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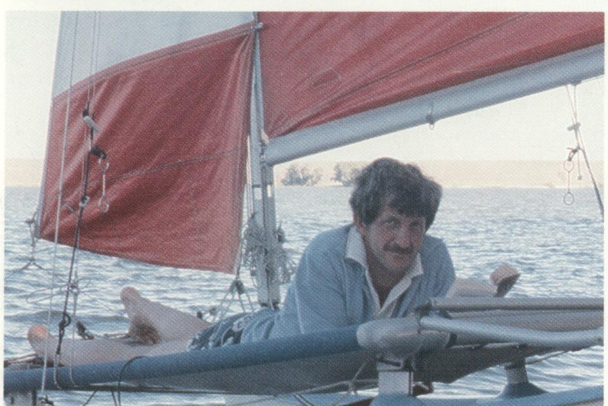

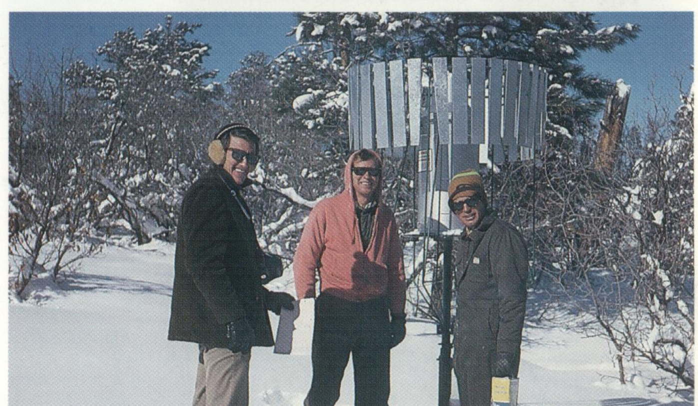

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COVER PHOTOGRAPHS

Olin H. Foehner, Jr., was lost at sea while scuba diving near St. Martin in the West Indies, May 27, 1983. During his active and productive career, Olin was a strong proponent of weather modification operations and research programs at the international level.

With the Bureau of Reclamation in the U.S., Olin served as the first Director of the Sierra Cooperative Pilot Project. He exercised a leading role in the initial planning and design of the SCPP until he was reassigned as Director of the Colorado River Enhanced Snowpack Test.

While SCPP Director, the project moved from the initial planning stage to the full design phase. During the same period, the project's field office was established at Auburn, California, the Skywater X Conference was held, the Sierra Ecology Project was initiated in cooperation with the Forest Service Pacific Southwest Forest and Range Experiment Station, and a variety of cooperative activities were initiated with the states of Nevada and California, several universities and private sector groups.

Olin's energy, his dedication to the long-term Skywater objectives, and his appreciation of new ideas contributed immensely to the progress and success of the SCPP and other Bureau of Reclamation weather modification programs under their Division of Atmospheric Resources Research. As a professional and good friend, many colleagues will miss both his expertise and good humor.

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A NEW NUMERICAL SIMULATION TECHNIQUE FOR WEATHER MODIFICATION EXPERIMENTS

A. Mary Selvam, A. S. Ramachandra Murty
and
BH. V. Ramana Murty

Indian Institute of Tropical Meteorology
Pune 411 005 India

Abstract. A new numerical simulation technique for cloud seeding experiments is developed. The technique involves application of ratio estimators and requires coefficients of rainfall variation and correlation of rainfall of the target and control areas as input data. Results of the simulation experiments for the Indian region and the merits of the new technique are described.

1. INTRODUCTION

The probability of detecting prescribed increases in rainfall due to seeding with a specified degree of confidence can be determined by the numerical simulation of cloud seeding experiments (EXP-TR) developed by Twomey and Robertson (1973). These computer simulation experiments involve collection of long period historic rainfall data and considerable computer time even on high-speed modern computers. A different numerical simulation technique (EXP-MMM-I) has been developed and tested by Mary Selvam et. al. 1979. This technique not only reduces the computational time by an order of magnitude but also defines the exact lower limit for the double ratio value which can be detected at 5 percent level of significance.

In the present paper the authors have developed a new simulation technique (EXP-MMM-II) involving application of ratio estimators. This technique requires coefficients of rainfall variability and correlations of rainfall of the target and control areas as input data for the computer simulation of cloud seeding experiments. Such experiments were carried out and the probability of detection of prescribed increases in rainfall due to seeding for the experiments with (i) double-area cross-over design and area randomization and (ii) the fixed target-control area design and day randomization. For these experiments coefficients of rainfall variation computed from the weekly total rainfall of the 35 meteorological subdivisions in India for the 5-year period (1976-80) were used. Also, numerical simulation of cloud seeding experiments using the historic rainfall data of a few regions in India, and the results of EXP-MMM-II and EXP-TR are compared. The theory relating to the new numerical simulation technique (EXP-MM-II), results of comparison between EXP-TR and EXP-MMM-II, nomograms for detection of prescribed increases in rainfall due to seeding and a map showing probabilities of detecting prescribed increases in rainfall due to seeding in different regions in India are presented below.

2. EXPERIMENTAL DESIGNS

2.1 Double-area cross-over design

In this experiment two areas A and B are separated by a buffer area and cloud seeding experiment is carried out in one of the areas on a random basis. The change in rainfall due to seeding is estimated by the root double ratio, R_S:

$$R_S = \left[\frac{\Sigma A_S}{\Sigma A_{NS}} \times \frac{\Sigma B_S}{\Sigma B_{NS}} \right]^{1/2} \quad \ldots(1)$$

where the subscript S refers to the seeded rainfall and NS to the not-seeded rainfall for the areas A and B.

For an experiment with the duration of N days, each of the areas A and B will be seeded on N/2 days and this number is designated as n.

2.2 Fixed target-control area design

In this experiment the target area is seeded on random basis on certain days. The change in rainfall due to seeding is estimated by the double ratio, r_S:

$$r_S = \left[\frac{\Sigma A_S}{\Sigma B_S} \Big/ \frac{\Sigma A_{NS}}{\Sigma B_{NS}} \right]$$

$$= \left[\frac{\Sigma A_S}{\Sigma A_{NS}} \times \frac{\Sigma B_{NS}}{\Sigma B_S} \right] \quad \ldots(2)$$

where S refers to the seeded rainfall and NS to the not-seeded rainfall for the two areas A and B.

For an experiment with the duration of N days, which is long enough, the number of seeded days n will be almost equal to N/2.

In the case of the experiment with fixed target-control area design, A_S and B_S relate to the same day. Similarly in the case of the experiment with double-area cross-over design (Section 2.1) A_S and B_{NS} also relate to the same day. Hence for the same historic rainfall data set, R_S^2 (Equation 1) and r_S (Equation 2) will be the same.

3. DISTRIBUTION OF DOUBLE RATIO/ROOT DOUBLE RATIO

Flueck and Holland (1976) studied some of the properties (mean and standard deviation) of ratio estimators and used the results of their study for the re-evaluation of three well known cloud seeding experiments. The mean, standard deviation, skewness and kurtosis of the double ratio and root double ratio distributions relating to the cloud seeding experiments are derived in the following using the ratio method of estimation (Sukhatme and Sukhatme 1970).

3.1 Experiment with double-area cross-over design

Let $A_1, A_2 \ldots\ldots A_n$ and $B_1, B_2 \ldots\ldots B_n$ denote the historic daily rainfall data of the areas A and B respectively for an experiment with the duration of N days.

The double ratio r is expressed as :

$$r = \left[\frac{\left(\sum_1^n A_i\right)_S}{\left(\sum_1^n A_i\right)_{NS}} \times \frac{\left(\sum_1^n B_i\right)_S}{\left(\sum_1^n B_i\right)_{NS}} \right]$$

$$= \left[\frac{\bar{A}_S}{\bar{A}_{NS}} \times \frac{\bar{B}_S}{\bar{B}_{NS}} \right] \qquad \ldots(3)$$

The mean rainfall of the two areas is indicated by $\bar{A}$ and $\bar{B}$. In the above experiment there are $^N C_n$ possible ways of choosing n seeded days out of the total N days. Hence $\bar{A}_S$, $\bar{A}_{NS}$, $\bar{B}_{NS}$ are distributed normally, since they come from a very large population of $^N C_n$ values.

Let ρ be the correlation coefficient (which is generally significant at 5% level) between the rainfall of the two areas A and B, S_A and S_B the standard deviations, C_A and C_B the coefficients of variation in rainfall of the two areas A and B.

As there is good correlation between the rainfall of the two areas A and B the mean rainfall $(\bar{A}_S)$ of seeded days of the area A, can be expressed as

$$\bar{A}_S = \bar{A}_N \pm \bar{\varepsilon}'_n \qquad \ldots(4)$$

where $\bar{A}_N$ is the mean rainfall of the total experimental days and $\bar{\varepsilon}'_n$ is a small variation in rainfall from $\bar{A}_N$. Similarly the mean rainfall $(\bar{B}_S)$ of seeded days of the area B can be expressed

$$\bar{B}_S = \bar{B}_N \mp \bar{\varepsilon}_n \qquad \ldots(5)$$

In case of not-seeded days the above equations can be expressed as

$$\bar{A}_{NS} = \bar{A}_N \mp \bar{\varepsilon}'_n \qquad \ldots(6)$$

$$\bar{B}_{NS} = \bar{B}_N \pm \bar{\varepsilon}'_n \qquad \ldots(7)$$

In the above equations the magnitude of $\bar{\varepsilon}'_n$ and and $\bar{\varepsilon}_n$ are very small when compared to the mean rainfall i.e. $\bar{\varepsilon}'_n / \bar{A}_N << 1$ and $\bar{\varepsilon}_n/\bar{B}_N << 1$.

3.2 Experiment with fixed target-control area design

In this experiment the seeded day for the target area (A) will be the not-seeded day for the control area (B). Hence expressions for $\bar{A}_S$, $\bar{B}_{NS}$, $\bar{B}_S$ and $\bar{A}_{NS}$ (Equations 4 to 7) are valid for the experiment with fixed target-control area design. The expected values of $\bar{\varepsilon}'_n, \bar{\varepsilon}_n, \bar{\varepsilon}'^2_n, \bar{\varepsilon}^2_n$ & $\overline{\varepsilon'_n \varepsilon_n}$ can be expressed (Sukhatme and Sukhatme, 1970) in the following form.

$$E(\bar{\varepsilon}_n) = 0$$

$$E(\bar{\varepsilon}^2_n) = \frac{N-n}{N\,n} S^2_B = \frac{S^2_B}{N} = S^2_b$$

$$= \text{Variance of } \bar{B}_S(\bar{B}_{NS}) \qquad \ldots(8)$$

$$E(\bar{\varepsilon}'_n) = 0$$

$$E(\bar{\varepsilon}'^2_n) = \frac{N-n}{N\,n} S^2_A = \frac{S^2_A}{N} = S^2_a$$

$$= \text{Variance of } \bar{A}_S(\bar{A}_{NS}) \qquad \ldots(9)$$

$$E(\overline{\varepsilon_n \varepsilon'_n}) = \frac{\rho S_B S_A}{N}$$

$$= \text{Cross-covariance between } \bar{A}_S, \bar{B}_S \text{ and between } \bar{A}_{NS}, \bar{B}_{NS} \qquad \ldots(10)$$

3.2.1 Mean of the double ratio estimator, r.

The mean of the double ratio estimator r, can be expressed as follows:

$$r = \frac{(\bar{A}_N \pm \bar{\varepsilon}'_n)}{(\bar{A}_N \mp \bar{\varepsilon}'_n)} \times \frac{(\bar{B}_N \mp \bar{\varepsilon}_n)}{(\bar{B}_N \pm \bar{\varepsilon}_n)}$$

$$r = \left[1 \pm \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right] \left[1 \mp \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^{-1} \left[1 \mp \frac{\bar{\varepsilon}_n}{\bar{B}_N}\right] \left[1 \pm \frac{\bar{\varepsilon}_n}{\bar{B}_N}\right]^{-1} \qquad (11)$$

Expanding the terms involving negative powers of one by Taylor's theorem and neglecting terms higher than $\left[\frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^2$ and $\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N}\right]^2$,

the following expression for, r, is obtained

$$r = 1 \pm 2 \left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N} \right] + 2 \left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N} \right]^2 \qquad \ldots(12)$$

The expected value of r, i.e., E(r) can be expressed as follows:

$$E(r) = 1 \pm 2E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right] + 2E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^2$$

$$= 1 + \frac{2}{N}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right] \quad \ldots(13)$$

3.2.2 Variance of the double ratio estimator, r.

The variance of r is given by the second moment (m_2) about the mean and expressed as follows:

$$m_2 = E\left[r - E(r)\right]^2$$

$$= E\left[\pm 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right) + 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^2\right]^2$$

$$m_2 \cong 4E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^2 \pm 8E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^3 \quad (14)$$

Since $\bar{A}_N$, $\bar{A}_{NS}$, $\bar{B}_N$, $\bar{B}_{NS}$ are normally distributed, the second term on the R.H.S. of Equation (14), i.e.,

$$E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^3 = 0 \text{ as shown below.}$$

$$\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^3$$

$$= \frac{\bar{\varepsilon}_n^3}{\bar{B}_N^3} - \frac{3\bar{\varepsilon}_n^2\,\bar{\varepsilon}'_n}{\bar{B}_N^2\,\bar{A}_N} + \frac{3\bar{\varepsilon}_n\,\bar{\varepsilon}'^2_n}{\bar{B}_N\,\bar{A}_N^2} - \frac{\bar{\varepsilon}'^3_n}{\bar{A}_N^3} \quad \ldots(15)$$

Writing the above in terms of the moment notation given by

$$\mu_{\alpha,\,\alpha} = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_i^{\alpha}\, \varepsilon_i'^{\alpha}$$

the expected values of the product moments (Sukhatme and Sukhatme, 1970) are obtained.

$$\mu_{r+s} = 0 \quad \text{if } (r+s) \text{ is odd} \quad \ldots(16)$$

Hence

$$E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^3 = 0 \quad \ldots(17)$$

Therefore the second moment (m_2) about the mean for the r distribution i.e., the variance can be expressed as follows.

$$m_2 = 4E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^2$$

$$= 4E\left[\frac{\bar{\varepsilon}_n^2}{\bar{B}_N^2} \quad \frac{\bar{\varepsilon}'^2_n}{\bar{A}_N^2} - 2\frac{\bar{\varepsilon}_n\,\bar{\varepsilon}'_n}{\bar{B}_N\,\bar{A}_N}\right]$$

$$m_2 = \frac{4}{N}\left(C_A^2 + C_B^2 - 2\rho\, C_A\, C_B\right) \quad \ldots(18)$$

3.2.3 Skewness of the distribution of r

The moment coefficient of skewness = $\dfrac{m_3}{\sqrt{m_2^3}}$ ...(19)

where m_3 is the third moment about the mean for the r distribution and can be expressed as follows:

$$m_3 = E\left[r - E(r)\right]^3$$

$$= E\left[\pm 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right) + 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^2\right]^3 \quad \ldots(20)$$

Neglecting powers of $\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]$ higher than 4, Equation (20) can be written as

$$m_3 = E\left[\pm 8\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^3 \pm 24\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_n}\right)^4\right]$$

$$= 24E\left[\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_n}\right)^4\right]$$

Since the first term $E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right]^3$ has been shown to be equal to zero for bivariate normal distribution.

$$m_3 = \pm 24\, E\left[\frac{\bar{\varepsilon}_n^4}{\bar{B}_N^4} - 4\frac{\bar{\varepsilon}_n^3 \bar{\varepsilon}_n'}{\bar{B}_N^3 \bar{A}_N} + 6\frac{\bar{\varepsilon}_n^2 \bar{\varepsilon}_n'^2}{\bar{B}_N^2 \bar{A}_N^2} - 4\frac{\bar{\varepsilon}_n \bar{\varepsilon}_n'^3}{\bar{B}_N \bar{A}_N^3} + \frac{\bar{\varepsilon}_n'^4}{\bar{A}_N^4} \right] \quad (21)$$

The expected values of the product moments (Sukhatme and Sukhatme, 1970) are given as follows:

$$E\left[\bar{\varepsilon}_n^4\right] = \frac{3}{N^2} S_B^4 \quad (22)$$

Similarly for large values of N the approximate expressions for the higher product moments are written as follows:

$$E\left[\bar{\varepsilon}_n^3 \bar{\varepsilon}_n'\right] = \frac{3}{N^2} \rho S_B^3 S_A$$

$$E\left[\bar{\varepsilon}_n \bar{\varepsilon}_n'^3\right] = \frac{3}{N^2} \rho S_B S_A^3$$

$$E\left[\bar{\varepsilon}^2 \bar{\varepsilon}'^2\right] = \frac{1}{N^2}\left[1 + 2\rho^2\right] S_B^2 S_A^2$$

and $E\left[\bar{\varepsilon}_n'^4\right] = \frac{3}{N^2} S_A^4$

Hence $E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right]^4$

$$= \frac{3}{N^2}\left[C_A + C_B - 2\rho C_A C_B\right]^2 \quad (23)$$

and $m_3 \approx \pm \frac{72}{N^2}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right]^2$

$$= \pm \frac{72}{16} m_2^2 = \frac{9}{2} m_2^2 \quad (24)$$

Moment coefficient of Skewness $= \pm \frac{72}{16} \frac{m_2^2}{m_2^{3/2}}$

$$= \pm \frac{9}{2}\sqrt{m_2}$$

$$= \pm \frac{9}{2}\sqrt{\text{Variance}} \quad (25)$$

The standard error of skewness $= \sqrt{6/n}$

Hence the r distribution is symmetrical if,

$$= \pm \frac{9}{2}\sqrt{m_2} \leqslant 2\sqrt{6/n}$$

or Variance $\leqslant 1.182/N$

3.2.4 Kurtosis of the distribution of r

The moment coefficient of Kurtosis $= m_4 / m_2^2$ (26)

where m_4 is the fourth moment about the mean for the r distribution and can be expressed as

$$= E\left[r - E(r)\right]^4 \quad (27)$$

$$= E\left[\pm 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right) + 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right)^2\right]^4$$

$$\approx E\left[16\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right)^4 \pm 64\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right)^5\right]$$

$$= 16\, E\left[\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right]^4$$

$$\approx \frac{48}{N^2}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right]^2 = 3 m_2^2 \quad (28)$$

Hence the moment coefficient of Kurtosis = 3

i.e. Kurtosis of the r distribution is the same as that for the normal distribution.

The skewness is however positive for the distribution when $r > 1$ and negative for distribution when $r < 1$.

The double ratio estimator r is used to evaluate the seeding effect in the experiment with fixed target-control area design.

3.3 Experiment with double-area cross over design

3.3.1 Mean of the root double ratio estimator R

The mean of the root double ratio estimator R can be expressed as follows:

$$R = \sqrt{r} \quad (29)$$

Using equation (12) the above expression can be written as

$$R = \left[1 \pm 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right) + 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}_n'}{\bar{A}_N}\right)^2\right]^{\frac{1}{2}} \quad (30)$$

$$\approx 1 + \frac{1}{2}\left[\pm 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right) + 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^2\right]$$

$$- \frac{1}{8}\left[\pm 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right) + 2\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^2\right]^2$$

$$R \approx 1 \pm \left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right) + \frac{1}{2}\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^2 \mp \left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^3 - \frac{1}{2}\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^4 \quad (31)$$

The expected value of R, i.e., E(R) can be expressed as follows:

$$E(R) \approx 1 + \frac{1}{2N}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right] \quad (32)$$

3.3.2 Variance of the root double ratio estimator, R.

The variance of R is given by the second moment (m_2) about the mean and can be expressed as follows:

$$m_2 = E\left[R - E(R)\right]^2 \quad (33)$$

$$m_2 \approx E\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^2 + E\left[\pm\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^3\right]$$

$$= \frac{1}{N}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right] \quad (34)$$

3.3.3 Skewness of the root double ratio estimator R.

The moment coefficient of Skewness $= \frac{m_3}{\sqrt{m_2^3}}$ (35)

where M_3 is the third moment about the mean for the root double ratio and can be expressed as follows:

$$m_3 = E\left[R - E(R)\right]^3$$

$$= E\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^3 + E\left[\pm\frac{3}{2}\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^4\right]$$

$$= \frac{9}{2N^2}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right]^2 = \frac{9}{2} m_2^2 \quad (37)$$

Hence the distribution of the root double ratio is symmetric about the mean if the variance is $<\frac{1.182}{N}$.

Since the variance of the root double ratio (R) is 1/4th of the variance for the double ratio (r) the skewness of the root double ratio is reduced by half as compared to that for the double ratio. For most of the cases considered in this study the skewness of the root double ratio distribution is less than twice the standard error for skewness and hence the root double ratio distributions are normal. However, from the computations it is found that when the coefficients of rainfall variability exceed 2.0, the correlation coefficient between the rainfall of the target and control areas should be more than 0.7 for the root double ratio to be normal.

3.3.4 Kurtosis of the root double ratio estimator R.

The moment coefficient of Kurtosis $= \frac{m_4}{m_2^2}$

where m_4 is the fourth moment about the mean for the R distribution and can be expressed as:

$$m_4 = E\left[R - E(R)\right]^4 \quad (38)$$

$$= E\left(\frac{\bar{\varepsilon}_n}{\bar{B}_N} - \frac{\bar{\varepsilon}'_n}{\bar{A}_N}\right)^4$$

$$= \frac{3}{N^2}\left[C_A^2 + C_B^2 - 2\rho C_A C_B\right]^2 = 3 m_2^2 \quad (39)$$

Hence the moment coefficient of Kurtosis for the R distribution $= \frac{m_4}{m_2^2} = 3$

Hence the Kurtosis for the distribution of R and for the normal distribution is the same. The root double ratio is thus proved to be distributed normally for large values of N.

3.4 Detection of significant root double ratio values

For the root double ratio values which are distributed normally the 5 percent level of significance can be evaluted as follows:

The standard deviation (S) of the root double ratio distribution is equal to $\sqrt{\text{variance}}$.

Let R_d denote the value of R (>1.0) which is significant at 5 percent level and can be expressed as

$$R_d = E(R) + 1.655\ S = R_m + 1.65\ S \qquad (40)$$

where R_m is the mean value of the root double ratio distribution and $R_m = E(R) \cong 1.0$

Hence the values of $R \geqslant R_d$ in the R distribution can be detected i.e., significant at $\leqslant 5\%$ level of significance.

4. SIMULATION OF SEEDING EFFECT

Let the percentage increase in rainfall in the target area due to seeding be designated as PERC.

4.1 Double area cross-over design

The distribution of the root double ratio values with simulated seeding effect (R_s) can be derived starting from the R distribution as follows:

$$R_s = \left[1 + \frac{PERC}{100}\right] R \qquad (41)$$

The percentage probability of detection (P) of a simulated percentage increase PERC in the rainfall of the target area can be evaluated as follows:

Let P be equal to the percentage number of R_s values which are significant at the 5 percent level. The lower limit of detection is R_d for the root double ratio values greater than one.

All values of $R \geqslant \left[\frac{R_d}{1+\frac{PERC}{100}}\right]$ in the R distribution will have values greater than or equal to R_d in the R_s distribution.

Let $$R_p = \left[\frac{R_d}{1 + \frac{PERC}{100}}\right] \qquad (42)$$

The percentage probability of detection (P) will thus be given by the percentage probability of occurrence of values of $R \geqslant R_p$ in the R distribution.

Since R is distributed normally the P value can be determined by computing the standardized normal deviate (Z) using the following expression.

$$Z = (R_p - R_m) / S \qquad (43)$$

The probability of occurrence of Z can be read from the tables of the standardized normal probability integrals (Fisher and Yates, 1974).

4.2 Fixed target-control area design

The percentage probability of detection (P) in the case of a fixed target-control design can be determined as follows:

In Section 2.2 it was shown that R^2 and r are equal. The distribution of the root double ratio values for fixed target-control design with simulated seeding effect (R_s) can be derived from the R distribution as follows:

$$R_s = \left[\sqrt{1 + \frac{PERC}{100}}\right] R \qquad (44)$$

All values of $R \leqslant \frac{R_d}{\sqrt{1+\frac{PERC}{100}}}$ in the distribution will have values greater than or equal to R_d in the r_s distribution where,

$$R_s = \left[\frac{R_d}{\sqrt{1 + \frac{PERC}{100}}}\right] \qquad (45)$$

5. ESTIMATION OF ERROR IN THE EVALUATION OF PROBABILITY OF DETECTION DUE TO LIMITED SAMPLE SIZE.

The error in the evaluation of the probability of detection (P) of seeding effect due to limited sample size can be determined as follows:

The standard error (C) of the standard deviation (S) is expressed as

$$C = \left[\frac{S}{\sqrt{2N}}\right] \qquad (46)$$

Let $$f = \frac{C}{S} \qquad (47)$$

The range of values for the standard deviation will be $(S \pm C) = (S \pm fS)$. Hence the range of variation in R_d due to the standard error C will be:

$$[r_m + 1.65\ (S \pm fS)]$$

and from Equation (40) it can be expressed as....

$$[(R_d \pm 1.65\ fS)]$$

5.1 Double-area cross-over design

The range of variation R_p due to the standard error of the standard deviations can be written from Equation (42) as:

$$\left[\frac{R_d \pm 1.65\ fS}{(1 + \frac{PERC}{100})}\right]$$

Let dZ be the change in the value of the standardized normal deviate due to change in the R_p values:

$$dZ = \left[\frac{R_d}{1 + \frac{PERC}{100}} - R_m \right] \frac{1}{S} - \left[\frac{R_d \pm 1.65\ fS}{1 + \frac{PERC}{100}} - R_m \right] \frac{1}{S}$$

$$dZ = \pm \left[\frac{1.65\ f}{1 + \frac{PERC}{100}} \right]$$

5.2 Fixed target-control design

$$dZ = \pm \frac{1.65\ f}{\sqrt{1 + \frac{PERC}{100}}} \qquad (49)$$

The deviation in the probability of detection (P) due to the standard error of the standard deviation can be computed as follows:

The standardized normal probability integral (p) is expressed as:

$$p = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \qquad (50)$$

Taking logarithams and differentiating both sides of the above equation we get

$$\frac{dp}{p} = -ZdZ \qquad (51)$$

Where $\frac{dp}{p}$ is the fractional change in probability due to a change (dZ) in the standardized normal deviate Z. Using the above method, variation in the probability of detection, dp, due to the error of the standard deviation can be computed for any set of P, Z and dZ values.

6. RESULTS AND CONCLUSIONS

Numerical simulation of cloud seeding experiments using the new technique (EXP-MMM-II) described in this paper were carried out for the Indian region and the results are given in Table 1. Also, results of the numerical simulation experiments (EXP-TR) carried out using the technique of Twomey and Robertson (1973) for north India (Delhi region) and for Maharashtra State (Mary Selvam et al., 1979, 1980, a,b) are given in Table 1 for comparison. The results of (EXP-MMM-II) and (EXP-TR) are in good agreement and the technique of (EXP-MMM-II) can be used for evaluating the probability of detection of prescribed increases in rainfall due to seeding in any region when data relating to the coefficients of rainfall variation and correlations are available. The error in the determination of the percentage probability of detection due to the limited sample size can also be evaluated as described in Section 5 of this paper. Also, the characteristics of the root double ratio distribution can be used to evaluate the significance of the results of the actual cloud seeding experiments as described in Section 3.

The nomograms for detection of prescribed increases in rainfall due to seeding are shown in Figure 1-3. The probabilities of detection of 10 and 15 percent increases in rainfall due to seeding were computed for different regions in India and maps showing the results are given in Figures 4 and 5 respectively.

In the numerical simulation experiments it is considered that for the successful detection of the seeding effect the probability of detection should be greater than 80 percent (Smith and Shaw, 1976). If this criteria is adopted the regions which are suitable for undertaking weather modification experiments in India during the summer monsoon (June-September) season are identified to be (i) northeast India, (ii) central India, (iii) west-coast and (iv) south India (Figure 5).

A cloud seeding experiment with double-area cross-over design and area randomization is in progress in the Pune region of Manharashtra state since 1973. The duration of the experiment required to detect the assigned percentage increases in rainfall due to seeding in the Pune region has been evaluated using the new numerical simulation technique (Section 4) and the results given in Table 2. These results indicate that increases in rainfall exceeding 10 percent can be detected sucessfully. The experiment should continue for a minimum period of 14 years for the detection of 10 percent increase in rainfall due to seeding.

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EVAPORATION DECAY OF ORGANIC ICE NUCLEUS PARTICLES*

H. R. Vasquez** and N. Fukuta
Department of Meteorology, University of Utah, Salt Lake City, Utah 84112

Abstract. Evaporation rates have been determined for two organic ice nucleus particles: 1,5-Dihydroxynaphthalene and metaldehyde aerosols, produced by powder vaporization-condensation method and by vapor activation method, respectively. The aerosols are injected into a large smoke chamber inside a walk-in environmental room and allowed to evaporate under dry conditions at different temperatures. The decay rates of aerosols are determined in a mixing chamber at -15 C with intermittent sampling at predetermined time intervals. The aerosol concentration losses are compared with cumulative size distributions, and assuming that the decay proceeds from smaller sizes, lifetimes of particles for different temperatures are determined as a function of minimum size. Metaldehyde particles less than 0.6 μm in diameter decay within 20 minutes at temperature as cold as -20 C, and 1,5-dihydroxynaphthalene particles within several hours, if particle diameters are smaller than 0.2 μm at the same temperature. These data are expected to provide the basis for estimating, as well as minimizing, the extent of possible downwind and environmental contamination through use of these organic ice nucleants.

1. INTRODUCTION

For cloud seeding, choice of ice nucleant characteristics and proper application of the nucleant in terms of space and time, if seedability of the cloud is established, will provide an opportunity to improve the seeding technique.

A widely used ice nuclant, silver iodide (AgI), has features attributable to its physico-chemical characteristics. The high efficiency of ice nucleus particle production per gram of the compound is related to its relatively high melting point, or latent heat of condensation. The large condensation heat gives a sharp vapor pressure drop during cooling of smoke production, leading to generation of high supersaturation and resulting in production of a large number of small particles. However, the same physico-chemical characteristic leads to extremely low vapor pressure of the compound, virtually undetectable under cloud seeding temperatures. Naturally, AgI particles as small as hundredths of one micron are thus stable against possible evaporation loss.

The lifetime of a small particle before evaporation, t_e, is proportional to the square of the diameter d, if the effects of accommodation coefficients can be ignored (Fukuta and Walter, 1970), or

$$t_e \propto d^2. \qquad (1)$$

Small aerosol particles of a compound which appears stable in powder form at room temperature can evaporate surprisingly fast if the vapor pressure of the compound is not vanishingly small. Silver iodide does not belong to this category and the non-evaporating nature of AgI particles permits its application from a warm or dry zone, or from a place remote to the target area, so that eddy diffusion of the particles into sufficiently large cloud volume can take place effectively. In this regard AgI has advantages over homogeneous ice nucleants such as dry ice. This stability of AgI particles in air, however, may lead to their survival and let them work later in unwanted areas.

Increasing evidence is available that the effects of cloud seeding operations reach beyond the geographic areas for which they are intended (Elliott and Brown, 1971; Grant and Mulvey, 1971; Warburton, 1971). The low active number of AgI particles at warm temperatures (Garvey, 1975) is often compensated by introducing a large number of nuclei into the cloud, usually resulting in an overseeded or glaciated condition at high altitudes. Large number of unactivated nuclei may drift downwind together with millions of small ice crystals. Silver, in such cases, has been detected in precipitation by atomic absorption and thermal neutron activation analysis (Warburton and Young, 1968). Grant and Mulvey (1971) documented downwind phenomena in eastern Colorado. During the Climax and Wolf Creek pass projects, AgI drifted 130 miles (215 km) downwind and underwent lee wave subsidence into upslope cloud system. Freshly fallen snow on 29 unseeded days and 12 seeded days, analyzed by the atomic absorption technique, showed that cloud seeding produced five times the normal background silver concentrations present in the atmosphere.

Small particles of a given organic nucleant can evaporate to lose their activity, depending primarily on particle size and air temperature (Fukuta et al., 1966). In past studies (Fukuta, 1963, 1972 and 1974; Fukuta et al., 1966; Fukuta and Paik, 1976; Fukuta et al., 1976; Fukuta et al., 1977; Schaller and Fukuta, 1979), two organic ice nucleants showed promise for weather modification and were subsequently tested: metaldehyde (MA) and 1,5-dihydroxynaphthalene (DN). Apart from their cost advantages over AgI (Fukuta et al., 1977), the organic nucleants are more attractive as far as possible environmental effects are concerned, although AgI does not seem to pose any serious danger to the environment under normal cloud seeding operations

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** Current affiliation: Center Weather Service Unit, FAA, ARTCC, 2555 E. Ave. P., Palmdale, CA 93350.

(Cooper and Jolly, 1970; Teller, 1972). However, care must be exercised when massive seeding dosages are anticipated (Sokal and Klein, 1975). Fresh water fish are known to be sensitive to pollutants (Table 1).

Table 1

Changes in reproductive and mortality rates for small fish exposed to seeding agent chemicals (Church et al., 1975).*

Aquaria Age (week)	No Seeding Agent	MA 1	MA 10	MA 100	PG** 1	PG** 10	PG** 100	DN 1	DN 10	AgI 1	AgI 10
1	8	4	3	2	4	3	2	4	3	4	2
2	8	4	3	2	3+	3	2	4	4	2	2
3	7+	4	4	3+	3	4	2	4+	4	4	0
4	8+	4+	4+	3	4	4	3	4	3+	3	2
5	7+	3+	4	3	4	3	2	3+	4	3	2
Total Fish Loss	2	1	2	7	2	3	9	1	2	4	12
Total Fish Hatch	3	2	1	1	1	0	0	2	1	0	0

Seeding Agents (mg/ℓ)

* Numbers are fish surviving each week of aquaria life. Plus signs represent delivery of young by one gravid female.
** Phloroglucinol.

Considering these advantages of organic ice nucleants, if evaporation of the smoke particles could be programmed to occur at a proper time after the ice nucleation period in the cloud, a new basis would be provided for selecting seeding materials. For this reason the evaporation decay of ice nucleating ability was investigated experimentally for MA and DN smokes as a function of size and temperature.

2. GENERATION AND SIZE DISTRIBUTION OF ORGANIC SMOKE PARTICLES

To investigate the activity decay of organic smoke particles by evaporation, the particles must be generated properly and their size distribution determined.

2.1 1,5-Dihydroxynaphthalene

A simple aerosol generation method was used: a soldering iron with its heating element wound with one-eighth inch (3.2 mm) ID copper tubing with a syringe attached to it by a rubber tube. To generate the smoke, a small amount of DN powder is placed into one end of the copper tubing and blown by the syringe through the heated copper coil. The powder vaporizes in the coil, producing a high concentration of needed smoke particles at the exit.

Particle evaporation rate is highly dependent upon size and temperature, so size distribution must be determined. Particle sizes were determined by measuring their fall speed under dark field illumination in an ultra-microscope (Green and Lane, 1964). Aerosol sizes greater than 1 μm in diameter can then be estimated through Stokes' fall velocity equation (Hesketh, 1977),

$$v = d^2 \, g \, \Delta\rho \, / \, 18 \, \eta, \qquad (2)$$

where d is the particle diameter, g the gravitational acceleration, $\Delta\rho$ the density difference between particle and air, and η the viscosity of air. When the particle diameter is smaller than 1 μm, Cunningham's correction factor must be used in Stokes' equation:

$$C = 1 + 2\lambda A/d, \qquad (3)$$

here λ is the mean free path of air molecules, and A a constant close to unity. Figure 1 shows the

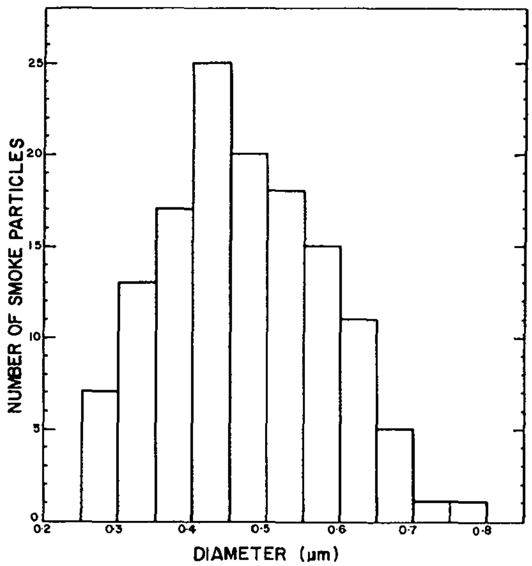

Fig. 1. *Stokes-Cunningham size distribution of 1,5-dihydroxynaphthalene smoke particles.*

Stokes-Cunningham size distribution obtained for DN particles. The average particle diameter of DN smoke is 0.41 μm.

The effective DN nuclei concentration per gram of material produced by the present smoke generation device was estimated. The temperature spectrum of smoke particle activity helps us determine the most efficient temperature setting for an ice nucleation test in the mixing chamber. This estimation also helps determine a smoke dilution factor, or number of particles per cm^3, necessary to avoid saturation of the air environment with DN vapor after evaporation. The concentration of organic particles should be low enough so that they can evaporate freely in unsaturated air. To make smoke, a known amount (about 2 mg) of DN powder was put into the generator and injected through the heated copper tube into Box 1. A portion of the aerosol was then extracted and diluted again in Box 2. Then 10 cm^3 of the diluted sample was taken from Box 2 and tested in the mixing chamber. An effective nuclei number of 10^{12}/g was determined at both -15 and -20 C, but dropped to 10^9/g at -10 C. A temperature setting of -15 C was subsequently selected for the mixing chamber experiments.

2.2 Metaldehyde

Unlike DN, MA aerosol particles cannot be produced effectively by vaporization through the handheld aerosol generator. When MA and water are boiled together and the vapor mixture quenched, water vapor condensing onto the formed MA particles nucleates a large number of ice crystals. This technique, called "Vapor Activation" (Fukuta, 1968), is applied to the smoke particle generation. The smoke generating device consists of a 1 ℓ Erlenmeyer flask containing MA and water, a rubber stopper and a copper tubed orifice which vents the vapors, and a rubber hose connected to a 1.5 ℓ syringe. The smoke generation method is similar to that for DN. After boiling and filling the flask with the vapor mixture, the syringe air is pushed into it, purging the vapor mixture into Box 1.

The MA aerosol particle size was determined in the same manner as for DN, from fall velocity measurement and the Stokes-Cunningham equation. The average particle diameter of MA is 0.79 μm (Fig. 2).

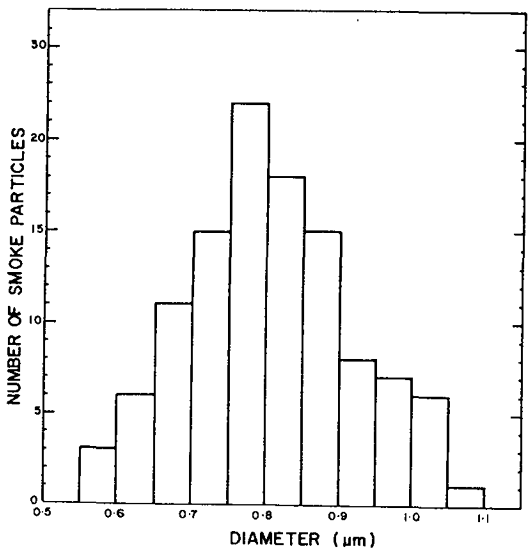

Fig. 2. *Stokes-Cunningham size distribution for vapor-activated metaldehyde smoke particles.*

Small particles, microscopically visible, disappeared several minutes after injection into the observation cell, as a result of evaporation. The number of ice crystals produced per gram of MA by vapor-activation method is 2×10^{13} at -20 C and 5×10^{11} at -10 C (Fukuta et al., 1970).

