1}, the situation improves somewhat at the 1000-m level and dramatically at 1500 m where over half the area now contains concentrations >50 nuclei liter^{-1}. The distribution of nuclei at 1500 m resulting from the higher rate of silver iodide consumption is shown in Fig. 3. This distribution may be compared with the distribution shown in Fig. 1 in the previous section, where the consumption rate was 30 gm hr^{-1}.

Considering these results in conjunction with the results from the previous sections, a question arises concerning the problem of the effectiveness of using fewer sources with a high yield of AgI (e.g., 300 gm hr^{-1}) or a larger number of sources with a relatively low yield of AgI (e.g., 30 gm hr^{-1}).

A comparison of experiments 1C (6 generators, 30 gm hr^{-1}), 5C (6 generators, 300 gm hr^{-1}), and 3C (12 generators, 30 gm hr^{-1}) gives an indication of the problems involved. Experiment 5C produced the most desirable results, but it must be remembered that the rate of consumption of silver iodide is five times greater than it is in Experiment 3C.

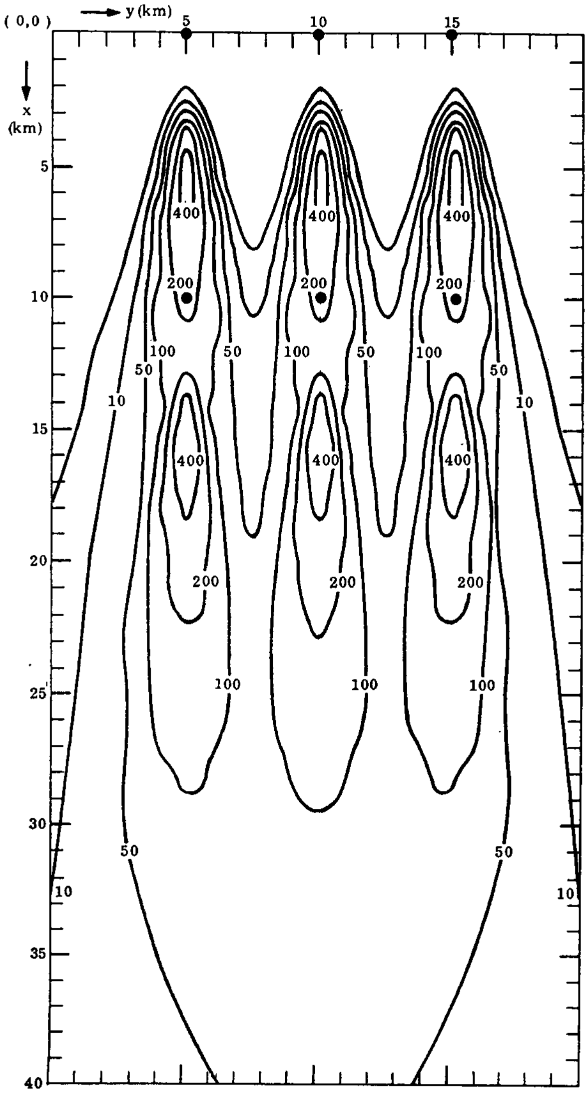

Fig. 3. Same as Fig. 1 except for experiment 5C.

