LIMITATIONS TO DYNAMIC SEEDING OF NORTH DAKOTA SUMMER CLOUDS

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ABSTRACT. During the summer of 1981 cumulus clouds in North Dakota were unlikely candidates for dynamic seeding. Ice particle concentrations were well below 100/ℓ in feeder type clouds associated with seeded convective storms. Comparisons of aircraft measurements and the output from a one dimensional steady state cloud model were also made.

1. Introduction

Cloud seeding programs which are run entirely for research purposes offer the ideal means to study the effects of cloud seeding. In ongoing operational seeding projects, measuring effects is much more difficult. Seeding effects must be measured without undue impact on the operational program, randomization of seeding operations is usually not possible and control of the seeding operation is often outside of the research program.

Nevertheless, operational projects do need evaluation (Weather Modification Advisory Board, 1978). Some questions which must be addressed include: Is the seeding hypothesis used in the program appropriate for the types of clouds which are treated? Does the method of treatment deliver the seeding agent properly? Is the agent itself effective, i.e., is it actually having any effect on the cloud? Do the effects bear out the seeding hypothesis?

This paper describes the results of measurements taken during the summer of 1981 for the research program to evaluate the seeding hypothesis used in the North Dakota state cloud seeding project. The University of North Dakota (UND) provided microphysical measurements from its instrumented seeding aircraft, a Piper Cheyenne II, equipped for basic meteorological and cloud physics measurements, including temperature, dewpoint, rate of climb, liquid water concentration and ice particle concentration (Table 1). More information on the instrumentation and data collection procedures are given by Stith (1981).

2. The North Dakota Seeding Hypotheses

The goal of the North Dakota seeding program, given in an operations manual (North Dakota Weather Modification Board, 1980), is to provide between 1 and 10 ice nuclei per liter (active at the -10 C region in the cloud) for rain increase operations, and 100 ice nuclei per liter for hail suppression. Hygroscopic seeding is not attempted.

An in-depth review of the North Dakota operations manual (Grant et al., 1982) suggested that both microphysical and dynamic seeding hypotheses might apply to the North Dakota operations. For clouds having the potential for rain only, the rain increase operations should affect the clouds along the lines of the conceptual model used in the HIPLEX program (U.S. Bureau of Reclamation, 1979), via microphysical seeding. In more vigorous clouds which are treated for hail suppression, seeding should produce dynamic effects in portions of these systems, along the lines of the FACE conceptual model (Simpson, 1980). Both of these models provide for rainfall increase via glaciogenic seeding.

Most of the seeding during the 1981 season was at cloud base, from aircraft equipped with acetone-type silver iodide generators and end-burning pyrotechnics. More information on the seeding rates, seeding locations and method of delivery is provided in the State Operations Manual.

3. Frequency Distributions

By far the most common cloud systems sampled (or seeded) during the program were thunderstorms, ranging in size from moderate rain-producing systems to vigorous storms. Most had a region too intense to allow aircraft penetration and measurement, and measurements were limited to individual cloud elements associated with the main cell. These are usually referred to as "feeder clouds" or "daughter clouds", terms often used to describe several types of clouds:

1) New cells which will eventually grow and become the main cell (e.g. Dennis et al., 1970). Browning (1977) suggests these be referred to as "daughter clouds", since they do not feed the mature system but grow and become it. However "feeder clouds" is more commonly used.
2) New (smaller) cells which eventually merge with the main cells but are ancillary to the main system (e.g. Jameson and Heymsfield, 1970).
3) Smaller convective cells that grow and die adjacent to main cell.

Some combinations of these probably occur during the life cycle of most convective systems.