To assure free evaporation of MA particles during the experiments, preliminary runs were made using the mixing chamber at a few environmental temperatures. Computations confirmed that the evaporation decay was sufficiently faster than particle settling and other losses.

3. EXPERIMENTAL

3.1 Evaporation

A 6 m^3 aerosol chamber was constructed of masonite for the evaporation experiments. A small, electrically driven fan stirs the air containing the aerosol particles. Several holes are bored on the side for application of a thermometer, thermister unit, microscope lamp, and laser for optical detection of ice crystals, for injecting steam for ice crystal growth and two large holes for post clean-up operations. A service door cut into the bottom allowed insertion of formvar covered glass slides for ice crystal collection and replication.

A walk-in environmental room 3.3 x 2.7 x 2.2 m^3 holds the aerosol chamber under controlled temperatures ranging from 50.5 down to -15 C. The environmental room was originally designed for low temperature operations, and to maintain a constant high temperature a portable heater was installed with an Omega Engineering thermoregulator and thermistor.

The mixing chamber used for this study was a 10-ℓ copper cylinder held in a large temperature-controlled circulating bath. It has a lid, a cellulose acetate tube filled with warm water for moisture source, and a sugar solution. The interior of the chamber is painted black and a glycerine solution coats the walls to avoid ice crystal fall from them. In the lid, made of plexiglass, a small hole provides an entrance for smoke particles and a large hole serves as a handle and support for the moisture source, a cellulose acetate semipermeable membrane tube filled with warm water. In measurements, this tube is warmed in a water-filled beaker to 50 C, and subsequently attached to the mixing chamber lid several minutes before aerosol injection. Vapor produced by the membrane provides supercooled fog needed for contact-freezing and deposition ice nucleation measurements.

A supercooled sugar solution tray, painted black, is placed on the floor of the mixing chamber which receives nucleated ice crystals. To count all the nucleated ice crystals for a sufficiently long period of time, the ice crystal growth rate in the solution has to be controlled through adjustment of the concentration. For this reason, the growth rate of ice crystals in the sugar solution was determined as a function of the specific gravity at various temperatures (Fig. 3).

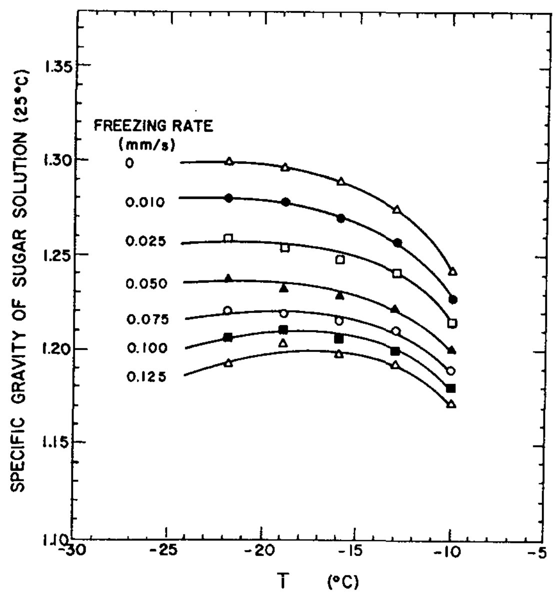

Fig. 3. *Ice crystal growth rates as a function of temperature and specific gravity of sugar solution.*

The study involves evaporation measurements of organic aerosols held in a large smoke box under different temperatures. Smoke samples in the large smoke chamber are periodically withdrawn and introduced into a mixing chamber where particle activity loss is determined as a function of time.

Aerosol particles can be lost by mechanisms other than evaporation, such as coagulation, sedimentation, and sticking to the walls. To determine the evaporation loss of aerosol particles, contribu tions from other mechanisms were estimated theoretically.

3.2 Other Losses

The coagulation rate of an aerosol containing n particles per cm^3 is given by

$$\frac{dn}{dt} = -Kn^2, \qquad (4)$$

where t is the time and K the coagulation constant (Green and Lane, 1964). In a series of experiments to determine coagulation rates and constants as a function of particle number concentration, size, turbulence, and chamber size, Gillespie and Langstroth (1951) found the coagulation constant to be little affected by turbulent motions less than 40 m/min through a given volume. Experiments using a similar size, light mixing, and relatively low particle numbers, produced $K = 0.4 \times 10^{-8}$ cm^3/min. Using these data, concentration loss was determined to be very small: 99.9% of the particles remain after 6 hours, assuming an initial aerosol population of 10^3 per cm^3. Particle concentration for both DN and MA were estimated to vary between 1 and 3 per cm^3; in this regard, their losses by coagulation in our experimental periods were negligible.

Gravitational fallout of particles in the chamber is also important because it reduces the particle number available for measurements. The rate of particle deposition while being stirred is given by (Green and Lane, 1964)

$$n = n_0 \exp(-v\, t / h), \qquad (5)$$

where n_0 is the initial particle concentration, v the average particle terminal velocity, t the time, and h the chamber height. Concentration loss due to gravitational fallout under our conditions was negligible, with 99% remaining after 6 hours.

A turbulent medium inside a chamber will continually bring air into contact with its surfaces, and all particles striking the walls will stick to them, reducing aerosol concentrations. The chance that a particle will strike the surface is proportional to particle number concentration and the rate of concentration loss can be represented by the surface loss equation,

$$n = n_0 \exp(-B\, t), \qquad (6)$$

where B is the particle surface loss rate constant, affected by size of particles, turbulence, and size of chamber. Smaller particles favor deflection with air currents near the surfaces, while momentum of large particles influences surface collisions and results in a high loss rate. According to Gillespie and Langstroth (1951), under our experimental conditions, $B = 0.4 \times 10^3$ min^{-1}. Surface concentration losses were therefore calculated to be about 10% within 4 hours. However, with our small DN and MA concentrations and with nearly total evaporation during this period, losses were considered negligible.

Another anticipated problem was whether particle evaporation would be hindered through the possible chamber air saturation with the vapor of the organic compound during the evaporation measurement. To avoid this problem, vapor density was computed as a function of temperature from DN and MA vapor pressure values measured in our laboratory (Fig. 4).

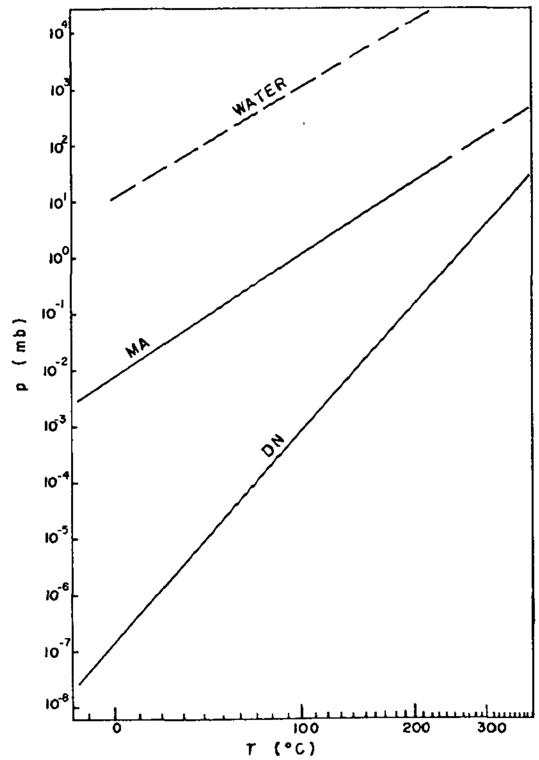

Fig. 4. *Saturation vapor pressures of 1,5-dihydroxynaphthalene, metaldehyde and water.*

From the average organic particle diameter and density, particle mass was estimated, and compared to the vapor density to indicate the number of particles required to saturate one cubic centimeter of air as a function of temperature. Particle number concentrations used in our experiments were 1 to 3 per cm^3, far below the limits.

4. EXPERIMENTAL RESULTS

4.1 1,5-Dihydroxynaphthalene

The first step in our evaporation measurement was to inject a predetermined number of organic smoke particles into the large smoke chamber, where the particles were continuously stirred and contained for several hours at a given temperature, while evaporation tests were performed. Initially, we were to expose this organic smoke to sub-freezing temperatures and monitor the decay rate for 5 to 10 hours, but because of the slow evaporation rate of the DN smoke particles, we decided to speed up the decay process by heating the chamber. A subsequent extrapolation sheme was used to determine the decay rates at temperatures more representative of the real atmosphere. Four temperatures were used; 35.5, 40.5, 45.5, and 50.5 C.

After the organic smoke had been injected into the large aerosol chamber, samples were taken at predetermined intervals and tested in the mixing chamber. Samples were drawn ten minutes after initial injection and thereafter every half-an-hour for 3 to 6 hours. One liter aerosol samples were withdrawn periodically with the syringe and slowly injected into the supercooled fog held at -15 C.

After injection, a waiting period of five minutes allowed ice crystals formed on the DN nuclei to develop into visible white spots in the supercooled sugar solution. Measurements were made every other day due to the necessary chamber clean-up process, by heating to evaporate all existing particles and to vent out the vapor during the intervening day.

Our experiments consistently showed a decrease in the number of collected ice crystals with time, indicating that evaporation was indeed taking place within the large aerosol chamber. After a series of experiments at each desired temperature level was completed, data were plotted immediately to check the evaporation trend. Figures 5 through 8 co-

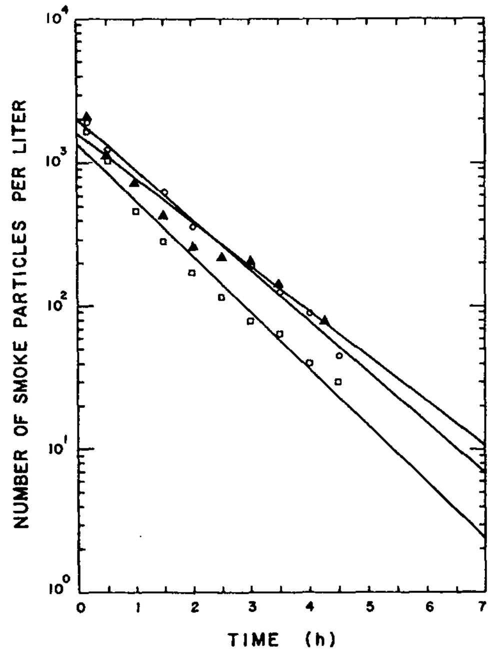

Fig. 5. *Evaporation decay for 1,5-dihydroxynaphthalene smoke particles determined at 35.5 C.*

mpare the differences in evaporation rates for particle concentrations determined at four temperature levels. As expected the slowest concentration loss was observed at 35.5 C. With increasing temperature, the decay slope steepened.

The decay curves were fairly easy to determine, with the exception of that at 50.5 C, where evaporation was so rapid that the number of smoke particles dropped beyond the detection limit of the chamber. However, because the injection procedure was identical to the runs at other temperatures, initial ice crystal concentration could be inferred, and using small number of crystals experimentally detected, a concentration loss curve was estimated. The 50.5 C decay curve seemed to follow the same pattern as others, illustrated by the near linear concentration loss slope profile given in Fig. 9. Concentration losses can be calculated for temperature levels more realistic to our atmosphere by using the empirical equation

$$n = n_0 \exp [-b\ t \exp (m\ T)], \qquad (7)$$

where b = 0.0007, m = -0.132 and T the temperature.

4.2 <u>Metaldehyde</u>

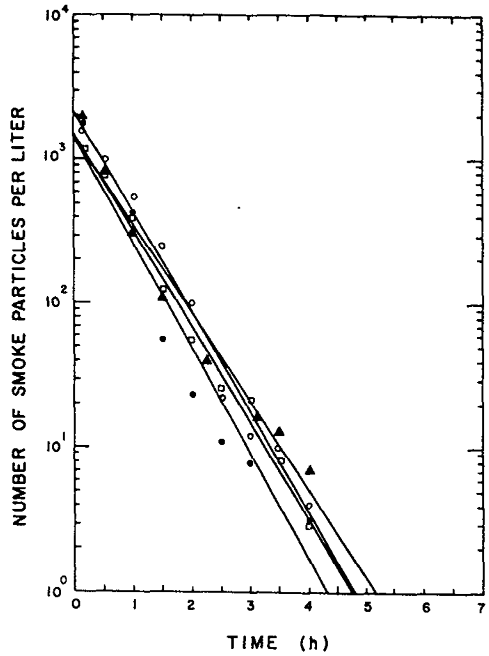

Fig. 6. *Evaporation decay for 1,5-dihydroxynaphthalene smoke particles determined at 40.5 C.*

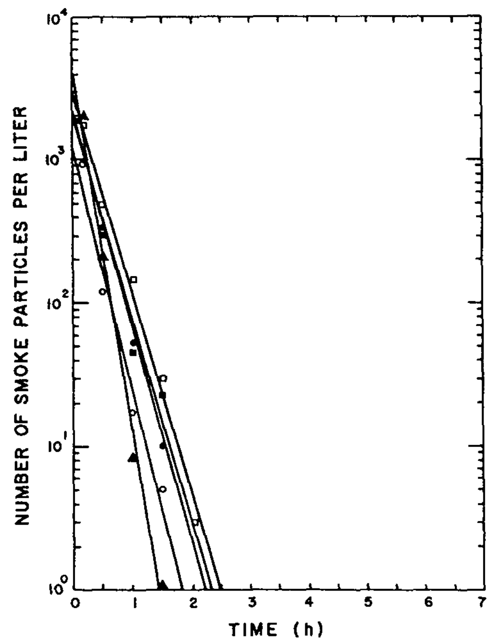

Fig. 7. *Evaporation decay for 1,5-dihydroxynaphthalene smoke particles determined at 45.5 C.*

The measurement technique for evaporative concentration loss for MA was similar to that for DN, except for the method of particle generation, which reflects the difference in material characteristics. Vapor-activated MA (Section 2.2) was dispensed into the large chamber to produce a high concentration of ice crystals, which subsequently sublimated, exposing the small MA particles. To assure that the formed ice crystals sublimate, a dry environment was created in the chamber through heating and injection of compressed air, with ventilation to

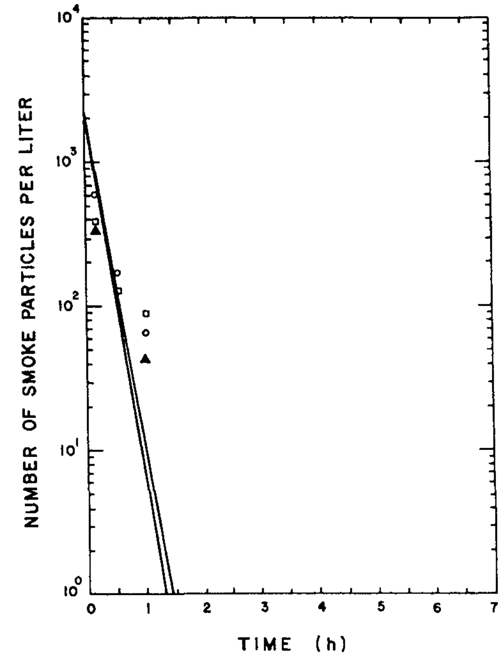

Fig. 8. *Evaporation decay for 1,5-dihydroxynaphthalene smoke particles determined at 50.5 C.*

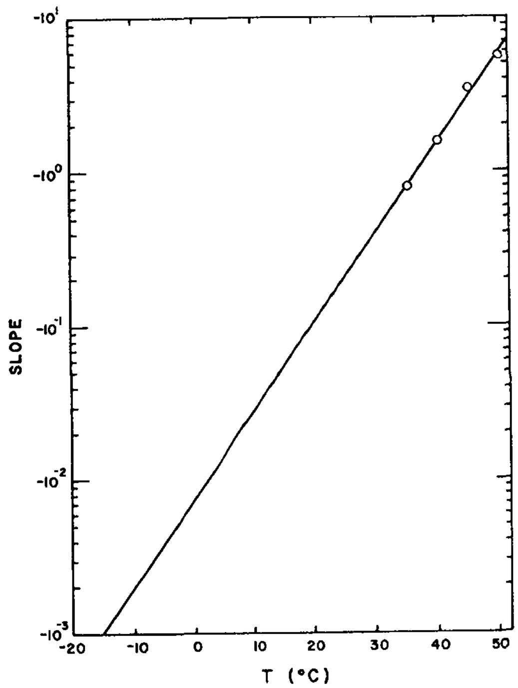

Fig. 9. *Slopes of evaporation curves for 1,5-dihydroxynaphthalene particles plotted as a function of temperature.*

lower the amount of water vapor inside the chamber. Ice crystal sublimation was confirmed by lack of visible signs of ice crystals in a light beam from a laser or microscope lamp directed into the chamber ten minutes after vapor activation.

The particles thus produced were continually stirred throughout the entire experimental run at subfreezing temperatures of -5, -10, and -15 C. Samples were drawn as described in Section 4.1, and results were analyzed immediately to check the evaporation trend. Figures 10 through 12 compare the

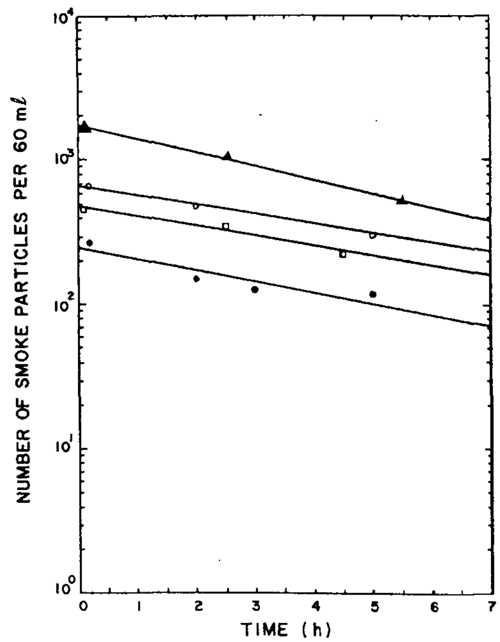

Fig. 10. *Evaporation decay for metaldehyde smoke particles determined at -15 C.*

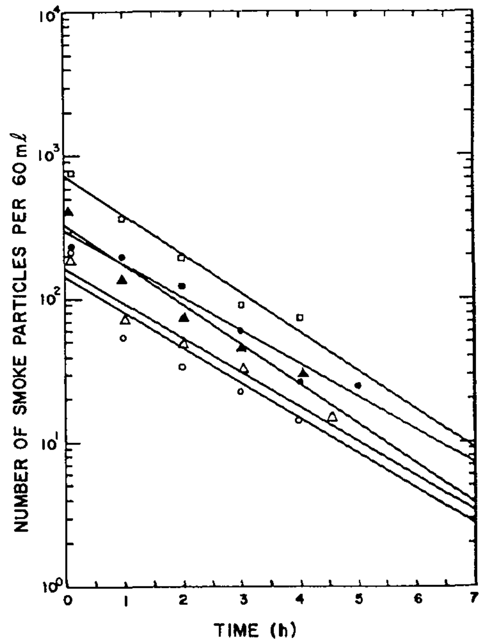

Fig. 11. *Evaporation decay for metaldehyde smoke particles determined at -10 C.*

differences in particle concentration decay rates for the three temperatures used. As expected, -15 C data showed the slowest evaporation rate, while concentration losses were fastest at -5 C. The number concentrations at t = 0 did not show good reproducibility as seen in the graphs; however, the decay slopes were consistent.

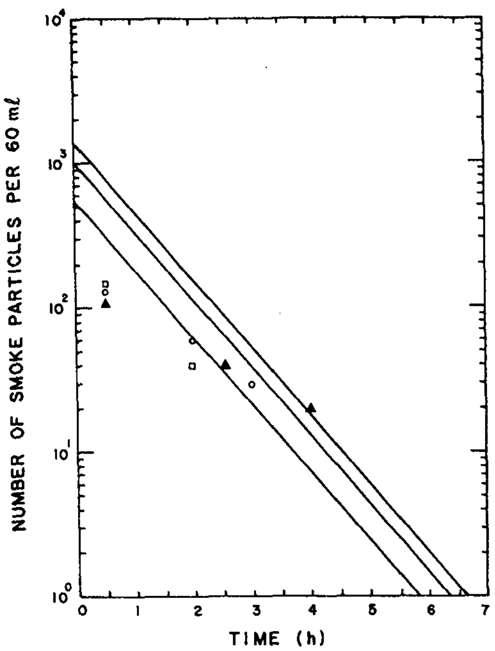

Fig. 12. *Evaporation decay for metaldehyde smoke particles determined at -5 C.*

When we tried to determine the evaporation curve for -5 C, the fast decay rate at this temperature again caused trouble. Estimation of the initial particle concentration from experiments of lower temperatures, and use of small ice crystal counts detected experimentally, helped determine this decay curve. The -5 C concentration loss curve followed the same evaporation trend as those of lower temperatures. The slopes of evaporation curves are plotted as a function of temperature in Fig. 13. Aerosol

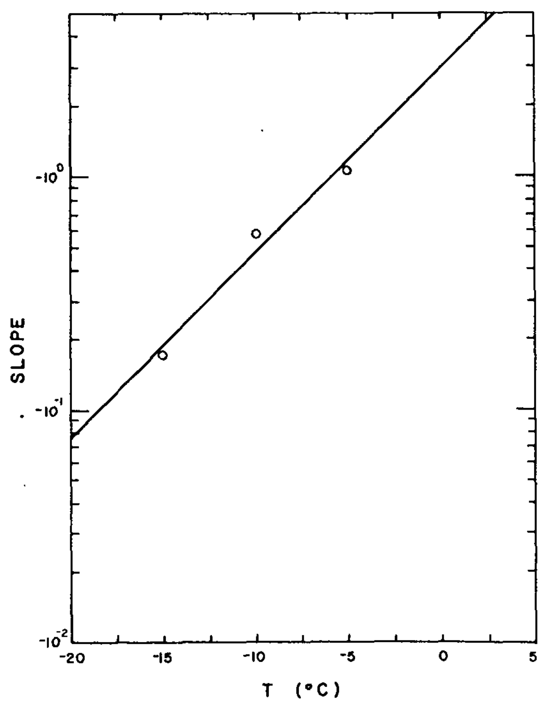

Fig. 13. *Slopes of evaporation curves for metaldehyde smoke particles plotted as a function of temperature.*

evaporation losses can be calculated for any given temperature using empirical Eq. (7) with b = 2.978 and m = -0.183.

5. ESTIMATION OF LIFETIME FOR ICE NUCLEUS PARTICLES

To estimate decay of lifetime of organic ice nucleus particles as a function of temperature and size, the activity decay data already obtained must be interpreted with respect to evaporation behavior of the particles in the size distribution curve. Therefore, using the cumulative frequency probability curves representing the aerosol size distribution, and assuming the activity decay proceed from the smaller end of the size distribution because smaller the size, shorter the evaporation lifetime, a relation between nuclei size and decay time for any given temperature can be obtained. To carry out this analysis, the skewed Stokes-Cunningham size spectrum was normalized into a symmetrical distribution (Kottler, 1950), using the log-normal equation,

$$F(d) = \frac{i\ \Sigma N}{d\ \sqrt{(2\pi)}\ \ln \sigma_g} \exp\left[-\frac{\ln d - \ln M}{2\ \ln^2 \sigma_g}\right], \quad (8)$$

where F(d) is the frequence of occurrence of particle diameter d, i the size interval, ΣN the total number of particles in the initial distribution, σ_g the geometrical standard deviation, and M the geometrical mean diameter (Fig. 14). Integration of

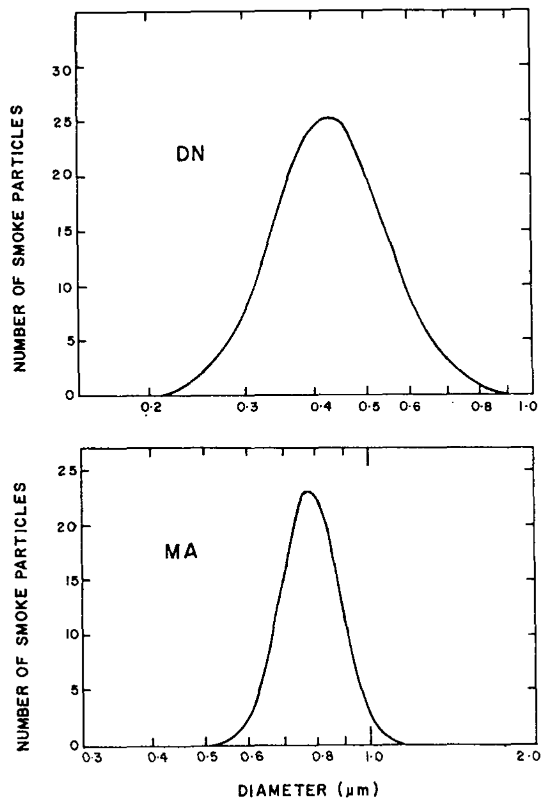

Fig. 14. *Log-normal Stokes-Cunningham size distributions for 1,5-dihydroxynaphthalene and metaldehyde smokes.*

this function gives the cumulative size distribution curve. Fig. 15 illustrates the cumulative plots for both DN and MA. These graphs reveal, for exam-

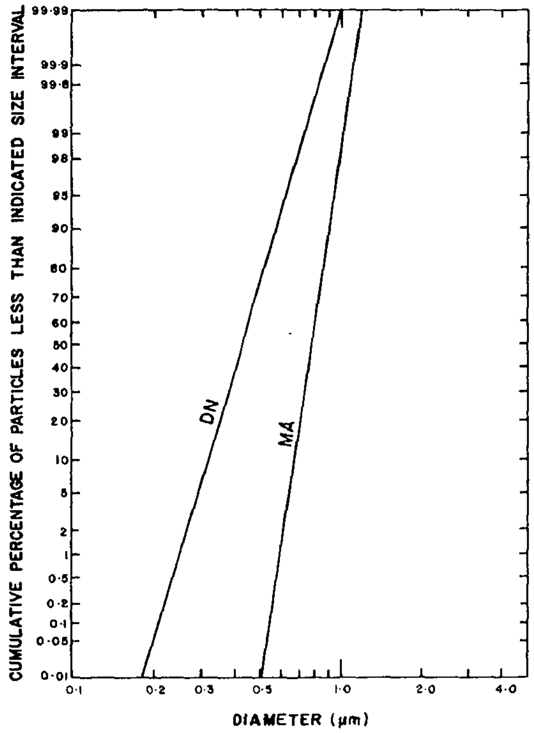

Fig. 15. *Cumulative percentage curves plotted as a function of size for 1,5-dihydroxynaphthalene and metaldehyde smoke particles.*

ple, that 75% of the total DN aerosol population has diameters smaller than 0.51 μm, while 90% of MA population is smaller than 0.90 μm. The percentage of particle activity loss experimentally determined as a function of time can then be correlated with the cumulative percentage distribution in the probability graphs.

5.1 1,5-Dihydroxynaphthalene Particle Lifetime

According to Eq. (7), the percentage of DN aerosol concentration decay as a function of temperature can be determined empirically and then compared, with cumulative size frequency. Figure 16 shows the lifetime of DN particles due to evaporation determined by the above procedure, extended down to representative temperature levels of the real atmosphere. About 90% of the DN aerosol population is analyzed in these results. Since the lifetime of Maxwellian particles is proportional to the square of their sizes, particle evaporation, thus estimated, proceeds very fast for the smaller sizes, especially for those below the detectable size value of 0.17 μm. Evaporation times are subsequently extended as the size increases

The presence of non-volatile impurities on the particle surface was thought to be responsible for the faster activity decay of small particles, inactivating them as ice nuclei well before complete evaporation. This decay behavior is too complex to predict with the Maxwellian model or the diffusion-kinetic model of constant accommodation coefficients (Fukuta and Walter, 1970). Green and Lane (1964) state that particles of many aerosols are unlikely to evaporate ideally. Non-volatile impurities, formed by slow oxidation or decomposition during evaporation, or even acquired by collision with dust particles, may retard or hinder evaporation.

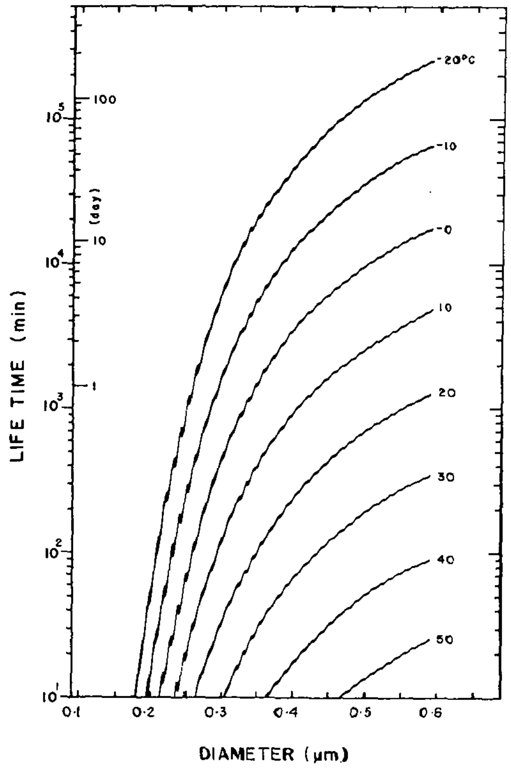

Fig. 16. *Lifetime of active 1,5-dihydroxynaphthalene smoke particles estimated as a function of diameter at different air temperatures.*

The Maxwellian theory predicts particle evaporation, on the average, six times faster than the experimentally determined rates. Therefore, particle size decay must be estimated graphically. For particles of diameters greater than 0.59 μm, evaporation times were greatly increased. These few large particles were generally not representative of the remaining distribution, nor of practical use in weather modification, and their slow decay behavior greatly extended the remaining 10% of the evaporation curve. Thus they were not included in these results.

Evaporation of DN particles is strongly temperature dependent. At temperetures warmer than 10 C, less than one day is required for most of the present aerosol to evaporate. Particles exposed to colder atmospheric temperatures would, however, survive longer with possible short-range downwind implications. Experimental and theoretical studies of ice forming nuclei indicate that the optimum cloud seeding particle size is near 0.2 μm in diameter, or slightly smaller (Fukuta, 1974). This suggests that reducing DN particle diameter to 0.2 μm could shorten lifetime of evaporating DN particles by several days, at temperatures as cold as -20 C.

5.2 Metaldehyde Particle Lifetime

The lifetime for MA particles determined by the same procedure is given in Fig. 17. Evaporation results again represent 90% of the total Stokes-Cunningham size distribution. Particle evaporation is extremely fast for smaller sizes, especially for those below the detectable size of 0.54 μm. Evaporation rates subsequently decrease, as time and size increase, as in the case of DN. This effect can be interpreted also as the result of non-volatile

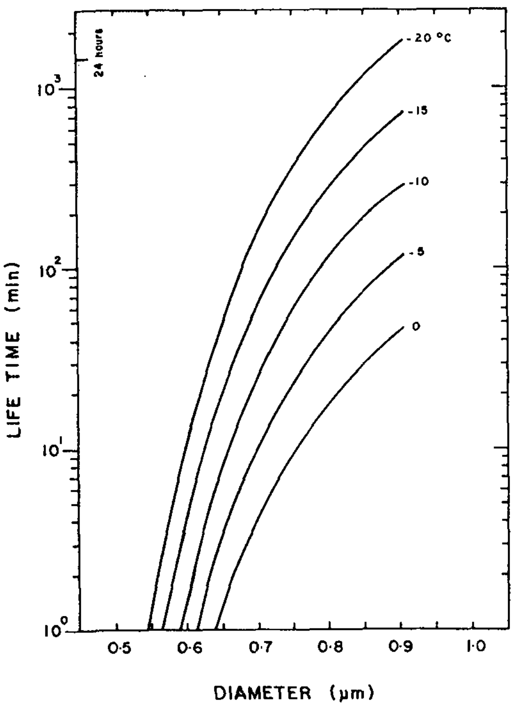

Fig. 17. *Lifetime of active metaldehyde smoke particles estimated as a function of diameter at different air temperatures.*

impurity accumulation. Slow decay of large particles extended the curve, which were not totally representative of MA particles for cloud seeding use, and hence not plotted. Some 90% of the particles decay within 24 hours, in the temperature range used. According to Green and Lane (1964), aerosol particles of substances with vapor pressures as low as 10^{-4}mb decrease in size perceptibly, which is also recognizable to some degree in our results. MA smoke particles, therefore, not participating in the ice nucleation process, are expected to evaporate quickly and not contribute to any downwind or environmental problems.

Evaporation rates of MA particles can also be calculated from the Maxwellian theory and compared with experimental results. This theory predicted the MA decay rate as considerably faster than that experimentally determined, suggesting retardation mechanisms for evaporation or decay. A continuing shift in size distribution from smaller to larger must therefore occur in the chamber. Hence, evaporation rates for this spectrum can be considered as the slowest possible values, assuming that aerosol particles employed in cloud seeding would be much smaller.

An analytical expression to predict size decay as a function of temperature, vapor pressure, and time, based on either Maxwellian or non-Maxwellian theory, similarly could not be produced. A large difference between size decay predicted by theory and activity loss measured was again noted, and graphical methods had to be employed to estimate the decay behavior of MA (Fig. 17).

6. WEATHER MODIFICATION IMPLICATIONS

As discussed earlier, two of the undesirable effects associated with the current operational weather modification agents include downwind nuclei contamination, and, to a lesser extent, ecological repercussions. Both environmental problems are directly related to the inability of AgI to decompose under atmospheric conditions. We have estimated the evaporation rates of two potential organic cloud seeding agents, DN and MA, which can provide new insight into when, where, and how to apply these agents to clouds.

We have demonstrated that DN and MA aerosols definitely decay with time through evaporation, depending on particle size and temperature. Particles of MA less than 0.6 μm in diameter are shown to evaporate within 20 minutes at temperatures as cold as -20 C (Fig. 17). Particles smaller and more suitable for cloud seeding would definitely produce no undesirable downwind problems. Evaporation of DN is slower, but particles smaller than 0.2 μm in diameter should still evaporate and lose activity within a few hours at equally cold temperatures (Fig. 16).

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ASCENT OF SURFACE-RELEASED SILVER IODIDE INTO SUMMER CONVECTION

ALBERTA 1975

James A. Heimbach, Jr.
Institute of Natural Resources
Montana State University
Bozeman, MT 59717

Newton C. Stone
Irving P. Krick Associates of Canada, Ltd.
611 S. Palm Canyon Drive
Palm Springs, CA 92202

Abstract. During the summer of 1975, an experiment was conducted near Calgary, Alberta, Canada, to test the hypothesis that surface-released silver iodide can reach the inflow regions of cumulonimbus clouds. Effluent from point and quasi-area sources of AgI-impregnated coke-fueled generators were traced using airborne NCAR ice nucleus counters. The evidence shows that it is possible for plumes to ascend to give concentrations up to two orders of magnitude above background at -20°C (>200 nuclei per liter) in cloud-base inflow areas. Targeting was difficult and the horizontal dispersion of the plume less than anticipated. Ice nucleus concentrations were usually above background levels to the top of the mixing layer. Three case studies having relevance to the application of ground-based AgI generators are discussed and a summary of flights during convective periods is given.

1. INTRODUCTION

There has been much speculation regarding the potential for surface released cloud seeding material to be entrained during convective periods. The National Academy of Sciences (NAS-NRC, 1973) has stated that orographic cloud systems may be treated by ground-based units because of the forced vertical motion; however, they recognized that vertical transport processes may be complex. For situations lacking orographic influences, evidence of predictable vertical transport of ground-released material has not been convincing.

Ground-based cloud seeding has been used by many projects. Among the first was the Salt River Arizona, project during 1948 and 1949 (Krick, 1949; MacCready, 1952). Winter orographic clouds have commonly been treated with ground-based units because of the vertical motion forced by the orographic regime, long system life and broad area coverage characteristic of these systems (Hess, 1974; Silverman, 1976). Some skepticism regarding routine targeting effectiveness of ground-based summer cloud treatment was expressed by NAS-NRC (1973). Super and McPartland (1978) and Heimbach et al. (1975) report the ascension of concentrations several orders of magnitude above background from the surface to the top of the mixing depth in Montana, 2000-to-3000m AGL. The former study specifically addressed cloud base concentration of silver iodide, whereas the latter was primarily concerned with the rate of diffusion of silver iodide as a tracing material.

Further suggestions regarding the characteristics of surface-originated plumes come from investigations of inadvertent weather modification. Schickedanz (1974) and Changnon et al. (1976) reported that, besides thermodynamic and mechanical influences of the St. Louis area, there appeared to be a microphysical change to the clouds which produced increased precipitation downwind of the city. This was presumed to be the result of giant nuclei which would have to ascend from the surface to cloud base.

There is uncertainity regarding the accumulation of suitable concentrations of ground-released seeding material in convective updraft regions. The questions of effectiveness of area treatment, lead time required for treatment, emission rates, and predictability of plume behavior have also brought criticism to ground-based procedures. The photodeactivation of silver iodide has been the topic of much speculation (Changnon, 1975). Marked photodecay of silver iodide was reported in several early experiments (Mason, 1971); however, later work by Super et al. (1975) indicates that this deactivation is limited or nonexistent for the AgI-NH_4I-Acetone complex.

In view of these uncertainties, the Alberta Weather Modification Board (formerly Interim Weather Modification Board), Alberta, Canada, (AWMB) conducted a ground-based diffusion experiment during the summer of 1975 (Stone et al. 1976). During the years 1956 through 1968 and also 1973 to the present, operational hail suppression and concurrent research have been in process in Alberta. Currently, the operational aspects are the responsibility of the Alberta Hail Project (AHP) based in Red Deer, under the auspices of the Alberta Research Council (ARC). During the earlier period the operations were the responsibility of Irving P. Krick Associates of Canada, Ltd., who used coke ground-based silver iodide generators. The 1975 experiment had the mandate of investigating the earlier ground-based seeding effectiveness, with hopes of clarifying operational aspects for possible future implementation of surface releases.

Further research in ground-based seeding of convective events has been carried out by the Alberta Research Council and Irving P. Krick Associates over roughly the same target area during the summers of 1981, 1982, and 1983. The data from this effort are currently being analyzed.

Presented below are three case studies from the 1975 plume study program which document the rise of ground-based plumes in convective conditions, the broad ascension of ice nuclei in response to a lifting mixing layer and the characteristics of a plume during inversion conditions. These cases were culled from a total of thirty tracing missions, sixteen of which were in unstable conditions ($\gamma \geq \Gamma_d$). A summary of the unstable cases is given in Section 5.