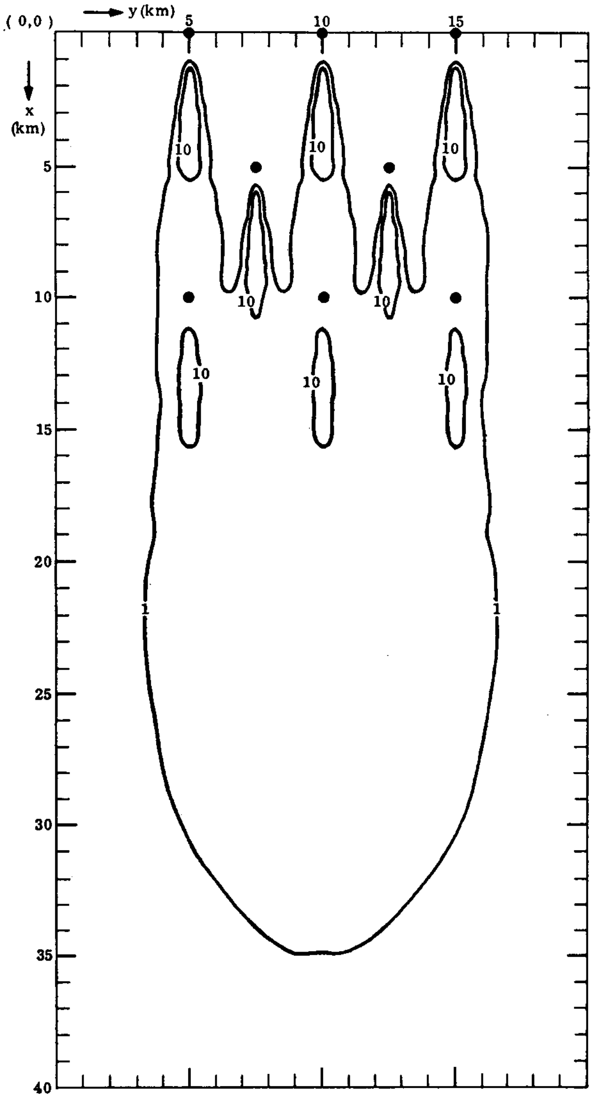

Fig. 4. Same as Fig. 1 except for experiment 1A.

c. *Vertical temperature structure: Effects on distributions of AgI nuclei when varied*

Because silver iodide nuclei are not active above temperatures of about −4C, the temperature structures specified for the numerical experiments were those typical of cold season conditions in middle latitudes. In one experiment an isothermal lapse rate was specified between 500 and 1500 m and in a second experiment a near-moist adiabatic lapse rate was used.

d. *Isothermal lapse rate*

A temperature of −9C in the layer from 500–1500 m was used in the numerical experiments. This temperature gives an effective source strength of 5×10^{12} nuclei gm^{-1} for a generator that burns 30 gm AgI hr^{-1}. All input data are contained in Table 4 along with the results of the experiment. The outstanding information

TABLE 4. Numerical experiments illustrating effect of isothermal lapse rate on nuclei concentrations at different levels.

Experiment no.	1A	6C
Sampling level (m)	500	1500
Temperature at sampling level (°C)	−9	−9
Effective source strength (nuclei gm^{-1} AgI)	5×10^{12}	5×10^{12}
Rate of AgI output (gm hr^{-1})	30	30
Number of generators	8	8
$\Delta T = T_2 - T_1$ (°F)*	−1	−1
α,β	1.2	1.2
Decay	0	0
Peak concentration from one generator (nuclei liter^{-1})	47	5
Distance downwind (km)	1.9	5.2
Nuclei liter^{-1}	Percentage of area covered	
1–9.9	39.8	39.3
10–49.9	2.8	0
50–99.9	0	0
100–199.9	0	0
200–399.9	0	0
400–699.9	0	0

* T_1, temperature 0.5 m above the ground; T_2, temperature 4 m above the ground.

obtained from these experiments is that while the peak concentration was about an order of magnitude greater at 500 m than at 1500 m, the area of coverage of concentrations between 10 and 40 nuclei liter^{-1} was very small (only 2.8%) with little difference apparent in the area covered at both of the levels by concentrations between 1 and 9 nuclei liter^{-1}.

Another important result from these experiments is that with the number of generators used, a temperature of −9C is too warm for activating sufficient AgI nuclei to obtain concentrations in the desirable range for precipitation enhancement.