In practice, it is not always possible to separate these, either by real time observation or in post analysis. We will use the term feeder cells to refer to each of these. Understanding the physical mechanisms behind the development of the

Table 1.. Cheyenne Instrumentation and Special Equipment

Parameter	Sensor	Resolution (Nominal)
Time	Internal quartz clock	1 sec
Position	VOR/DME (aircraft)	1 deg/.1 NM
Airspeed	Gulton Industries Differential Pressure Transducer	1 knot
Pressure altitude	Aerosonic encoding altimeter	100 feet
Liquid Water Content*	Johnson-Williams LWC Meter	.1 g/m³
Temperature	Rosemount total temperature, model 102B	.1 C
Ice particle concentration*	Radke/Turner type Ice Particle Counter	1 particle/ sample volume
Event	Manual or auto switch	---
Rate of climb	Ball Variometer, Model 400/6	.1 m/sec
Dew Point	Cambridge Systems	0.3 C
Aircraft icing**	Rosemount Instruments, Model 871FA	---

Special Equipment
Aero Systems Inc./Science Engineering Associates Data Acquisition System*
Aero Systems Inc. Droppable Flare Rack*
Avcon Industries Dual Hopper Dry Ice Dispensing Equipment
Bendix Weather RADAR
Dual King Area Navigation Equipment
Dual King Nav/Com
King Flight Director

*Equipment has been modified or upgraded
**Not available in 1981

ice phase in these systems is one of the major problems in cloud physics. In the North Dakota Program newer feeder clouds are seeded, usually from cloud base.

Cloud penetrations for the research aircraft were at approximately the -12 C level (some deviations were necessary so that this ranged between -10 and -14 C). This was chosen for two reasons: The seeding agent should be activated and the growth of the ice phase is most favorable at -12 C. Repeated penetrations of the younger portions of the feeder clouds, at roughly the point where the tops pass through -12 C, were followed by penetrations in the older feeder cells next to the main echo region (Fig 1).

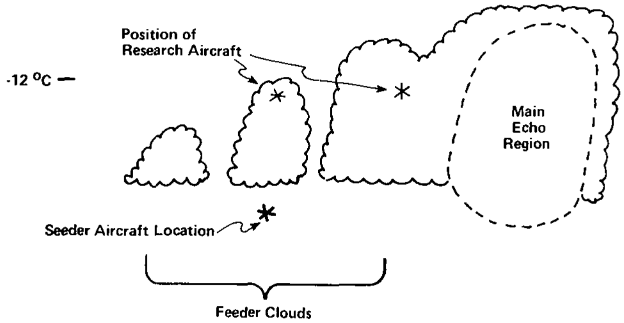

Fig. 1 Schematic cross section of idealized feeder cloud system, showing locations of seeding and of measurements.

Frequency distributions were made of data from some 200 feeder cloud penetrations, 150 in seeded systems and 50 in non-seeded (primarily out of the target area) systems. Penetrations were designated as "seeded" if seeding was conducted on the particular storm system which was sampled, with no attempt to isolate individual seeded clouds. The objective of the seeding was to seed, primarily from cloud base, feeder clouds associated with these storm features. The measurements should reflect the effectiveness of the operational procedures (i.e., the number of feeder clouds treated) as well as the effectiveness of the seeding agent.

To compute frequency distributions from measurements every two seconds in-cloud, we first determine the path length (meters) in cloud, ΔL, with concentration (g/m³,) between c and c + Δc, determined from

ΔL = (true airspeed) x (2 seconds) x ΔN

where ΔN is the number of samples with a concentration between c and c + Δc. Total path length in cloud, L, is the sum of the ΔL's. The Δc intervals are small enough to provide a reasonably continuous curve rather than a histogram type display (which would be obtained from $\Delta L/L$). Since $\Delta c << c$ and $\Delta L << L$ we use differential notation. Then

$$\int_0^\infty \frac{dL}{dc}\, dc = L \quad \text{or} \quad \frac{1}{L}\int_0^\infty \frac{dL}{dc}\, dc = 1$$

Therefore when dL/dc is plotted versus concentration, the area under the curve represents the total path length in cloud. For comparison of different sets of cloud samples we plot (1/L) (dL/dc) or (1/L) (dL/d log c) versus c (for liquid water) or log c (for ice concentrations). Threshold values of c = 0.08 g/m³ for liquid water, and 0.3/ℓ for ice concentrations are used to avoid noise in the measurements. Data below these values represent clouds taken to be free of liquid water or ice particles. In addition, a cloud must be at least 800 m in diameter to be included.