2. EXPERIMENTAL PROCEDURES

Figure 1 shows the placement of the study area among other relevant points. The foothills of the Highwood and Kananaskis Ranges are 32 to 56 km to the west of the study area. Most of the target area is flat to gently rolling hills, sloping from approximately 1120m MSL on the west to 950m at the northeast corner. Seventeen generator sites in and around the area were operated by private citizens; and active sites were monitored by project personnel at least once during each operation day. The sites to be used depended upon wind conditions and the type of tracing mission.

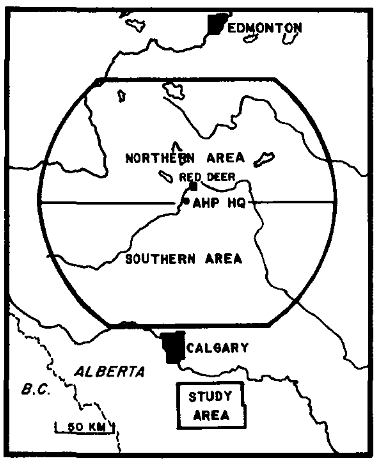

Fig. 1. The Ground-Based Plume Study Area in Relation to the Alberta Hail Project.

The tracing aircraft usually arrived upwind of the operating generators at 3000m MSL or more, then spiraled downward to obtain a temperature sounding, as well as background ice nuclei concentrations, as quickly as possible. The flight profiles were generally 15-to-35 km and were made from 100m (sometimes lower) to 2000m AGL or until background concentrations were reached. Most of the tracing was done without cumulonimbus development, reducing the mission to the exercise of finding the plume and remaining with it until it was lost above the mixing layer. However, several days had significant convective development and particular attention was given to sampling the inflow regions of these systems.

Typically, the wind would have an easterly component during the first portion of an experimental day, shifting to westerly by afternoon. The direction varied not only with time but over short distances; e.g., 180 deg shifts were often observed in the study area. Intermingled plumes of the various sources made inflight assessment of plume behavior very difficult, and the plume often was lost during these conditions. Consequently, several generators were placed at one point source to yield a larger emission rate and reduce the complexity of the plume structure. This made tracking an individual plume far more practical.

It was planned to use VOR/DME coordinates to define the traverse paths, but because of the uncertainties in the electronics and recording systems, later substantiated, a series of clearly visible check points was relied upon. The crossing of a check point was logged on the ice nucleus counter strip chart along with the altitude.

The day's first forecast was completed at the control office by 08 MDT, assigning a "go", "likely", or "no-go" status to the day. If affirmative, the flight crew and field personnel were alerted and briefed. The aircraft instrumentation, in particular the ice nucleus counter, were attended to at least an hour prior to take-off and the generator operators were alerted to start their units at least a half hour, and if possible two to three hours, prior to the arrival of the aircraft, so that conditions could approach steady state. Tracing missions were usually initiated by 1400 MDT.

3. INSTRUMENTATION

3.1 Silver Iodide Generators

Krick Model 15 generators provided silver iodide for most of the experiments. These are basically composed of a fuel hopper, feed mechanism, vaporizing furnace and a blower for maintaining the proper air flow through the furnace.

The fuel burned in the generator consisted of sized quarter-inch foundry coke impregnated with an AgI-NaI complex yielding a burn rate of *approximately 0.5 gm silver iodide per minute*. This type of generator was tested at the Cloud Simulation and Aerosol Laboratory, Colorado State University (1974). The results showed 2 X 10^{14} to 10^{15} ice nuclei per gram of silver iodide effective at -20°C for natural draft and maximum flow, respectively. This testing also showed less than 20% loss of activity for ice nuclei exposed to ultraviolet radiation over the sampling period of five hours. This is considered to be insignificant. Tests of the coke generator in 1981 (Finnegan, 1981) showed similar nuclei production at -20°C, higher efficiencies above -20°C and a more rapid drop off at -10°C. There was also more scatter in the derived efficiencies. The 1981 tests showed higher and more consistent efficiencies for the Krick electric arc type generator.

3.2 Aircraft

The primary aircraft was a Piper Cherokee 6. This single-engine aircraft, furnished by INTERA Ltd. of Canada, was based at Calgary International Airport, approximately 45 km north of the study area.

Metrodata M8 and 620 systems were installed on the Cherokee for in-flight monitoring of basic parameters. Some problems in the system were not resolved, and use of the recorded data had to be abandoned. All in-flight data used in the analysis came from flight logs and Rustrak recordings of ice nucleus counts.

"REVIEWED"

A Cessna 411 (also provided by INTERA) assigned to the AHP as a cloud physics aircraft was used on the experiment on an as-available basis. This aircraft had an ice nucleus counter similar to that on the Cherokee 6, and comparison flights were made to test the two systems.

3.3 Ice Nucleus Counter

The operation of the NCAR ice nucleus counter is described by Langer et al. (1967); Langer and Weickmann (1971); and Langer (1973). Both counters had their cloud chamber maintained at -20°C, and had been modified slightly by G. Langer. Most of the ice nucleus data for the ground-released plume study came from counter in the Cherokee 6, belonging to the Alberta Research Council. The other NCAR counter was loaned to the AHP by NCAR and was installed in the Cessna 411.

Counts were integrated over 120 sec., 12 sec., or 1.2 sec. intervals, depending upon the choice of scales. Background sampling was usually over 120 sec. integration periods and normal plume tracing was over 12 sec. intervals. Recorded units counts per minute were converted later to counts per liter, using the techniques described by Heimbach et al. (1977). The time required to grow acoustically detectable ice crystals around ice nuclei makes response times on the order of a minute, and smoothing of counts, are inherent in the NCAR counter.

Tests of the Cherokee counter with 120 mm Hg flow rate showed the lag to average 35 sec. to the first detection of an input, 65 sec. to mode response, and 97 sec. to median response from input. The time-to-mode would seem the most appropriate response parameter to apply for purposes of time-to-distance conversion for peak counts. The testing also showed that the Cherokee 6 ice nucleus counter contributed an induced standard deviation of approximately 30 sec. to the true input. For all the case studies described in this paper the response lag was removed. The ice nucleus profiles depicted in Fig. 7 have also been adjusted by removing the counter induced smoothing.

Since the 1975 experiment, the ARC counter and its electronics have been rebuilt. This counter, as well as one belonging to the Colorado State University Cloud Simulation Laboratory, were calibrated for efficiencies at that facility. The 10% efficiency factor (actually a chamber fallout correction suggested by Langer, 1973), for the ARC counter, as run in its recent configuration, was too large. For reasons not discussed herein, it is certain that the counter as run in 1975 was more efficient than shown in the recent tests, and the 10% factor is applied in this paper, i.e., one ice nucleus registered by the counter was assumed to represent ten nuclei. This is a conservative approach since the counts reported in this paper represent the maximum counter efficiency possible, i.e., reality must have concentrations that high or higher. Applying the 10% factor and using a sample flow rate of 10 ℓpm gives an approximate one-to-one ratio to convert counts per minute to counts per liter.

4. SURFACE-RELEASED SILVER IODIDE PLUME CHARACTERISTICS

Many factors contributed to the difficulty of sampling cumulus inflow areas. Very often the winds would be light and variable, making plume tracing difficult. Also, inflow regions had to be recognized and sampled in a timely fashion. On several occasions, a line of cumulonimbus appeared to flush the air mass containing the AgI, leaving a background concentration until a new plume would reach the area. Also, the normal technical difficulties with instrumented aircraft had a limiting effect. Although thirty tracing missions were flown in twenty-eight days, only five of these sampled days had cumulus buildups over the area; only one had a plume traced directly into a developing inflow, presented as a case study below. Concurrently, with this major thrust, several other investigations were carried out, examples of which are also described.

4.1 Transport Into Inflow Areas

August 8, 1975, is presented as a case study. A series of squall lines passed the Calgary area producing showers, thunderstorms, and some pea-size hail during the afternoon. A 500 mb long wave trough crossed northern Alberta at 06 MDT (Fig. 2) and cooler air was advected into Alberta during the afternoon. The usual inversion was not present on the morning Calgary sounding; however, the air mass was fairly stable from the surface to slightly above 1800m AGL. The air mass became considerably less stable with time, as shown by the 18 MDT Calgary sounding (Fig. 3).

Originally most of the activity was expected to remain to the north of the study area and the day was given a "test not likely" forecast. However, the Cb potential did increase over the study area, and a single generator was started at 1615 MDT to the northwest of the target area. At 1700 MDT, two more generators were started at the same site (Fig. 4). The Cherokee 6 aircraft took off at 1632 MDT and arrived over the Study Area at 1650 from the west, the upwind direction. The background ice nuclei concentration was the usual 0 to 1 nuclei per liter.

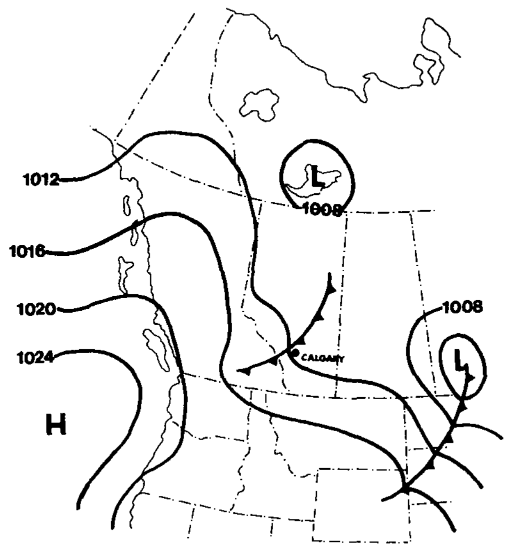

Fig. 2. Surface Synoptic Situation, 0600 MDT, 8 August 1975.

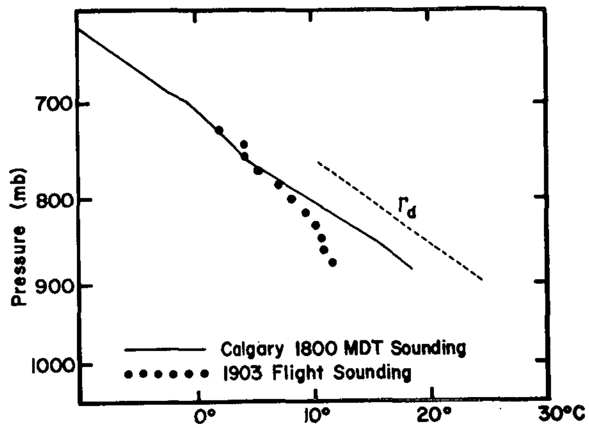

Fig. 3. Afternoon soundings of 8 August 1975.

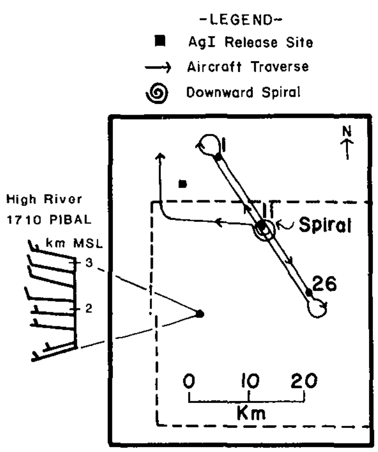

Fig. 4. Flight Path for Mission of 8 August 1975.

The traverses began at 1655 MDT, with only scattered cumuli over the study area, but cumulonimbus activity was observed to the north, moving toward the study area. At 1735 MDT, the flight technician logged a line of cells extending from west-northwest to east-southeast, forming and intensifying over the northern half of the study area. The buildups continued to intensify, and updrafts, as well as showers and small hail, were noted. During sampling the cloud bases lowered to 1800m AGL. Well defined updrafts were detected as low as 1000m AGL.

Shifting winds made locating the plume difficult. Several exploratory passes at approximately 200m AGL indicated that the plume had stabilized to an east-to-northeastward direction. A stacked series of passes was made perpendicular to this observed plume to a level of 3050m MSL. A Cb formed to the east of this path, and moving under this formation was considered but it was decided to complete the series of passes. Shortly thereafter, a line of cumulonimbus cells began to form directly overhead, giving the unique opportunity of sampling developing inflow areas.

Figure 5 is a height-versus-time plot of this series of passes depicting counts lagged by one minute, while Fig. 6 plots the positions of peak concentrations of the same series in which the plume was consistently detected. The first inflow penetration was at flight level 2750m MSL (approx.

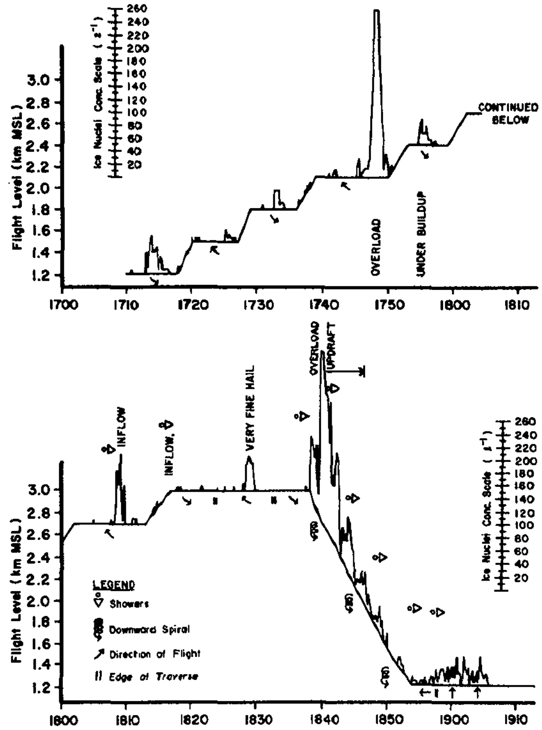

Fig. 5. Aircraft Altitude Versus Time for Stacked Series Taken on 8 August 1975. (Counts, scaled above altitude plots, have been lagged by one minute.)

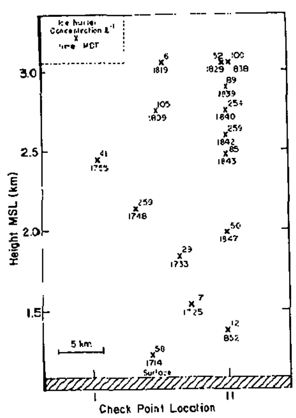

Fig. 6. Peak Concentrations of Ice Nuclei as a Function of Location From Data of Fig. 5. (Peak counts and time located above and below position respectively. See Fig. 4. for check point locations.)

1750m AGL) and up to 105 nuclei per liter measured within this area. The first inflow area sampled at 2050m AGL brought concentrations barely above background; however, on the return pass, a new inflow area showed concentrations significantly above background: 52 and 100 nuclei per liter. The next pass at the same altitude was terminated prematurely due to deteriorating weather conditions, and a spiral descent in an updraft, estimated by the pilot to be as strong as 2-to-3 mps. At this time the (lagged) counts reached 259 nuclei per liter, just after rice-size hail was observed. Significant counts were observed throughout the remainder of the descent, although they tapered off below 700m AGL.

The results of this flight show that, for this particular case at least, the developing Cb provided adequate transport of ground-released seeding material to the cloud base at 2750 to 3050m MSL (approx. 1750 to 2050m AGL). On other days when Cb were present, this transport was enough to rapidly deplete the seeding material in the vicinity. At such times the counts were barely above background in areas that had significant counts prior to the system's passage.

4.2 A Case Study of a Silver Iodide Plume Ascension Rate

On August 3, 1975, a mission was initiated to sample the ascension speed of a ground-released plume. A cold front had passed through the study area, and by late afternoon the air mass was moderately stable below 150m AGL.

When the Cherokee 6 took off from Calgary at 1411 MDT, the sky was clear over the study area, light turbulence was formed up to the maximum measured height of 3050m MSL (approx. 2050m AGL). Four Model 15 generators were started when the aircraft flew past the ground-release site near the center of the study area at 1510 MDT. After the flyby, the aircraft began making a series of traverses at 150-200m AGL in an east-southeast to west-northwest path two miles south-southwest of the generator site at its nearest point.

The first three passes at this level detected nothing above the background of 0-to-1 nuclei per liter. On the fourth pass, a sparse broad plume with a maximum of 17 nuclei per liter was encountered at 1518 MDT (lagged to account for instrument response) at a flight level of approximately 110m AGL. A concise plume peaking at 52 nuclei per liter was found at 1521 MDT. The traverses then increased in altitude, and the aircraft encountered a plume for each traverse through 1150m AGL at 1618 MDT, where a peak count of 41 nuclei per liter was recorded. At 1450m AGL a sparse broad plume was encountered having a peak count of 17 nuclei per liter several minutes later.

No valid ascension rate can be estimated from these data, but it was faster than the ascension rate of the aircraft while sampling. The AgI impregnated coke-burning generators take several minutes to start and need ten minutes of operation to reach normal output. Moreover, the winds were light and variable. Smoke plumes from local industry were seen to rise almost vertically despite a slight drift from the northeast in the lower levels. At approximately 600m AGL, a shear line was found, above which the wind flow was westerly. The silver iodide plume may have drifted southwestwardly, until, upon reaching the shear level, the upper portions doubled back to be transported to the east, explaining the broader plume found at 1450m AGL.

4.3 Plume Characteristics During Inversion Conditions

Several morning missions were conducted to investigate the possibility of seeding air masses prior to dissipation of the morning inversion. In the target area these conditions had light and variable winds, and the silver iodide remained in relatively undispersed pockets which were still broad enough to find easily by aircraft sampling.

August 6, 1975, illustrates such a day. In addition to the usual early morning surface-based inversion, the morning sounding showed a stable layer between 2700 and 3200m MSL (approx. 1700 and 2200m AGL). By late afternoon, the lapse rate had become almost dry adiabatic to 3400m AGL. The first generators were started at 0715 MDT in the northwest portion of the study area. At five sites the Cherokee 6 took off at 0930 MDT and began a north-northwest to south-southeast series (Fig. 7).

In the plume cross-section derived from this series of passes (Fig. 7), the counts have been lagged by one minute and adjusted to remove the smoothing induced by the NCAR counter. Only two plumes were penetrated, but the counts were very high. The winds were not constant in direction with height, and vertical diffusion may have merged the five plumes so as to make only two distinguishable plumes. The top of the mixing layer sloped downward to the south, as verified by

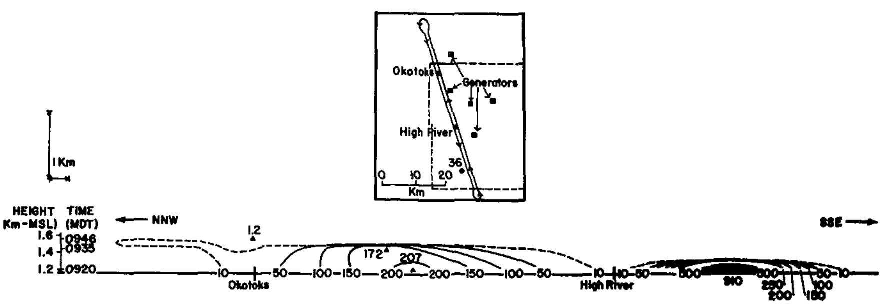

Fig. 7. Plume Cross Section and Flight Pattern for Morning Inversion Mission of 6 August 1975.

observations of haze tops. Ice nucleus concentrations were slight at 1800m MSL. This was to be expected, since the inversion base was below 1675m MSL at 1000 MDT. As the surface temperature increased, the base continued to rise. By about 1100 MDT a series of west-to-east traverses were made in the northern part of the test area. By about 1115 - 1120, a peak count of 259 nuclei per liter was encountered at approximately 675m AGL. Concentrations dropped to slightly above background at approximately 1000m AGL. The remainder of this test found rapid mixing; the peak concentration was approximately 25 nuclei per liter at 1000m AGL.

5. SUMMARY OF OTHER TRACING MISSIONS UNDER UNSTABLE CONDITIONS

Sixteen out of thirty tracing missions were flown over unstable conditions defined as $\gamma \geq \Gamma_d$. Stabilities were defined by the 1800 MDT sounding released at Calgary specifically for the Alberta hail project, and by aircraft temperature profiles. Table 1 summarizes the missions carried out in the vicinity of cumulonimbus clouds and Table 2 lists the remainder of the unstable cases.

The peak counts for each respective mission usually were found at the lowest level flown, on the order of 100 to 200m AGL, as would be expected from diffusion theory. Plumes were routinely traced to the top of the mixing layer except under light and variable wind conditions which hampered the prediction of plume positions.

6. DISCUSSION AND CONCLUSIONS

The case study of 8 August 1975 shows that silver iodide released from ground-based generators can ascend into inflow regions of cumulonimbus clouds. Not only were high ice nucleus concentrations observed beneath a cumulonimbus on this day, but AgI was found to have been lifted without the presence of clouds in the experiments. The ascension was found to be reasonably rapid once the morning inversion was dissipated. However, the 8 August case study was fortuitous, in that the aircraft was properly positioned in time and space to observe a plume being ingested into a developing Cb. Sampling in this as well as in the vicinity of other cumulonimbus activity suggested that the organized mesoscale convective motion rapidly depleted ice nuclei concentrations in the seeded volume. What this means in terms of in-cloud effective ice nucleus concentrations cannot be determined by this study.

The horizontal dispersion rates of the plumes were less than anticipated, possibly a relic of averaging time. In commonly used Gaussian diffusion models, an averaging time must be specified to judge the model results. This gives a quantitative assessment of the meandering of a narrow-dense plume. For example, the well known workbook by Turner (1969) lists diffusion coefficients for 10 minute averages. Aircraft sampling provides a nearly instantaneous viewpoint of plumes, which does not necessarily negate the use of ground-based generators. For example, if a seeding strategy requires a broader plume, the generator(s) could be placed further upwind and/or a generator array spaced further apart.

Ice nuclei were found to rise rapidly in conditions favorable for convection, even without the presence of clouds. The rising plumes were not well dispersed, which is characteristic of "looping" conditions expected during convective periods. Seeding during stable conditions showed a buildup of ice nuclei beneath the inversion as anticipated. The height of the seeded airmass increased as the mixing layer rose, then there was rapid vertical dispersion when the inversion was broken.

The results of this experiment are encouraging in the sense that ground-released AgI was observed to mix vertically within unstable layers. Predicting the trajectory of a ground-based plume remained difficult. Days having cumulonimbus potential often had light and variable winds over the target area. The use of multiple sources in these conditions made tracing confusing and for this reason only a single point source was used on the 8 August case. Moreover, when large cumulonimbus systems passed the vicinity of a plume, counts significantly above background were not found until steady-state conditions began to be re-established, suggesting a flushing of the treated air mass.

Table 1. Summary of Tracing Mission Flown in Vicinity of Cumulonimbus.

Date	No. of AgI Release Points	Peak Ice Nuclei Counts & Approximate Height (min^{-1})	(m AGL)	Maximum Observed Plume Count & Height (min^{-1})	(m AGL)	Remarks (Hgts. in m AGL)
31 July 1975	4	350	330	10	1100	Cloud bases at 700 unstable to 800.
2 Aug 1975	4	350	790	350	1400	Cloud bases at 1100-1400.
8 Aug 1975	1	200	1100 & 1700	100*	2000	Cloud bases lowered to 1700 during mission.
15 Aug 1975	13	100	489	15	1400	Conditions stabilized

*Recorder off X100 scale but not corrected until peak count rate passed.

Table 2. Summary of Tracing Missions Flown During Unstable Conditions. (Cases of Table 1 excluded).*

Date	No. of AgI Release Points	Peak Ice Nuclei Counts & Approximate Height (min^{-1})	(m AGL)	Maximum Observed Plume Count & Height (min^{-1})	(m AGL)	Remarks (Hgts. in m AGL)
21 June 1975	5	85	150	3.5	1400	Recorder malfunction.
23 June 1975	7	70	150	4.5	1400	Recorder malfunction.
30 June 1975	4	150+	1100	45	1400	
3 July 1975	3	45	150	4	1400	Very unstable below 1100, cloud chamber temperature questionable.
4 July 1975	10	100	150	2.5	1400	Cloud chamber temperature questionable.
5 July 1975	4	150+	790	7	1100	Slightly unstable. Cloud chamber temperature in question.
18 July 1975	10	150	150	20	1400	
26 July 1975	3	100	150	45	2000	AgI flares used as sources.
1 Aug 1975	6	200	150	15	1400	
3 Aug 1975	1	250	330	10	1700	Slightly stable above 1400.
6 Aug 1975	6	200	1400 & 1700	90	2000	
7 Aug 1975	6	80	150 & 1400	35	2000	

*Unstable implies ambient lapse rate greater than or equal to Γ_d.

7. ACKNOWLEDGEMENTS

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SEEDING RESULTS FAVOR SMALL CLOUDS IN CHINA, SOUTH DAKOTA, AND YUGOSLAVIA

James R. Miller, Jr.
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
Rapid City, SD 57701

Abstract. A comparison of four cloud seeding projects on three continents indicates that smaller clouds may give much greater percentage increases in rainfall than do larger ones in weather modification efforts. Project Cloud Catcher, a randomized single-cloud project in South Dakota 1969-1970 (Dennis et al., 1975) is compared here to a randomized two-area project in Fugian province, China, 1975, 1977, 1981 (Yeh et al., 1982). Also compared are rainfall results from two non-randomized, hail suppression efforts in South Dakota, 1972-1976 (Pellett et al., 1977) and in Serbia, Yugoslavia, 1970-1979 (Curić, 1981).

1. RESULTS FROM TWO RAIN SIMULATION RESEARCH PROJECTS

In Cloud Catcher, updrafts were seeded near cloud base with either salt or AgI. Figure 1 shows seed (AgI and salt) and no-seed regression lines relating radar estimated rain volumes to cloud depths. The seed line lies above the no-seed line suggesting greater rainfall production from a seeded cloud when compared to a no-seed cloud of the same depth. In view of the cube-root scale on the ordinate, the percentage differences in rainfall between the seed and no-seed cases are much larger for the smaller clouds.

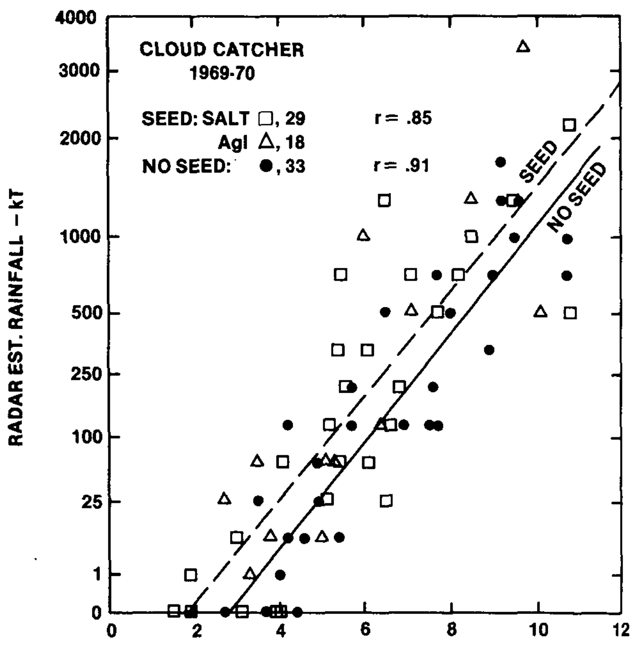

Figure 1. Scatter plot of cube root of radar estimated rainfall (RER) vs. cloud depth (CDP) for 1969-1970 Cloud Catcher cases. [Adapted from Fig. 4, Dennis et al., 1975].

No-seed line (solid): $RER^{1/3} = -4.02 + 1.43$ CDP
Seed line (dashed): $RER^{1/3} = -2.63 + 1.39$ CDP

Figures 2a and 2b, reproduced from Yeh et al. (1982) show fourth roots of areal precipitation in target and control areas and the seed and no-seed target-control regression lines for the cumuliform and total cloud stratification schemes, respectively (additional stratifications are included in the original paper). For larger rainfall events, smaller percentage increases in rain seem due to seeding.

Estimated percentage differences in rainfall are shown as a function of cloud depth for the Cloud Catcher project and the fourth root of rainfall for the China project in Fig. 3; the enhancement due to seeding is indicated by a solid line for Cloud Catcher and by dashed lines for China. It is well known that taller clouds produce more rainfall, and the scales are chosen to elucidate the possibility that similar seeding effects occur in the convective clouds of both regions.

Of interest is the "comparability" of these projects halfway around the world from one another. Smaller, weaker clouds, and/or cloud systems respond with greater percentage increases, whereas larger, stronger clouds show lesser effects. These results strengthen the development of seedability criteria for operational cloud seeding projects such as the North Dakota Cloud Modification Project (NDWMB, 1980). In North Dakota, seeding for rainfall enhancement is aimed primarily at moderate-sized clouds/cloud systems (cloud depths less than 30,000 ft or 9 km).

2. RAINFALL EFFECTS ASSOCIATED WITH OPERATIONAL HAIL SUPPRESSION

Rainfall in South Dakota during the State project, 1972-1976, was evaluated by Pellett et al. (1977); (see also Leblang and Pellett, 1976). The State supported operational project had goals of reducing hail damage and enhancing rainfall, with hail suppression operations having priority. Seeding in South Dakota was primarily by AgI released into updraft regions from aircraft flying below cloud base. Comparison of target-control (T/C) ratio developed for the historical period 1941-1970 and the seeding years T/C ratios indicated rainfall enhancements as shown in Table 1.

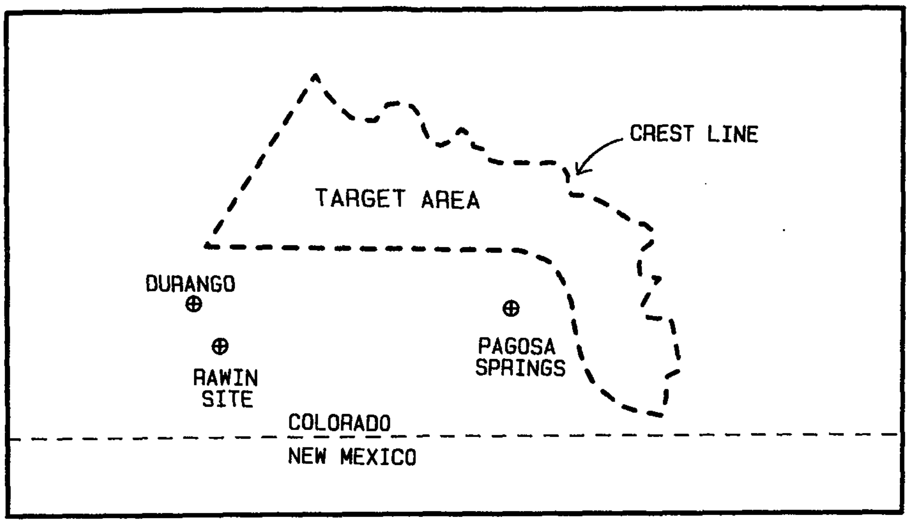

Fig. 1 COLORADO RIVER BASIN PILOT PROJECT AREA

Table 1 **Ratios of seeded to not seeded precipitation in three-hour blocks for unstable cases.**

Precipitation Group	Hours before (-) or after (+) Tropas (trough passage)						
	+9	+6	+3	0	-3	-6	-9
Wrn upwind flank	1.09	.79	.33	1.08	1.33	1.32	1.75
Wolf Creek Pass	1.15	.81	.62	.78	.85	2.26	1.37
Downwind flank	.73	.76	.65	.65	1.38	1.79	1.60

To test this hypothesis, the entire sample, without reference to position with respect to tropas, was divided into two groups. In one the top of the positive area shown on the upwind sounding (found associated with convection tops over the barrier) was higher than the cloud top calculated to exist over the barrier by lifting the top of the main deck, using the Durango upwind sounding. This will be referred to as the "emergent" case. In the second the reverse was true. This will be referred to as the "embedded case". However, it is not the same as the "embedded band" precipitation echo type employed in the Sierra Cooperative Pilot Project. The cases employed were subject to the various exclusions used by Shaffer, but in addition the base of convection, as determined from the sounding, had to lie below the crest level so as to insure entrainment of the ground generator plumes into convection.

Results of this division (Table 2) show that the Wolf Creek group of precipitation stations experienced a low ratio of seeded to not seeded precipitation in the emergent case. The rankings of the precipitation values for the seeded and not-seeded samples were compared using the Mann-Whitney U test. This indicated that the probability of a null effect was .008 for Wolf Creek pass. The other groups do not appear to be adversely affected. In the embedded case all groups show a positive ratio, with a probability of .073 in the downwind flank group. It should be mentioned that the crest group used in Shaffer's article included stations covering a larger area than used in this analysis.

2. DISCUSSION

In the embedded case, constituting 72% of the unstable sample, positive effects of seeding seem to be indicated. In the emergent case the crest zone shows an adverse effect with a seed/no seed precipitation ratio of 0.55. The region of adverse effect appears at about the same place in the synoptic sequence that has been chosen by Cooper and Marwitz (1980) in their analysis of aerial observations over the San Juan Mountains as a region favorable

Table 2 **Group precipitation (mm/3 hr) statistics for embedded and emergent convection.**

State of Instability	Item	Wm. Upwind Flank	Wolf Creek Pass	Downwind Flank	No. of cases
		Precipitation Group			
	S precip	1.36	2.47	1.43	63
Embedded	NS precip	.95	2.05	.98	53
	Ratio	1.43	1.20	1.46*	
				Total	116
	S precip	1.70	1.53	1.60	22
Emergent	NS precip	1.71	2.80	1.54	24
	Ratio	.99	.55**	1.04	
				Total	46

* Probability = .073 for two tail Mann-Witney U test.
** Probability = .008 for two tail Mann-Witney U test.

for seeding from ground generators. The generalized criteria developed by Vardiman and Moore (1978) suggest that with a greater depth of convective instability, such as would occur in this region, the odds for a favorable response to seeding diminishes. This supports the author's analysis.

From the viewpoint of a purely microphysical effect of seeding, it is difficult to identify a reason why seeding effects in the mergent cases would be radically different from seeding effects in the embedded cases. One possible reason would be that in the emergent cases there are more high tops than in the embedded cases, thus leading to excessive nucleation and therefore to overseeding. As a test of this idea, all the cases with a positive thermodynamic area exceeding 200 mb in depth were examined and a table (Table 3) similar to Table 2 constructed. In the Wolf Creek Pass group the same adverse effect appears in the emergent case and again, the embedded cases do not show this effect. Therefore, a purely microphysical explanation is ruled out.

There is an argument for relative seeding losses in the emergent case due to dynamic effects. In presenting this argument we first refer to Weinstein's (1972) analysis of numerous soundings by means of a one-dimensional convection model, in which he showed that the effect of a dynamically produced (by seeding) rise in convection top could be associated with precipitation loss, as well as a gain. In the former case, the loss resulted from the reduction in time for growth of the particles due to the stronger updraft, even though the top was raised and total condensation increased. His analysis showed that the model did predict this outcome on a substantial fraction of the soundings he analyzed. A logical extension of this thesis is that the adverse effect on precipitation would be more pronounced in emergent convection due to the entrainment of relatively dry air at higher levels. Also, a factor not considered by Weinstein is the possibility of some evaporation of ice particles ejected from convection tops in their passage through dry air to the lower orographic cloud deck.

In the embedded case, although seeding growth time would be reduced due to dynamic effects, precipitation could be increased simply because of the added growth of the ice particles as they fell through a greater depth of cloud.

On the basis of this argument, an adverse dynamic seeding effect in the CRBPP in connection with the seeding of convection having a potential for emergence is quite likely. It might be argued that seeding with ground based generators would not provide an adequate concentration of nuclei to produce such a dynamic effect. However, this argument fails to consider that the nuclei concentrations were adequate to glaciate the available liquid water, which was small in comparison to that found in summer convection, but which is just as large in proportion to the size of the convection systems involved.

This conceptual model for adverse dynamic effects of seeding cannot safely be extended to very large convective systems, or to banded mesoscale systems, both of which generate their own embedding cloud mass. Nor can it be extended to convection under a limiting stable layer where tops cannot rise into the drier upper region. Since it appears

Table 3 **Group precipitation (mm/3 hr) statistics for embedded and emergent convection for cases with positive area deeper than 200 mb.**

State of Instability	Item	Wm. Upwind Flank	Wolf Creek Pass	Downwind Flank	No. of cases
	S precip	2.29	2.86	2.13	11
Embedded	NS precip	1.72	3.13	1.80	11
	Ratio	1.33	.91	1.18	
				Total	22
	S precip	2.01	1.33	1.73	14
Emergent	NS precip	1.99	2.98	1.73	20
	Ratio	1.01	.45	1.00	
				Total	34

* Probability = .003 for two tail Mann-Whitney U test.

at the crest only, the effect is keyed to a time period of about 100 minutes from the average nucleant source in an average wind flow.

The relatively low frequency of occurrence of conditions favoring such an adverse seeding effect under convective conditions in the winter orographic setting can cause this effect to be easily lost in analyzing a sample that includes all convective cases. In the much larger fraction of cases (embedded) that appear to have a positive reponse to seeding, the response quite likely is also dynamic in character. Therefore, future seeding experiments should be designed to detect dynamic responses to seeding, including enhancement of vertical circulation as well as direct effects on precipitation, even though the intent of the seeding is to produce only a microphysical effect.

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SEEDING EFFECTS ON CONVECTIVE CLOUDS IN THE COLORADO RIVER BASIN PILOT PROJECT

R. D. Elliott
North American Weather Consultants
1141 East 3900 South, Suite A-230
Salt Lake City, Utah 84124

Abstract. This paper addresses the matter of probable seeding effects during unstable air mass conditions in the target area of the Colorado River Basin Pilot Project (1970-1975). Various reports and articles have covered the neutral/stable condition which were the intended subject for testing, but not the unstable cases which had been inadvertently seeded as well. It is shown that when the upwind sounding gave indications that convection would be shallow enough to be embedded within the orographic cloud over the barrier, seeding effects appeared to be positive. However, for those cases in which there were indications that convection would be deep enough to emerge above the orographic cloud, there were indications of a negative effect. Reference is made to convection models in an attempt to explain how such a result is possible through the action of dynamic effects, which can diminish as well as enhance net precipitation.

The final analysis of the Colorado River Basin Pilot Project (CRBPP) (Elliott et al., 1976) and summary article (Elliott et al., 1978) indicated by means of post-hoc stratifications using three and six hourly time blocks that the original Climax (Grant and Mielke, 1967) hypotheses concerning seedability of orographic clouds as related to cloud top temperature appeared to be valid during stable and neutral orographic flow over the San Juan Mountains of this experimental area. A recent reanalysis (Shaffer, 1983) shows a strengthening of the support for such a seedability window when the height of the -5C level relative to the crest height is employed to eliminate cases in which ground generator plumes are unlikely to reach an effective nucleation level.

The original analysis eliminated seeded cases in which the anemometer network had indicated flow around rather than over the barrier, as well as non-seeded cases susceptible to contamination from pooling of nucleant during a prior seeded day. The additional removal of cases where the ground generator plumes would be unlikely to attain the -5°C level, even though flow up and over the barrier was assured, has eliminated additional noise from the seeding signal.