Figs. 4 and 5 illustrate the nuclei distribution obtained from the numerical computations with the diffusion model.

e. Near-moist adiabatic lapse rate

The number of active nuclei produced by burning 1 gm of silver iodide will vary significantly with the temperature of the air. Fig. 6 shows a theoretical activity curve (dashed) derived by Fletcher (1962) and a second activity curve approximating results from several measurement studies.

A group of three experiments for which a near-moist adiabatic lapse rate was assumed from 1000–2000 m are discussed in this section. The temperatures at each level were −9C at 1000 m, −12C at 1500 m and −16C at 2000 m. Again, six generators were used at the locations indicated in previous sections, with each generator consuming 30 gm AgI hr^{-1}. The description of the experiment and results are shown in Table 5.

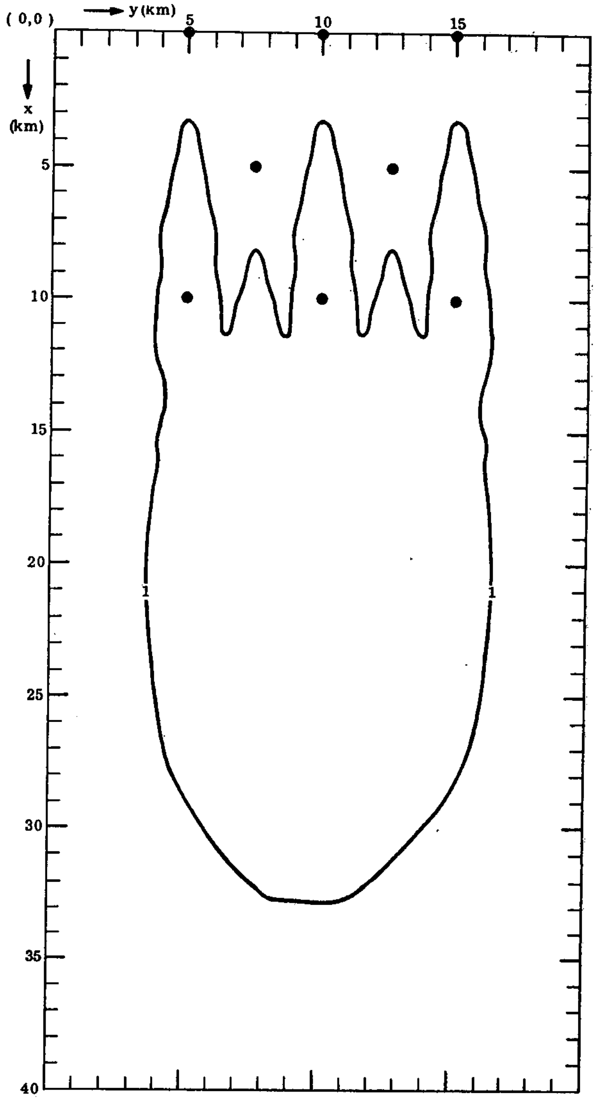

FIG. 5. Same as Fig. 1 except for experiment 6C.

The peak concentrations given in the table clearly show that the effect of having more nuclei active at the colder temperature at the 2000 m level far outweighs diffusive effects from 1000–2000 m. The peak concentration is almost 25 times greater at 2000 m. Thus, while only 0.5% of the area at the 1000-m level has a concentration as great as 10 nuclei liter^{-1}, at 2000 m 50% of the area is covered by concentrations >50 nuclei liter^{-1}. The contrast in the distributions of concentrations at the 1000- and 2000-m levels is vividly shown in Figs. 7 and 8.

A more complete picture of the variation of artificial nuclei in the vertical with the type of lapse rate assumed can also be obtained by examining the distribution of nuclei at 1500 m which was shown previously in Fig. 1.