The value plotted on the ordinate in Fig 2 represents the portion of the cloud with a concentration below the threshold value. For example, the frequency distribution for a set of clouds with ice but no liquid water would contain a single point with a value of 10 (100%) on the ordinate of the liquid water distribution.

The distribution of liquid water in the seeded and non-seeded groups is approximately exponential (Fig 2). These curves are fairly well fit by straight lines, indicating an exponential relationship, i.e.,

$$P(c) = Be^{-Mc}$$

where P(c) is the probability of observing a concentration c, B and M are constants which can be determined from the intercept and slope of the lines.

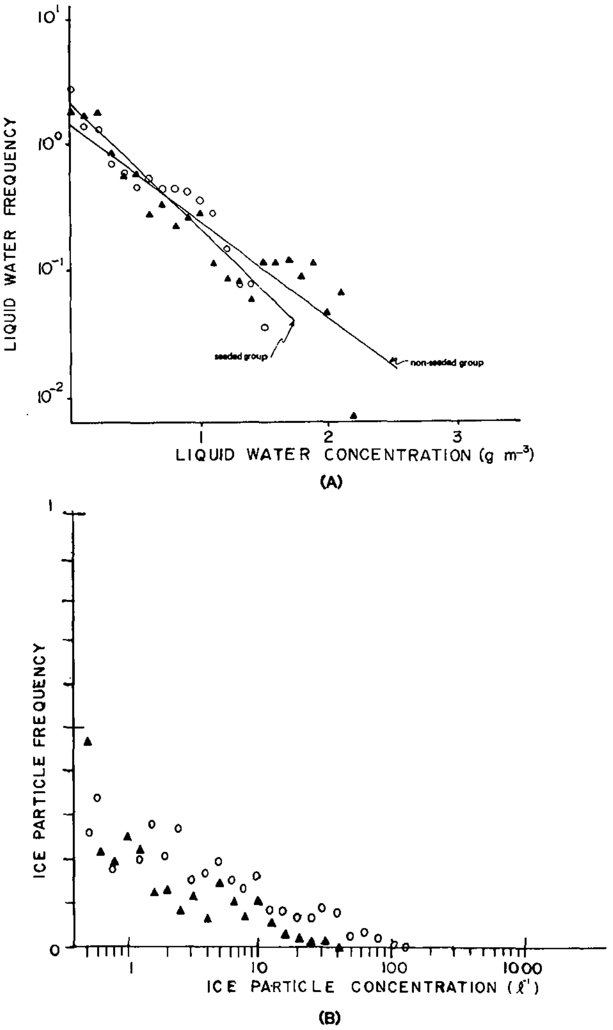

Fig. 2 Frequency distributions of liquid water (A) and ice concentration (B) for seeded (circles) and unseeded (triangles) feeder type cumulus clouds in North Dakota, during June and July, 1981. Data from seeded clouds were obtained in 150 penetrations, in ten separate storms on six days, while data from unseeded clouds were obtained in 50 penetrations in eight separate storms on seven days. The linear regression lines (B) were fit to the data.

The distributions of ice and liquid water for the seeded group are quite similar to those for the non-seeded group (Fig 2). The slight differences in the curves (favoring more ice and less liquid water in the seeded group) could be due to natural variability in the clouds which comprise the two groups, rather than an effect of seeding.

4. Comparison of Cloud Model Results With Aircraft Measurements

One dimensional (1-D) steady state cloud models are often used to predict dynamic seedability. For example, the 1-D model of Hirsch (1971) was used in the North Dakota Pilot Program (Dennis et al., 1975). The results of this program indicated increases in rainfall due to seeding on days when the model predicted dynamic seedability and no increases on days without dynamic seedability. The same model is being used in the current program as a measure of dynamic seedability (Smith et al., 1982).