The CRBPP was a Bureau of Reclamation five year randomized orographic seeding test where experimental units were selected by a forecaster in Durango Colorado, and were seeded or not according to random selection. The target area included the higher elevations of the San Juan mountains (see Figure 1), and the seeding was carried out by a network of ground based silver iodide smoke generators; one condition for seeding was that there be no deep convection present. Unfortunately, some convective periods did occur within many of the experimental 24 hour blocks. Such periods of convective activity were sorted out in a post-hoc analysis that broke the 24 hour experimental units down into 3 hour blocks. The convective 3 hour blocks showed variable effects with respect to seeding. Under certain circumstances, a negative seeding response seemed to have occurred. This was revealed when seed-no seed precipitation ratios were arranged with respect to the time of the 700 mb trough passage ("tropas"). Table 1 displays ratios for three different precipitation groups extending from the southwestern slope up over the crest to the north-eastern (downwind) slope. Rather low seed/no seed precipitation ratios appear near the 700 mb tropas and for six hours thereafter. Elsewhere ratios are greater than unity more often than not. This is the same region, relative to tropas, where convection tends to be deepest, and where the orographic cloud over the barrier is thinning out most rapidly. This suggests that the negative seeding window occurs where the tops of convection over the barrier rise above the top of the main orographic cloud top.

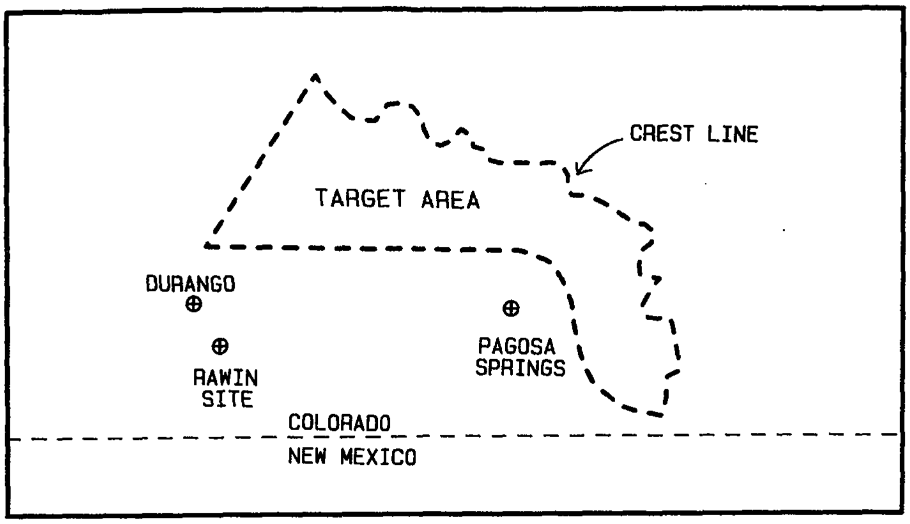

Fig. 1 COLORADO RIVER BASIN PILOT PROJECT AREA

Table 1 **Ratios of seeded to not seeded precipitation in three-hour blocks for unstable cases.**

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Wolf Creek Pass	1.15	.81	.62	.78	.85	2.26	1.37
Downwind flank	.73	.76	.65	.65	1.38	1.79	1.60

To test this hypothesis, the entire sample, without reference to position with respect to tropas, was divided into two groups. In one the top of the positive area shown on the upwind sounding (found associated with convection tops over the barrier) was higher than the cloud top calculated to exist over the barrier by lifting the top of the main deck, using the Durango upwind sounding. This will be referred to as the "emergent" case. In the second the reverse was true. This will be referred to as the "embedded case". However, it is not the same as the "embedded band" precipitation echo type employed in the Sierra Cooperative Pilot Project. The cases employed were subject to the various exclusions used by Shaffer, but in addition the base of convection, as determined from the sounding, had to lie below the crest level so as to insure entrainment of the ground generator plumes into convection.

Results of this division (Table 2) show that the Wolf Creek group of precipitation stations experienced a low ratio of seeded to not seeded precipitation in the emergent case. The rankings of the precipitation values for the seeded and not-seeded samples were compared using the Mann-Whitney U test. This indicated that the probability of a null effect was .008 for Wolf Creek pass. The other groups do not appear to be adversely affected. In the embedded case all groups show a positive ratio, with a probability of .073 in the downwind flank group. It should be mentioned that the crest group used in Shaffer's article included stations covering a larger area than used in this analysis.

2. DISCUSSION

In the embedded case, constituting 72% of the unstable sample, positive effects of seeding seem to be indicated. In the emergent case the crest zone shows an adverse effect with a seed/no seed precipitation ratio of 0.55. The region of adverse effect appears at about the same place in the synoptic sequence that has been chosen by Cooper and Marwitz (1980) in their analysis of aerial observations over the San Juan Mountains as a region favorable

Table 2 **Group precipitation (mm/3 hr) statistics for embedded and emergent convection.**

State of Instability	Item	Precipitation Group: Wm. Upwind Flank	Wolf Creek Pass	Downwind Flank	No. of cases
	S precip	1.36	2.47	1.43	63
Embedded	NS precip	.95	2.05	.98	53
	Ratio	1.43	1.20	1.46*	
				Total	116
	S precip	1.70	1.53	1.60	22
Emergent	NS precip	1.71	2.80	1.54	24
	Ratio	.99	.55**	1.04	
				Total	46

* Probability = .073 for two tail Mann-Witney U test.
** Probability = .008 for two tail Mann-Witney U test.

for seeding from ground generators. The generalized criteria developed by Vardiman and Moore (1978) suggest that with a greater depth of convective instability, such as would occur in this region, the odds for a favorable response to seeding diminishes. This supports the author's analysis.

From the viewpoint of a purely microphysical effect of seeding, it is difficult to identify a reason why seeding effects in the mergent cases would be radically different from seeding effects in the embedded cases. One possible reason would be that in the emergent cases there are more high tops than in the embedded cases, thus leading to excessive nucleation and therefore to overseeding. As a test of this idea, all the cases with a positive thermodynamic area exceeding 200 mb in depth were examined and a table (Table 3) similar to Table 2 constructed. In the Wolf Creek Pass group the same adverse effect appears in the emergent case and again, the embedded cases do not show this effect. Therefore, a purely microphysical explanation is ruled out.

There is an argument for relative seeding losses in the emergent case due to dynamic effects. In presenting this argument we first refer to Weinstein's (1972) analysis of numerous soundings by means of a one-dimensional convection model, in which he showed that the effect of a dynamically produced (by seeding) rise in convection top could be associated with precipitation loss, as well as a gain. In the former case, the loss resulted from the reduction in time for growth of the particles due to the stronger updraft, even though the top was raised and total condensation increased. His analysis showed that the model did predict this outcome on a substantial fraction of the soundings he analyzed. A logical extension of this thesis is that the adverse effect on precipitation would be more pronounced in emergent convection due to the entrainment of relatively dry air at higher levels. Also, a factor not considered by Weinstein is the possibility of some evaporation of ice particles ejected from convection tops in their passage through dry air to the lower orographic cloud deck.

In the embedded case, although seeding growth time would be reduced due to dynamic effects, precipitation could be increased simply because of the added growth of the ice particles as they fell through a greater depth of cloud.

On the basis of this argument, an adverse dynamic seeding effect in the CRBPP in connection with the seeding of convection having a potential for emergence is quite likely. It might be argued that seeding with ground based generators would not provide an adequate concentration of nuclei to produce such a dynamic effect. However, this argument fails to consider that the nuclei concentrations were adequate to glaciate the available liquid water, which was small in comparison to that found in summer convection, but which is just as large in proportion to the size of the convection systems involved.

This conceptual model for adverse dynamic effects of seeding cannot safely be extended to very large convective systems, or to banded mesoscale systems, both of which generate their own embedding cloud mass. Nor can it be extended to convection under a limiting stable layer where tops cannot rise into the drier upper region. Since it appears

Table 3 **Group precipitation (mm/3 hr) statistics for embedded and emergent convection for cases with positive area deeper than 200 mb.**

State of Instability	Item	Wm. Upwind Flank	Wolf Creek Pass	Downwind Flank	No. of cases
	S precip	2.29	2.86	2.13	11
Embedded	NS precip	1.72	3.13	1.80	11
	Ratio	1.33	.91	1.18	
				Total	22
	S precip	2.01	1.33	1.73	14
Emergent	NS precip	1.99	2.98	1.73	20
	Ratio	1.01	.45	1.00	
				Total	34

* Probability = .003 for two tail Mann-Whitney U test.

at the crest only, the effect is keyed to a time period of about 100 minutes from the average nucleant source in an average wind flow.

The relatively low frequency of occurrence of conditions favoring such an adverse seeding effect under convective conditions in the winter orographic setting can cause this effect to be easily lost in analyzing a sample that includes all convective cases. In the much larger fraction of cases (embedded) that appear to have a positive reponse to seeding, the response quite likely is also dynamic in character. Therefore, future seeding experiments should be designed to detect dynamic responses to seeding, including enhancement of vertical circulation as well as direct effects on precipitation, even though the intent of the seeding is to produce only a microphysical effect.

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"REVIEWED"

SELECTED ANALYSES OF A UTAH/NOAA COOPERATIVE RESEARCH PROGRAM CONDUCTED IN UTAH DURING THE 1982-83 WINTER SEASON

Don A. Griffith
North American Weather Consultants

1. INTRODUCTION

A major weather modification research program was conducted in south central Utah during the 1982-83 winter season. This research was conducted in a "piggyback" fashion upon an on-going operational program being conducted in Utah. The goal of the operational weather modification program in Utah is to increase higher elevation snowpack in much of central and southern Utah to provide augmented streamflow to a variety of irrigation water users.

The piggyback research program was funded by the National Oceanic and Atmospheric Administration (NOAA) as part of an ongoing program designed to evaluate certain state and/or locally supported operational weather modification programs. Such a cooperative research program was first suggested by a special committee appointed by the Department of Commerce in 1976 to address national weather modification policy issues (Cleveland, **et al.**, 1978). The on-going operational program in Utah was selected as one program on which piggyback research would be supported by NOAA. An earlier year of research was funded by NOAA and conducted in the Tushar Mountains region of south central Utah during the 1980-81 winter season.

NOAA awarded a contract to Colorado State University (CSU) in 1979 to develop a design for the piggyback research to be conducted in Utah and North Dakota (Grant, **et al.**, 1982). The research conducted in the 1980-81 and the 1982-83 winter seasons was based upon the recommendations of this earlier CSU design work. This work was conducted in the Tushar Mountains area near Beaver, Utah. A summary of the research field activities has been prepared by NAWC (Swart and Griffith, 1983). NAWC also was awarded some contracts to perform subsequent analysis of some of the data collected in the 1982-83 field program. Other contracts were awarded to other groups to perform different types of analysis. All contracts, both for field activities and subsequent data analysis activities, have been administered by the State of Utah, Division of Water Resources operating under a cooperative agreement with the NOAA-ERL offices in Boulder, Colorado. This paper summarizes the analysis activities of NAWC as related to the 1982-83 field data collected in the Tushar Mountains region. A more in depth technical report has been prepared describing the various analyses (Griffith **et al.**, 1983).

2. DATA ACQUISITION NETWORK AND RESEARCH AREA

The area of intensive research is shown in Figure 1. Table 1 lists all field equipment, suppliers, and operators. The designated primary area (A1) is approximately 40 miles E-W by 30 miles N-S, extending north to south from the northern end of the Mineral range to 10 miles south of Beaver. West to east it encompasses the area from 10 miles west of the Mineral range to 10 miles beyond the crest of the Tushar Mountains. An additional area (A2), 10 miles further east, was used for sampling snow for chemical determination of transport of seeding aerosols and their possible involvement in the precipitation process.

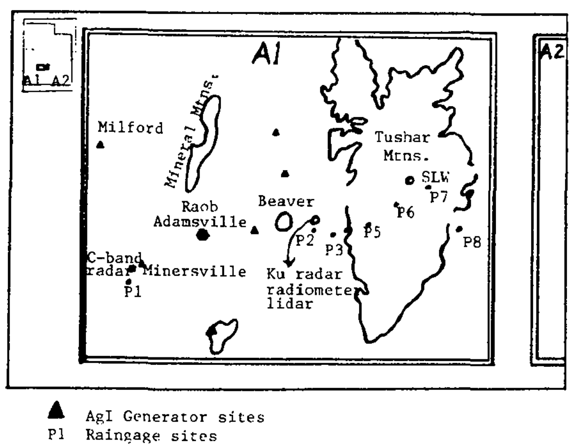

Fig. 1 NOAA/Utah research equipment locations, 1983.

Table 1 Major Project Equipment.

Type	Supplier/Operator
Ku-band radar	CSU
Dual frequency microwave radiometer	NOAA-WPL/NAWC
C-band radar	WMI
Rawinsonde	UDWR/UDWR
Polarized lidar	Univ. of Utah/U of U
Precipitation gages	UDWR/NAWC
Supercooled liquid water (SLW) detector	AI/NAWC
Cloud physics aircraft	CIC/CIC
AgI generators	NAWC/NAWC
Aerosol generators (indium)	NAWC/NAWC

3. RESEARCH GOALS AND FIELD OPERATIONS

The research program was conducted during the two month period of January 15 - March 15, 1983. The primary goals of the research were to examine: 1) the spatial and temporal distribution of supercooled liquid water and 2) the delivery of seeding material.

There were 20 storm periods that were observed during the two month intensive field period. A storm consisted of any occurrences of middle or lower cloud cover over the Tushars. Some of these storm periods produced little or no precipitation in the research area. Storm periods ranged from 6 to 80 hours in length with an average of 23.8 hours. Data collection during these storm periods was highly successful for most of the instrumentation listed in Table 1. Consequently, a significant data set was acquired upon which a variety of analyses could be performed.

4. NAWC ANALYSES OF THE 1983 DATA

NAWC performed a variety of analyses utilizing data collected by a subset of the total instrumentation available from the research period. The data sets NAWC utilized were acquired from the following: 1) recording precipitation gages, 2) the C band radar, 3) the K band radar, 4) the Adamsville rawinsonde, 5) the dual frequency microwave radiometer, 6) the icing rate meter, and 7) geostationary satellite and other synoptic weather data. Results from these analyses should be tempered by the realization that they are based upon two months of data. Additional data from other years would refine the climatological information described in the following sections. One of NAWC's primary analysis tasks was to classify the Minersville 5 cm weather radar echo patterns into specific types. These types were patterned after an earlier classification scheme developed by NAWC under contract to the Bureau of Reclamation for the Sierra Cooperative Pilot Project (Sutherland and Kidd, 1978). This classification scheme was further refined by Electronic Techniques Inc. on subsequent SCPP contractual work (Huggins, 1981). This scheme came to be identified by the acronym PETS which stands for Precipitation Echo Types. This designation is also utilized in this paper to represent different radar echo patterns.

The half-hourly Plan Position Indicator (PPI) slides and the 16 mm movie films from the 5 cm radar site near Minersville along with the radar operator logs which contained preliminary PET listings at 1/2 hour intervals were used to establish a PET catalog. PET's initially included area echoes, bands, cells, orographic, and none (no echo). The PET catalog was developed for both the Tushar experimental area (roughly the area east of Beaver) and the remaining region of the scope. The radar was operated on the 50 nm range and at a 4^{o} elevation angle (to overshoot ground clutter) during the research period.

After the catalog had been completed, the cell and no echo PET's were subdivided. The two cell categories were embedded and emergent, the difference being whether or not the observed echo tops exceeded the Adamsville rawinsonde-estimated cloud tops. No echo PET's were separated into sub-classes dependent on the occurrence of precipitation at any of the five precipitation gages between Beaver and Mt. Holly (gages P2 to P6 on Fig. 1).

Table 2 provides the hours of PET occurrence over the Tushar experimental area. In general terms, the NP PET (no echo but Tushar precipitation) was the most prevalent. It occurred during 18 of the 20 storms and accounted for 50% of all PET's. The next most frequent PET was cells, which occurred during 15 storms and totaled approximately 25% of all PET observations. No echo (and no precipitation) PETS and area PET's followed, each occurring in about half the storms and about 12% of the time. Bands were very infrequent, occurring during only two storms. Orographic echoes also occurred during only two storms. These results suggest that the no echo but Tushar precipitation PET is probably a shallow orographic cloud situation that was not deep enough

Table 2. Hours of PET occurrence in Tushar experimental area for each storm.

Storm #	AREA	BAND	TUSHAR CELL	ORO	NO PRECIP	PRECIP*	TOTAL
1	4 hrs.	0	9 hrs	0	7 hrs	9 hrs.	29 hrs.
2	0	0	1	0	1	1	0
3	0	0	2	0	0	0	2
4	5	0	1	0	3	0	9
5	3	1	4	0	7	1	16
6	3	0	0	0	1	1	5
7	0	0	0	0	17	0	17
8	0	0	6	0	10	0	16
9	2	0	4	0	1	0	7
10	4	0	3	0	3	1	11
11	0	3	0	1	6	0	9
12	0	0	3	0	1	0	4
13	0	0	3	0	1	0	4
14	0	0	0	0	19	0	19
15	0	0	1	0	2	1	4
16	0	0	0	0	0	2	2
17	0	0	2	1	17	5	25
18	2	0	2	0	1	0	5
19	0	0	5	0	0	1	6
20	2	0	3	0	7	3	15
TOTAL	25 hrs	4 hrs	49 hrs	2 hrs	104 hrs	25 hrs	208 hrs
%	12	<1	24	<1	50	12	

* - Radar echoes elsewhere

to be observed by the 5 cm radar operating at a 4° elevation angle.

4.1 Recording Precipitation Gage Analyses

The recording precipitation gage data were digitized in half hourly precipitation amounts for seven gages. The eighth gage installed for the project provided unreliable data during the field program. Statistics were prepared on storm amounts by gage location. An obvious orographic contribution to storm precipitation was documented over the barrier as depicted in Figure 2.

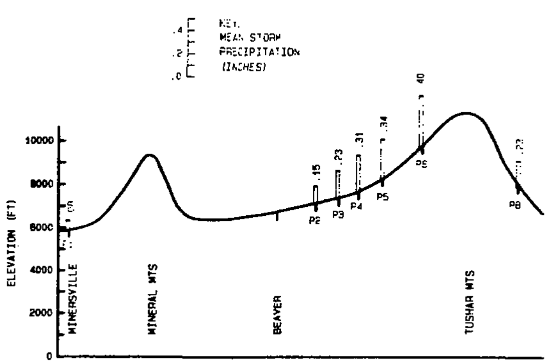

Fig. 2 Mean storm precipitation by gage location (Jan. 15-Mar. 15, 1983).

Precipitation gage data for sites P2 - P6 and P8 were accumulated by PET. The total amount of precipitation that occurred at each site (disregarding the missing data at some of the sites) was used to calculate the percentage of the total precipitation observed during the two month research period by PET. Table 3 provides the results of this summarization. From this figure it is seen that the area PET (A) produces more of the total accumulation in the foothill region of the Tushars and in the lee of the Tushars. Cell precipitation is an important contributor in higher elevations. The no echo precipitation PET (NP) contributed the highest percentage of the two month accumulation in the foothill to mid-elevations.

4.2 Supercooled Liquid Water Analyses

Several different types of supercooled liquid water analyses were performed. A series of time cross-sections utilizing parameters calculated from the Adamsville rawinsonde data were prepared. Indications of liquid water from the radiometer and the Mt. Holly ground based icing rate meter (a Rosemount probe) were related to these cross-sections. Some tentative conclusions were drawn from this analysis which are as follows:

o In stable atmospheric conditions, liquid water is usually associated with a water saturated cloud as indicated on the Adamsville raob with the base of this cloud below the mean crest height and moderate to strong upslope windflow.

Table 3. Precipitation amounts and percentage contribution by PRT for the 1983 research period.

PET	P2		P3		P4		P5		P6		P8	
	Amount	%	Amount	%	Amount	%	Amount	%	Amount	%	Amount	%
A	.47	31	.76	32	.46	21	.83	23	.73	23	.68	45
B	.01	0	.25	11	.20	9	.43	12	.39	12	.22	14
Cell	.27	18	.71	30	.59	27	1.07	29	1.25	39	.45	30
NP	.79	51	.66	28	.93	43	1.34	37	.83	26	.17	11
Total	1.54		2.38		2.18		3.67		3.20		1.52	

o In unstable conditions, with a low level water saturated layer, liquid water seems to occur regardless of wind flow up the barrier.

o Liquid water often occurs with precipitation.

o There is a correspondence between radiometer and ground based indications of liquid water approximately 75 - 80% of the time.

Multiple regressions were developed to predict Mt. Holly liquid water amounts from various Adamsville rawinsonde parameters. The highest correlated parameters were the wind component normal to the barrier at crest height (a positive correlation) and some measure of atmospheric stability (a negative correlation). These results, although the correlations were not exceptionally high, lend support to the earlier tentative conclusions listed above.

A limited direct comparison of the indication of liquid water from the radiometer versus the Mt. Holly measurements was made for two storm periods. Figure 3 provides a plot of the data for the two periods. This comparison indicates that liquid water appears to be observed at the same time by both systems indicating that the liquid water may be distributed through a relatively sizable region of the clouds passing over the Tushars.

The radiometer indicated liquid water was a common component of most storms especially over the Tushars. An examination of the occurrence of liquid water over the Tushars during observation periods from the radiometer indicated liquid water was present 69 percent of the time in area, cell and no echo but precipitation PETS. Liquid water was indicated to occur most frequently in no echo but precipitation PETS. This observation would indicate a potentially seedable event occurs frequently in the Tushars consisting of a shallow orographic cloud.

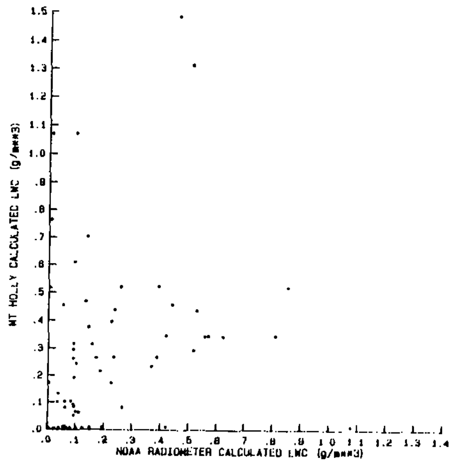

Fig. 3 Comparison of calculated NOAA radiometer vs Mt. Holly liquid water contents (gm^{-3}).

4.3 Guide Modeling

NAWC, in it's work on the Bureau of Reclamations' Sierra Cooperative Pilot Project (SCPP) in California, has developed several computer models to assist in the real-time decision making and subsequent analysis of the SCPP research program. These models have the potential of more general application to other weather modification research programs. The Utah Division of Water Resources contracted with NAWC to apply some of these models to the 1983 Utah/NOAA data analysis effort. Two different versions of GUIDE were utilized in this work. One version deals with the orographic prediction of seeding plume dispersion, interaction with the cloud microphysics, and subsequent predicted fallout locations and differences between natural and seeded precipitation. The other version deals with the prediction of the natural water balance in stable orographic clouds (called OROGWATER). Both versions of the GUIDE model have been described by Elliott **et al.** (1983).

The results of the orographic seeding modeling will be discussed first. Seeding occurred during the research period from January 15 - February 8, 1983. Seeding was terminated on February 9th due to above normal snowpacks and relatively full reservoirs. Seeding decisions during this time were made on a 2:1 seed, no seed randomized basis. Only those storms or storm periods that met NAWC's seeding criteria were randomized.

Consequently, there was not a large amount of seeding conducted during the research period. Of the seeding that was conducted, the GUIDE model indicated limited success in terms of enhanced snowfall at ground level. The primary problems were warm temperatures which restricted silver iodide nucleation and light winds which limited transport of the seeding material. An example of a GUIDE predicted plume transport and precipitation fallout case is provided in Figure 4.

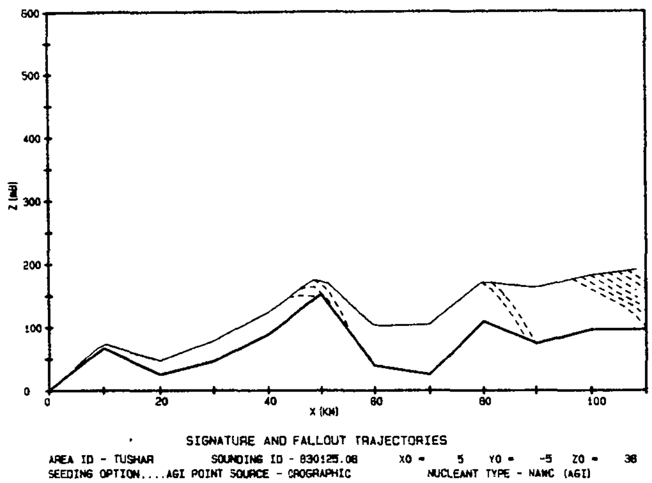

Fig. 4 GUIDE X-Z plot from generator site 17-11 for January 25, 1983, 0600 Z.

The GUIDE modeling indicated an advantage of using high elevation generator locations in certain atmospheric situations versus lower elevation locations. Using activation curves from Colorado State University for a NAWC manual generator utilizing a silver iodide-ammonium iodide-ammonium perchlorate-acetone solution, the GUIDE model indicated a significant advantage in using this solution over that currently used (silver iodide-ammonium iodide-acetone), primarily due to the higher number of active nuclei at warm temperatures (i.e., -4 to -10°C).

The GUIDE orogwater predictions of liquid water indicated an accumulation zone upwind of the Tushars at fairly low elevations for five priority simulation cases. This model calculates the water balance between liquid water and precipitation rates. The predictions of these parameters were compared to liquid water observations from the radiometer and icing rate meter and ground level precipitation. This comparison is depicted in Figure 5. From this figure it is seen that the trends were predicted well but that the relative magnitudes of liquid water and/or precipitation were generally underpredicted.

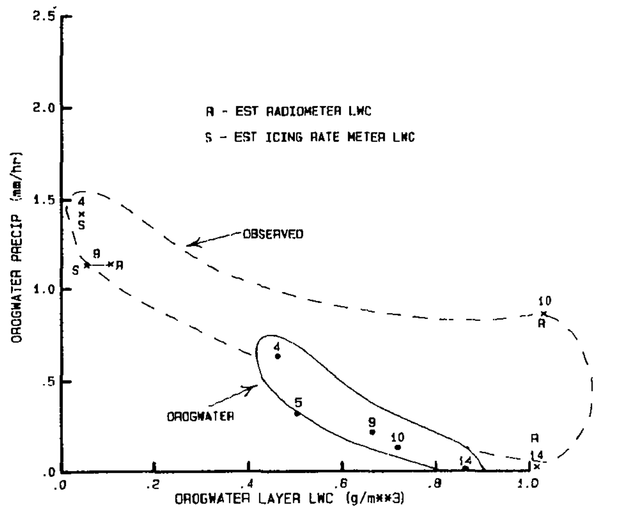

Fig. 5 Comparison of physical measurements of precipitation rate and liquid water vs OROGWATER prediction. (Numbers refer to storm number.)

4.4 Climatological Representativeness of the 1983 Research Period

A study was conducted of the climatological representativeness of the data collected for the 1983 intensive field period. This study was conducted because of a perception that the field period was dominated by upper-level split flow which resulted in fast moving, relatively weak and relatively warm storms. The main indications from this study, which was based upon precipitation and rawinsonde observations for the research period were:

- o wetter than normal.
- o warmer minimum temperatures than normal.
- o there were more storms of short duration and fewer storms of longer duration (> 8 hours) than normal.

- higher than normal heights of constant pressure surfaces on the Ely and Las Vegas rawinsondes when clouds present.
- winds more southerly than normal at Ely and Las Vegas.
- higher than normal freezing levels at Las Vegas.

5. CONCLUSIONS

Various analyses of data collected for a two month period in south central Utah have provided a better understanding of the structure and potential seedability of winter storms. Most of the storm periods observed during the period exhibited at least some periods when supercooled liquid water was present. A storm classification scheme indicated the relative importance of a shallow orographic cloud. This particular type contributed a substantial portion of the research period precipitation and also contained significant periods of supercooled liquid water occurrence. A model of the effectiveness of seeding indicated limited success during a portion of the research period. Limitations to effectiveness included relatively warm airmass temperature, light winds, and low level inversions. High elevation generators were generally indicated to be more effective than low elevation generators. A comparison of the two month research period with longer term records indicated several departures from what could be referred to as "normal" conditions. Collection and analysis of similar data from future seasons would increase the representativeness and therefore usefulness of the climatological analyses presented in this paper.

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USING HISTORICAL DATA TO EVALUATE TWO LARGE-AREA OPERATIONAL SEEDING PROJECTS

Chin-Fei Hsu, and Stanley. A. Changnon, Jr.
Illinois State Water Survey
Champaign IL 61821

Abstract. Two large-area operational seeding projects conducted in the Great Plains were evaluated statistically to determine if any seeding effects could be detected. Historical data were used in the evaluation, and statistiscal tests using permutational procedures were applied to the data in obtaining the significances of estimated seeding effects. The findings indicate a singificanct reduction of hail loss/cost values in the Muddy Road project, and nonsignificant rainfall changes in the Muddy Road project and the other project in northwestern Oklahoma.

1. INTRODUCTION

Large-area seeding projects have become common during the past few years (Hsu, 1981) and will continue to be so in the future as a viable means for managing water resources and reducing hail losses. However, evaluation of operational projects extending over 10,000 sq km or more produces complex spatial and temporal control problems relating to climatic homogeneity and temporal variability.

In the present paper, two large-area operational seeding projects conducted in the Great Plains were evaluated statistically to determine if any seeding effects could be detected using rainfall data from the National Weather Service's Cooperative Raingage Network and the hail insurance data furnished by the Crop Hail Insurance Actuarial Association. These projects included an aircraft-seeding program in southwestern Kansas called Muddy Road (hereafter called MR), and an operation using ground-based generators for seeding in northwestern Oklahoma (hereafter called OK). These 2 projects were evaluated as a part of an NSF-sponsored research - project called Operational Seeding Evaluation Techniques (OSET) for testing statistical techniques developed in the project.

2. USE OF HISTORICAL DATA

In evaluating the seeding effect of a weather modification operation, the response deemed as caused by the seeding must be compared with other responses not affected by the seeding. For a randomized experiment, these other "responses" are usually those of the "unseeded" units in the target area during the operational period set aside randomly in the project design. However, in a non-randomized operation it is statistically undesirable to make such a similar comparison for two reasons: 1) there might exist natural rainfall excess in favor of the seeded units over unseeded units in the target area (Gabriel, 1979; Hsu el al, 1984); and 2) there might exist a natural rainfall excess in favor of the selected seeded units in the target than those in the neighboring control areas (Hsu el al., 1981b). An approach which accounts for these two "selection biases" has to be used to properly address the evaluation of non-randomized operations (WMAB, 1978; Hsu and Changnon, 1983).

The approach presented in this paper for evaluating non-randomized seeding operations uses a relatively long sampling unit as well as historical climatic data. A sampling unit as long as a month or a season lumps together the responses of both seed and unseed occasions. Use of such long units eliminates the first kind of bias and still allows for the detection of seeding effect, although their use might render the statistical test conservative (i.e., less powerful in detecting a seeding effect). Use of historical climatic data provides a partial answer to the second kind of bias by adjusting target values with control values. It is this issue of adjusting target values using historical data that our research has been focused on.

The use of a long sampling unit and historical climatic data therefore provides a solution for reducing potential biases in evaluating non-randomized projects. A critical question concerning such an approach is the temporal stationarity, i.e., whether the historical (unseed) target-control relationship holds in the seed periods had no seeding been done (Brownlee, 1967). Recent simulation studies (Hsu et al., 1981; Gabriel and Petrondas, 1983) have shown that in the worst possible scenario the significance values of the statistical tests using regression were twice as much as what would be expected. Thus, use of historical comparison would be appropriate if the critical value of the test is selected to correspond to half of the nominal significance level.

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3. MUDDY ROAD AIRCRAFT SEEDING PROJECT

The Muddy Road project was conducted in southwestern Kansas and encompassed a target area varying between 12 to 15 counties over the years studied (Fig. 1). The project was intended for both rainfall enhancement and hail suppression in the warm season of April to September. It began in 1975 and continues to the present. A description of the project and a summary of the seeding operations can be found in a report by Kostecki (1978). The 1975-1979 operations were selected for evaluation in the present study.

Two sets of data were employed in the evaluation: (1) monthly and seasonal rainfalls, with data from 1931-1971 used as historical controls, and (2) annual hail insurance loss-cost ratios (L/C), defined as 100 x hail damage / insurance liability, with data from 1948-1971 used as historical controls. The (historical) years of 1972-1974 were not included in the study mainly to avoid the possibility of contamination due to other cloud seeding activities carried out to the south of the MR target areas during this period.

To discern possible geographical differences in seeding effects, the target was divided into a west (W) and an east (E) sub-targets. Controls having sizes similar to the 2 sub-targets were selected from the neighboring counties and grouped into near-upwind (N-U), mid-upwind (M-U), far-upwind (F-U), and downwind (D) controls (Fig. 1). The N-U control consisted of areas 1, 2, 3, 4, 5, 6, and 7; the M-U control consisted of areas 8, 9, 10, 11, and 12; the F-U control consisted of areas 13, 14, 15, and 16; and the D control consists of areas 17, 18 and 19.

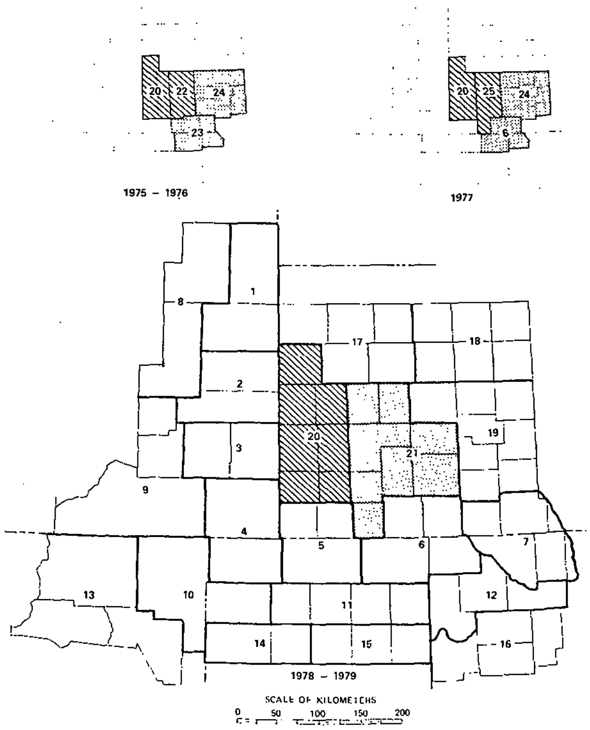

Figure 1. Muddy Road Project Area.

3.1 Evaluation of the Hail Suppression

Ratios of seeded average L/C (1975-1979) to historical average L/C (1948-1971) show that the ratios in the target were all less than 1.0 except two small areas in the northwestern and southeastern corners, where they were between 1.0 and 2.0 (Fig. 2). Portions of the south and west controls also had ratios less than 0.5. A large portion of the target ratios were less than 0.5, part of which was significant at the .10 level using a 2-sample Wilcoxon test. Some control ratios were also significant at the 0.10 level.

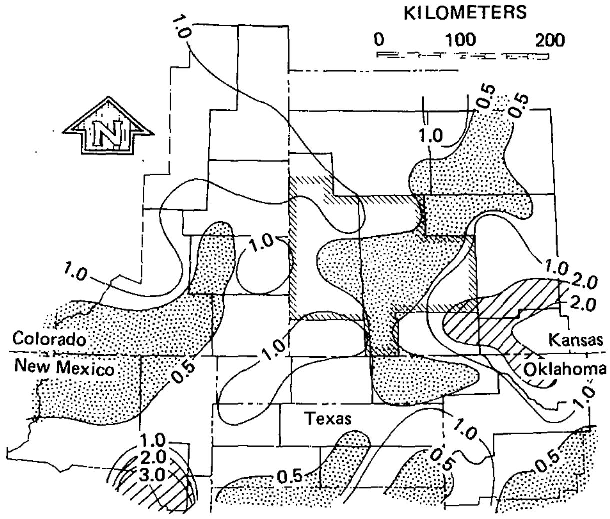

Figure 2. Ratio of Hail LOST-COST, 1975-1979 Average to 1948-1971 Average, MR.

Fig. 3 shows a plot of ratios of the west sub-target L/C to the N-U L/C. No noticeable trend existed. Most ratios were larger than 1.0. The ratio in 1954 was considerably more than the others, and thus might render the mean 1948-1971 ratio (shown in the plot as the dashed line) unrealistically high. However, four out of five seed years experienced ratios well below the historical mean and were very close to the minimum. Thus, the reduction appeared to be real. Similar

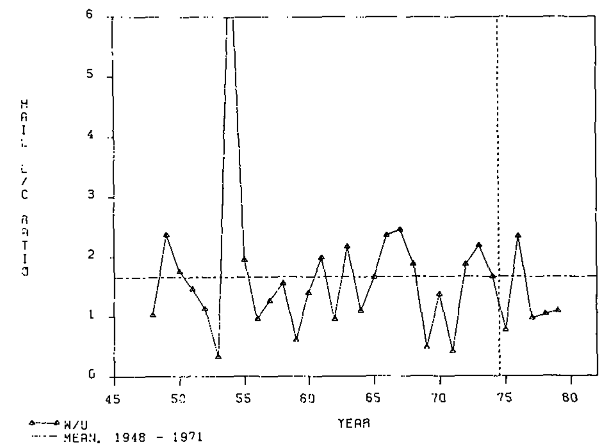

Figure 3. Ratio of Hail LOST-COST, West Target to Upwind Control Average, MR.

plot for the east sub-target (E/U) is shown in Fig. 4. No trend was indicated. The 1954 ratio was also high. Four out of 5 ratios were below historical mean, though only 3 appeared to be real.

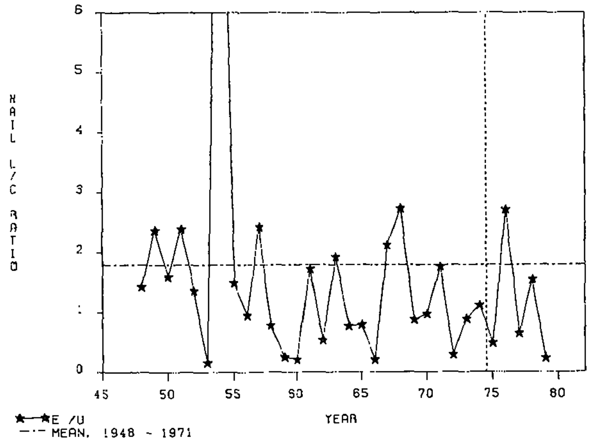

Figure 4. Ratio of Hail LOST-COST, East Target to Upwind Control Average, MR.

The correlation coefficients between the sub-targets and controls varied from 0.0 to 0.7 according to the distances (Hsu and Chen, 1981). The techniques of multiple regression (MREG) and principal component regression (PCR[3]), as described in Hsu et al (1981), were applied to the L/C data. The mean differences between the estimated and observed seeded values, and their permutational significances (Gabriel and Hsu, 1983) are shown in Table 1 for the east and west sub-targets compared with N-U controls, N-U and M-U controls, and All controls.