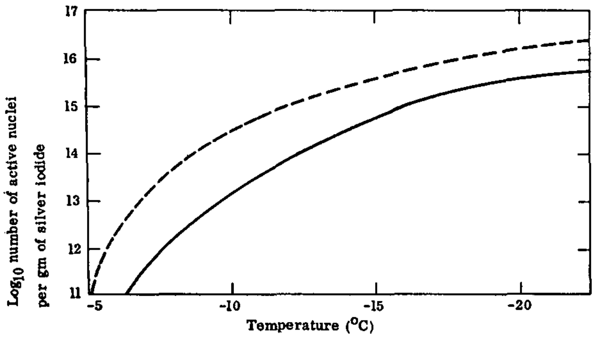

FIG. 6. Theoretical activity curve (dashed) if silver iodide smoke particles are assumed to act as sublimation nuclei (from Fletcher, 1962) and actual curve (solid) used in study.

f. Variations in low-level stability: Effects on distribution of AgI nuclei

The low-level stability is determined from the temperature difference between 0.5 and 4 m above the ground.

In four numerical experiments, nuclei concentrations at 1500 m were computed, with only the low-level stability allowed to vary between experiments. Results from these experiments are contained in Table 6. Examination of the table reveals that the distribution of AgI nuclei is strongly affected by changes in the stability. With unstable turbulent conditions ($\Delta T = -1.5$F) the AgI smoke diffuses rapidly upward with peak concentrations only 1.8 km downwind from the generators. Concentrations of 10–99 nuclei liter^{-1} are only evident (figure not shown) from 1.5–4.5 km downwind from each generator with lesser concentrations over the remainder of the area. With more stable conditions ($\Delta T = 0$F), the peak concentrations are 39.7 km downwind from the generator and large elongated areas of 10–49 nuclei liter^{-1} extend downwind from 20 km to beyond 80 km. The numerical experiments indicated portions of the plumes from the six generators would overlap.

TABLE 5. Comparison of results at 1000-, 1500- and 2000-m levels with a near-moist adiabatic lapse rate assumed.

Experiment no.	1B	1C	1D
Sampling level (m)	1000	1500	2000
Temperature at sampling level (°C)	−9	−12	−16
Effective source strength (nuclei gm^{-1} AgI)	5×10^{12}	5×10^{13}	5×10^{14}
Rate of AgI output (gm hr^{-1})	30	30	30
Number of generators	6	6	6
$\Delta T = T_2 - T_1$ (°F)*	−1	−1	−1
α,β	1.2	1.2	1.2
Decay	0	0	0
Peak concentration from one generator (nuclei liter^{-1})	12	51	291
Distance downwind (km)	4.0	4.7	6.0
Nuclei liter^{-1}	Percentage of area covered		
1–9.9	22.7	53.6**	
10–49.9	0.5	20.7	24.4**
50–99.9	0	0.4	31.0**
100–199.9	0	0	13.5
200–399.9	0	0	5.9
400–699.9	0	0	0

* T_1, temperature 0.5 m above the ground; T_2, temperature 4 m above the ground.

** Indicated percentage is for that within the grid only; concentrations in the range extend beyond the 20- by 40-km grid.