The 1-D cloud model simulates one dimensional steady state storm cloud properties which cannot be compared with the aircraft observations directly. In actual clouds these properties (updraft velocity and size, liquid water, ice content, etc.) vary considerably with time. For the comparison to have any meaning, an objective means of selecting the appropriate aircraft observations must be found. The model input specifies the initial updraft size as well as the atmospheric sounding, so it is appropriate to match the size of the updraft used in the cloud model to the size of the updrafts measured by the aircraft. A reasonable choice would be to compare average observed cloud properties with cloud model output. However, a single day does not have enough observations to adequately characterize clouds of a given average updraft size. Instead the cloud penetration which yielded the maximum liquid water content on a given day was selected, because clouds with high liquid water values are likely to have substantial updrafts and the cloud pass with the maximum liquid water is more likely to have been made through the central portion of the cloud. The initial cloud base updraft input to the model was varied until the size of the model updraft at the sampling altitude matched the observed updraft (Table 2).

The observed rate of climb is an approximate measure of the cloud updraft, because the pilot maintains a constant altitude during the penetration. The model uses an exponential freezing function to convert cloud liquid water to ice between -20 C and -40 C, so no ice is output from the model (at the -12 C temperature level of the aircraft observations). However, substantial ice concentrations were observed on each day. The modeled cloud water contents are two to four times larger

Table 2. Cloud Model Output and Actual Aircraft Observations.

Date	6/17	6/20	7/01	7/10	7/11
Model Updraft Speed, m/s	12.5	25	20	29	33
Observed Peak Rate of Climb, m/s	3.5	4.0	10.5	8.7	11.0
Model Liquid Water Content, g/m^3	2.2	2.9	2.4	3.1	4.2
Observed Peak Liquid Water, g/m^3	1.29	1.46	1.29	1.1	1.05

than those observed. Both the model and the measured updrafts were positive; otherwise, there is little correlation.

The model water concentration for non-seeded clouds on June 20 falls off with the development of the ice phase (Fig 3). Since substantial ice concentrations were found at -12 C in both the seeded and non-seeded groups, the model could possibly benefit by introducing the ice phase at a lower temperature for non-seeded clouds. This should also reduce the modeled liquid water values. However, even prior to the development of the ice phase, the feeder clouds do not develop liquid water concentrations as high as the model results. The feeder clouds on June 20 all had rather similar peak liquid water contents of slightly higher than 1 g/m^3, well below the model results of 3.8 g/kg (1 g/kg$\simeq$0.76 g/m^3 of water).

5. Discussion

The results presented in Fig 2 indicate that operational seeding is not producing a large net impact on the ice and water concentrations in feeder clouds associated with seeded storm systems.

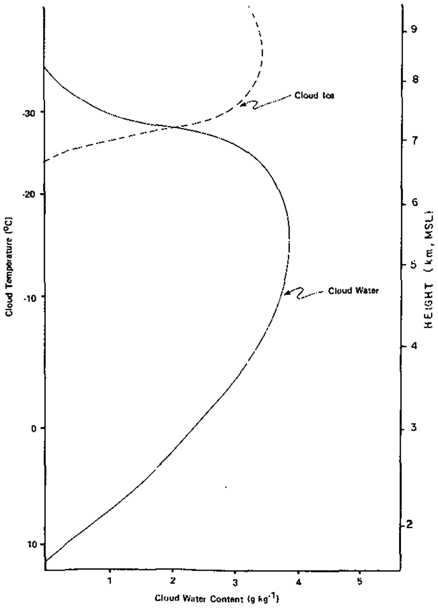

Fig. 3 Cloud water and ice concentrations predicted by the 1-D cloud model for June 20, 1981.

Virtually all of the clouds in both the seeded and non-seeded groups had ice concentrations of less than 100/ℓ, the target for hail suppression seeding. Several factors could contribute to these observations:

1) The seeding agent is diluted to near natural levels by the time the cloud is sampled.
2) The number of feeder clouds treated is small.
3) The seeding material is not reaching the proper location in the cloud.
4) The seeding material is not sufficiently active.

