Time-Integrated Radar Echo Tops as a Measure of Cloud Seeding Effects

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ABSTRACT

Radar echo tops of individual cells, integrated over their duration above 7.6 km, are used to define an overall storm magnitude, a growth factor after seeding, and an average seeding rate. The growth factor is then plotted as a function of the average seeding rate for 23 seeded cells and 23 randomly selected non-seeded cells. The results show an appreciable decrease not only in the range of growth factors but also in the average growth factor as the average seeding rate is increased.

Time-integrated values of other radar measures, such as reflectivity and echo coverage, that can be better related to precipitation intensity than echo tops, are suggested as more accurate and sensitive measures of the effects of cloud seeding on the radar characteristics of convective storms.

1. Introduction

In recent publications (Goyer, 1975a,b), the author seriously questions the validity of the measures, total crop damage or total hail mass, generally used in the evaluation of hail suppression experiments. Moreover, since the hailfall intensity is a measure integrated over a whole day, he proposes time-integrated radar measurements, such as echo reflectivity, echo coverage, and echo top, as measures of overall storm magnitude most strongly correlated with total hailfall intensity. Finally, he suggests that such measures permit the calculation of a storm growth factor and an average seeding rate, with which the response of the radar characteristics to seeding can be evaluated.

To test these new concepts, radar echo top data gathered in the Alberta Hail Studies (Renick, 1972) were used to compare the behavior of 23 seeded cells to that of 23 randomly selected non-seeded cells.

2. The data

The characteristics of the 10 cm radar used (Barge, 1974) and the seeding method employed (Summers *et al.*, 1971) were fully described elsewhere. Briefly, individual storm cells or turrets were seeded by dropping AgI flares into them from an overflying aircraft. Echo tops, continuously measured at a few minutes intervals, were obtained from PPI displays recorded on film, and computer generated plots of echo tops as a function of time throughout the life cycle of identifiable cells were produced (Fig. 1).

3. The data analysis

Several assumptions were made at the outset.

First, the hailstorm is defined by echo tops greater than 7.6 km, and only such tops are considered in this analysis.

Second, the initial hailstorm magnitude (before seeding), T_0, is defined by its echo top integrated from 20 min before, to the time of initiation of seeding. In other words, T_0 (km min) is the area under the curve of Fig. 1, between the time t_0 of initiation of seeding and 20 min prior to that time. It is thus assumed that the behavior of the storm prior to 20 min before seeding has no bearing on its response to seeding. In the case of non-seeded storms, there is of course no data for the time of seeding. Then the time of seeding is defined as the time when the echo top first reaches the average echo top at which seeded storms were first seeded, 10 km. The time of seeding for non-seeded storms is then the time when their echo tops first reached 10 km.

The total storm magnitude, T_1 is defined by its echo top integrated from 20 min before seeding to the time the echo drops below 7.6 km. In other words, T_1 is the area under the curve of Fig. 1, between the time the echo drops below 7.6 km and 20 min prior to the initiation of seeding, t_0.

The growth factor GF is then the ratio, T_1/T_0, of the total storm magnitude over the initial storm magnitude as defined by their time-integrated echo tops.

The seeding rate N/T_1 is defined as the ratio of the number N of grams of AgI dispersed into the storm over the total storm magnitude T_1. It is then expressed as the average number of grams AgI generated per minute per kilometer of echo above 7.6 km. It thus takes into account not only the storm duration over which the AgI was generated but, most importantly, the total magnitude of the storm, as measured by its time-integrated top, into which the AgI was dispersed. Obviously the seeding rate is only a measure of the average mass of AgI made available per unit time and height to a seeded storm. How effectively the nuclei were dispersed or the

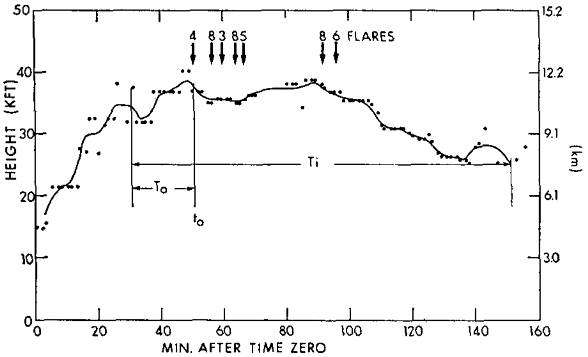

Fig. 1. Radar echo top versus time, and time and number of flares dropped into storm turret.

storm used them in modifying its radar characteristics is still unknown.