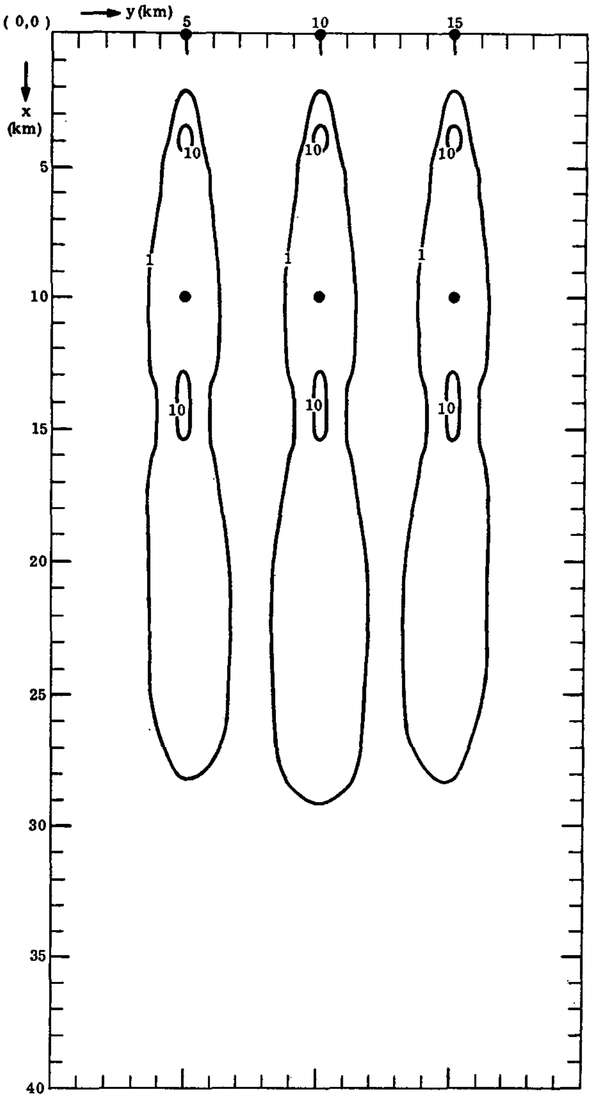

FIG. 7. Same as Fig. 2 except for experiment 1B.

g. Decay

Although the problem is not of central concern to the main questions being considered in this paper, the effects of decay or deactivation of artificial nuclei in daylight were considered in one experiment. For this experiment, the nuclei had a decay rate of a factor of 1000 in 2 hr. The distribution of nuclei at the 2000-m level resulting from 6 generators burning silver iodide at a rate of 30 gm hr^{-1} was calculated, with the decay rate included in the calculations. Other pertinent information and a comparison with the results obtained when no decay occurs is presented in Table 7. With the moderate decay factor included, the peak concentration is reduced from 291 to 236 nuclei liter^{-1} and the peak is 0.3 km closer to the source. The percentage of area containing nuclei concentrations >50 nuclei liter^{-1} is correspondingly reduced from 49.4 to 23.2%. Thus, if decay rates indicated by earlier field experiments conducted by Smith *et al.* (1958) frequently occur, this may significantly affect the number of generators or individual generator capacities required for efficient cloud seeding operations with silver iodide during the daytime.

4. Conclusions and recommendations

Our conclusions are valid if one accepts the reasonable assumption that the mathematical model employed provides at least a gross approximation of the processes at work in the atmosphere. The experiments showed:

1) That widely spaced, low-yield generators, such as those used in many previous cloud seeding operations, do not produce adequate nuclei concentrations except in a very small fraction of the area seeded.