Table 1. Mean Difference and 1-Sided Permutational Significance Level, Muddy Road Project, Hail Loss-Cost

Target	Control	MREG		PCR	
West	N-U	-1.09	(.33)	-1.70	(.23)
	N-U & M-U	-1.94	(.30)	-1.76	(.26)
	All	-1.16	(.41)	-0.75	(.39)
East	N-U	-3.79	(.14)	-4.39	(.06)
	N-U & M-U	-6.09	(.09)	-3.98	(.09)
	All	-4.97	(.16)	-2.62	(.16)

All the estimated mean differences were negative. The decrease in the east sub-target was more significant than the west sub-target in all comparisons, and we have no explanation for this. When the D controls were excluded in the evaluation, the estimated decreases were more pronounced and were more significant, an indicattion that there might have existed a downwind seeding effect. Generally, the results by PCR[3] were more significant than MREG, as expected in the previous simulation studies (Hsu et al, 1984); though MREG showed larger decrease of L/C values in the cases of N-U and M-U controls and All controls.

3.2 Evaluation of the Rainfall Enhancement

Seasonal rainfall was computed as the mean of May-August monthly rains. Ratios of average seed seasonal rains (1975-1979) to average historical seasonal rains (1931-1971) show that most of the ratios in the target area were above 1.0 (Fig.5). The ratios in the eastern part of the target were higher than those in the western part. Outside of the target area, most rain ratios were not much different from 1.0 except one area in northern Oklahoma and one area in eastern Colorado where the ratios were larger than the target's.

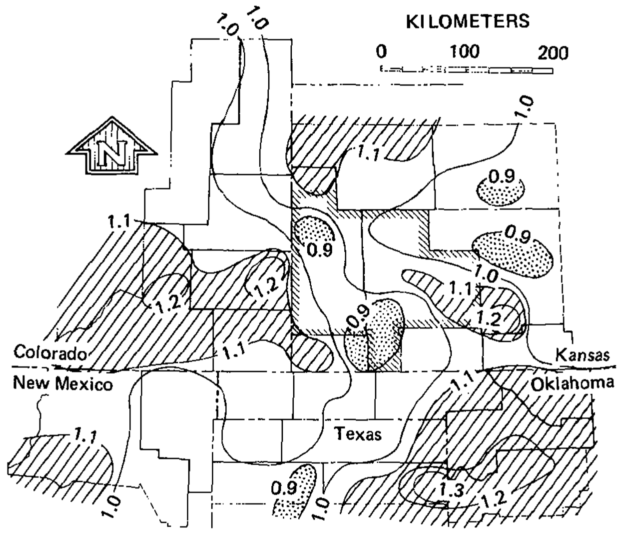

Figure 5. Ratio of Seasonal Rain, 1975-1979 Average to 1931-1971 Average, MR.

Fig. 6 shows a plot of ratios of W vs N-U seasonal rains. No noticeable trend existed. Most ratios were close to 1.0. The 1931-1971 mean (shown in the plot as the dashed line) was very close to 1.0. Three out of 5 seed years had ratios slightly above the historical mean; while one ratio (1979) was very close to the minimum. A similar plot for the east sub-target is shown in Fig. 7. No trend was indicated. The variability in this plot was noticeably larger than that in

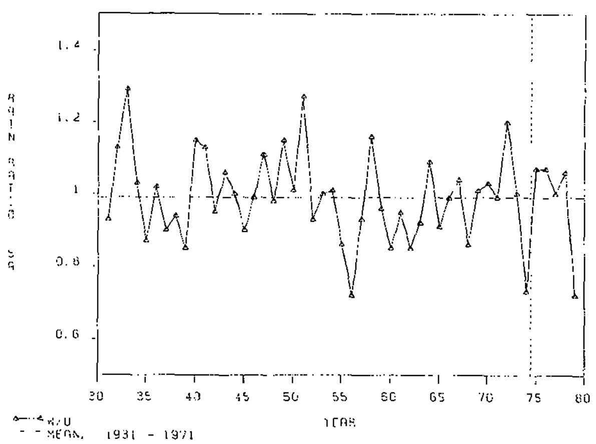

Figure 6. Ratio of Seasonal Rain, West Target to Upwind Control Average, MR.

Fig. 6. Two years (1949 and 1971) had high ratios, and thus rendered the historical mean larger than 1.0. Only 2 (1975 and 1977) out of 5 ratios in seeded years were above the historical mean, and one (1976) was very close to the minimum.

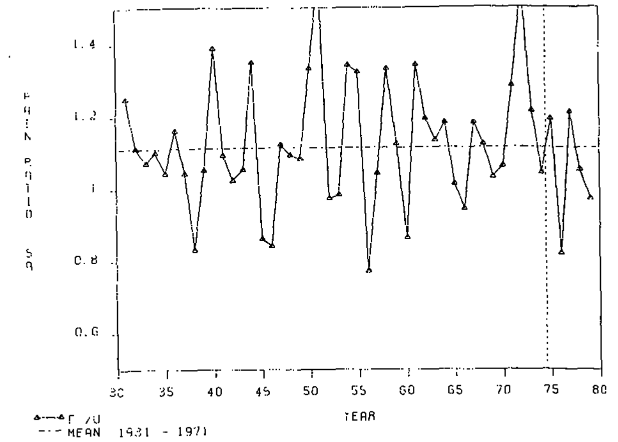

Figure 7. Ratio of Seasonal Rain, East Target to Upwind Control Average, MR.

The correlation coefficients between the the sub-targets and the controls seasonal rainfalls were in the range of 0.5 to 0.9 (Hsu and Chen, 1981), higher than those of the annual L/C values. The techniques of MREG and PCR[3] were applied to the seasonal and monthly rains for evaluation. The mean differences between the estimated and observed seasonal seeded rainfalls, and their permutational significances are shown in Table 2. All the estimated mean differences were negative and not statistically significant. The decrease of seasonal rainfall in the W vs N-U & M-U comparison, -0.25 cm, amounted to 4% of the 1931-1971 mean (6.45 cm); while that in the E vs N-U & M-U comparison, -0.20 cm, amounted to 3% of the historical mean (6.45 cm). Obviously, nothing was significant.

Table 2. Mean Difference and 1-Sided Permutational Significance Level, Muddy Road Project, May-August Average Rainfall (in cm).

Target	Control	MREG		PCR[3]	
West	N-U	-.36	(.79)	-.28	(.76)
	N-U & M-U	-.25	(.68)	-.36	(.79)
	All	-.71	(.88)	-.31	(.73)
East	N-U	-.46	(.76)	-.53	(.85)
	N-U & M-U	-.20	(.61)	-.61	(.84)
	All	-.23	(.82)	-.61	(.88)

Results of the target-control comparisons for the monthly rainfall show that most estimated rain changes were statistically non-significant except for 3 cases: April in the east sub-target (rain increase), April in the west sub-target (rain decrease), and May in the east sub-target (rain decrease). In general, the technique of PCR indicated more increases or fewer decreases than the MREG. Overall, the results in the east sub-target were more favorable than the west sub-target in April, June, July and August.

Table 3. Mean Differences and One-Sided Permutational Significance Level, Muddy Road Project, Monthly Rainfall (in cm).

	West Sub-Target vs			East Sub-Target vs		
Month	N-U	N-U&M-U	All*	N-U	N-U&M-U	All
Principal Component Regression						
April	-.86	-.28	-.08	1.60	2.11	2.13
	(.87)	(.59)	(.47)	(.00)	(.00)	(.00)
May	.05	.58	.58	-1.91	-1.27	-1.22
	(.50)	(.25)	(.25)	(.97)	(.86)	(.82)
June	.23	.25	.15	.33	.36	.03
	(.40)	(.42)	(.47)	(.35)	(.34)	(.49)
July	-1.22	-.91	-.84	-.58	-.25	-.08
	(.92)	(.89)	(.87)	(.69)	(.57)	(.50)
Aug	.08	-.15	-.41	.76	.41	-.10
	(.44)	(.55)	(.67)	(.30)	(.32)	(.50)
Sept	-.48	-.46	-.38	-.68	-.53	-.33
	(.73)	(.69)	(.67)	(.74)	(.67)	(.61)
Multiple Regression						
April	-1.37	-1.65	-2.03	1.47	.69	.18
	(.95)	(.94)	(.96)	(.02)	(.16)	(.36)
May	-.08	.05	-.20	-1.93	-2.77	2.11
	(.54)	(.49)	(.58)	(.96)	(1.00)	(.97)
June	-.25	-.76	-1.02	.48	-.08	-.18
	(.60)	(.76)	(.84)	(.32)	(.55)	(.63)
July	-.71	-.18	.08	-.38	-.18	.28
	(.82)	(.61)	(.47)	(.61)	(.57)	(.41)
Aug	.18	.23	.81	.81	.33	.56
	(.39)	(.35)	(.16)	(.31)	(.32)	(.21)
Sept	-.48	-.33	-1.09	-.48	-.61	-1.19
	(.72)	(.67)	(.93)	(.70)	(.71)	(.94)

* "N-U", "M-U" denote respectively near- and mid-upwind controls, "All" denotes all controls.

4. OKLAHOMA PROJECT

The Oklahoma program encompassed a target area of 3 counties - Harper, Woodward, and Ellis (Fig. 8). It was carried out to increase the growing season (May-September) precipitation in 1972-1976. Monthly and seasonal rainfalls from 1935-1971 were used as historical controls. Rainfall data from Kansas, Oklahoma, and Texas were

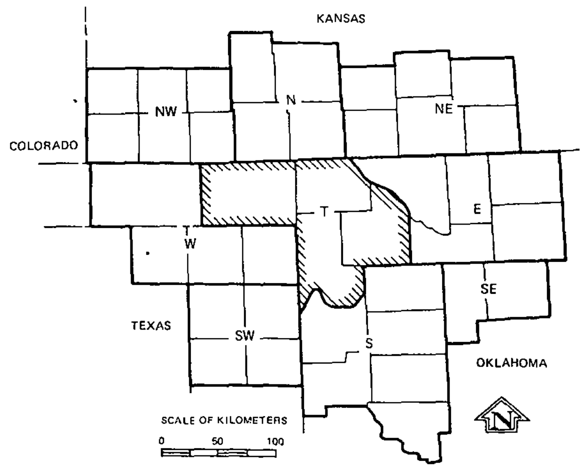

Figure 8. Oklahoma Project Area.

used to form 8 areal controls with size similar to the target's (Fig. 8). The climatic monthly rainfall normals in the area indicate that there existed relatively strong precipitation gradients in May and June, with a general east-to-west decrease; and much weaker gradients in July and August (Hsu et al., 1984).

Ratios of 1972-1976 seasonal rainfalls to historical seasonal rainfalls show that most of the study area received less rain during the seeding period than the historical period (Fig. 9). The differences among ratios were small, however. There was a general NW-SE gradient of rainfall ratios. The region of minimum ratios (<0.9) ran from southwest to northeast, and interestingly had a peak in the target area. The eastern portion of the target had higher rainfall ratios than the western portion. The highest ratios in the entire study area occurred in Kansas, north of the target area.

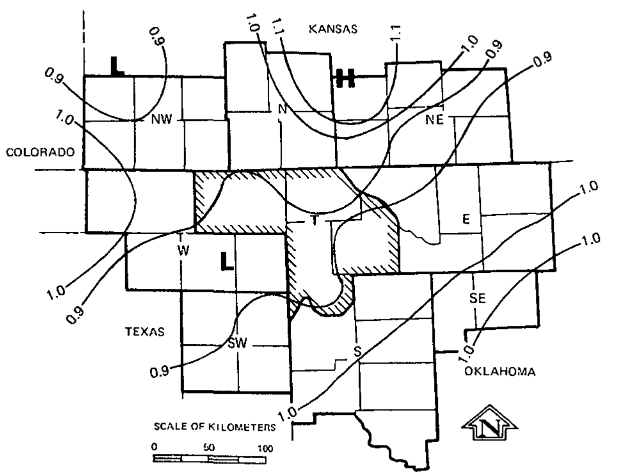

Figure 9. Ratio of Seasonal Rain, 1972-1976 Average to 1935-1971 Average, OK.

The techniques of multiple regression (MREG) and principal component regressions with 1 (PCR[1]) or 3 components (PCR[3]) were applied to the seasonal and monthly rains using the 8 areal controls (Fig. 8) and the 1935-1971 historical controls. The mean differences between the estimated and observed seeded values, and their permutational significances are shown in Table 4.

All the estimated mean differences were not statistically significant. There was a minor seasonal rainfall deficiency in the target greater than what would be expected. For the monthly rainfalls, most estimated rain differences were small and statistically non-significant. The biggest target rainfall excess, 0.66 cm, occurred in August when using All controls and PCR[1]. The largest rainfall decrease, all greater than 1 cm, occurred in June. Generally, the technique of PCR[1] indicated more increases or fewer decreases of target rainfalls than did MREG in June and August, but the opposite in May and July.

5. CONCLUSION

The evaluation of the hail suppression of the Muddy Road project indicated that there was a general reduction of annual hail loss-cost values in the target area during the 1975-1979 seeding period. When compared with the historical data and the neighboring areas, the 39% decrease of hail loss/cost values in the eastern portion of the target area was statistically significant at 6%; however, the decrease of L/C values in the western portion was not significant. The evaluation of the rainfall in the Muddy Road project using historical data and target-control comparison indicated that, overall, there was a non-significant rainfall decrease in the target area. Rain excesses occurred largely in the east subtarget in April (significant), June and August.

Table 4. Mean Difference and 1-Sided P-value, Oklahoma Ground Seeding Project, Monthly Rainfall (in cm).

Month	MREG	PCR[1]	PCR[3]
		All Controls	
May	-.10	-.18	-.30
	(.54)	(.56)	(.63)
June	-1.78	-1.30	-1.42
	(.96)	(.91)	(.92)
July	.08	-.30	-.15
	(.50)	(.68)	(.61)
August	.25	.66	.36
	(.50)	(.24)	(.38)
September	-.64	-.66	-.79
	(.78)	(.80)	(.88)
Seasonal Average	.03	-.25	-.25
	(.47)	(.71)	(.71)
		West Controls Only	
May	.20	.00	.03
	(.39)	(.48)	(.42)
June	-1.37	-1.27	-1.50
	(.87)	(.84)	(.87)
July	.53	.03	.25
	(.27)	(.51)	(.37)
August	.23	.36	.25
	(.47)	(.38)	(.46)
September	.00	.05	-.36
	(.49)	(.44)	(.62)
Seasonal Average	-.13	-.18	-.13
	(.56)	(.60)	(.54)

The evaluation of the 1972-76 ground-based project in northwestern Oklahoma indicated that there was a non-significant 5% decrease of seasonal rain in the target area. Non-significant rain excesses in the target area occurred largely in August, and major rain decreases in June.

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CLEAR-AIR SEEDING: OPPORTUNITIES AND STRATEGIES

A. Detwiler* and R. Pratt
Atmospheric Sciences Research Center
State University of New York at Albany
Albany, New York 12222

Abstract: Clear-air seeding is the artificial creation or enhancement of cloud cover in clear air which is between saturation with respect to ice and saturation with respect to liquid water. Previous work has demonstrated that clear-air seeding is possible, and may be economically worthwhile through its effects on the radiation balance near the ground. Order-of-magnitude arguments, contrail observations and direct measurements are used to assess the frequency and horizontal extent of opportunities for clear-air seeding in the upper troposphere. Clear, ice-supersaturated air is a common occurrence in the mid-latitude upper troposphere at all times of year, typically appearing over 100 km-wide regions downstream of cyclonic or convective storm systems.

The frequency of opportunities was also estimated for a particular application of clear-air seeding--cloud cover enhancement during winter nights to reduce space heating costs. Opportunities were studied for the middle and lower troposphere through a careful analysis of radiosonde humidity data, and for the upper troposphere through observations of natural cirrus. Under suitable cloud cover and wind conditions, five to ten opportunities each season are estimated for locations in the northeastern United States, a frequency sufficient for economic advantage based on a previous analysis.

Two methods are discussed for seeding clear, ice-supersaturated air to create clouds. Seeding with ice crystals is studied using a numerical simulation of ice crystal cloud growth, which includes both ice physics and radiative transfer. Ice crystal seeding is most effective when the seeding rate is greatest and the moist layer seeded is deepest. Aircraft contrails generally utilize only a small fraction of the available water vapor in excess of ice saturation, before they settle out of the moist layer in which they were created.

The development of clouds seeded with ice-nucleating aerosols, rather than ice crystals, depends greatly on the rate at which the seed material nucleates ice crystals. This type of seeding would produce a longer lasting, lower density cloud than would seeding with ice crystals.

1. INTRODUCTION

Cloudiness has a strong influence on temperatures near and at the ground, both during the day and at night. Detwiler (1983) estimated the damping effects of cloudiness on the amplitude of the diurnal temperature cycle. This property may be exploited for economic benefit. For example, Detwiler and Cho (1982) showed that the cost of producing modest increases in nighttime cloudiness may be much lower than savings in space-heating expense for cities in the northeastern United States. Johnson et al. (1969) have also suggested that the artificial increase of daytime cloudiness during the warm season could reduce electrical power consumption for air conditioning.

Clear-air seeding is one means of increasing natural cloud cover to alter temperatures near the ground. Dry ice or ice-nucleating smokes are dispersed in clear or mostly clear ice-supersaturated air to create cloudiness or enhance natural cloudiness. Other methods available for enhancing cloudiness, such as direct dispersal of large masses of cloud material or heating to stimulate convection, generally may be used under a wider range of conditions but are orders of magnitude more costly than clear-air seeding. In this paper we discuss first the frequency of occurrence and horizontal extent of clear, ice-supersaturated layers of air that provide an opportunity for clear-air seeding. Of interest are time scales of one to several hours and space scales of 100 to 10,000 km^2. Then we

*Current address: 7684 Jonathan Court, West Chester, Ohio 45069

will deal with some of the technical aspects.

Natural clouds usually form only when air is near saturation or slightly supersaturated with respect to the liquid phase, conditions which permit condensation of liquid water on natural cloud-condensation nuclei. If such condensation occurs at temperatures below about -30°C, the tiny liquid droplets formed by condensation soon freeze. Liquid-phase saturation implies a large degree of supersaturation with respect to the ice phase at such low temperatures. Once droplets are frozen they will grow rapidly by direct vapor deposition, until the vapor density of their environment is lowered to equilibrium with the ice phase.

If suitable deposition ice nuclei were common, cloud formation by direct deposition would occur at much lower humidities, for temperatures below freezing, than the humidities at which natural cloud formation is observed. But suitable deposition ice nuclei are relatively rare in the atmosphere, especially far above the earth's surface, and often widespread regions of the troposphere are supersaturated with respect to ice but nearly cloudless (Ludlam, 1980, p. 361). Evidence of these regions is often created in the upper troposphere when aircraft deposit trails of tiny frozen water droplets (contrails) that grow and spread across the sky.

Several reports describe the use of ice nucleating smokes (Vonnegut and Maynard, 1952) and dry ice (Fraser, 1949; Bigg and Meade, 1971; Jayaweera and Ohtake, 1972; Jayaweera et al., 1975) to produce clouds in clear, ice-supersaturated volumes of the troposphere. In these experiments a small region (up to several kilometers wide) was seeded once, and the evolution of the resulting cloud was followed.

Around 9 km MSL, with temperatures near -44°C, over Schenectady, New York, Vonnegut and Maynard observed immediate cloud formation in the aircraft wake, which persisted at least until it drifted out of sight nearly an hour later. The other workers seeded with dry ice generally between 1 and 8 km MSL at temperatures of -10 to -30°C. They were able to find regions, usually near naturally forming clouds, in which seeding immediately produced additional cloudiness that persisted up to several hours, covered horizontal areas up to several tens of square kilometers, and had depths up to several hundred meters.

Bigg and Meade seeded over the ocean between Tasmania and Australia, and the cloudiness generally lasted for several hours. Although they sometimes initiated explosive, convective cloud formation in clear air with dry ice, the resulting cloud was usually stratiform.

Jayaweera and Ohtake reported that with dry ice they could produce stratiform cloudiness several kilometers in horizontal extent over the Tanana River Valley near Fairbanks, Alaska. Their clouds, which were less than 1 km above ground, tended to disperse and drift away after about half an hour.

These clear-air seeding experiments have shown that additional cloudiness can indeed be created on a relatively small scale, typically near regions where clouds are forming naturally. Studies of persisting aircraft contrails (reviewed in Section 3) show that it is also possible to enhance cloudiness in regions many tens of kilometers wide in the upper troposphere.

As background for our observational studies of seeding opportunities, we first discuss estimates of the areal extent of clear, ice-supersaturated air, based on observed dimensional properties of atmospheric circulation types (Section 2). Sections 3 and 4 then describe general estimates of frequency and extent of seeding opportunities in the upper troposphere based on two types of data. Sections 5 and 6 give estimates of opportunities under more specific conditions for which clear-air seeding would be beneficial (winter nights), and together cover the entire depth of the troposphere.

Having discussed the frequency of occurrence and size of areas suitable for clear-air seeding in the troposphere, we next deal with the technology of dispersing seeding material to initiate cloud growth. Although Winterberg (1975) has proposed high-altitude seeding with rockets, any large-scale clear-air seeding done in the near future will likely use aircraft that disperse trails of seed material as they fly horizontally. Section 7 discusses the expected width of resulting clouds based on the contrail observations of Section 3.

Section 8 demonstrates that the lifetime of a cloud resulting from seeding is in general determined by the time it takes the ice particles to grow, fall into drier layers of the atmosphere and evaporate. The longer a cloud lasts, the more it spreads horizontally by natural turbulent diffusion. Both long lifetime and large horizontal extent contribute to the desired modification of the radiative energy balance near and at the ground.

Two major types of clear-air seeding are possible. One involves creating an initial population of ice crystals, all of which immediately begin to grow in the ice-supersaturated air. Using a numerical simulation, we investigate in Section 8 some strategies for maximizing cloud cover enhancement with this type of seeding. In the other approach, substances capable of nucleating ice directly from the vapor phase (ice nuclei) are dispersed in air which already exceeds ice saturation, or which is expected to become saturated soon after. Cloud development in this case is more difficult to predict, because it depends greatly on the rate at which seed particles nucleate ice crystals. Section 9 discusses some important properties of ice nuclei, and how those properties would influence the development of artificially created cloud.

2. ORDER-OF-MAGNITUDE ESTIMATES

If the separation between frost point and dew point exceeds 3°C (i.e., temperatures are lower than -30°C) and the lapse rate ranges from 8 to 10°C/km, then rising air can be supersaturated with respect to ice, but less than saturated with respect to liquid water, for several hundred meters of ascent. If suitable ice nuclei are present, cloud will form soon after the frost point is reached; otherwise it will not form until the rising air cools almost to its dew point.

At cirrus cloud levels, some reports are available on the nature of the cloud-scale air circulations (Conover, 1960; Yagi et al., 1968; Yagi, 1969; Heymsfield, 1975a and 1977). The ratio of vertical to horizontal wind speeds ranges from ∿1/10 (jet stream bands) to ∿1/1000 (cirrostratus associated with large-scale "slope convection," or warm-frontal ascent). Based on these ratios, the humidity of rising air in jet stream band circulations will be between saturations with respect to ice and liquid water while the air moves horizontally for several kilometers. This means that the zone of clear, ice-supersaturated air near the bands will have approximately the same width as that observed for cloud bands themselves.

Similarly, clear, ice-supersaturated air may extend several hundred kilometers horizontally ahead of an advancing warm front. Smaller scale motions (such as jet stream band circulations) will usually occur and the resulting variations in humidity will be superimposed on the large-scale pattern. So within the broad, generally clear region will be zones where the dew point is approached and natural cloud formation occurs, and other zones a few hundred meters deep where the dew point is approached but not reached. The latter are suitable for clear-air seeding. The ratio of natural cloud area to the area of clear, ice-supersaturated air will vary, but should have the same average as jet stream cirrus bands (one).

These estimates correspond well with subjective impressions from the studies of time-lapse films and LANDSAT images reported in Section 3. On the days with the most contrails, oriented in a variety of ways to the pattern of natural cloudiness, contrail coverage appeared to be comparable to the natural cloud coverage.

At lower altitudes, wind speed ratios associated with cloud formation range from ∿1/2 (fair weather cumulus) to ∿1/100 (large-scale ascent of layers to form altocumulus). Since higher temperatures at lower altitudes mean the separation between dew point and frost point is less than a degree or two, the horizontal extent to which cloudiness can be enhanced should be less than at higher altitudes. On the other hand, the created clouds would usually be optically denser at low altitudes (Detwiler, 1983), and horizontal advection of cloud by wind would generally be less.

3. CONTRAIL STUDIES

Aircraft contrails will form whenever engine exhaust mixes with ambient air that is colder than some aircraft-specific threshold temperature, usually below -40°C (Appleman, 1953). Under these conditions, condensation occurs as the wake cools and on the order of 10^{10} droplets per meter of flight path are condensed (Knollenberg, 1972). The droplets quickly freeze unless the environment is so dry that they evaporate first. The persistence of the contrail is solely a function of the humidity of its environment; if it persists as it disperses, the environment must be supersaturated with respect to ice. So spreading, persisting contrails indicate an opportunity for creating additional cloudiness by artificial seeding at altitudes where they occur.

3.1 Previous studies

During nearly 300,000 km of flights over domestic US air routes from November 1964 through January 1972, persisting contrails were formed by the observer's aircraft about 25% of the time whether or not natural clouds were already present, and 7% of the time in clear or only partly cloudy skies (Beckwith, 1972).

At Champagne-Urbana, Illinois, from September 1979 through October 1981, the monthly percentage of all clear and partly cloudy days on which contrails were sighted during daylight ranged from 0 to 67 (Wendland and Semonin, 1982). Contrails were sighted more frequently from January through June than from July through December, paralleling the annual variation of natural cloudiness. Individual contrails, observed every 5 min during daylight with an all-sky camera, persisted an average of about 15 min and had a mean length of 105 km and a mean width of 8.5 km. About half of all film frames indicating any contrails showed just one, while 21% showed two contrails and 29% showed three or more. Once an area of multiple contrails started to form, it could be seen for an average of 45 min, which corresponds to the observed mean length (105 km) at a typical cirrus level wind speed of 40 m/s. Contrails tended to be observed ahead of the natural cloud shield of advancing cyclones or convective complexes.

3.2 Time-lapse contrail studies

In a similar study at Albany, New York, from November 1976 through May 1981, a camera aimed at the western horizon exposed one frame every 7 min during daylight, yielding about 100 observations each day. Typically, more than 100 aircraft per day pass over Albany at high altitudes, so the probability that any clear, ice-supersaturated regions in the upper troposphere (150-300 mb) will be revealed by persisting contrails is high.

Figure 1 shows the percent of days per roll of film (roughly, per month) on which at least one contrail was observed during daylight over most of the study (bars). On every day that contrails were observed, natural cirrus were also observed at some time (circles). The high cloudiness deduced from the films agreed well with observations of high cloudiness made at a National Weather Service forecast office about 5 km away. The monthly percentage of days on which contrails were observed ranges from 10 to 57 with an average of 32, about the same as observed by Wendland and Semonin (1982).

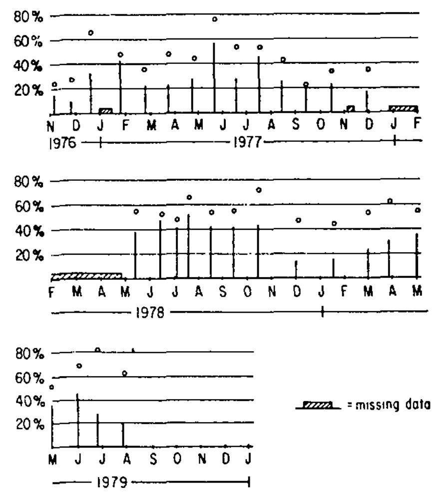


Figure 1. Percent of days on each roll of time lapse film during which at least one contrail (solid bar) or natural cirrus (circle) was observed.

Since the Weather Service also reports cloudiness at night (although thin, high clouds may be under-reported), we compared in its reports the number of days with daytime cirrus to the number of days with cirrus either at day or at night. Frequencies of high cloud based on hourly daylight observations, divided by the fraction of daylight hours in a day, provided a reliable estimate of the frequency with which high clouds were observed at least once in a 24-hour day. We assume this holds for contrails as well; if they are observed on 30% of all days during 12 hours of daylight, they probably are present on 60% of all days, either at day or at night.

That summer has more daylight hours seemed to account at least partially for the larger fraction of summer days than winter days at Albany with at least one contrail. In addition, the greater prevalence of low clouds may have led to an under-reporting of contrail frequencies in winter months. In view of these two factors, the overall percent of whole days on which at least one contrail would be observed over Albany, based on Figure 1, is at least 40.

Since contrails were almost always observed for several hours or more, if they were oberved at all, sky samples for assessing clear-air seeding opportunities must be at least several hours apart to be independent. However, the number of independent samples per day depended on the weather situation. On the time-lapse films independent samples averaged about 4 hours once the first contrail appeared. Persisting contrails tended to appear ahead of the high cloud decks of advancing cyclones, leading them by about 2 hours (∿100 km) on the average. Mixed contrails and natural clouds typically lasted another 2 hours. These time periods varied from less than one hour up to 12 hours, a variability typical of the movement and development rate of mid-latitude cyclonic circulations, which are largely responsible for the transport of water vapor to the high troposphere.

Persisting contrails tended to appear in a more patchy and less continuous manner in summer than in winter. In summer they seemed to appear downstream from convective cloud complexes at distances ranging up to one day's travel time downstream.

3.3 Contrail statistics based on LANDSAT images

A second set of contrail statistics was derived from a survey of ∿14,000 LANDSAT images stored on 16 mm microfilm. The images covered 180 km square areas of the United States during the latter half of 1972 and the first half of 1975. The sun-synchronous orbiting satellite collects images roughly an hour before local solar noon, and high contrast features as small as 100 m can be resolved.

Roughly 3% of all images contained identifiable contrails, which almost never began or ended on the image. When one contrail was present there were almost always several or more, and natural clouds as well. The contrail-containing regions were located on archived National Weather Service synoptic charts. Just as the time-lapse film study showed, contrails tended to appear ahead of cyclonic storms or downstream from convective cloud complexes. They occurred predominantly between the subtropical and polar jet streams.

In view of results from other sources, the fact that only 3% of all LANDSAT images contained contrails is more an indication of the small area of the United States covered by high-altitude jet routes than of the scarcity of clear, ice-supersaturated air. Beckwith was aboard the source of the contrails he was observing; the Wendland and Semonin study and our time-lapse study were conducted in locations subject to dense aircraft traffic.

3.4 Summary of contrail studies

There are often opportunities to create additional cloudiness at levels in the troposphere where temperatures are lower than ∿ 40°C. High-altitude aircraft routinely do so as much as 25% of the time, and other contrail observations imply that daily occurrence of ice-supersaturated clear air is at least this much. Such regions average 100 km in horizontal extent, and in the mid-latitudes are usually but not exclusively found ahead of advancing cyclones and south of the associated polar jet streams. The frequency with which clear-air seeding opportunities at such altitudes occur at a given location will be proportional to the frequency of passage of major cyclones or convective weather systems.

4. PARTICLE AND HUMIDITY MEASUREMENTS FROM AIRLINERS

To study the occurrence of clear, ice-supersaturated regions in the mid-latitude upper troposphere, we have examined an extensive body of data collected by automated instruments on commercial airliners. The data were collected under the Global Atmospheric Sampling Program of the National Aeronautics and Space Administration from September 1978 through February 1979. The instrument system included a cooled-mirror frostpoint hygrometer and a particle counter sensitive to natural cloud particles. The instruments and this study are described in more detail in Falconer et al. (1983).

Data were normally recorded every 75 km along the flight path while the aircraft were above 6 km (altitudes generally coinciding with those at which contrails can form). Relatively clear ice-supersaturated regions were found in about 7% of all records. Figure 2 shows the frequency with which nearly clear, ice-supersaturated regions of various lengths were encountered by the instrumented aircraft. At the altitude of these measurements (180-250 mb), 41% of the regions were at least 75 km wide, and 13% were at least 150 km wide.

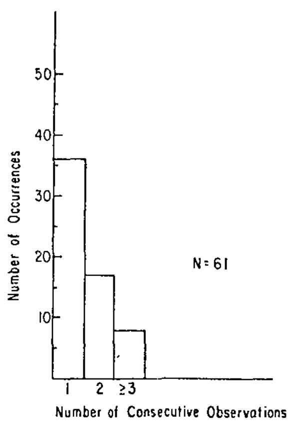


Figure 2. Frequency of one, two or more successive observations of clear, ice-supersaturated air. The horizontal distance between successive observations was about 75 km; the number of records surveyed was 875.

Defense Meteorological Satellite Program visible and infrared images coinciding with the aircraft data showed that these regions tended to occur south of jet streams and downstream of cyclones. This confirms the conclusion from the contrail studies that the frequency of seeding opportunities in the upper troposphere over a particular mid-latitude region would be proportional to the local frequency of cyclone passage.

5. OBSERVATIONS OF NATURAL CLOUDS

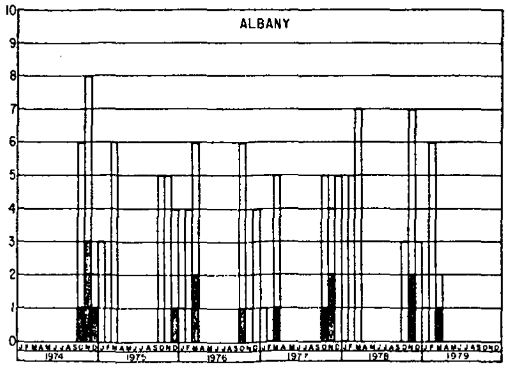
Contrail observations from the ground and from satellites described in Section 3 show that persistent contrails are usually found near natural cirrus clouds. Therefore the presence of scattered cirrus cloud cover is an indication of an opportunity for cloud enhancement by clear-air seeding. This association was the basis of a study to estimate the cirrus-level seeding opportunities useful for reducing winter energy consumption.

Five years of surface observations at Albany, New York, and Boston, Massachusetts, were analyzed. Wintertime nights were considered seedable if scattered or broken cirrus cloudiness was observed for at least 3 consecutive hours, but only if this interval occurred within 6 consecutive hours which were essentially free of lower-level clouds. We assumed that under these conditions clear-air seeding would result in additional cloudiness that would have beneficially contributed to the suppression of radiational cooling.

Based on these cloudiness criteria alone, the number of opportunities is about 25 per season at each location (Figure 3). Monthly frequencies averaged 3 or 4, roughly the frequency of cyclone passage during these months.

Cloud making would obviously be fruitless if upper-level winds were so strong that the created clouds were rapidly carried away from the target area on the ground. When wind speeds at 25,000 ft MSL are required to be ≤ 20 m/sec in addition to the cloudiness criteria, the number of opportunities is reduced to an average of 3 per season (Figure 3). Since the maximum wind speed for useful operations is not certain, the comparisons in Figure 3 should be considered only a qualitative indication that wind speed limitations may be important.

In this 5-year survey, opportunities at Albany and at Boston (generally downwind) occurred on the same night less than a third of the time. This means that an operation established to seed over a number of possible target areas on different occasions would be able to seed more frequently, and thus more efficiently, than an operation designed to cover a single area. There would be few occasions which would require choosing between more than one feasible target on a given night.



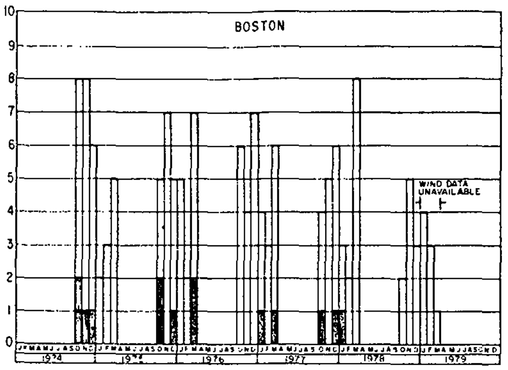


Figure 3. Monthly estimates of winter days suitable for high-altitude cloud seeding at Albany, N.Y. and Boston, Mass. Shaded bars indicate seedable days which also had wind speeds at cirrus level ≤ 20 m/s.

6. RADIOSONDE HUMIDITY MEASUREMENTS

All of the assessments described above relate to the upper troposphere. One technique for detecting clear, ice-supersaturated layers at lower altitudes has been used by Lala (1970) and Jayaweera et al. (1975). A piece of dry ice suspended from an ascending balloon will precipitate ice crystals upon penetration of clear, ice-supersaturated air. Such cloud trails are visible from the ground in favorable lighting, but become difficult to see when the balloon is high and has drifted far away.

We have surveyed soundings from the National Weather Service radiosonde network to estimate directly from humidity measurements the frequency of occurrence of clear, ice-supersaturated layers. Careful consideration was given to the various sources of error in the carbon hygristor system used on radiosondes; these are summarized in detail by Pratt (1984). Unlike dry ice observations, the availability of radiosonde relative humidity data is not strongly biased toward lower altitudes. It is reported for all temperatures down to $-40^{o}C$, and neatly complements assessments based on contrails, which form at that or colder temperatures. The survey was limited to winter nights, during which increased cloudiness could reduce space heating demands.

In view of the large errors possible in low temperature relative humidity measurements, a conservative approach was adopted. The goal of the survey was an estimate of the lower limit of clear, ice-supersaturated layer frequencies, and of excess water vapor contents above ice saturation (available for cloud formation). Conservative criteria were established first for excluding observations which could have been taken in clouds, since surface observations of cloud cover are inadequate for making such a determination. Conservative here means excluding all cases in clouds even at the risk of excluding some clear, ice-supersaturated layers as well. Secondly, conservative values of relative humidity (less than or equal to actual values) were used to determine the presence of clear, ice-supersaturated layers, and to calculate the excess water vapor content of each layer. Details of the data treatment are given in Appendix A.

Nighttime soundings were examined for Albany, New York, for December, January and February of the three winters of 1975 through 1978, using the Northern Hemisphere Data Tabulations. Soundings were considered only if total cloud cover reported in the surface observation for the nominal sounding time (00 or 12 GMT) was ≤ 3/10, and cloud cover averaged ≤ 3/10 for the 5 hours centered on the sounding time. These cloud cover conditions specified a pool of soundings for which cloud cover enhancement would have been beneficial. Natural clouds need not be entirely absent for clear-air seeding between them to be beneficial. The conservative exclusion of soundings in clouds mentioned above was necessary because those soundings would not be representative of the clear, ice-supersaturated air which might exist between natural clouds at those times.

Of the 457 soundings examined, about 25% met the cloud cover requirements. Five percent were excluded as possibly having entered cloud, and an equal number indicated a column water vapor excess of at least 1 g/m^2 for the entire depth of the layer. Figure 4 describes the height, thickness and a conservative calculation of the excess vapor content of each layer found in the latter group of 25 soundings. Excess column vapor contents of about 10 g/m^2 are sufficient to create cloud of significant optical thickness (Detwiler, 1983); 2.2% of all soundings (10 in Figure 4) met this criterion.