4. The results

The growth factor and the seeding rate, so defined, were evaluated for 23 seeded cells and for 23 randomly selected non-seeded cells. The non-seeded cells were selected at random from a total of 108 available echo tops vs time plots. Only those whose echo tops, in a continuous set of data, exceeded 10 km at least 20 min after the first data point and dropped below 7.6 km some time after exceeding 10 km were accepted as sample cases. A total of 89 cases were selected, and 66 were rejected in the selection process, leaving an acceptable sample of 23 non-seeded cells.

Fig. 2 is a plot of growth factors GF as a function of the seeding rates SR for all 46 cases. Seeded cases are represented by open squares and non-seeded cases by black dots, all located on the ordinate. The vertical lines show the range of growth factors and the open circles on the lines the average growth factor within 0.3 g $(\text{km min})^{-1}$ ranges of seeding rates. The curve represents the best fit through the average growth factors.

This plot shows that the range of growth factors, as well as the average growth factor, decreases as the seeding rate increases. The wide range of growth factors at the small seeding rates can be interpreted, in the light of that for nonseeded storms, as a determination of a lower seeding rate limit, say 0.9 g $(\text{km min})^{-1}$, below which seeding has no effect. However, the number of cases with seeding rates greater than this lower limit is so small that this conclusion may be premature. However, in spite of the wide range of growth factors at small seeding rates, the average growth factors can be rather well fitted with a smooth curve describing a decrease in the storm growth factor as the seeding rate is increased. This result implies that seeding decreases the duration and/or the height of echo tops greater than 7.6 km.

A cumulative frequency plot of the measured growth factors is shown in Fig. 3 for seeded and non-seeded cells, which clearly appear on this graph as two distinct samples. The graph shows, for example, that 70% of the non-seeded cells yield a growth factor smaller than 10 whereas 70% of the seeded cells yield a growth factor smaller than 3. Or, 31% of the non-seeded cells but only 13.5% of the seeded cells yield a growth factor greater than 10. Consequently, these data strongly suggest that the overall magnitude of the seeded cells is indeed different from that of the non-seeded cells. The overall cell magnitude, as measured by its time integrated echo top, is considerably smaller for seeded cells than for non-seeded cells.

Finally, the average growth factor of all seeded cells is about 75% smaller than that of all non-seeded cells.

5. Discussion

Smaller growth factors could obviously result from larger initial storm magnitudes T_0. The frequency distribution of initial storm magnitudes (Fig. 4) shows that the seeded cells indeed comprise greater initial storm magnitudes than the non-seeded cells, which in

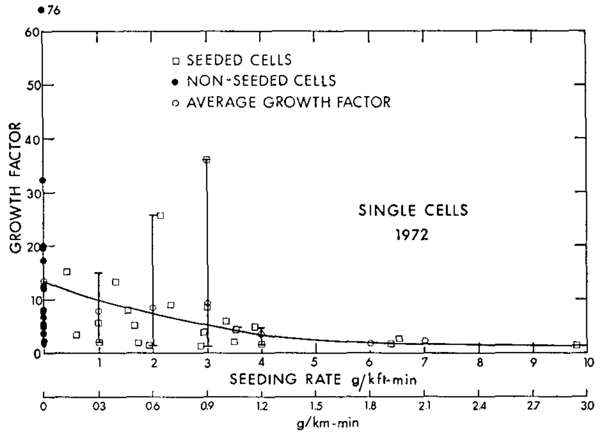

Fig. 2. Growth factor of time integrated echo top versus seeding rate for seeded and non-seeded storm turrets.