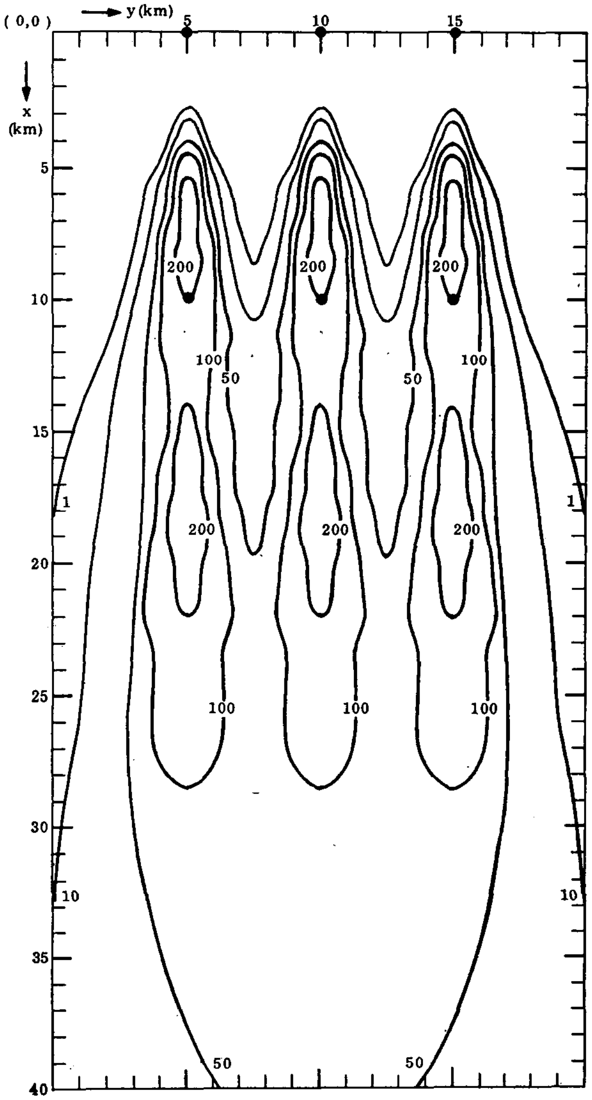

Fig. 8. Same as Fig. 2 except for experiment 1D.

Table 6. Numerical experiments illustrating effect of varying low-level stability.

Experiment no.	1C	7C	8C	9C
Sampling level (m)	1500	1500	1500	1500
Temperature at sampling level (°C)	−12	−12	−12	−12
Effective source strength (nuclei gm^{-1} AgI)	5×10^{13}	5×10^{13}	5×90^{13}	5×10^{13}
Rate of AgI output (gm hr^{-1})	30	30	30	30
Number of generators	6	6	6	6
$\Delta T=T_2-T_1$ (°F)*	−1	−1.5	−0.5	0
α,β	1.2	1.5	1.0	0.88
Decay	0	0	0	0
Peak concentration from one generator (nuclei liter^{-1})	51	84	38	31
Distance downwind	4.7	1.8	15.1	39.7
Nuclei liter^{-1}	Percentage of area covered			
1–9.9	53.6**	37.7		
10–49.9	20.7	3.6	25.0**	
50–99.9	0.4	0.4	3.5	3.8**†
100–199.9	0	0	0	0
200–399.9	0	0	0	0
400–699.9	0	0	0	0

* T_1, temperature 0.5 m above the ground; T_2, temperature 4 m above the ground.

** Indicated percentage is for that within the grid only; concentrations in the range extend beyond the 20- by 40-km grid.

† Concentrations in this range extend beyond the 20- by 80-km grid.

Table 7. Comparison of results with and without decay.

Experiment no.	1D	2D
Sampling level (m)	2000	2000
Temperature at sampling level (°C)	−16	−16
Effective source strength (nuclei gm^{-1} AgI)	5×10^{14}	5×10^{14}
Rate of AgI output (gm hr^{-1})	30	30
Number of generators	6	6
$\Delta T=T_2-T_1$ (F°)*	−1	−1
α,β	1.2	1.2
Decay	0	1000(2 hr)$^{-1}$
Peak concentration from one generator (nuclei liter^{-1})	291	236
Distance downwind (km)	6.0	5.7
Nuclei liter^{-1}	Percentage of area covered	
1–9.9		
10–49.9	24.2**	43.2**
50–99.9	31.0**	13.3
100–199.9	13.5	7.9
200–399.9	4.9	2.0
400–699.9	0	0

* T_1, temperature 0.5 m above the ground; T_2, temperature 4 m above the ground.

** Indicated percentage is for that within the grid only; concentrations in the range extend beyond the 20- by 40-km grid.

2) To achieve efficient seeding, the number of generators needed, their location, and the rate at which silver iodide is burned are highly dependent on the temperature of the level at which the desired nuclei concentrations are required.

3) A relatively uniform distribution of desired concentrations for a particular area can very likely be obtained by proper placement at the ground of medium-yield generators. Proper placement will vary with local meteorological conditions.