These results can be compared with surveys based on the cloud trails from dry ice made by Lala (1970) in Albany, and Jayaweera et al. (1975) in Fairbanks, Alaska. For the same winter months and cloud cover conditions used in this survey, they found clear, ice-supersaturated layers in 8% and 15% respectively of the balloon launches. Our result of 5% of soundings with calculable excess water vapor compared with Lala's 8% lends confidence to our approach for conservatively estimating the presence and excess water content of clear, ice-supersaturated air. The Fairbanks frequency of 15% probably reflects the influence of strong winter inversions on the local climate.

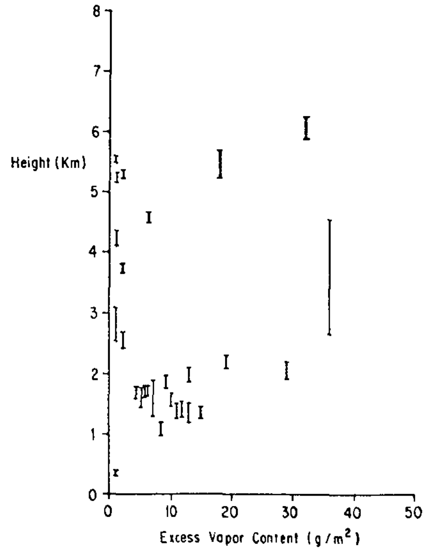


Figure 4. Height distribution and excess water vapor contents of clear, ice-supersaturated layers deduced from 3 winters of radiosonde data. Thickness in cases of single moist reports was taken as 1/4 the distance between adjacent reports for plotting. 27 layers are plotted; two of the 25 soundings had two layers.

The vertical distribution described by Figure 4 also agrees with Lala's finding that clear, ice-supersaturated layers were concentrated between 0 and 2 km, with a secondary concentration between 5 and 6 km. Low altitude layers are more favorable for practical seeding. Lower clouds are generally more effective at influencing surface radiative cooling (Detwiler, 1983), they are more accessible from the ground, and advection of created clouds away from the target area will be slower than at higher altitudes. Other differences between seeded clouds at low and high altitudes are discussed later.

To estimate the frequency of opportunities for clear-air seeding from this survey of twice-daily soundings, we must know something about the time and space continuity of clear, ice-supersaturated layers, and the implied time between independent samples for this property of the atmosphere at a single location. Soundings from stations near Albany were inspected at the same time that clear, ice-supersaturated air was judged to be present over Albany based on its sounding. Some sign of the moist layer was always found over at least one or two other stations, but neither the layers nor cloud cover conditions were ever uniform over the seven-station network. The width of the apparently favorable region for seeding was generally comparable to, but no larger than, synoptic station spacing (up to about 200 km). At typical wind velocities encountered within the layers (10-40 m/s), this implies a time interval for seeding or for independent samples of a few hours. This is comparable to our estimate of this property based on contrail observations (which apply to altitudes generally above those for which radiosonde humidity data is reported). If three such intervals constitute each winter night, 2.2% of them would be about 6 several-hour intervals each 3-month winter that would be suitable for nighttime clear-air seeding over Albany.

As discussed in the previous section, wind velocity at seeding level will influence the success of an operation. For example, the estimate of 6 seeding occasions per season is reduced to 4 if wind speed at the level of the clear, ice-supersaturated layer is required to be ≤10 m/s.

7. CLOUD DISPERSAL ESTIMATES

Effective clear-air seeding depends not only on the presence of clear, ice-supersaturated air, but also on the technological capability of dispersing seeding material efficiently to initiate cloud growth. Although clear-air seeding is performed every day by contrail-producing aircraft, they make no attempt to disperse seed ice particles over a wide region. Thus the typical width of persisting contrails gives only a lower bound on the size of cloud that might result from intentionally dispersing seed nuclei. The distribution of widths of the widest contrail on each of our LANDSAT images containing contrails is shown in Figure 5, and a sample image in Figure 6. Contrails much wider than 3 km were seldom observed. Such a limit is a result of the limited speed of atmospheric dispersion; the fall of growing ice crystals into drier layers where they evaporate, and the fact that as contrails disperse they become optically thinner and harder to detect. Under typical upper tropospheric conditions, a line of material might be expected to disperse to several kilometers width in about an hour (Hage, 1964). On the average, then, most of the contrails in the LANDSAT images were probably an hour old or less. Contrail length statistics could not be derived from the LANDSAT images because the contrails rarely began and ended on the 180 km square images.

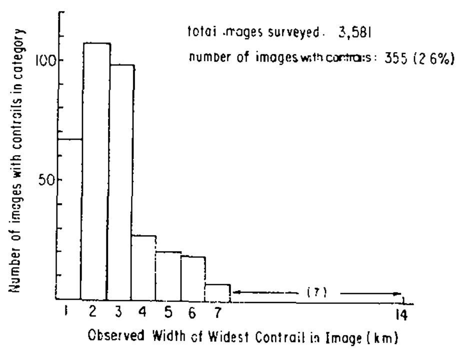


Figure 5. Contrail widths in LANDSAT image survey. (7 images had between 8 and 14 km.)

Figure 6. Sample of LANDSAT images used in the survey, showing several contrails.

The mean width derived from our study of LANDSAT images is less than half that derived by Wendland and Semonin (1982), but the cause of the discrepancy is unclear. One possibility is that central Illinois has conditions that favor enhanced growth of contrails compared to the United States as a whole. Another is the difference in the two data sources used. For our LANDSAT image study we estimated overall error, including error in satellite position and in the image reproduction process, to be less than 0.75 km.

The two sets of contrail width statistics suggest that aircraft dispersal of seeding material within ice-supersaturated regions will result in cloud trails ranging from 1 or 2 to perhaps 10 km in width. However, contrails are not formed with the intention of creating cloudiness, and the numerical simulation of ice crystal growth described next indicates that contrails typically use only a small fraction of the excess water vapor available for cloud formation. The widths of deliberately created clouds could be significantly higher than those typical of contrails.

Enhancement of cloudiness over a large area will require many aircraft passes over the region in a limited period of time. A jet aircraft flying at 600 km/hr, seeding in such a way that a 10 km wide cloud trail eventually develops behind it can generate only 6,000 km^2 of cloudiness per hour, enough to fill a square area ∿75 km on a side. In some cases the extent of cloudiness enhancement will not be limited by the extent of ice-supersaturated regions, but by the available seeding technology.

8. SEEDING WITH ICE CRYSALS

Two methods can create a population of ice crystals to initiate cloud growth. In one dry ice, liquid propane or a similar substance is dispersed so that the air is chilled sufficiently to nucleate large numbers of ice crystals homogeneously. The other method corresponds to the process of inadvertent contrail formation by aircraft. Sufficient water vapor is dispersed to bring the air to saturation with respect to water; droplets condense, and then freeze rapidly if the temperature is low enough (usually -40°C or lower).

The simple numerical model described here simulates the evolution of a cloud of ice crystals in the wake of an aircaft, regardless of how they were formed. The simulation begins when the trail has a width and thickness of some tens of meters, and is far enough from the aircraft to be free of its turbulence. The cloud is divided into homogeneous layers and the changing vertical profile of ice crystal sizes and concentrations are calculated as the cloud particles fall through the atmosphere. Growth of ice crystals and the distance they fall in each layer are calculated independently of the other layers for each time step. At the end of each time step, ice particle masses and concentrations and water vapor concentrations in the (now) irregularly spaced layers are interpolated to an equal number of regularly spaced, uniform layers.

The environment is assumed to be free of wind shear and horizontally uniform, but the vertical profile of temperature and relative humidity can be arbitrarily specified. At each time step cloud properties are diluted uniformly within each layer with environmental air at the same altitude, to simulate clear-air entrainment associated with dispersion of the cloud. A single, constant entrainment rate is applied to all layers to represent the particular horizontal and vertical dispersion rates specified for a simulation. Other details of the model, including treatment of radiative transfer, are given in Appendix B.

In Figures 7 through 10 a standard simulation is compared to another which differs in one of the initial or boundary conditions. The standard simulation, intended to represent a typical aircraft contrail, starts with a trail of 10 µm-long crystals, initially 100 m wide by 100 m deep, with an initial concentration of $1/cm^3$. This corresponds to Knollenberg's measurement (1972) of 10^{10} crystals per meter in a contrail. The trail is at 250 mb where the temperature is -45°C, and is initially at the top of a layer 600 m deep, within which the ice saturation ratio is 1.35. Air below this moist layer has an ice saturation ratio of 0.5. The entrainment rate corresponds to expansion of the cloud boundaries at 2 m/sec in width and 0.2 m/sec in height due to small-scale turbulence. Additional spreading in the vertical is produced by the difference in fall speeds of particles at the top and bottom of the layer. The vertical extent of the standard cloud is indicated by shading in the top portions of Figures 7 through 10.

The evolution of the cloud is controlled by three factors: (1) the thickness of the supersaturated layer and the vertical placement of the contrail in it, (2) the rate at which the cloud disperses, and (3) the initial concentration of ice particles per unit length of cloud trail.

Supersaturated layer thickness has a major effect on cloud lifetime (Figure 7). A cloud initiated in a layer only half as thick as the standard case has less time to grow before its crystals begin to fall into drier air below. Clouds seeded in thicker layers (or closer to the top of a layer) will last longer and have larger crystals.

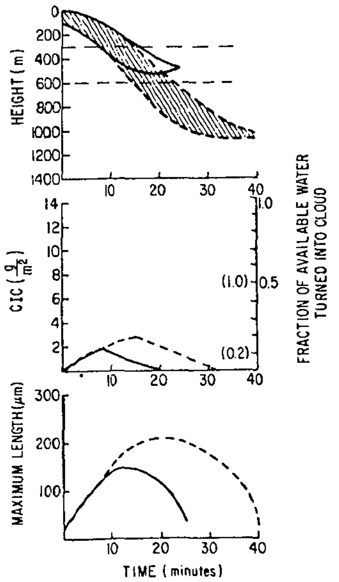


Figure 7. Time variations of vertical cloud extent, column ice content, and maximum ice crystal length. The standard case (dashed) is compared to a case that is similar except that the supersaturated layer is only 300 m deep. Values of fraction of available water in parentheses refer to the thinner layer.

Figure 8 shows the effect of increased dispersion. The faster the cloud disperses, the more rapidly its ice particles grow and fall through the supersaturated layer. This is due to lateral entrainment of supersaturated air, which increases the vapor available for growth. The larger the particles become before they fall into the dry layer below, the longer they take to evaporate there. Because of these two opposing tendencies, faster fall speeds balanced by longer evaporation times, cloud lifetime does not vary greatly for a wide range of dispersion rates.

Figure 8 shows that a cloud with twice the dispersion rate of the standard case reaches a little over half the column ice content, reflecting the increased dilution in each layer. However, that very dilution means that each layer will be twice as wide as in the standard case, resulting in a slightly larger **total** ice content for the entire cloud.

A simulation using higher initial ice particle concentration (Figure 9) yields a several-fold increase in column ice content over the standard case. The greater the initial concentration, the more slowly the cloud particles grow and fall through the supersaturated layer into the dry air below. Higher initial ice particle concentrations imply more competition for the available vapor and slower growth of individual particles. This leads to lower fall speeds, and more efficient utilization of the water vapor in excess of ice saturation.

Since the standard case corresponds to a seeding rate typical of contrail formation, the simulation in Figure 9 shows that (inadvertently created) contrails typically use only a

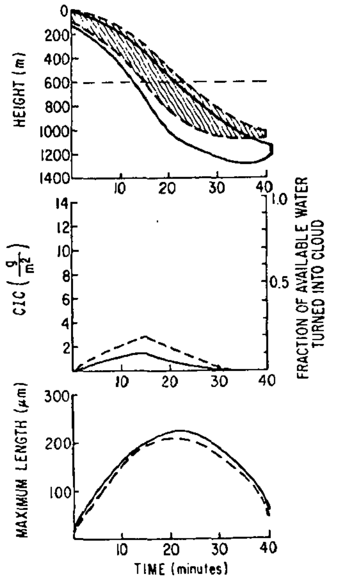


Figure 8. As in Figure 7 where the standard case is compared to one for which the turbulent dispersion is twice as large.

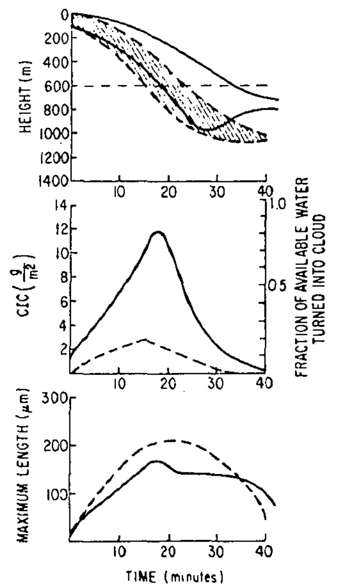


Figure 9. As in Figure 7 where the standard case is compared to one for which the initial particle concentration is 10 times greater.

small fraction of the water vapor available for cloud growth in a supersaturated layer. Seeding rates higher than those typical of contrail formation would apparently lead to greater utilization of the available water vapor.

Figure 10 compares cloud development at lower, warmer altitudes with the standard case. The lower layer was specified to be thinner for this comparison, since the temperature difference between dewpoint and frostpoint is less at higher temperatures. The higher temperature permits a much larger column ice content for the same saturation ratio, but the shallowness of the layer shortens cloud lifetime compared to the standard case.

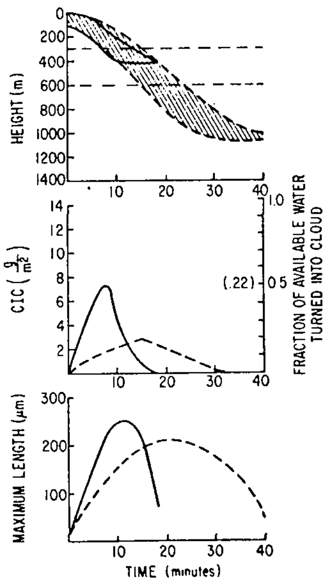


Figure 10. As in Figure 7 where the standard case is compared to a case that is the same except the trail is initiated at -25°C and 500 mb. The ice saturation ratio in the supersaturated layer is only 1.2 (the frostpoint should not exceed the dewpoint, which would be the case if the saturation ratio were 1.35) and the layer is only 300 m deep, since the dewpoint and frostpoint are closer together at this temperature (See Detwiler, 1983).

From these simulations it is clear that the most important factor determining cloud lifetime is the time necessary for ice crystals to grow to sufficient size that they drop into drier air below and evaporate. Exploiting this principle to artificially prolong the lifetimes of natural clouds may thus be feasible as another means of enhancing cloud cover. For example, observations (Heymsfield, 1977) and calculations applicable to jet stream cirrus uncinus (Heymsfield, 1975b) suggest that deliberate "overseeding" of convective clouds in the high troposphere would prolong cloud lifetime by increasing ice particle concentrations.

9. SEEDING WITH ICE NUCLEI

The previous section dealt with cloud development from dispersed ice crystals. If ice nucleating particles are dispersed instead, the rate at which these particles nucleate ice crystals determines subsequent cloud development. Laboratory results (DeMott et al., 1983) show that smokes currently used in weather modification nucleate ice much more slowly by vapor deposition than by contact freezing or by condensation freezing at liquid-water saturation.

We have carried out clear-air seeding trials using LW-83 (similar to TB-1) pyrotechnic flares attached to aircraft, which produce particles containing silver iodide. In trials carried out at temperatures between -10°C and -45°C, nearly instantaneous cloud formation followed seeding only when the humidity in the seeding trail was very close to liquid water saturation.

Detwiler and Vonnegut (1981) have studied ice nucleation by direct vapor deposition on various silver iodide and lead iodide aerosols, in a parallel-plate thermal diffusion chamber. These iodides are commonly used for nucleating ice in supercooled clouds, but have only rarely been used to nucleate ice in clear air by direct deposition (Vonnegut and Maynard, 1952).

Estimates of the threshold ice saturation ratios required to produce various rates of ice nucleation onto an aged population of aerosol particles are shown in Figure 11. They were made by drawing a known population of aerosol into a parallel-plate diffusion chamber, and observing the fraction nucleated in the first few seconds after the initial ice particles formed. At temperatures of -30°C or higher, the relative humidity with respect to liquid water must be at least 90% to produce nearly instantaneous nucleation of ice on almost all of the aerosol. Only at relatively low temperatures can high nucleation rates be observed at humidities appreciably less than water saturation.

Figures 11 shows that for any temperature below about -10°C, nucleation rate increased by ∿4 orders of magnitude when ice saturation ratio increased by ∿10%. This suggests that small-scale humidity variations will determine where cloudiness develops most rapidly within a seeded, supersaturated layer.

There are theoretical reasons to expect a strong dependence of nucleation rate on ice saturation ratio (Fletcher, 1969, Chapter 8). It is also clear that nucleation rates for any particular process, say deposition nucleation, can be radically affected by variations in size, chemical composition and surface structure of the particles. So although these experimental observations seem consistent with the theory, they should not be used to predict the nucleating behavior of other types of aerosols, or of aerosols of similar composition generated in a different way.

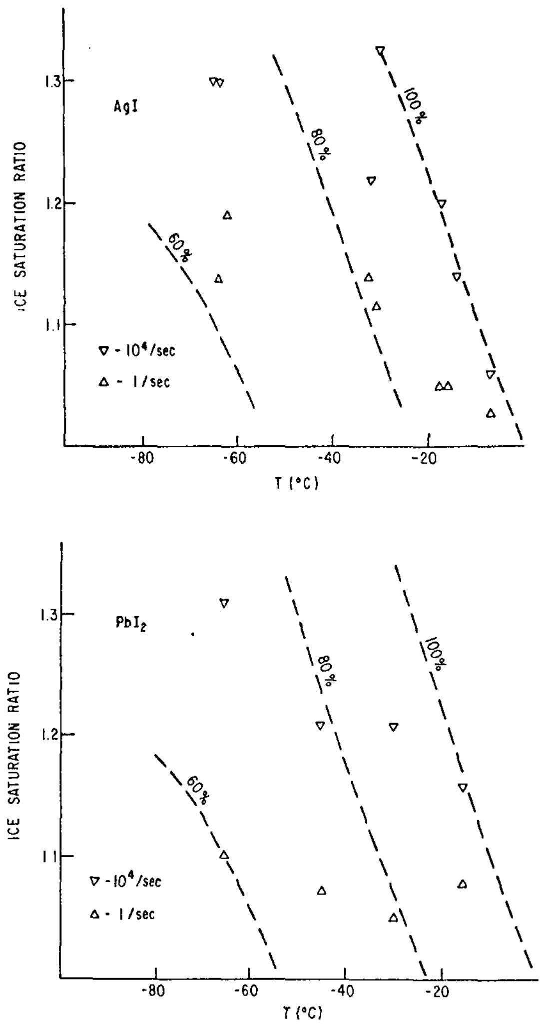


Figure 11. Observations from experiments discussed by Detwiler and Vonnegut (1981) show the variation of the rate at which aerosol particles of silver iodide (above) and lead iodide (below) nucleate ice as a function of temperature and humidity. The vertical axis is ice saturation ratio and the slanting dashed lines are percent relative humidity with respect to liquid water.

The result of clear-air seeding will be much different if slowly nucleating particles are dispersed in a supersaturated layer than if small ice particles are dispersed at the same rate. In the former case the nuclei themselves will disperse with negligible settling, and a low density cloud is likely to form slowly and continuously. Once ice nucleates on a seed particle, it will grow rapidly and fall out of the supersaturated layer, because the total ice particle concentration will remain small. Cloud life history will be determined by the balance between nucleation rate and the rate at which ice particles fall out of the moist layer. Creation of a very long lasting, low density cloud is possible.

By contrast, if small ice particles are dispersed, they will all begin to grow and fall out at the same time. Initially the cloud will be more dense than in the former case, but particle growth will cease earlier.

10. SUMMARY AND CONCLUSIONS

Order-of-magnitude arguments suggest that in the mid-latitude upper troposphere, potential areas for clear-air seeding are associated with synoptic waves and have a characteristic width of about 100 km. The studies described in Sections 3 and 4 confirm and augment this expectation. Contrails are present on at least 30% of all days, and probably more. In summer they are more likely to appear downstream of convective cloud complexes, in a less regular manner than their usual association with cyclonic storm systems. The duration and monthly frequency of clear, ice-supersaturated conditions has a wide variation at any location. When clear-air seeding is possible, the area of additional cloud that can be created is at least equal to the area of existing natural cloud. We conclude from these general observations that the presence of clear, ice-supersaturated air is a common occurrence in the mid-latitude upper troposphere, at all times of year.

Together, Sections 5 and 6 describe an assessment of seeding opportunities for the entire depth of the troposphere, under restrictions suitable for the particular application of reducing infrared cooling at the surface during winter nights. We estimate 25 opportunities at high altitudes and 6 at lower altitudes each season. Reasonable wind restrictions reduce these estimates respectively to 3 and 4, for a total of 7 per season (which were mutually exclusive at Albany during the common period of the two surveys).

This result suggests as many seeding opportunities in the lower as in the upper troposphere, a conclusion not necessarily limited to any particular seeding application. Seeding opportunities at lower levels have the advantages of easier access from the ground, lower advecting wind speeds, and greater radiative influence for the same ice content.

Cloud trails created by seeding from aircraft would grow to at least several kilometers in width. Numerical simulation of seeding with ice crystals suggests that the maximum amount of cloudiness will be created by dispensing the largest concentration of seed particles possible. For this reason, aircraft contrails do not utilize much of the water in excess of ice saturation.

If ice nuclei are used for seeding instead of ice crystals, a longer lasting but less dense cloud will result. Only at temperatures below -30°C will ice nuclei nucleate rapidly, at relative humidities with respect to liquid water less than 90%. We have not attempted a comprehensive study of all criteria relevant to the technical feasibility of clear-air seeding, although wind restrictions, altitude, seed dispersal capability (Section 7), and other

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details of seeding (Sections 8 and 9) will be important.

A seasonal frequency as low as that estimated here for winter nighttime seeding at Albany (7) may still be economically beneficial, according to the analysis by Detwiler and Cho (1982). Only through relatively pointed investigations, such as those described here for winter nighttime seeding, can the feasibility of other applications of clear-air seeding be determined.

11. ACKNOWLEDGMENTS

Phillip Falconer carried out the study of natural clouds (Section 5). Nizam Ahmed assisted with the radiosonde survey in Section 6, and V. Ramaswamy helped develop the numerical simulation of Section 8. Marilyn Peacock drafted the figures, and Oscar Neilson photographed them and prepared the prints for publication. This material is based on work supported in part by the Department of Energy under contract DE-AC02-80ER10691, in part by the National Science Foundation under grant ATM791080, and in part by the Office of Naval Research under contract number N00014-80-C-0312. The first author was supported during the writing of this paper and the calculations described in Section 8 by the Convective Storms Division and the Advanced Study Program of the National Center for Atmospheric Research. (The National Center for Atmospheric Research is supported by the National Science Foundation.)

APPENDIX A

Soundings that met the cloud cover conditions described in the text usually showed signs of high relative humidity (RH) in distinct layers. Figure A1 indicates schematically a typical moist layer. Significant level selections (by observer or computer) would usually be prompted by the start of abruptly increasing RH at the lower edge of the layer (RH_1); attainment of relatively constant RH within a layer (RH_2), and an abrupt decrease at the top edge of the layer (RH_3). The goal of the sounding study was to estimate conservatively the amount of excess water vapor above ice saturation (stippled area), taking into account the known sources of error of the RH data. By conservative here we mean the minimum amount available for clear-air seeding.

Of all the documented sources of low-temperature relative humidity error (Pratt, 1984) the two most important to this study are the **thermal** lag and the **time** lag of the hygristor. The **thermal** lag results from the finite time needed for the temperature of the hygristor to adjust to changing ambient air temperature, and has been thoroughly analyzed by Brousaides and Morrissey (1974). This error contributes to a lower than actual reported RH when temperature decreases with

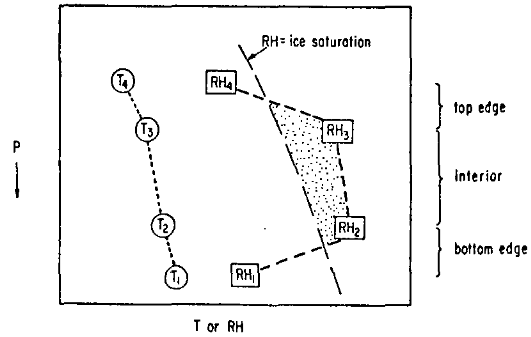

Figure A1. Schematic plot of relative humidity and temperature reports through a typical moist layer in the sounding survey.

height in the atmosphere; and to higher than actual reported RH in inversions. Reports in inversions were excluded from the survey altogether. For the remaining data, the average RH error, based on average lapse rates given by Brousaides and Morrissey, was used (Table A1), but only for excluding reports in clouds, as explained below. Thus the use of **reported** RH for calculating excess water contents was influenced conservatively (lower than actual) by this error. A similar error resulting from solar heating of the hygristor was avoided by using only soundings taken in darkness.

Table A1

MEAN THERMAL LAG ERROR
(Brousaides and Morrissey, 1974)

Level (mb):	1013	700	500	350	250
Thermal Lag (% RH):	3	4	6	9	

The **time** lag refers to the hygristor response to changing humidity at **constant** temperature. This lag becomes large at low temperatures but is poorly documented. Based on National Bureau of Standards test results at -40°C and -50°C (supplied by R. Hixon, Pacific Missile Test Center, Point Mugu, California), we have adopted for this study a time of at most a half minute for the reported humidity to indicate 90% of an imposed step change in RH, for temperatures down to -30°C. Examination of pen recorder strip charts for National Weather Service soundings indicated this to be a conservative value. The time lag error contributes to under-reporting of RH in the bottom edges of moist layers (Figure A1), little error in the interior, and to over-reporting in the top edge portion of moist layers.

Since the two major sources of error usually contribute to under-reporting of humidity, it was important in this survey to establish criteria for excluding reports of high RH which may have been made in cloud. Most moist layers occurred at temperatures above -30°C, for which RH would usually be 100% for existing natural clouds. Our criterion was to exclude layers for which the maximum reported humidity exceeded 99% RH, after adding the appropriate average thermal lag (Table A1) as well as another 4% RH. Hygristor elements can be as much as 4% too low (or too high) and pass manufacturing tests (Potts, 1982). An extra 5% RH was added to the few reports below -30°C to allow for increased time response at colder temperatures. These criteria conservatively excluded reports in clouds based on thermal lag and possible manufacturing tolerance error, but time lag error could also contribute to under-reporting when RH is rising in the bottom edge of a moist layer. In the cases selected, times between reports were such that this effect should have accounted for at most a fraction (1% or 2%) of the 4% allotted for manufacturing tolerance. We feel that the criteria used for cloud exclusion were reasonable and conservative on average.

A check on the exclusion of soundings penetrating clouds can be made by estimating the average area covered by clouds, based on surface observations in the four categories 0 to 3/10 cloud cover. Reasonable allowance for poor observation at night, and conversion from sky-dome coverage to areal coverage, yields a range of 10 - 30% area covered. This easily encompasses the 23% of soundings which were actually excluded based on the cloud penetration criteria.

Reported RH **without** corrections was used to calculate the excess water content of remaining soundings. This approach was conservative (used RH values probably lower than actual) because of thermal and time lag in the bottom edge of moist layers, and because of thermal lag in interior layers. In the upper edge portion where RH is falling, the time lag contributes to higher than actual reports. However, upper edge moisture was significant in only 7 of the 25 soundings showing calculable excess water vapor, and in each case the estimated time lag error was insufficient to negate the conservative influence of the thermal effect. Interpolation on layer edges was done in terms of water vapor pressure.

This survey was designed to provide a conservative estimate of the distribution of excess water vapor contents indicated in Figure 4, rather than accurate calculations for individual layers. Figure A2 indicates the sensitivity of excess vapor density to changes of only a few percent RH, which limits the certainty of such calculations for individual cases (manufacturing tolerance alone allows ± 4% RH accuracy). A less conservative but reasonable alternative to using reported RH in the calculations would have been to add the minimum thermal lag correction (3%) first; a trial calculation showed this would have doubled on the average the excess water vapor contents of the layers shown in Figure 4. In Figure A3 is plotted the maximum indicated RH for each layer in the sounding pool which had at least 60% RH. It can be seen that adding 3% prior to calculation would also have increased the number of layers exceeding ice saturation, assuming the same procedure for excluding reports in clouds had been used. So

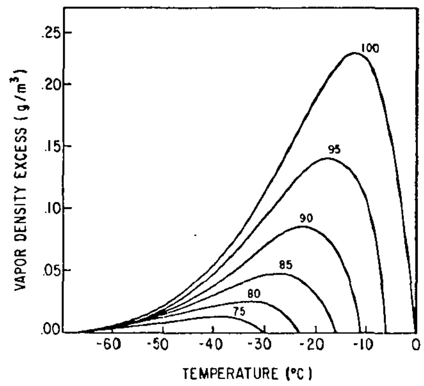

Figure A2. Dependence of excess vapor density above that corresponding to ice saturation, for various relative humidities. Derived from the Goff-Gratch formulas for equilibrium vapor pressure.

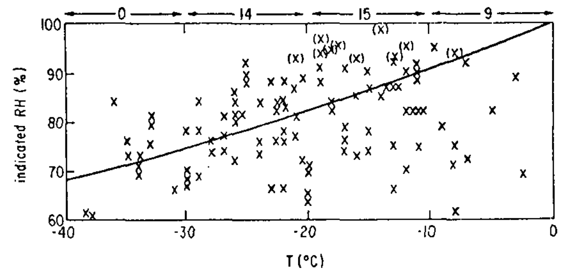

Figure A3. Maximum reported relative humidity in each moist layer, in the 110 soundings meeting the cloud conditions, for which reported RH exceeded 60%. Numbers of reports of 100% for four temperature ranges are indicated above the RH = 100% line. Those layers plus the ones plotted in parentheses were excluded as likely having been made in cloud. Some soundings had more than one moist layer, which accounts for any apparent lack of correspondence between this plot and the sounding statistics in the text.

the actual average excess water vapor content and frequency of clear, ice-supersaturated layers may be considerably higher than the conservative estimate given in Section 6.

APPENDIX B

The equations governing particle growth in a layer follow those of Barkstrom (1978). Particle growth is determined by water-mass continuity and total energy conservation at the surface of an ice particle in an environment with specified temperature, vapor pressure, and net radiative flux divergence.

$$\frac{dM}{dt} + 4 \pi C D f_1 (\Delta \rho) = 0$$

$$L\frac{dM}{dt} + Q - 4 \pi C K f_2 (\Delta T) = 0$$

where M is the particle mass, C is a capacitance factor which is the equivalent spherical radius of non-spherical particles for diffusive processes, the f's are combination ventilation and kinetic correction factors for the motion of vapor and air molecules near the surfaces of small falling particles, $\Delta\rho$ is the difference in vapor density between the equilibrium value at the surface and the environment, D and K are the diffusivities of vapor and heat, respectively, L is the latent heat of deposition/sublimation, Q is the rate of radiant energy gain by the particle, and ΔT is the temperature difference between the particle and the air.

Barkstrom derived analytical expressions for the rate of change of mass with time and for the particle temperature by solving these equations simultaneously. He used a linearized form of the Clausius-Clapeyron equation for the variation of saturation vapor pressure with temperature, the ideal gas law, Kelvin's expression for the vapor pressure over curved surfaces, and he included the effects of a solute on equilibrium vapor pressure. His resulting equations are basically the classical microphysical particle growth equations (Howell, 1949) with the addition of a radiant energy term.

The diffusivity of vapor and heat through air are taken from relations given by Pruppacher and Klett (1978). The relations between particle length, mass, and fall speed are from Heymsfield (1972) for bullet-shaped crystals. Particle surface area is estimated as 20% higher than that of a hexagonal column with the same width and length.

The flux through the cloud of radiant energy in the 0.4-4 μm and 8-12 μm spectral regions is calculated assuming the cloud is horizontally infinite, with fluxes specified at the upper and lower boundaries. The effects of water vapor and other gases in these spectral regions can safely be ignored. The delta-Eddington radiative transfer formulation is used (Shettle and Weinman, 1970; Joseph et al., 1976) and is solved by the matrix inversion technique described by Wiscombe (1977). The net absorbed flux is determined for each layer and is divided equally among the particles in that layer. Cloud microphysical evolution is then calculated assuming these fluxes stay constant for 60 seconds until the next flux calculation is made.

Calculations using the model show that the mixing ratio of ice in air is typically small in cirrus clouds at low temperatures. So heating processes important to the ice crystals will be relatively unimportant to the volume of air in which they are dispersed. Even strong particle heating and cooling by latent heat exchange during growth or evaporation, or by radiative absorption or emission, will not usually influence air circulations. At high concentrations (10^4 per cubic meter) of large particles (approaching a millimeter in length), latent heat or radiative heat exchanges may become important to the circulation dynamics of the cloud. High concentrations of large crystals in cirrus clouds are usually found only in convective types, like the cirrus uncinus discussed by Heymsfield (1975a). While clear-air seeding may occasionally result in the formation of such convective clouds, past experiments show that this will not often be the case (See Introduction). We assume that the particles' energy exchange with its environment will not affect cloud circulations, and have focused attention on stratus clouds in this study.

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NATIONAL CLOUD-SEEDING OPERATION 1982-83

J.S. Stevens
Department of Meteorological Services
Zimbabwe, Africa

1. GENERAL BACKGROUND

The Meteorological Department Cloud-Seeding Research Programs have carefully observed more than 250 cloud seedings under controlled experimental conditions so that many fundamental aspects are reasonably well understood. In general, clouds in Zimbabwe are suitable for seeding if they are well-rounded cumulus types, with tops reaching to the -10°C level, which is about 6,400 meters above sea level.

In 1972 the National Cloud-Seeding Operation (NACSO) was organized to enhance rainfall amounts over areas where marginal rainfall and occasional drought conditions can produce a severe stress on the agricultural community.

NASCO was originally organized under the control of a broad based committee consisting of representatives from the Ministry of Agriculture, the Division of Water Development, Air Force Zimbabwe, with the Director of Meteorological Services representing the Ministry of Transport. The function of the committee has been to decide the broad thrust of operations within the overall national interests.

During the 1982-83 season, this Control Committee was comprised as follows:

- Mr. C.B. Archer, Chairman, Director of Meteorological Services, Representing the Ministry of Transport
- Mr. N. Thomas, Agritex, Ministry of Agriculture
- Mr. R. H. G. Howden, Agritex, Ministry of Agriculture
- Mr. P. Silk, Agritex, Ministry of Agriculture
- Eng. J. C. Johnston, Division of Water Develop.
- Mr. J. Kreft, Deputy Director of Meteorological Services
- Mr. J. S. Stevens, Coordinator, NACSO
- W/Cdr. D. Thorne, Air Force Zimbabawe

The Committee met at Meteorological Service Headquarters on 12 October 1982 and approved the arrangements for the 1982-83 season.

2. BASIC PROJECT DESIGN

The Zimbabwe cloud seeding program has been designed to utilize the airborne dispersal of silver iodide particles by direct injection into cumulus cloud developments at the -10°C level. Three aircraft with a pool of fully instrument rated pilots were organized from United Air Charters (UAC). The disposition of the aircraft in the project area were as follows:

Harare Airport:
One turbocharged 56 TC Baron
One standard C55 Baron

Bulawayo Airport:
One standard C55 Baron

A map of the cloud-seeding areas is shown in Figure 1.

For the two aircraft based in Harare and for the one in Bulawayo, the cloud seeding pilots need to be fully competent to fly the aircraft on instruments, in severe turbulence, and during heavy icing conditions. It requires training and practice to enable the cloud seeding operator to carry out the basic procedures in the aircraft, fire the pyrotechnic seeding devices at the critical moment, keep the recently seeded cloud under observation, and maintain a log sheet on aircraft height, ambient air temperature, geographical position, and observe results of the seeding.

During the 1982-83 season, the Project Coordinator carried out preliminary training and reviewed each day of the season from 15 November through 14 April for the feasibility of cloud seeding. Because the season opened with serious water shortages, it was emphasized that every effort must be made to enhance rain by seeding whenever, and wherever possible.

Each day the Project Coordinator makes provisional arrangements for the requirements of aircraft, pilots and cloud seeding operators in both Harare and Bulawayo for the following day. On the day in question, the PC usually begin a decision making sequence at 0730. Seeding potential is continuously reviewed up to the time of take-off or of cancellation for the day.

Accurate timing of take-off is probably the largest single factor in determining the economics of the operation. Ideally, each aircraft should complete its climb to the -10°C level over its seeding area just as the cloud top reaches this level. In such a case, seeding can begin without any waste of flying time, and the maximum possible number of clouds can be seeded before fuel and oxygen consumption enforce a return to base.

If indecision or any other reason causes the aircraft to still be on the ground when it can be clearly seen that clouds are seedable, then $20,000 worth of yield could easily be forfeited while the seeding aircraft is climbing to the proper altitude. The simple alternative of being on station ahead of time is also expensive. Some $500 or more worth of flying time could be wasted while waiting for the clouds to mature. Even more expensive is the risk that a further $20,000 of yield may have to be forfeited because fuel has run too low for the aircraft to remain on station and seed clouds which later reach the -10° msl altitude.