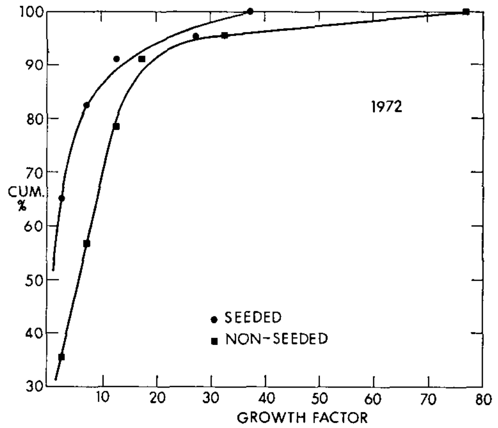

Fig. 3. Cumulative frequency distribution of the growth factors of seeded and non-seeded storm turrets.

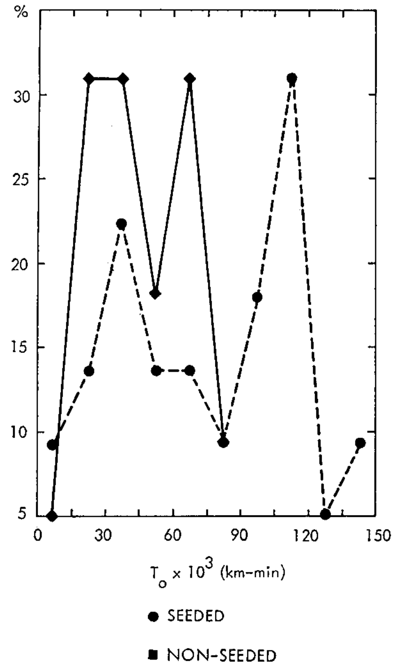

FIG. 4. Frequency distribution of initial storm magnitudes (T_0).

itself could explain at least partly, the smaller growth factors observed for the seeded cells. However the plot of growth factors (GF) as a function of initial storm magnitudes (T_0), in Fig. 5, shows that this is not the case. Indeed in 91% of the cases (GF's smaller than 20), the growth factors are not strongly related to the initial storm magnitudes. What is even more striking is that the strong dependence of the growth factor on the seeding rate is obvious throughout the whole range of initial storm magnitudes, from 20 to 120 km min, which comprises 93.5% of the total sample. Consequently, the growth factor of the seeded cells is strongly correlated with the seeding rate and not with the initial storm magnitude. The statistical significance of the differences observed between seeded and non-seeded cases was evaluated.

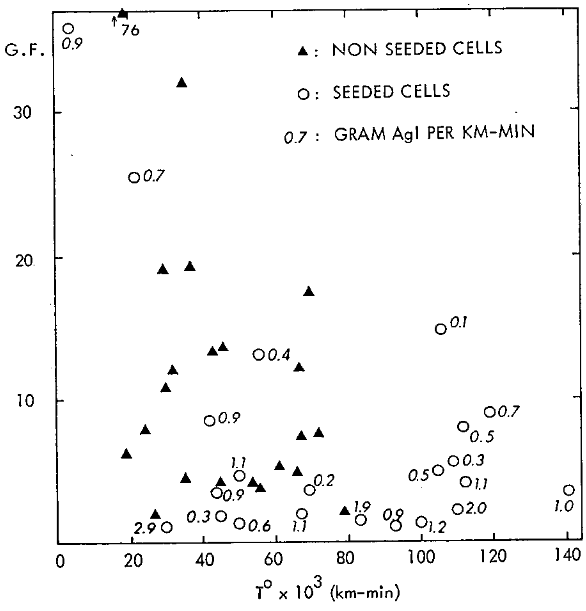

FIG. 5. Growth factors (GF) as a function of initial storm magnitudes (T_0).

The growth factors (T_1/T_0) from 23 seeded and 23 non-seeded turrets were compared. The Mann-Whitney test was used in testing the null hypothesis that the two samples were from the same population. The use of a non-parametric method in this case was considered appropriate because of the unknown distribution. The sample sizes were too small for distribution investigation, although it was obvious from the samples that both seeded and non-seeded data were highly skewed, and probably with long tails. Under such conditions, it is likely that this test would have comparable if not superior efficiency than the t test (Hodges and Lehman, 1956). In this test, the hypotheses are:

$$H_0 : f_s(x) = f_n(x),$$

$$H_A : f_s(x) \neq f_n(x),$$

where $f_s(x)$ is the probability density function for seeded storm growth factors and $f_n(x)$ for non-seeded storm growth factors. It is a two-tailed test.