Lawson et al. (1980) have measured the growth rates of seeding plumes in 31 different seeding trials in convective clouds over a three year period, as part of the USBR HIPLEX program. An average of their results (their Fig 4.1.1), suggests that the diameter of a seeding plume should grow from 100 to 1300 m in about 11 minutes, which represents a dilution factor of 170. A typical hail suppression treatment method with 2 generators (total output of 8 x 10^{13} nuclei per minute) would produce a concentration of about 2500/ℓ when the plume was 100 m in diameter. After 11 minutes this would be reduced to about 15/ℓ, or about an order of magnitude lower than the 100/ℓ hail suppression goal. This assumes that there are no loss of ice nuclei. Lawson et al. included less vigorous convective clouds than those typically encountered in the North Dakota seeding operations; dilution may be even more rapid for the North Dakota clouds. Based upon these estimates, the seeding plumes may have been well diluted by the time they were sampled at the -12 C level by the Cheyenne (most clouds were seeded at cloud base).

Conditions 2), 3) and 4) would obviously reduce the impact of the seeding even further. Perhaps only a fraction of the seeding material attains the -10 to -14 C level, and dilution subsequently reduces the concentrations of ice nuclei or ice particles to near natural levels fairly rapidly.

For the dynamic seeding hypothesis to apply, the treated cloud must have a significant bouyancy advantage over non-treated clouds. Further, this bouyancy should promote cloud growth to enable the cloud to penetrate a stable layer. The bouyancy, B, is primarily responsible for the vertical accelerations, dw/dt,

$$\frac{dw}{dt} \cong B = g\left[\frac{T-T_e}{T_e} + .61\ (q-q_e) - q_L\right] \qquad (3.1)$$

where g is the acceleration due to gravity, T and T_e are the in-cloud and environmental temperatures, q and q_e are the cloud and environmental mixing ratios and q_L is the mixing ratio of cloud water. The dynamic seeding hypothesis involves seeding to promote extensive conversion of cloud liquid water to ice, relying on the latent heat of freezing to produce increased cloud temperature and buoyancy. The temperature rise which would result from a change in the mixing ratio, Δq, from water to ice is

$$\Delta T = L_f \Delta q / C_p \qquad (3.2)$$

Here L_f is the latent heat of freezing and C_p the specific heat at constant pressure. About 0.4 C increase in temperature for each gram/m³ of liquid water is predicted by Eq. 3.2.

However, not all of the heat liberated is available to increase the sensible heat: some is used in evaporating condensed water, as described by Orville and Hubbard (1973), Lamb et al. (1981), and others. Roughly 1/2 to 3/4 of the latent heat is available for sensible warming of the cloud. The results of Fig 2 indicate that only 10% of the natural feeder type cloud regions have liquid water concentrations greater than 1 g/m³; only 5% had concentrations greater than 1.5 g/m³, typically associated with hailstorms. The maximum liquid water concentration observed during 1981 was 2.2 g/m³. Thus, even if all the cloud water were converted to ice, only 10% of the feeder cloud regions would respond with a temperature increase of greater than 0.3 C. This would produce only a small increase in bouyancy (Eq 3.1) of about 1 cm/s².

6. Conclusions

These results indicate that seeded cloud regions which could have a significant buoyancy advantage over natural clouds are probably limited in North Dakota. Although dynamic seeding of a few clouds could be significant, the major opportunities seem to exist with microphysical seeding. In contrast to these results, the clouds considered for dynamic seeding in Florida often have liquid water contents well in excess of 2 g/m³ (e.g., Lamb et al.).

Smith et al. (1982) have used the 1-D model to predict the change in height (ΔH) associated with a dynamic seeding response in the 1981 clouds. Of 39 days tested, only 6 days indicated a ΔH of greater than 0.5 km. Only 2 days indicated a ΔH of greater than 1.2 km. Their results also suggest that any dynamic seeding response is likely to be limited to only a small fraction of the 1981 clouds.

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