3. THE 1982-83 RAIN SEASON AND SEEDING OPERATIONS

The 1982-83 season followed immediately upon a serious 1981-82 season which produced drought

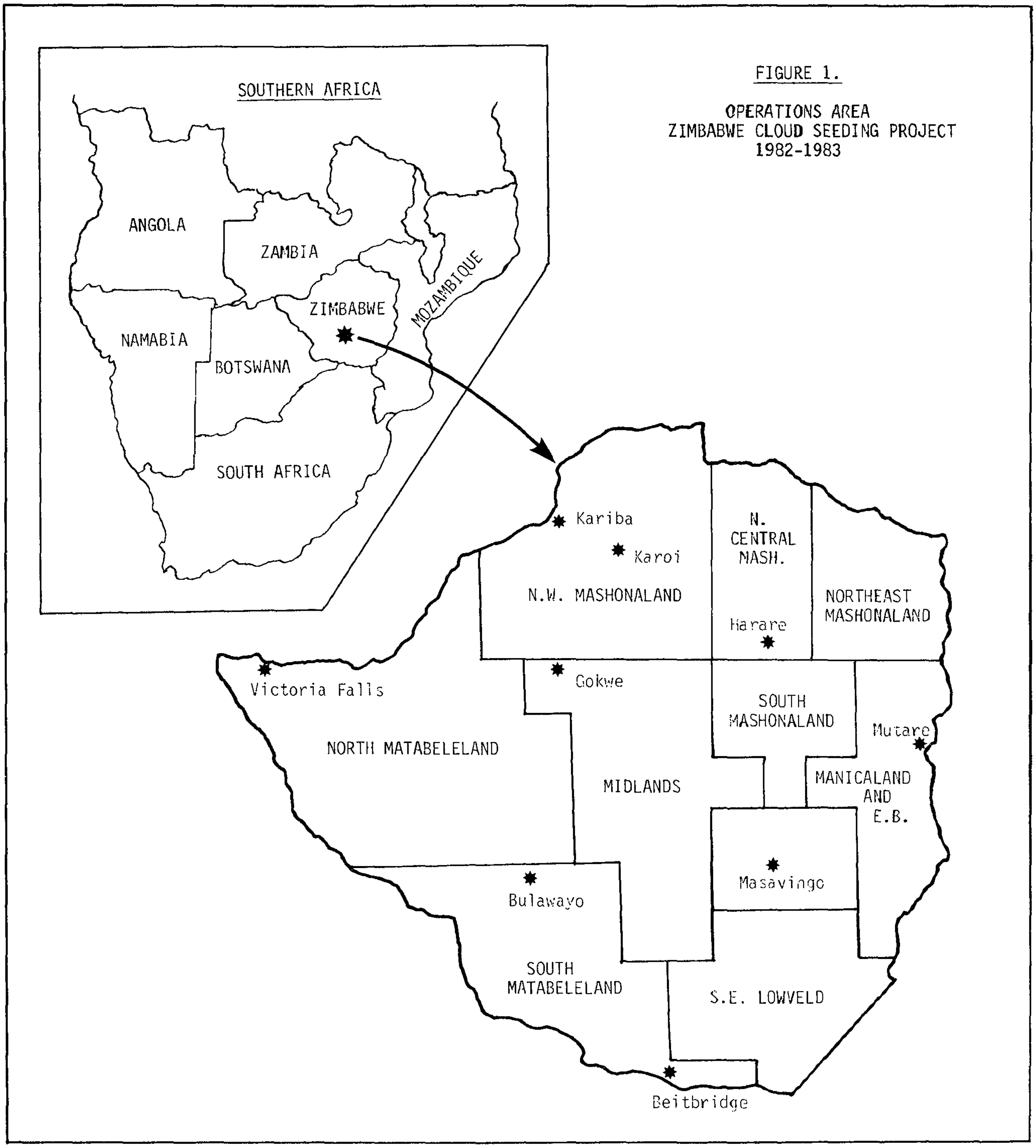


FIGURE 1.
OPERATIONS AREA
ZIMBABWE CLOUD SEEDING PROJECT
1982-1983
SOUTHERN AFRICA
ANGOLA
ZAMBIA
ZIMBABWE
MOZAMBIQUE
NAMABIA
BOTSWANA
SOUTH AFRICA
Kariba
Karoi
N.W. MASHONALAND
N. CENTRAL MASH.
Harare
NORTHEAST MASHONALAND
Victoria Falls
Gokwe
SOUTH MASHONALAND
Mutare
NORTH MATABELELAND
MIDLANDS
MANICALAND AND E.B.
Masavingo
Bulawayo
SOUTH MATABELELAND
S.E. LOWVELD
Beitbridge

conditions over most of Zimbabwe except for the northeast corner. Since records have been organized dating to 1887, this is the first known case of two successive droughts of such severity. The odds against this occurrence are on the order of 100 to 1.

From about 10 November until 28 December, there were several occasions when the onset of "the rains" seemed likely within the next two days. At Christmas the prospect seemed no worse than a late start to the rain period. However, on 29 December the Botswana Upper High reformed and seriously restricted the approach of rain. Hopes revived on about 13 January as Cyclone Elinah moved into the Mozambique Channel. Welcome scattered rain and showers occurred until 23 January, although south of the watershed the showers were few.

On 25 January hopes returned for resumption of rain in northern areas but were once again dashed on the 28th with clear weather. A spell of intermittent rainshowers beginning on 1 February brought some relief to most areas and this situation continued until the 14th. Very dry air generally prevailed from February 16th until about March 2nd. From March 3rd to 10th there was some rain in most districts. After another dry interval, the period from March 20th until the 25th offered many convective clouds but relatively few showers. The first half of April gave unusually hot humid weather which offered only a scattering of convective clouds.

By the end of the season about half of the country, much of the northeast, most of the central watershed area, plus southeast and south Matabeleland had received only 40% to 60% of normal rainfall. Many districts expecting 900mm of rain received a scant 600mm, while districts which usually averaged 600mm received only 300mm.

The main cause of this serious shortage of rainfall was the recurring formation in the middle levels of the atmosphere, of an anti-cyclonic circulation which was much more extensive than the notorious "Botswana Upper High" and much more serious. Much of the southern half of Malawi and Southern Zambia also suffered drought.

During the first seven weeks of the season, moisture in the lower levels often produced apparently favorable cumulus clouds to develop, only to be overlayed by very dry air at about the -6°C level. In spite of the favorable appearance to farmers desperate for rain on the ground below, these clouds were simply not quite high enough for successful seeding.

During early January, a time when the atmosphere would normally contain high moisture content, there was exceptionally dry middle level air down to 4,000m above sea level. Instead of the main rains being in full spate, there were blue skies and searing hot sunshine.

Throughout the operations area, the numbers of clouds seeded totaled 2,184. The seeding events in each quarter square are shown in Figure 2. A comparison between seeded clouds in the 1981-1982 and 1982-1983 seasons are listed as follows.

	82-83	(81-82)
Northwest Mashonaland	179	769)
North Central Mashonaland	315	)
Northeast Mashonaland	110	517)
North Matabeleand	460	571)
Midlands	307	358
South Mashonaland	252	321
Manicaland/Eastern Border	125	89
Victoria	25	7
South Matabeleland	411	366
Southeast Lowveld	-	8
	2,184	3,006

The program provided three aircraft each day, except for Christmas Day and New Year's Day. Following is a tabulation of general operational information relevant to the 1981-82 and 1982-83 seasons:

	82-83	(81-82)
Number of days programmed for operation	149	151
Number of days selected for seeding	75	85
Selected days as percentage of programmed days	50.4%	56%
Number of days suitable for all three aircraft	14	11
Number of days suitable for only two aircraft	34	32
Number of days suitable for only one aircraft	36	44
Number of days unsuitable for any aircraft to try	65	
Total number of programmed aircraft days	447	447
Number of aircraft days weather unsuitable (too dry/too wet)	301	306
Number of aircraft days selected and flown) Number of sorties flown)	146	141
Number of successful sorties	133	139
Percentage of sorties on which seeding carried out	91%	98%

It is interesting to note that most of the seeding was achieved on relatively few days. Twenty-five percent of the seeding was accomplished on 5% of the days, and 50% of the seeding was accomplished on 13% of the days. By contrast, the last 6% of the seeding required the effort of 14% of the days.

Due to the pressing need for rain, aircraft had to be flown in barely marginal conditions with the hope of fortuitous success, which seldom materialized. It is noted that 65 days, or 44% of the working period, was spent in readiness and anticipation for seeding that had to be cancelled, usually because the atmosphere was too dry for development of suitable clouds.

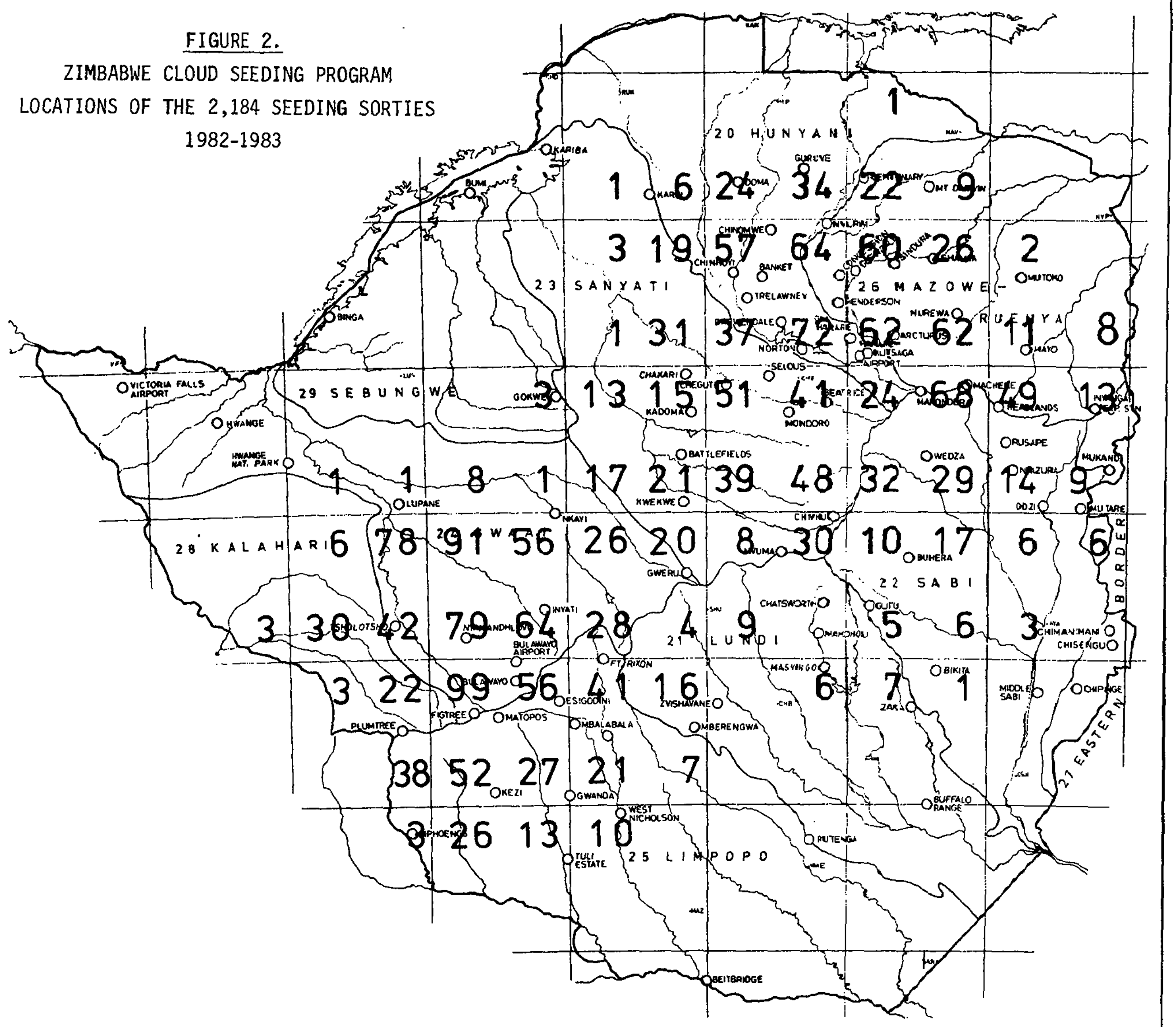
Three aircraft are deployed on days when clouds suitable for seeding are scattered over a wide area. Normally at least 60 clouds, and

FIGURE 2.

ZIMBABWE CLOUD SEEDING PROGRAM

LOCATIONS OF THE 2,184 SEEDING SORTIES

1982-1983



hopefully more than 100 clouds, can be seeded on days when all three aircraft are flown.

The following tabulation of data from airborne observations illustrates the differences between the 1981-82 and 1982-83 seasons:

	1982-83	(1981-82)
Number of cartridges fired	2,642	(3,886)
Number of clouds seeded	2,184	(3,006)
Number of clouds observed	1,283	(1,679)
Number of clouds observed to rain	198	(301)
Number of clouds observed to grow but not possible to observe base	942	(1,294)
Number of observed no change	23	(3)
Number of observed collapses	120	(81)
Number of clouds not observed	901	(1,327)

4. COST AND YIELD

The monetary outlay for the 1982-83 operation was approximately $303,000.

Research programs carried out in Zimbabawe from 1968 through 1978 designed to evaluate the average yield of one cloud seeding sortie, gave an answer of more than 120 x 10^3 m^3 or 120,000 tons of additional water.

Of the 2,184 clouds seeded during the 1982-83 season, a total of 1,283 clouds were observed from cloud-top height after seeding. It was possible to observe rain falling from the base of 198 clouds. Vertical development was seen in the case of 942 clouds where the cloud base was obscured from view. These last two figures represent a positive reaction in the case of 1,140, out of 1,283 clouds, about 89%.

In 120 cases the clouds collapsed, probably because the stimulation of marginal clouds in a dry atmosphere accelerated their dispersal by evaporation. Counting the 23 cases where seeding made no change, in 143 or 11% of the cases seeding was unsuccessful.

If the 89% success rate is applied to all 2,184 clouds seeded by aircraft, then 1,940 clouds produced a positive response.

The total cost of the 1982-83 operation includes the purchase of 5,000 pyrotechnic cloud seeding cartridges. Including training and test firings, 2,660 cartridges were used. To arrive at a reasonable estimate of cost, a credit of $45,967 must be applied for the 2,340 cartridges still held in stock. A fair estimate of costs attributable to the 1982-83 cloud seeding season is approximately ZIM. $257,100. Thus, the estimated cost of one successful seeding sortie to give 120,000 tons of additional water is calculated as:

$$\frac{\$257,100}{1,940} = \$132.53 \quad (\$85.59)$$

The cost of additional precipitation per 100,000 tons or 100 x 10^3 m^3 was:

$110.50 ($71.00)

The cost of seeding a single cloud in 1982/83 was greater than in 1981-82 as shown by the figures in brackets. The explanation is relatively simple. In 1981-82 a record number of 3,006 clouds were seeded compared with 2,184 clouds during the 1982-83 season. Input costs also escalated. Following a general rise, there was the devaluation of the Zimbabwe dollar in December and a very large increase in the cost of aviation fuel on 9 February 1983.

5. FINAL COMMENTS

The 1982-83 season was disappointing for all concerned. Being the second drought season in succession for so much of the country, the need for rain was greater than ever before yet the recurring persistence of a very dry layer of air in the middle elevations definitely ruled out the chance of seeding on many days.

The cost data show how vitally important it is for the success of seeding, especially in a poor year, that aircraft and crews are always available on call and that the coordinator is alert to every possible opportunity. There is a strong emphasis on the critical judgement required of the coordinator to identify the right seeding opportunity and to time the aircraft takeoff to achieve the greatest possible gain for the lowest cost.

Thanks for due to Messrs. United Air Charters and the pilots for their customary efficiency and cooperation, and to the Director of Civil Aviation and the Harare Airport Radar Controllers for their invaluable assistance. Finally, we offer thanks to all those persons who volunteered to act as seeding operators.

AN OVERVIEW OF WEATHER MODIFICATION ACTIVITIES IN ALBERTA

R.J. Deibert

Alberta Research Council, Atmospheric Sciences Department
4920-51 Street, Red Deer, Alberta, Canada, T4N 6K8

1. INTRODUCTION

Interest and activities in hail research and weather modification have been ongoing in Alberta for almost three decades. Crop loss from hailstorm damage has always been a major problem in Alberta. The economic losses associated with hailstorms are now up to $100 million annually. Following several years of costly hail losses in the early 1950's, independent research and operational programs began. The losses prompted farmers in a district and county north and east of Calgary to seek voluntary contributions to hire I.P. Krick and Associates of Canada Ltd. to carry out a commercial hail suppression program. Later, farmers from two additional counties joined the program and formed the Alberta Weather Modification Co-operative (AWMC). The Krick program operated from 1956 to 1968 using ground-based silver iodide generators; supplemental seeding from aircraft began in 1960 (Krick and Stone, 1975).

The farmers' concern about the effects of hail and their demonstrated support for weather modification encouraged the Alberta government to investigate the hailstorm problem. Consequently, in 1956 the Alberta Research Council persuaded the Canadian Atmospheric Environment Service and the National Research Council to join it in sponsoring the Alberta Hail Studies. The Stormy Weather Group at McGill University organized the project, with the goal of systematically observing the Alberta hailstorm in order to design and test ways of suppressing hail. This phase of research operated until 1969.

The installation of a polarization diversity S-band radar, in the late 1960's, led to single-cloud seeding experiments using droppable pyrotechnics. Area seeding experiments followed in 1972, and in 1974 a full-scale operational seeding program, the Alberta Hail Project, began under the direction of the Alberta Weather Modification Board. The Board was formed by Alberta Agriculture in 1973 to administer hail suppression and hail research programs. All provincial government funds for weather modification activities were directed through the Board. When its mandate was completed in 1980, the Board was dissolved.

The Alberta Research Council, on behalf of Alberta Agriculture (the principal funding agency), now acts as the central management and research agency for weather modification activities in Alberta. Alberta Agriculture's Advisory Committee on Weather Modification (which replaced the Alberta Weather Modification Board) provides guidance to the program.

The Research Council's Atmospheric Sciences Program is organized into two major projects, Weather Modification and Applications. These projects in turn are divided into subprojects, some of which are further divided into specific experiments. Although the program now centers on developing a weather management capability, it continues to be heavily committed to hail suppression research. It has also diversified into other areas of atmospheric and weather modification research. This paper summarized the current program and recent findings.

2. WEATHER MODIFICATION PROJECTS

2.1 Hail and Rain

The major thrust of the hail and rain project is to determine if cloud seeding can have a beneficial effect on the hail and rain processes occurring inside clouds. A secondary objective is to determine the most effective seeding techniques and agents. A third objective is to determine the economic benefits from successful cloud seeding. These benefits could be enormous, especially in southern Alberta, if significant increases in total precipitation result. A final objective of the seeding experiments on hailstorms is to document the effects of seeding later in the hail-growth process. Figure 1 depicts the project's measurement capabilities of the precipitation process chain for a typical Alberta hailstorm.

The seeding hypothesis is supported by the analysis of research aircraft cloud penetrations. Figure 2 shows marked seeding signatures in ice crystal concentrations and size distributions measured after seeding a cumulus cloud (Kochtubajda, 1983). Figures 3 and 4 also show the effects of seeding but, in this case, on a hailstorm feeder cloud (Krauss, 1983).

In conjunction with some seeding experiments, in-cloud rime ice samples were collected and analyzed for silver concentration. Generally, significant silver concentrations were found in cloud turrets seeded with silver iodide (AgI) and were not found in other turrets.

2.2 Operational Cloud Seeding - Aircraft

Each year, the project conducts an operational cloud seeding program in the southern half (24,000 km^2) of its project area (Figure 5). Four aircraft, capable of seeding from either cloud top or cloud base, seed all potential hailstorms during the operational period 20 June to 31 August. The aircraft are equipped with ejector racks containing four hundred 20 gram AgI 'pencil' flares for cloud top seeding plus either two acetone burners (2 gram AgI/min output) or two wing-mounted racks each containing sixteen 150 gram AgI fusees for cloud base seeding.

The current cloud seeding program is being

"NON-REVIEWED"

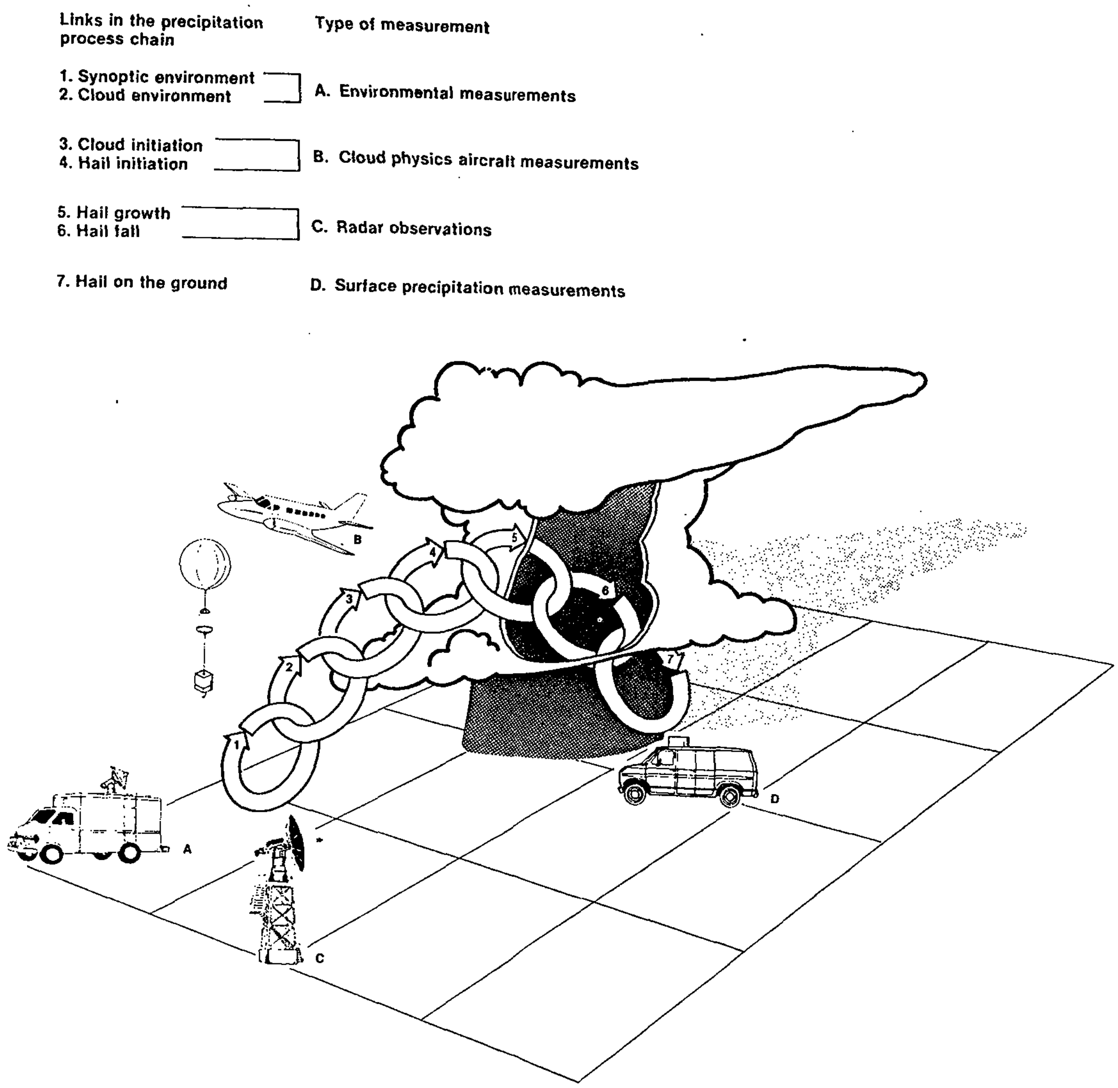


Figure 1. The precipitation process chain and its relation to the hailstorm and to various types of measurements. The macro-scale links of synoptic environment and cloud environment are investigated by means of temperature, humidity and wind measurements ahead of the storm. Droplet and ice crystal initiation processes (cloud initiation and hail initiation links) are investigated primarily through in situ research aircraft cloud physics measurements in the new growth zone. In the mature storm, the hail growth and hailfall links are studied primarily through radar observations. Finally, hail on the ground is investigated through precipitation sampling.

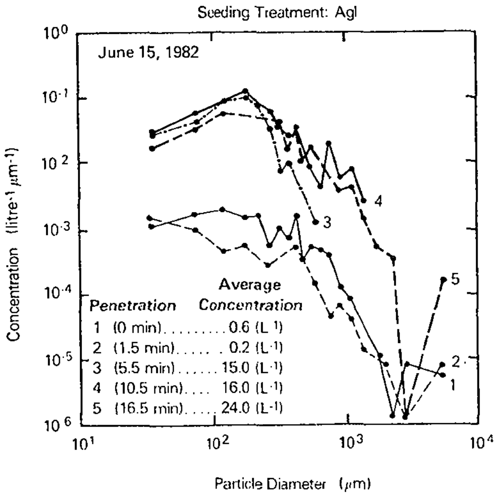


Figure 2. The ice crystal concentrations measured by the cloud physics aircraft during penetrations of a cloud seeded with AgI on June 15, 1982. Concentrations shown for the preseeding penetration are averaged over the whole cloud. For penetrations occurring after seeding, the concentrations shown are averaged over the extent of the ice crystal plume; the ice crystal plume being defined as that portion of the cloud where ice crystal concentrations are $\triangleq 10^{-1}$L (Kochtubajda, 1983)

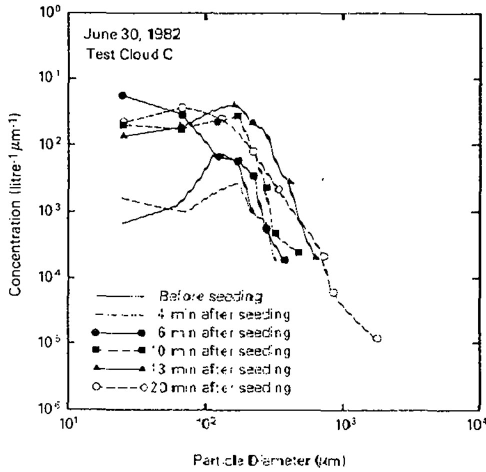


Figure 3. Evolution of the ice crystal size distribution after seeding test cloud C with AgI. The distributions are measured with a PMS 2D-C probe and are averages over the entire cloud width. The minimum detectable size is 25 µm (Krauss, 1983)

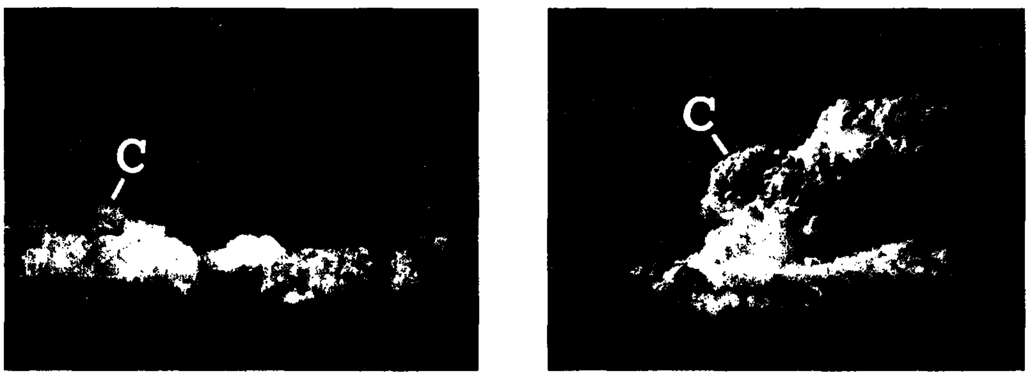


Figure 4. Two photographs of the 30 June 1982 hailstorm: (a) at 1554 looking southeast towards the southern end of the new growth zone and the seeded feeder cloud C as it appeared 5 min after seeding, and (b) at 1613 looking northwest towards feeder cloud C after it had merged with the main storm complex, 24 min after seeding.

evaluated through physical assessment of the hail and rain project described above and through a quantitative assessment that is developing statistical design and measurement criteria. Goyer and Renick (1980) discuss the results of the earlier program under the AWMB.

2.3 Operational Cloud Seeding - Ground Generators

Another operational cloud seeding project consists of a network of 92 ground-based, silver iodide generators at 69 sites in a 25,000 km² area south of Calgary. Irving P. Krick and Associates of Canada Ltd. operate the project with funding provided by Alberta Agriculture.

The Alberta Research Council will evaluate the ability of these coke and arc-type generators to deliver ice nuclei to the area of summertime convective cloud bases. Data from three seasons of research aircraft observations in the ground generator area are being analyzed. The final results of the evaluation will be available after

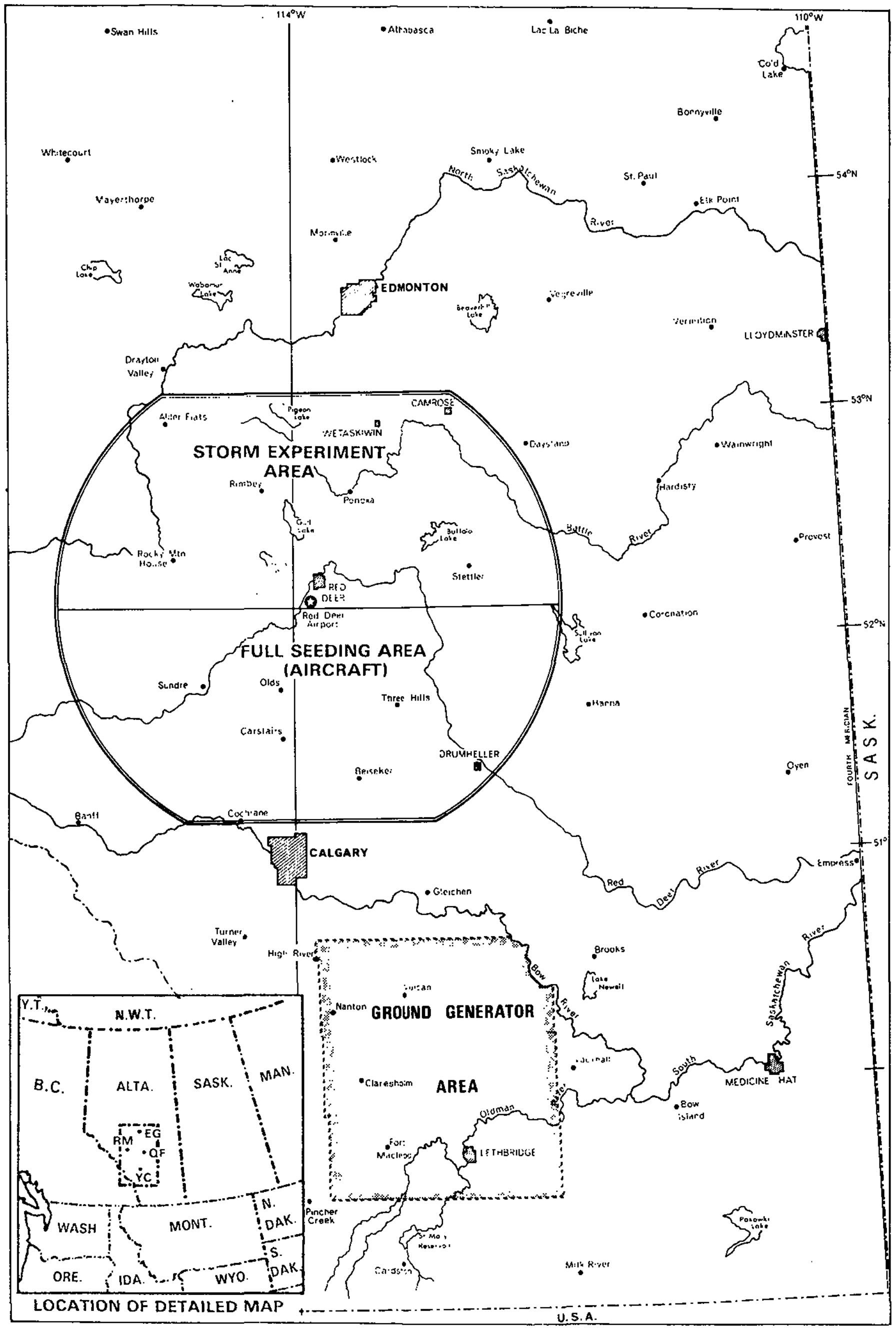


Figure 5. Atmospheric Sciences Program experiment areas. The area between Edmonton and Calgary is the principal target area of the Alberta Hail Project. The area south of Calgary is the I.P. Krick ground-based generator primary target area.

Alberta Agriculture's Advisory Committee on Weather Modification, and Alberta Agriculture, have thoroughly reviewed all data.

2.4 Sulfur and Precipitation

A project to determine if emissions from sour (natural gas) scrubbing plants affect precipitation processes was initiated. Statistical analyses of crop loss-to-risk data suggest that emissions from the gas plants help suppress hail (Wong and English, 1984).

Aerosols from gas plants and coal-fired power plants have been measured by the research aircraft on flights in both clear air and in clouds. Preliminary analyses of cloud water collections show air that is relatively clear of sulfates and nitrates.

2.5 Snow

Cloud seeding has some potential for increasing the water supply in southern Alberta by augmenting the mountain winter snowpack. Field work for the snow project has thus far been limited to four two-week periods from March 1982 to February 1984. This, unfortunately, limits data collection to only a few weather conditions that produce snow. A modest expansion will enable research aircraft, upper-air, and surface observations over a longer period. A study of the snowfall-weather system climatology will then determine the weather systems, clouds and the time periods most likely to be receptive to cloud seeding.

An analysis of measurements made in 1982 indicated that portions of one cloud system contained appreciable amounts of super-cooled liquid water that were not being effectively converted to precipitation (Krauss et al., 1983).

2.6 Weather Prediction

Statistical forecast studies center around the synoptic Index of Convection (Sc - Strong, 1979) and analyses of the boundary layer moisture field. The Sc, a statistical predictor, was originally developed as a forecast tool to predict maximum hail size for the Alberta Hail Project operations area. In recent years the Sc has been adapted as a regional predictor of maximum intensity of convective complexes. By combining the Sc with the surface Theta-E field and low-level flow fields, accurate predictions are possible of the location of storm initiation and motion, and storm intensity. Relative storm size and life history can also be inferred (Strong and Wilson, 1983). The Synoptic Index has been field-tested as far afield as Colorado and Oklahoma. Currently it is being considered for use by the Canadian Atmospheric Environment Service and agencies in the United States and abroad.

3. APPLICATIONS PROJECTS

3.1 Flow Forecasting

A spin-off project provides hydrologists at Alberta Environment with a facility for using weather radars for operational support. The River Forecast Center received a mini-computer system and color display monitor that produces real-time maps, tables and displays of radar-derived rainfall measurements (Humphries and Barge, 1979). The prototype system was successfully tested in August and September 1983. Delivery of the operational system to Alberta Environment is scheduled for the spring of 1984.

3.2 Rainsat

A research project for the Atmospheric Environment Service to improve short-term weather forecast combines the observational capabilities of the project's weather radars with GOES (Geostationary Orbiting Earth Satellite) data. The synoptic and meso-scale mechanisms that contribute to precipitation, especially from thunderstorms, are also being investigated (Bergwall et al., 1983; Strong, 1983).

Currently, both visible and infrared data sets are being examined on a particularly severe hail day, July 16, 1980. Qualitatively, the high resolution visible satellite data appears useful for determining the location of storm complexes. The infrared satellite data provide an estimate of the cloud-top temperature over a somewhat larger grid area but appear to be well correlated with the stage of storm development as determined from radar data. Quantitative comparisons between the two satellite data sets and various radar-derived quantities are presently underway.

3.3 Sulfur Removal

Alberta Environment and the Research Council are funding investigations into the dispersion of pollutants and the processes that produce acid rain downwind of energy plants in northeastern Alberta. This research is expected to provide more realistic monitoring procedures and emission control standards for such plants. Thus far, the maximum detected distance of sulfur dioxide transport (during the spring 1983 program) was 96 km. Gas to particle conversion to ammonium sulfate appears confined to distances close to the stack. The transformation rate of sulfur dioxide into sulfuric acid is relatively low at short travel times from the stack, equivalent to only a few tenths of one percent of SO_2/hr. An increase in sulfuric acid production seems to occur further downwind.

4. ATMOSPHERIC SCIENCES FIELD PROGRAM FACILITIES

Most projects in the program, which culminate during the summer months, share common data bases and support facilities. The facilities, decribed below, enable the various projects to obtain data to meet their stated objectives.

4.1 Research Aircraft

In 1981, it became imperative that if more advanced research in the field of weather modification was to continue, a full-time research aircraft must be developed. The aircraft would be equipped to penetrate clouds and instrumented for cloud physics measurements. Aircraft so equipped had been used at various times in the past, but only when funding permitted or an aircraft was available. A joint effort to purchase and equip such an aircraft was undertaken by the Research Council and INTERA, a Calgary based firm. The aircraft, a Cessna 441 "Conquest", was outfitted and tested in 1981 and used extensively during the 1982 and 1983 summer field programs. The aircraft now plays a key role in the Atmospheric Sciences Field Program by providing data for all the experiments. In addition to measurement of state parameters, the aircraft carries an array of PMS probes (FSSP, OAP-2D-C, OAP-2D-P), ice particle counter, liquid water meter, aerosol sampling manifold and cloud dynamics instrumentation. The computer-based data acquisition system permits real-time analysis and display of flight conditions and sensor data.

4.2 Radar

The project operates two radars for weather observing and one for aircraft tracking. The primary research weather radar is S-band with a beam width of 1.15 degrees. The variable polarization antenna rotates at 8 rpm and operates in a 1 degree per revolution spiral scan, programmed at either 8 or 20 degree elevation cycles. The antenna is capable of transmitting eliptically polarized radiation at any chosen axial ratio and orientation. The received radiation is then resolved into its main and orthogonal components. The radar provides information about the size, number density, shape and orientation state of hydrometeors.

The C-band, secondary radar is used for routine weather watch or if the S-band is not available. The radar has a beam width of 1.5 degrees per revolution, programmed for either 9 or 21 degree elevation cycle. During the operational field season, the C-band radar usually operates 24 hours a day, the S-band whenever research or operational usage is required.

The X-band radar is an aircraft tracking radar with a frequency adjustable receiver. The radar pulse interrogates project aircraft transponders which then reply with coded pulses at receiver frequency. This way, only the aircraft can be detected and weather echoes are not observed. Different transponder pulse codes allow identification of each aircraft. The radar has a 1.0 degree horizontal and 16.5 degree vertical beam width, eliminating the need for an elevation drive.

4.3 Field Computing

The project has three computers at the field site dedicated to a) radar data logging, display and calibration (DEC, PDP 11/34) b) research aircraft (DEC, VAX 11/750) and c) flow forecasting (DEC, PDP11/44). These computers also form part of a computer network, and support various data acquisition, display and monitor systems at Penhold and data analysis systems at the department's Edmonton office. Computer support in Edmonton includes a VAX 11/780 and a DEC PDP 11/50.

4.4 Weather Services

The project maintains and staffs its own weather office and two upper-air stations during the field season. Daily weather briefings are held before beginning operations. The briefings cover such vital details as on-set time, development area and intensity of convection, plus a maximum hail size forecast and next day outlook. The upper-air stations (Calgary and Panhold) each make a morning and afternoon sounding. Close liaison is maintained between project and Atmospheric Environment Service meteorologists to keep abreast of rapidly changing weather patterns.

4.5 Hail Surveys

Hail storms within the project area are surveyed routinely. A computer-produced map of maximum radar reflectivities for the day is used to define tne storm survey area. Telephone lists of farmers in the survey area are distributed to the project's operators who then request the information as outlined on the hail or rain reporting forms. Similar reporting forms are also mailed to all Alberta farmers in order to gather additional storm information throught the province.

4.6 Precipitation Recording Network

A volunteer-operated precipitation recording network is set up each year in a 34,000 km^2 area within the project's target area. Some 600 stations record daily rainfall for June, July and August. Monthly rainfall maps are produced for the annual field program report and distribution to the farming community.

4.7 Storm Chase

Crews in three specially modified and equipped vehicles are directed underneath the high reflectivity zones of hailstorms to collect sequential, time-resolved hailstone samples and rainfall rate measurements. The collected hailstones are quenched in heptane (at dry ice temperature) to preserve the crystal structure. The hail samples provide information on the changes (with time) in the size distributions, axial-ratio, internal structure, embryo type, isotope content and chemical composition of the hailstones. From the rainfall rate measurements, radar reflectivity values can be obtained.

5. SUMMARY

The Alberta Research Council has now completed the third year of its current five-year program, following which an assessment of all five years will be made. From this, decisions will be made as to the future and direction of research in weather modification and the Council's Atmospheric Sciences Program.

6. ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of J. Renick, Project Manager, for his guidance in preparing this paper, and to L. Shannon for her assistance in typing and editing the manuscript. The author also wishes to acknowledge the funding support of Alberta Agriculture, the Alberta Research Council, Alberta Environment and the Canadian Atmospheric Environment Service.