With $n_1 = n_2 = 23$, the H_0 was rejected at $\alpha = 0.025$. Thus with a 2.5% level of significance, it was concluded that the growth factors of seeded and non-seeded storms did not come from the same population.

The plot of the data on log-normal probability paper also clearly indicates that the samples are from different populations. Growth factors of the seeded storms are smaller than those of the non-seeded ones. Finally, although these preliminary results are statistically significant, the proposed time-integrated echo top measure will have to be correlated with hailfall intensity before its usefulness in the evaluation of hail suppression experiments can be determined.

The physical basis for a smaller growth factor in the case of seeded cells is not at all clear. However, a possible explanation for the decrease in height may be suggested. The hail suppression hypothesis, generally favored in the weather modification scientific community, implies a total or partial depletion of the liquid water available for the growth of a number of hail embryos considerably increased after the injection of freezing nuclei into the seeded storm. Hailstone embryos grow by collecting and accreting supercooled droplets and ice crystals, in the temperature range between −6 and −40°C, therefore in an approximate altitude range between 4.8 and 9.5 km in Alberta. Consequently, the concentration and the diameter of ice crystals above the hail growth region will decrease as the supercooled water is depleted in the hail growth region by the growth of a number of embryos substantially greater after seeding. Therefore, according to this hypothesis, the radar echo top should decrease, as the radar detectability of the water substances, depleted above the hail growth region, decreases.

One may think of the growing hailstones, in concentrations increased by a factor of 10 to 100, behaving as a filter and preventing water substances from penetrating above the hail growth region in large enough concentrations to be radar detectable. This hypothesis obviously neglects the dynamic effects of seeding which, at the seeding rates measured, are expected to be rather small. In any case, this is mere speculation, and further understanding of the dynamics and the microphysics of hailstorms and of their response to seeding is obviously a prerequisite to proposing a definite explanation for the observed results.

Although these statistically significant results strongly suggest that the overall storm magnitude decreases as the seeding rate is increased, above a lower threshold, they are not presented as definite proof of a positive seeding effect. A larger number of large seeding rate cases is obviously required before definite conclusions can be reached.

However, they are presented to illustrate the new concepts and procedures proposed by Goyer (1975b) for the evaluation of hail suppression experiments and to show, by a concrete example, their possible advantages over generally accepted methods.

The evaluation of hail suppression experiments has always rested on measured differences in total crop damage or, more recently, in total hail mass in a given area. These measures of hailfall intensity are not time-resolved but integrated over a whole day. Yet one finds that attempts at correlating hailfall intensity with radar measurements have always been made with time-resolved radar measurements such as the maximum echo top or the maximum radar reflectivity. It appears obvious that the strongest correlation between hailfall intensity and radar intensity should result from the measurement of both intensities integrated over the same time period. It is fully realized that echo tops, although strongly correlated with hail occurrences, are, in all probability, the radar measure least strongly correlated with total hailfall intensity at the ground. Radar echo powers or reflectivities, as suggested by Goyer (1975), should be the most strongly correlated.

One great advantage of using a time-integrated radar measure in the evaluation of cloud seeding experiments is that it permits the calculation of an initial (T_0) and a final (T_1) storm magnitude. Thus, the test samples can be stratified with respect to the measured characteristics of the hailstorm, and the seeding effects evaluated as a function of the initial storm magnitude (Fig. 5).

Finally, the time-integrated radar measurement permits the evaluation of a seeding rate which takes into account the total storm magnitude T_1. Consequently, the seeding effects can be evaluated, as reported here, as a function of the "quality" of the seeding. Generally, the seeding effects, however measured, are averaged for all seeded cases and for all non-seeded cases and the results compared. In this manner, substantial positive effects, on small initial storms, or at large seeding rates, may be totally masked by no effects or negative effects on large intense storms and at small seeding rates. Rapid progess in the optimization of seeding techniques implies that each test case be evaluated, as much as possible, on its own merit, and not be lost in a meaningless average taken over a large number of storms of widely different initial magnitudes and seeded with an efficiency varying over a very wide range indeed.

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