4) If there is an isothermal lapse rate between 1000 and 2000 m, the distributions of nuclei at the top and bottom of the layer will be similar (i.e., relatively uniform in the vertical). However, with the normal decrease of temperature upward within the layer, concentrations are much greater at the higher level, where because of the lower temperatures, more nuclei are active.

5) The distribution of artificial nuclei between 1000 and 2000 m is strongly affected by changes in the stability (and hence diffusivity) of the atmosphere. Under unstable turbulent conditions, the cloud of nuclei diffuses more rapidly resulting in very low concentrations at modest distances downwind of the generator.

6) The decay of silver iodide particles due to effects of daylight may significantly reduce the concentrations obtained at all levels.

Recommended future work, based on the results and conclusions of this study, should include better information concerning precipitation efficiency as a function of nuclei concentration and initial atmospheric conditions, the development and testing of more sophisticated mathematical models to aid in the design of successful weather modification field experiments, a continued atmospheric sampling of concentrations obtained in the field from generators having various silver iodide burning rates, and a comprehensive planning procedure for controlling operational seeding programs in a system sense, as a function of the source and atmospheric variables.

Acknowledgments. The authors are grateful to Dr. Vincent J. Schaefer of the State University of New York for stimulating discussions of several aspects of the cloud seeding problem and Mr. Robert C. Koch, formerly of TRC, for performing required program modifications to the diffusion model.

REFERENCES

Braham, R. R., B. K. Seely and W. D. Crozier, 1952: A technique for tagging and training air parcels. *Trans. Amer. Geophys. Union*, **33**, 825–833.

Crozier, W. D., and B. K. Seely, 1955: Concentration distributions in aerosol plumes three to twenty-two miles from a point source. *Trans. Amer. Geophys. Union*, **36**, 42–52.

DePena, R. G., E. A. Caimi and J. V. Irebarne, 1963: Measurements of diffusion of silver iodide nuclei in the atmosphere. Final Rept., Dept. of Meteorology, Univ. of Buenos Aires, 36 pp.

Fletcher, N. H., 1962: *The Physics of Rainclouds*. Cambridge University Press, 386 pp.

MacCready, P. B., Jr., and R. G. Baughman, 1968: The glaciation of an AgI-seeded cumulus cloud. *J. Appl. Meteor.*, **7**, 132–135.

Milly, G. H., 1958: Atmospheric diffusion and generalized munitions expenditures. Operations Research Group Study No. 17, U. S. Army Chemical Corp., Army Chemical Center, Md., 294.

National Academy of Sciences–National Research Council, 1959: Report of the skyline conference on the design and conduct of experiments in weather modification. NAS-NRC Publ. 722, Washington, D. C., 24 pp.

——, 1966: Weather and climate modification. Problems and prospects. 2 Vols., Washington, D. C.

Pasquill, F., 1955: Preliminary studies of particles at medium range from a ground level point source (summary only). *Quart. J. Roy. Meteor. Soc.*, **81**, 636.

——, 1962: *Atmospheric Diffusion*. New York, Van Nostrand, 121–178, 192–214.

Schaefer, V. J., 1946: The production of ice crystals in a cloud of supercooled water droplets. *Science*, **104**, 457–459.

——, 1954: The concentration of ice nuclei in air passing the summit of Mount Washington. *Bull. Amer. Meteor. Soc.*, **35**, 310–314.

Smith, E. J., K. J. Heffernan and W. J. Thompson, 1958: The decay of the ice-nucleating properties of silver iodide smoke released from an aircraft. *Quart. J. Roy. Meteor. Soc.*, **84**, 162.

Steele, R. L., 1966: Preliminary investigation of a new generator for silver iodide using isopropylamine as the carrier. Atmos. Sci. Tech. Paper 76, Colorado State Univ., Fort Collins, 9 pp.