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THE NATURE OF RURAL PUBLIC OPINION TO RAINMAKING IN WESTERN AUSTRALIA

G.R. McBoyle
Department of Geography, University of Waterloo
Waterloo, Ontario, Canada N2L 3G1

Abstract. The apparent success of cloud seeding attempts by local farmers in the Northern Wheatbelt of Western Australia in 1977 and 1978 led to the funding by local farmers and State Government of a three-year cloud study to ascertain the viability of a long-term cloud seeding program. To assess local social attitudes to the technology, a survey was carried out in early 1981 in the cloud study area and in two regions downwind. The results shed light on the rural public's perception of the technology; their belief in the efficacy of cloud seeding; their attitudes to liability and authority; their fears of side effects; and their views of economic benefits and losses.

1. INTRODUCTION

Much of the Australian continent is precipitation deficient and much of its farming a marginal activity, dependent each year on the arrival of suitable rains at the right time. Because of rainfall variability there is drought somewhere in Australia each year.

Parts of the Northern Wheatbelt of Western Australia were drought-affected between 1976 and 1981. The areas with severe and serious rainfall deficiencies for three months or more for the 1974-1981 period are indicated in Figure 1. In 1977-1978 2,600 farmers were hit by drought and in 1979-1980 1,380 farms were declared drought-affected (The West Australian, 1979a; 1980).

The effect on wheat production was marked. In 1975-1976, before the drought, the average wheat crop per farm in Mullewa, Morawa and Perenjori shires (Figure 2) had been 981, 840 and 938 tonnes respectively, whereas in 1979 the production for the same three shires was 775, 56 and 210 tonnes respectively (The West Australian, 1979b). Further estimates suggest that wheat farmers of the three shires of Mt. Marshall, Perenjori and Dalwallinu have lost well over $100 million in crop production alone between 1976 and 1980 (Zekulich, 1980).

2. CLOUD SEEDING ATTEMPTS

In 1977 a group of about 500 farmers in the Morawa region, calling themselves the "Northern Rain Seekers' Association", contributed $27,000 for a cloud seeding operation which lasted from late July to mid October. The group was aided in its mission by the Western Australia Department of Agriculture, and the operation was supervised by the senior Commonwealth Scientific and Industrial Research Organization (CSIRO) cloud seeding officer. Interest in the project was stimulated by his comments:

> There were good reasons why it would pay farmers, and the Government, to mount a fulltime cloud seeding programme... If farmers in a wheat growing area collected $60,000 for three months of cloud seeding it would have to pay off only one year in 10 for them to be in front. (McIntosh, 1977a)

An evaluation of the 1977 project suggested, however, that only rarely were the clouds cool enough to meet the seeding criteria for silver iodide, and then they were already raining (Halse, 1978). No scientific proof of effectiveness was thus possible, although a few unusual rainfall occurrences were noted, e.g. 27 mm at Morawa West on the first day of cloud seeding (McIntosh, 1977b). The real outcome was a growing inclination towards cloud seeding by the farmers who felt the operation had been worthwhile, despite the widespread crop failure in that year (Halse, 1978; The West Australian, 1978a).

In the same year three other weather modification groups were formed: the Elsewhere Rain Inducement Committee based at Northampton; the Dalwallinu and Districts Rain Inducement Committee, and the North East Weather Research Council of Mt. Marshall. Subsequently most merged with the Morawa group to form an umbrella organization - the West Australian Weather Research Association, representing about 1,000 to 1,500 farmers (The West Australian, 1978b).

Further cloud seeding attempts were carried out by the Northern Rain Seekers group from May until September of 1978, at a cost of $17,260 (Fallon, 1981). Due to changing weather patterns, once again no conclusion could be drawn about the project's effectiveness. The continuing problem lay in finding clouds suitable for seeding during dry periods.

The farmers, however, remained enthusiastic. "Cloud seeding has become a concrete operation", the Secretary of Northern Rain Seekers' Association and Chairman of the West Australian Weather Research Association was quoted as saying, pointing to the fact that two seeded areas had both received more rainfall on one occasion than had an unseeded area in the vicinity (Weekend News, 1978).

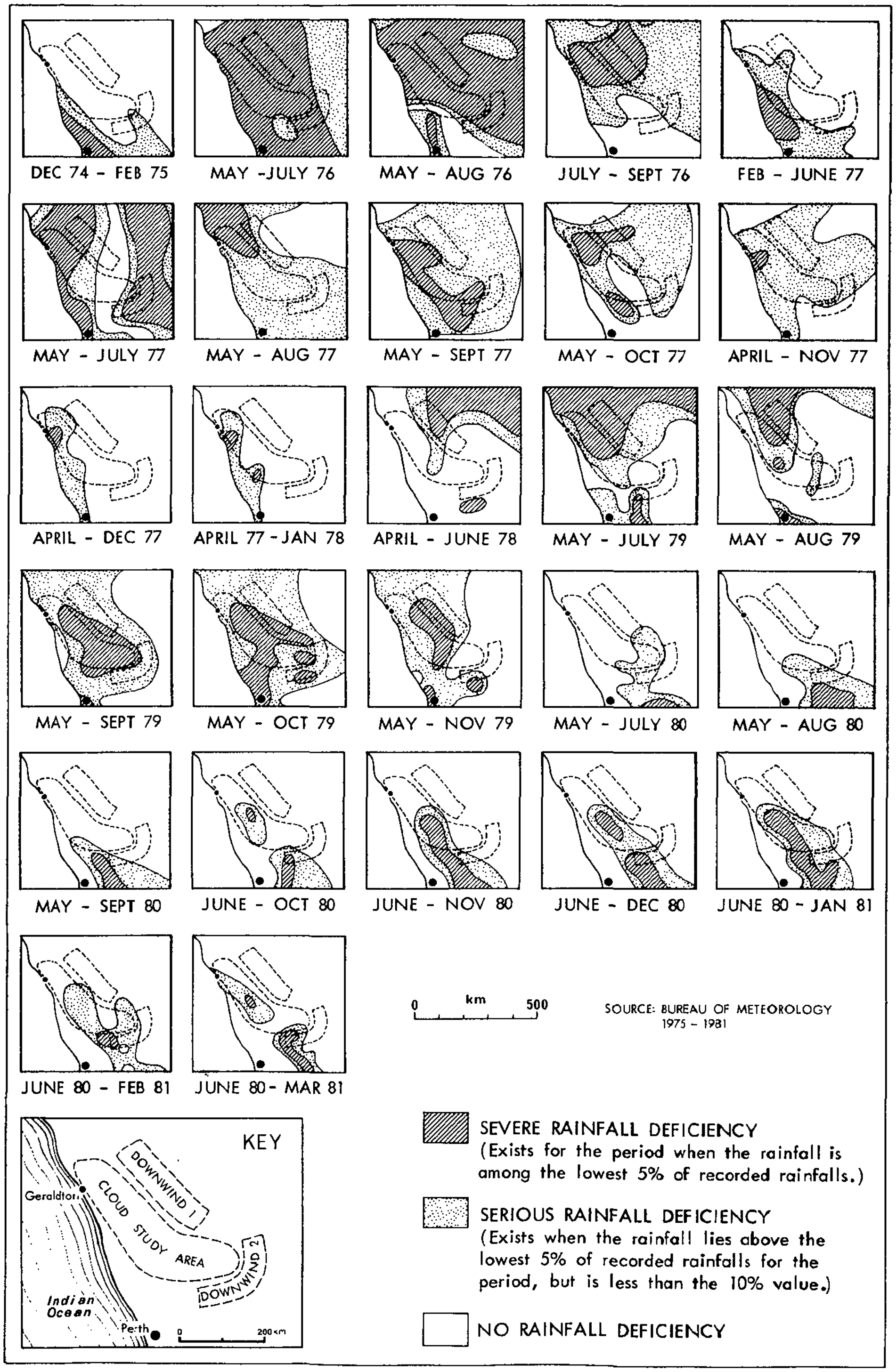

Fig. 1 Rainfall Deficiencies in the Northern Wheatbelt of Western Australia, Dec. 1974 to April 1981.

Discussions between the Western Australia Department of Agriculture and CSIRO led to the recommendation that two or three years of cloud observations in the Northern Wheatbelt were needed to ascertain whether a two to three year experiment with silver iodide seeding was warranted (The West Australian, 1978c; 1978d). Failing to receive backing from the Federal Government, the Western Australia State Government turned to the farmers themselves for additional funds (The West Australian, 1979c). Weather modification groups were requested to raise the necessary figure of $50,000 a year for three years to be subsidized on a two for one basis by the State Government (Hasleby, 1979).

The West Australian Weather Research Association collected or received pledges for the amount requested, with the Northern Rain Seekers' Association agreeing to make available to the Weather Research Association all the monies it collected from 1980 to 1982 inclusive for the cloud study (The West Australian, 1979d). On February 1980 the State Government gave the go-ahead to the Northern Wheatbelt Cloud Study which would research winter and spring cloud characteristics for three years. In the first year the Northern Rain Seekers contributed $23,800 (Fallon 1981) with each member of that group paying a levy of two cents per hectare with a minimum contribution of $50. Local businesses also made donations with one company contributing $800 (Fallon, 1981).

The Northern Wheatbelt Cloud Study, under the leadership of Dr. Bailey of the West Australian Institute of Technology, covered part or all of 12 shires (Figure 2). To oversee the cloud study the Western Australia Government set up both a management and a technical committee whose membership consisted of State, Federal and local farming interests (Western Farmer and Grazier, 1980).

The Cloud Study focussed on two major issues during the first year of operations:

a) the collection of cloud characteristics; and

b) the simulation of a cloud seeding experiment by CSIRO using data from the Northern Wheatbelt Cloud Study area.

Tentative conclusions from the cloud data suggested that "there are significant indications that a suitable number of occasions has occurred with a potential for successful seeding to give hope for a viable seeding operation" (Northern Wheatbelt Cloud Study, 1980). However it also appeared, from cloud top temperature measurements, that if a rainmaking project were to be carried out, dry ice would have greater potential as a seeding agent than silver iodide. Since some farmers in the area consider that the 1980 season had less cloud than normal, the above conclusions will have to be substantiated.

Since research was being carried out on cloud characteristics to assist in determining if a weather modification program was feasible, it was deemed an appropriate time by the author to gather public opinion data on rainmaking. The premise was that such information could be helpful in identifying concerns prior to the program's commencement.

3. THE NORTHERN WHEATBELT STUDY

The Northern Wheatbelt Cloud Study area was used as the target zone while two downwind areas were selected from zones to the east of that region. Parts of the cloud study area are known to have been previously seeded (McBoyle, 1980) but the downwind zones, as far as is known, have never been seeded. Downwind II zone is mainly a wheat producing region similar to the cloud study area while the downwind I zone is a drier, less densely populated region concentrating more on pastoral pursuits (Figure 2).

The objectives of the study were to ascertain:

a) the degree of awareness and knowledge of cloud seeding activities;
b) the degree of public approval for the use of cloud seeding technology;
c) the extent of public belief in the effectiveness of cloud seeding techniques;
d) whether any fear exists of side effects from cloud seeding activities;
e) public expectations of potential economic benefits or losses;
f) the public's knowledge of which groups support or oppose cloud seeding projects;
g) the public's awareness of legislation controlling cloud seeding operations; and
i) the public's view on compensation as it relates to cloud seeding activities.

A stratified random sample of 600 was taken from the areas' electoral rolls; 300 from the cloud study area and 125 and 175 from the downwind I and II zones respectively. The questionnaires were mailed in late February 1981 and an overall return of 40% (240) was obtained. The cloud study area had a return of 42.3% (127) and the downwind I and II zones had returns of 33.6% (42) and 40.7% (71) respectively.

3.1 Survey Results

Overall it may be said that the typical respondent in all areas was male, under 50 years of age with high school education, involved with production from the land and had lived in the area for at least 20 years.

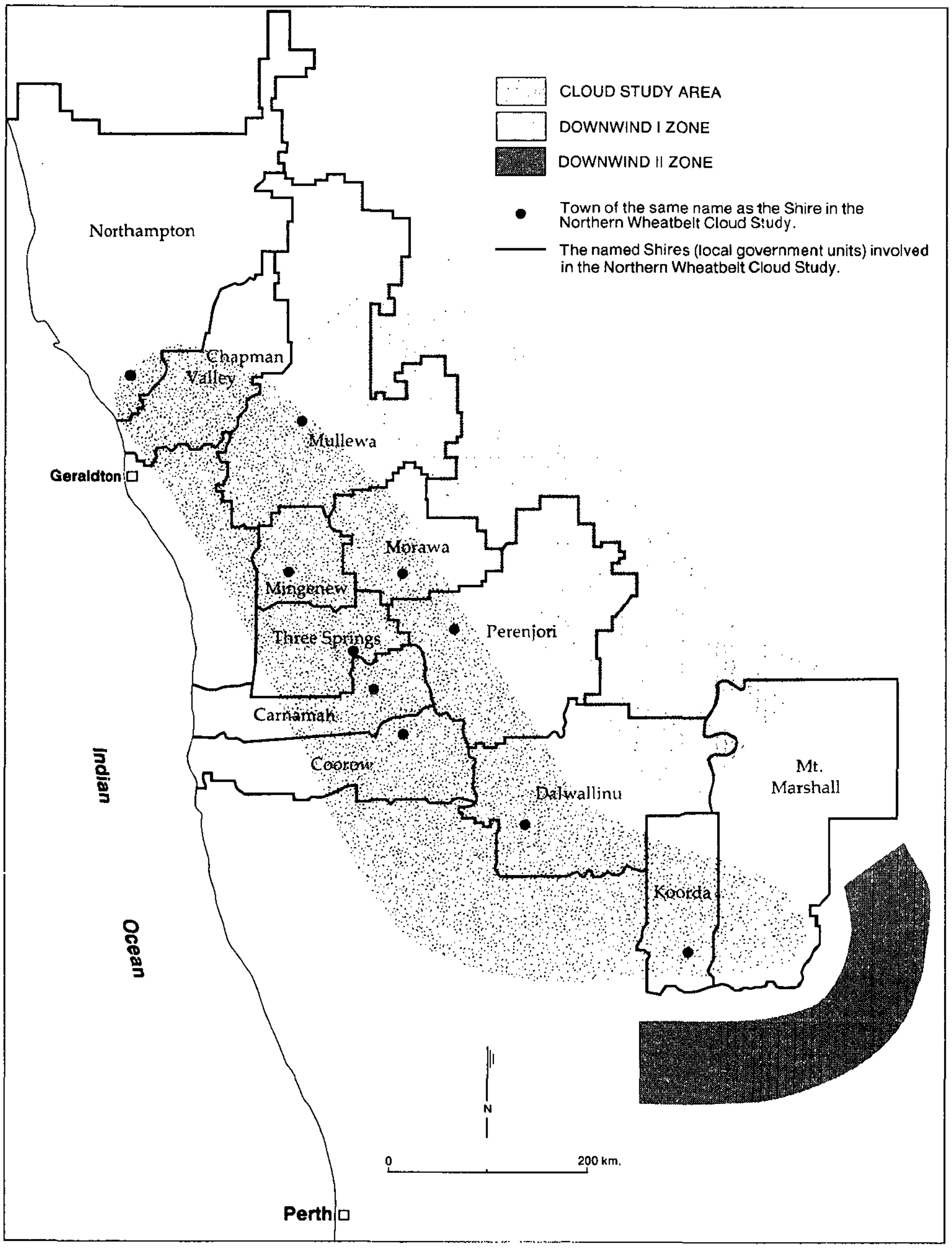

Fig. 2 Cloud Study Area and Downwind Zones I and II.

3.2 Awareness

Nearly everyone (more than 95% in every region) was aware of cloud seeding projects to increase rain with most of their information being obtained from media sources (Table 1). These percentages, although high, were not as high as those found by McBoyle (1980) in the only other attitudinal study done on rainmaking in Australia. However both studies indicate that the media appear to be the main information source on rainmaking in Australia whereas in North American studies (Haas, 1974) personal contact was rated of greater significance.

Table 2 shows that the majority of respondents (57.5%) in the cloud study area were aware that cloud seeding had occurred in their area. The percentage was lower in the other two zones. Although there have been no projects in the downwind I zone, 42.9% of respondents from that area were convinced that projects had been carried out in that zone, thereby reflecting a perception, right or wrong, of having been affected by downwind effects from the projects operating to the west of them. On the other hand, the downwind II respondents were certain (84.7%), and from the published material, correctly so, that no projects had been carried out in their area.

Although most people had heard of cloud seeding projects to increase rain it appears that the information sources were more complex in areas that have been affected or perceived themselves to have been affected by cloud seeding projects than in areas that have had no exposure to such programs (Table 2).

3.3 Belief in Effectiveness

As was the case with the information sources, there appears to be a gradation of belief in the technology's effectiveness from the cloud study area (63%) through the downwind I zone (59.5%) to least belief (48.6%) and highest uncertainty (38.9%) in the downwind II area (Table 3).

Since a belief in the effectiveness of the technique is reported to promote readier acceptance of the practice (Farhar, 1976) one would expect from the above figures that the respondents in the cloud study area would be the most open to a weather modification program with the downwind I zone respondents being the least receptive.

3.4 Side Effects

Lack of agreement about possible side effects was expressed in the figures of Table 4. However of those who were apprehensive about side effects, most cited potential problems related to an "imbalance" of rainfall (Table 5). Such a concern may relate to fears of lack of control of the technology rather than to its effectiveness. This could be viewed as similar to the "concern over risk" indicated by Farhar (1978). The idea that additional rain is gained only at the expense of rain loss in another area ("Robbing Peter to Pay Paul") was viewed as a potential problem of greater concern in the wheat growing areas than in the drier pastoral zone (28% and 13% respectively).

Questioned about possible side effects beyond the seeded area, overall uncertainty was again expressed, with the fear of precipitation loss from the "Robbing Peter to Pay Paul" concept being the dominant issue in all zones.

3.5 Information

Public meetings were considered the most suitable single means in all areas of prior notification of cloud seeding projects (Table 6). This was followed by advance notice in local newspapers in both the cloud study area and the downwind I zone (18.1% and 19.0% respectively) while the respondents of the downwind II area were equally content with advance notice in newspapers or an environmental impact statement (19.4% each). In all areas, however, more than one means of notification was favoured by 32% or more of respondents with the use of all three methods gaining the most support although being more dominant in the downwind zones.

The majority of respondents in all areas believed that there were organized groups in the State supporting cloud seeding. This belief was strongest in the cloud study area (78.7%) and weakest in the downwind II zone (69.4%). However, when it came to naming the group(s), the highest percentage of correct answers (64.6%) came, not unexpectedly, from the respondents living in the cloud study area (Table 7). However, it was surprising that only 2% of these respondents mentioned the Northern Wheatbelt Cloud Study, which had completed its first year of operations in 1980.

3.6 Economic Issues

The respondents in the two wheat-growing areas - the cloud study area and the downwind II zone - perceived the economic issue similarly; 61% considered that they would receive economic benefits from cloud seeding; 13% were unsure; and 25% were definite that there would be no economic benefits to them personally. In the drier downwind I zone, where grazing is more important, one in three saw no economic benefit while 54.8%, a smaller percentage than in the other two areas, considered that there would be economic benefits from the technology.

TABLE 1

Question: If you have heard of cloud seeding projects from what source did you obtain your information?

	CSA (Cloud Study Area)	DI (Downwind I zone)	DII (Downwind II zone)
From Friends	8.2 (%)	9.8 (%)	2.9 (%)
Public Meetings	2.5	7.3	0.0
Media (newspapers, radio, T.V.)	47.5	53.7	75.4
Government	1.6	0.0	1.4
Cloud Seeding Projects	2.5	4.9	2.9
More than one of the Above:			
Friends and Media	13.1	9.8	8.7
Media and Public Meetings	7.4 } 36.8	2.4 } 21.9	1.4 } 14.3
Other Combinations	16.3	9.7	4.2
Other	0.8	2.4	2.9
Total	99.9	100.0	99.8

TABLE 2

Question: To your knowledge, has there been any cloud seeding projects to increase rain in your area?

	CSA	DI	DII
Yes	57.5 (%)	42.9 (%)	12.5 (%)
No	37.0	52.4	84.7
Do not know	4.7	4.8	2.8
Missing	0.8	0.0	0.0
Total	100.0	100.1	100.0

TABLE 3

Question: Do you think that cloud seeding can actually increase rain?

	CSA	DI	DII
Yes	63.0 (%)	59.5 (%)	48.6 (%)
No	7.1	11.9	12.5
Do not know	28.3	28.6	38.9
Missing	1.6	0.0	0.0
Total	100.0	100.0	100.0

TABLE 4

Question: Do you think there could be undesirable side effects caused by cloud seeding activities?

	CSA	DI	DII
Yes	40.2 (%)	38.1 (%)	38.9 (%)
No	28.3	35.7	26.4
Do not know	30.7	26.2	34.7
Missing	0.8	0.0	0.0
Total	100.0	100.0	100.0

TABLE 5

Question: If yes (to question in Table 4), what kind of effects would you expect? (answers grouped).

	CSA (Cloud Study Area)	DI (Downwind I zone)	DII (Downwind II zone)
Upset the Balance of Nature	17.6 (%)	31.3 (%)	25.0 (%)
Excess Rain and Flooding	35.3 } 45.1	25.0 } 43.8	32.1 } 35.7
Rain at wrong place/time	9.8 }	18.8 }	3.6 }
Robbing Peter to Pay Paul*	27.5	12.5	28.6
Legal/Social Problems	7.8	6.3	0.0
Chemical Pollution	0.0	0.0	7.1
Other	2.0	6.3	0.0
No Answer	0.0	0.0	3.6
Total	100.0	100.2	100.0

*the idea that additional rain is gained only at the expense of rain loss in another area.

TABLE 6

Question: Which, if any, of the following do you think should be done before starting a cloud seeding project to increase rain?

	CSA	DI	DII
Advance notice in local newspapers	18.1 (%)	19.0 (%)	19.4 (%)
Public meetings	29.9	26.2	29.2
Environmental impact assessment	12.6	16.7	19.4
More than one of the above:			
Advance notice and public meeting	12.6 }	7.1 }	6.9 }
Advance notice, public meeting and environmental impact assessment	13.4 } 33.1	21.4 } 38.0	18.1 } 32.0
Other Combinations	7.1 }	9.5 }	7.0 }
None of these	6.3	0.0	0.0
Total	100.0	99.9	100.0

TABLE 7

Question: If you believe that there are organized groups in the State supporting cloud seeding, please name the organization(s).

	CSA	DI	DII
Correctly Named Organizations:			
Northern Rain Seekers	45.4 } (%)	21.9 } (%)	14.0 } (%)
The Elsewhere Rain Inducement Committee	4.0 }	6.3 }	0.0 }
The Dalwallinu and Districts Rain Inducement Committee	1.0 }	0.0 }	2.0 }
The North East Weather Research Council of Mt. Marshall	4.0 } 64.6	0.0 } 31.3	2.0 } 18.0
The West Australian Weather Research Association	2.0 }	0.0 }	0.0 }
More than one of the above	8.1 }	3.1 }	0.0 }
Northern Wheatbelt Cloud Study	1.0	0.0	0.0
Northern Wheatbelt Cloud Study and The West Australian Weather Research Association	1.0	3.1	0.0
Farmers' Groups	5.1	21.9	18.0
No Name	23.2	34.4	54.0
Others	5.0	9.3	10.0
Total	99.9	100.0	100.0

The main form of economic benefit perceived in all regions was increased agricultural production with economic spin-off being also valued in the two wheat growing areas.

Since 55% to 61% of all respondents perceived some personal economic benefit from a cloud seeding project it was interesting to note that at least one in three respondents in all areas considered that farmers alone (the group most respondents belong to) should foot the bill for such projects (Table 8). In the downwind I and II zones, 28.6% and 26.4% respectively considered that a joint payment venture between farmers and either or both State and Federal Government was also a suitable method while similar percentages of respondents in the same areas considered that government alone, either Federal, State or more frequently both, should pay the cost.

However, the reaction was different in the cloud study area. Here the respondents considered that payment should first come from a co-operative venture of farmers with the aid of Government(s) (37.8%), followed by farmers alone (34.6%) and then by either or both levels of Government on their own (22.1%) (Table 8). It was probable that the joint financial payment method was most favoured by these respondents since the Northern Wheatbelt Cloud Study, to which some of them had been contributing, was a co-operative financial venture between farmers and State Government with Federal technical assistance available when needed.

3.7 Liability

The questions in Tables 9 to 11 were designed to ascertain whether the respondents viewed commercial operations differently from scientific experimentation with regard to liability for possible damages, and to determine whom they felt ought to be held responsible for unexpected damages.

Most respondents in all areas felt that commercial operators should be liable for damages from their operations (Table 9). However, when the cloud seeding was intended for experimental purposes there was less agreement as to liability (Table 10). In this situation the percentage of those in favour of holding the operators responsible for liability dropped at least 25% in all zones. On the other hand, the percentage of those who felt that the operator should be free from liability for experimental purposes rose at least 21% in all areas.

These results tend to confirm the viewpoint determined from N. American studies (Haas, 1974; Farhar, 1975b) and the other Australian study (McBoyle, 1980), that experimental use of cloud seeding is viewed more favourably than operational use. However, with so many respondents against freeing the operator from liability for possible damage no matter the purpose of the project, it appears that some form of proof of financial responsibility needs to be included in the terms of reference of any potential weather modification progam. The use of such a safeguard has been discussed for U.S. states in Carswell and McBoyle (1983).

Regarding compensation, the respondents in the cloud study area make the same ordering of groups which should pay as respondents in the downwind II zone, but were less definite in their viewpoints. The respondents in these areas considered that the responsibility for payment should fall mainly on the shoulders of the project funders, followed by Government, either Federal, State or both (Table 11). Only a very small percentage of respondents considered that the State Government alone should bear the burden. However, one respondent in 10 in these areas considered that no one was responsible for paying compensation for the unexpected damages. On the other hand nearly one in five respondents (23.8%) in the downwind I zone considered that no one was responsible for compensation although the project funders were still viewed as the primary compensation source (40.5%) while 19.1% laid the burden on the Government. In the downwind I zone the higher percentage of respondents who considered that no one should pay compensation relates directly to the higher percentage favouring freedom from liability for operators for both commercial and experimental purposes in this area (Tables 9 and 10).

3.8 Authority

In all three areas there was uncertainty as to who holds the authority to cloud seed (Table 12). Local government was not presented in the questionnaire as one of the named categories because of two reasons. Firstly, Sato (1970) had questioned the suitability of local government as an authority unit and secondly no shire (the name of the local government unit) had ever been directly involved in the funding of a weather modification program in Australia while all the other five named categories had.

The uncertainty as to who held authority was not unexpected since there are no Australian or Western Australian statutes related to cloud seeding, although 64% of the respondents wished to see such a law. With no regulations what body did they think held the authority? What body did they think should hold the authority? and were there many differences between the answers to these two questions?

TABLE 8

Question: Who should pay for a cloud seeding project for agricultural purposes in a specific area?

	CSA (Cloud Study Area)		DI (Downwind I zone)		DII (Downwind II zone)	
Federal and/or State Government	22.1 (%)		28.6 (%)		26.4 (%)	
Farmers alone	34.6		38.1		34.7	
Farmers with State or Federal Government	14.2	37.8	11.9	28.6	4.2	26.4
Farmers with State and Federal Government	23.6		16.7		22.2	
Others	3.9		0.0		4.2	
Do not know	1.6		0.0		6.9	
Missing	0.0		4.8		1.4	
Total	100.0		100.1		100.0	

TABLE 9

Question: Do you think that cloud seeding operators, for commercial[1] purposes, should be free from any liability for possible damages as a result of their activities?

	CSA	DI	DII
Yes	17.3 (%)	28.6 (%)	18.1 (%)
No	70.9	69.0	75.0
Do not know	11.0	2.4	6.9
Missing	0.8	0.0	0.0
Total	100.0	100.0	100.0

[1]To increase rain on behalf of a client(s).

TABLE 10

Question: Do you think that cloud seeding operators, for experimental[1] purposes, should be free from any liability for possible damages as a result of their activities?

	CSA	DI	DII
Yes	45.7 (%)	50.0 (%)	44.4 (%)
No	45.7	42.9	50.0
Do not know	6.3	7.1	5.6
Missing	2.4	0.0	0.0
Total	100.1	100.0	100.0

[1]To further scientific knowledge of cloud seeding processes.

TABLE 11

Question: If there are unexpected damages as a result of cloud seeding who should pay compensation?

	CSA (Cloud Study Area)	DI (Downwind I zone)	DII (Downwind II zone)
Federal Government	6.3 (%)	4.8 (%)	2.8 (%)
State Government	0.8 } 23.6	2.4 } 19.1	0.0 } 18.1
Both State and Federal Governments	16.5	11.9	15.3
Those funding the project	38.6	40.5	52.8
More than one of the above	8.7	11.9	11.1
No one	11.8	23.8	11.1
Insurance Companies	6.3	0.0	5.6
Other	4.7	0.0	0.0
Missing	6.3	4.8	1.4
Total	100.0	100.1	100.1

TABLE 12

Question: Who do you think *holds* the authority to cloud seed an area?

	CSA	DI	DII
Federal Government	0.0 (%)	0.0 (%)	1.4 (%)
State Government	10.2	19.0	18.1
C.S.I.R.O.	13.4	19.0	11.1
Funding Bodies	12.6	9.5	6.9
Residents	17.3	21.4	11.1
More than one of the above	30.0	11.9	30.7
Do not know	15.7	19.0	18.1
Missing	0.8	0.0	2.8
Total	100.0	99.8	100.2

TABLE 13

Question: Who do you think *should hold* the authority to cloud seed an area?

	CSA	DI	DII
Federal Government	0.8 (%)	0.0 (%)	1.4 (%)
State Government	11.0	14.3	19.4
C.S.I.R.O.	18.1	28.6	15.3
Funding Bodies	3.9	4.8	2.8
Residents	22.8	26.2	16.7
More than one of the above	39.3	26.2	34.8
Do not know	3.9	0.0	6.9
Missing	0.0	0.0	2.8
Total	99.8	100.1	100.1

In the wheatbelt areas (the cloud study area and the downwind II zone) 30% of respondents considered that the authority to cloud seed an area did not lie with any single body but with some combination of the many interests involved, whereas single agencies were more favoured in the downwind I zone (Table 12). Of the single agencies, the "Residents" category received the largest number of replies in the cloud study and downwind I areas (17.3% and 21.4% respectively) while the downwind II zone respondents favoured the State Government (18.1%). In all three areas the Federal Government was considered by few respondents as having the authority to cloud seed an area although one of its agents, CSIRO, was considered the authority by 19% in the downwind I zone, 13.4% in the cloud study area and 11.1% in the downwind II area.

When the respondents were asked to name the agency which should hold the authority to cloud seed, their opinions were varied. The main contenders were the "Residents", CSIRO, State Government and a combination of authorities (Table 13). Interestingly enough the ranking of these agencies varied in each of the three areas.

The downwind II zone showed little change in proportion of respondents between Tables 12 and 13 while the other two areas indicated increases in the CSIRO, the "Residents" and the combination categories with the greater movement between categories occurring in the downwind I zone.

4. SUMMARY

Respondents living in the cloud study area previously exposed to cloud seeding appeared to have a greater belief in the effectiveness of the process, placed a greater emphasis on experimental activities and received their information about the technology from a greater variety of sources than those respondents in non affected areas.

Although uncertainty was evident in all three areas regarding the possibility of undesirable side effects from cloud seeding operations, those who were certain that there would be problems considered the main issue to be the lack of control of the rain induced. A secondary fear, more prevalent in the downwind zone than in the cloud study area, was the danger of upsetting the balance of nature as a result of the operations. Regarding the possibility of undesirable side effects beyond the area seeded, the major fear in all areas was the potential problem of "Robbing Peter to Pay Paul"; a fear which was stronger in the wheatlands than in the drier zone of downwind I.

In every area, if enough lead time was available, all three methods should be used to give prior notification of a cloud seeding project but if time was limited public meetings would be the next most suitable avenue to take.

Since most of the organized groups supporting cloud seeding were located in the cloud study area it was not surprising that three out of every five respondents from that area could correctly name such a group. Only 2% named the Northern Wheatbelt Cloud Study despite its public relations efforts at the agricultural shows in 1980 (Northern Wheatbelt Cloud Study, 1980). On the other hand, most respondents in the downwind zones could not correctly name a cloud seeding organization although most of the respondents knew of their existence.

Although respondents were divided as to whether cloud seeding operators carrying out experimental projects should be held liable for possible damages from their operations, they were much more convinced that commercial operations should be held liable. In all three areas many considered that the funders of projects should be held responsible for the compensation from the unexpected damages.

Most respondents in all areas considered that a law to control cloud seeding was needed. The group favoured most by wheatbelt respondents to be given the authority to cloud seed an area was the same one which they already believed held that authority, namely, a committee composed of many interest groups. On the other hand, the downwind I zone respondents put greater faith in CSIRO as the group to be given the authority to cloud seed an area although at the present time they believed the authority lay in the hands of the residents.

5. CONCLUSION

The findings from this survey reiterate many of those found in similar studies overseas (Haas, 1973; 1974; Haas and Krane, 1973; Farhar, 1974; 1976; 1978; Farhar and Mewes, 1976; McBoyle, 1978) and from the other Australian survey on weather modification (McBoyle, 1980). However, a crucial finding that needs reinforcing is that it would appear that where there is a stronger belief in the efficacy of cloud seeding to increase rain there will also be a greater variety of responses to questions; a greater fear of side effects within and beyond the target area mainly related to lack of control of the rain induced, and a greater belief in joint efforts whether it be payment for projects, compensation for unexpected damages or the tenure of authority for seeding, than in areas with less belief in its effectiveness.

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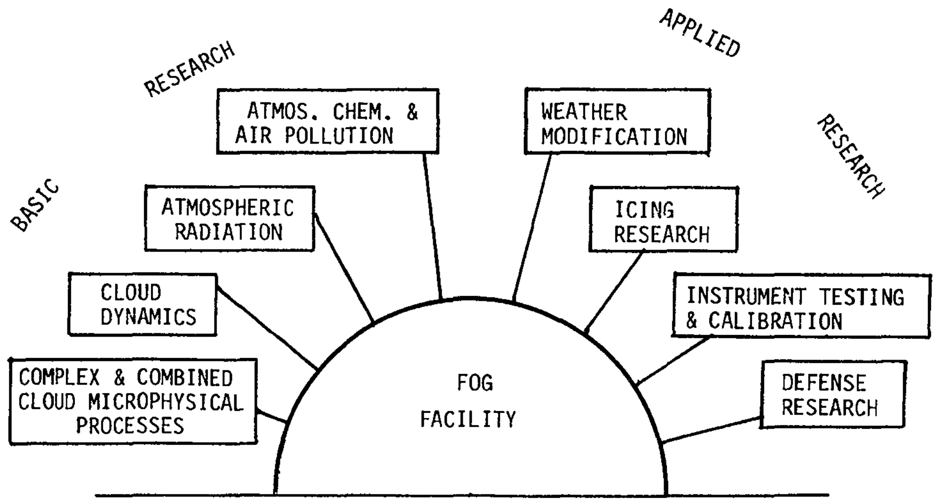
CLOUD SEEDING RESEARCH IN A FOG FACILITY



A large hemispherical balloon with a diameter on the order of 100 m (or alternatively a large air tank) containing an artificially generated fog in a Rocky Mountain high valley site making use of the cold, clean air which flows and accumulates there due to the daily radiation cooling, may prove to be useful for a variety of research studies involving clouds and fogs under supercooled and non-supercooled conditions. The facility may accommodate a horizontal high speed wind tunnel and a vertical one using the fog. An effort is currently underway to integrate interest of all federal agencies involved, and possibly of some private foundations, towards establishing a nationally or even internationally shared fog facility. Suggestions are made below for its use by the scientific and technological communities.

This facility is suitable to simulate phenomena of clouds and fogs on scales larger than the laboratory scale but smaller than in the free atmosphere. It is anticipated that the facility will find its utilization in the following major areas.

1. COMPLEX AND COMBINED MICROPHYSICAL PROCESSES:

   Ice phase and non-ice phase processes, coalescence of cloud and fog droplets, coalescence and disintegration of rain drops, diffusional growth of ice crystals, competitive growth, graupel and hail growth, heating and cooling due to phase changes, microphysics-induced dynamics, secondary ice crystal production, ice melting and evaporation, basic data generation for cloud modeling, charge generation and cloud electrification and ice aggregation.

2. INSTRUMENT TESTING AND CALIBRATION:

   Direct sensors; temperature, humidity, liquid water content, drop size distribution, ice crystal size distribution, in supercooled and non-supercooled clouds and fogs and in ice crystals of various forms, under moving or still conditions.

   Remote sensors; radar, lidar, sodar and microwaves, including ultra-high energy beams against liquid clouds, ice clouds and precipitation of various sorts.

3. ICING RESEARCH:

   Aircraft; wing performance, mechnism and instrument malfunction due to icing, helicopter rotor performance under icing condition, deicing testing.

   Automobile; wind shield glaciation due to freezing rain and melted snow and deicing device testing, highway fog and the shielding plantation.

   Ice crystal generation by sensing aircraft.

4. FORMATION AND DISSIPATION OF CLOUDS AND FOGS:

   Intermediate scale experiment of entrainment, cloud and fog formation by mixing and adiabatic expansion, effect of condensation nuclei including acid rain formation process.

5. RADIATION BALANCE:

   Simulation experiments, scattering, transmission, and reflection of electromagnetic waves in non-ice and ice phase clouds and precipitation, cirrus crystal behaviors, frost damage research involving fog and smoke method for protection.

6. CLOUD SEEDING RESEARCH:

   Special ice nuclei generator testing, homogeneous ice nucleants in particular, ice nuclei performance, nucleation mechanisms, initial behaviors of ice nuclei and ice crystals including their fall and diffusion, moisture depletion by growing ice crystals at the plume center, warm fog modification method testing.

7. AIR POLLUTION AND ATMOSPHERIC CHEMISTRY:

   Scavenging of aerosol particles by cloud droplets, ice crystals, and precipitation elements including thermo- and diffusiophoretic effect, chemical reactions and gas to particle conversion in cloud air space and droplets and resultant change of particulate characteristics after evaporation, condensation nuclei generation, residual nuclei, acid rain processes.

8. DEFENSE RESEARCH:

9. LOW TEMPERATURE TESTING OF EQUIPMENT:

   Preparation for polar and high altitude research.

10. OTHER APPLICATIONS:

    Base for other field studies, interaction between natural precipitation and artificial fog, natural fog and ice crystal studies.

Considering recent development in areas such as remote sensing, cloud modeling and airborne probing of clouds in addition to the steady progress made in laboratories, and looking into the direction of atmospheric research in the immediate and distant future, the fog and cloud facility is expected to find numerous and sometimes unique uses, some of which are not even forseen at present.

Those who have interest or suggestions on the facility, write or call Nori Fukuta

Before June 30, 1984;

NOAA/ERL/WPL/WP6
325 Broadway, Boulder, CO 80303
Tel: (303) 497-6773
FTS 320-6773

After July 1, 1984;

Department of Meteorology, University of Utah
Salt Lake City,
UT 84112
Tel: (801) 581-6136