Cloud Seeding Effects on Precipitation Intensity and Duration of Wintertime Orographic Clouds

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ABSTRACT

The nature of precipitation changes resulting from seeding cold orographic clouds is examined by separating the observed total precipitation change into duration and intensity change components. The total precipitation change and its two components are then evaluated as functions of cloud temperature using precipitation data recorded in the primary target area during the cloud seeding experiment conducted near Climax, Colo. The results show that the total change in observed precipitation is mainly controlled by changes in precipitation duration, rather than intensity. The main effects of seeding appear to be the initiation of a precipitation release for the warmer clouds during many hours when it would not have occurred naturally, and the suppression of precipitation for the coldest clouds during some hours when it would have occurred naturally. These results are consistent with the concepts of cloud microstability and cloud overseeding.

1. Introduction

It has been demonstrated with reasonable confidence that snowfall from cold orographic clouds in Colorado can be increased or decreased by seeding under certain meteorological conditions (Grant and Mielke, 1967; Chappell, 1967, 1970; Grant *et al.*, 1968; Rhea and Davis, 1970; Mielke *et al.*, 1970). In particular, attempts at snowfall augmentation have been most successful with warmer cloud conditions while decreases in snowfall have been observed for the very cold and relatively dry cloud systems. The nature of the precipitation changes that result from seeding is not well defined. It has not been established whether precipitation increases are due to higher precipitation rates during snowfall hours, longer precipitation duration, or some combination of both. Likewise, it has not been established whether observed precipitation decreases are due mainly to changes in precipitation duration or intensity.

These questions, in turn, relate to the reality of cold cloud microstability and overseeding. If cold cloud microstability that can be overcome by seeding exists, the major effect of seeding might be to increase the duration of precipitation. Otherwise the dominant effect of seeding would be to increase precipitation rates during snowfall hours. If overseeding is present, crystals which would have reached the mountain barrier in the absence of seeding no longer have trajectories to the mountain surface. Overseeding would therefore appear to be mainly a duration effect.

In order to investigate these concepts, total precipitation change has been separated into precipitation duration and intensity change components. These components are then evaluated as a function of cloud temperature using data gathered in the Climax experimental area in Colorado. Seeded and non-seeded precipitation durations are compared by considering the proportion of zero and positive precipitation hours for different cloud temperature stratifications of a randomized experiment. Also, a comparison of average daily precipitation durations is given for seeded and non-seeded experimental days under different cloud temperature stratifications.

2. Experimental design and data sample

The experimental design must satisfy two important requirements before the total precipitation change can be separated into meaningful components. The experimental sampling unit must be considerably longer than the average natural precipitation episode, and the experimental design must call for seeding irrespective of whether snow is occurring naturally.

The Climax experimental design fulfills these criteria quite well, for seeding generators were normally run regardless of current local weather, and the 24-hr sampling unit employed is two and one half times the average daily snowfall duration. Randomization was employed in obtaining the seeded and non-seeded samples of the Climax experiment. The randomization was restricted to the extent that large blocks (20–40) have the same number of seeded and non-seeded cases. The criterion which determines an experimental day is that at least 0.01 inch of precipitation be forecasted

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during a sampling unit at Leadville, Colo. This forecast was prepared by the U.S. Weather Bureau in Denver. A detailed account of the Climax experimental design has been presented by Grant and Mielke (1967).

The hourly precipitation data used in this study was from the Climax 2NW recording gage (U. S. Weather Bureau Station No. 05-1660). This gage is located at the High Altitude Observatory (HAO) of the University of Colorado and is very near the center of the designated primary target area of the Climax experiment. The data sample employed here consists of 623 experimental days obtained from the beginning of the Climax experiment in 1960 through 31 January 1970, at which time the original experimental design was altered. There were 44 other experimental days within this time period that are not included since the wind flow on these days was not from directions that would have carried the seeding material toward the specified target area. The criterion for the choice of the 623 experimental days is that the 500-mb wind direction was from 210° through west to 360° inclusive. These criteria were established before the experiment was begun in February of 1960 (Grant[4]). Analyses prior to the experiment indicated that this criterion included about 90% of all events and probably produced nearly all of the orographically-induced precipitation.

3. Precipitation change components

Precipitation during a 24-hr sampling unit can be expressed as the number of precipitation hours times the hourly intensities averaged over these same hours. The change in the 24-hr precipitation that results from seeding can therefore be described by intensity and duration change components.

The total change in precipitation associated with seeding is defined in terms of a ratio of the average precipitation on seeded days compared with non-seeded days within a given meteorological stratification or grouping. This is denoted by

$$T_s = \frac{\text{total precipitation in seeded group}}{\text{number of days in seeded group}},$$

$$T_n = \frac{\text{total precipitation in non-seeded group}}{\text{number of days in non-seeded group}},$$

where the total precipitation change is thus T_s/T_n.

The change in the intensity of precipitation (for all positive precipitation hours) is defined in terms of a ratio of the average hourly intensity on seeded days compared with non-seeded days within the grouping. This is denoted by

$$I_s = \frac{\text{total precipitation in seeded group}}{\text{number of seeded precipitation hours in group}},$$

$$I_n = \frac{\text{total precipitation in non-seeded group}}{\text{number of non-seeded precipitation hours in group}},$$

giving a precipitation intensity change of I_s/I_n.

The change in the duration of precipitation is defined in terms of a ratio of the average number of precipitation hours on seeded days compared with non-seeded days within the grouping. This is denoted by

$$D_s = \frac{\text{number of seeded precipitation hours in group}}{\text{number of days in seeded group}},$$

$$D_n = \frac{\text{number of non-seeded precipitation hours in group}}{\text{number of days in non-seeded group}}$$

resulting in a precipitation duration change of D_s/D_n.

Inspection of the defined ratios reveals that the product of the precipitation intensity change and precipitation duration change ratios yields the total precipitation change ratio, that is

$$T_s/T_n = (D_s/D_n)(I_s/I_n).$$

4. Ratios as a function of cloud temperature

The above ratios were generated as functions of the 700-mb equivalent potential temperature using a running mean over a 5K temperature interval. The 700-mb level is generally just below cloud base in the Climax area and the equivalent potential temperature at this level provides a measure of cloud system temperatures. The importance of cloud system temperatures upon the potential for seeding cold orographic clouds has been discussed previously (Grant and Mielke, 1967; Mielke *et al.*, 1970; Grant *et al.*, 1968; Chappell, 1970), Fig. 1 shows the three precipitation change ratios plotted as a function of the 700-mb equivalent potential temperature for the total Climax sample (623 days).

It is seen for temperatures <306K that all three precipitation-change ratios are nearly 1 until the very coldest temperatures are reached. At an equivalent potential temperature of ~290K, the total precipitation change and precipitation duration change ratios decrease and reach values near 0.5–0.6 for the very coldest temperatures. Above an equivalent potential temperature of 306K, there is an irregular rise in the total precipitation change ratio. It reaches a minor peak around 310K and attains a major peak of over 3.0 around 317–318K. It is interesting to note that, in general, fluctuations in the total precipitation ratio are mainly controlled by variations of the precipitation duration change ratio.

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[4] Grant, L. O., 1960: Colorado State University Climax study of the effect of cloud seeding on snowfall. General information packet supplied to participants.

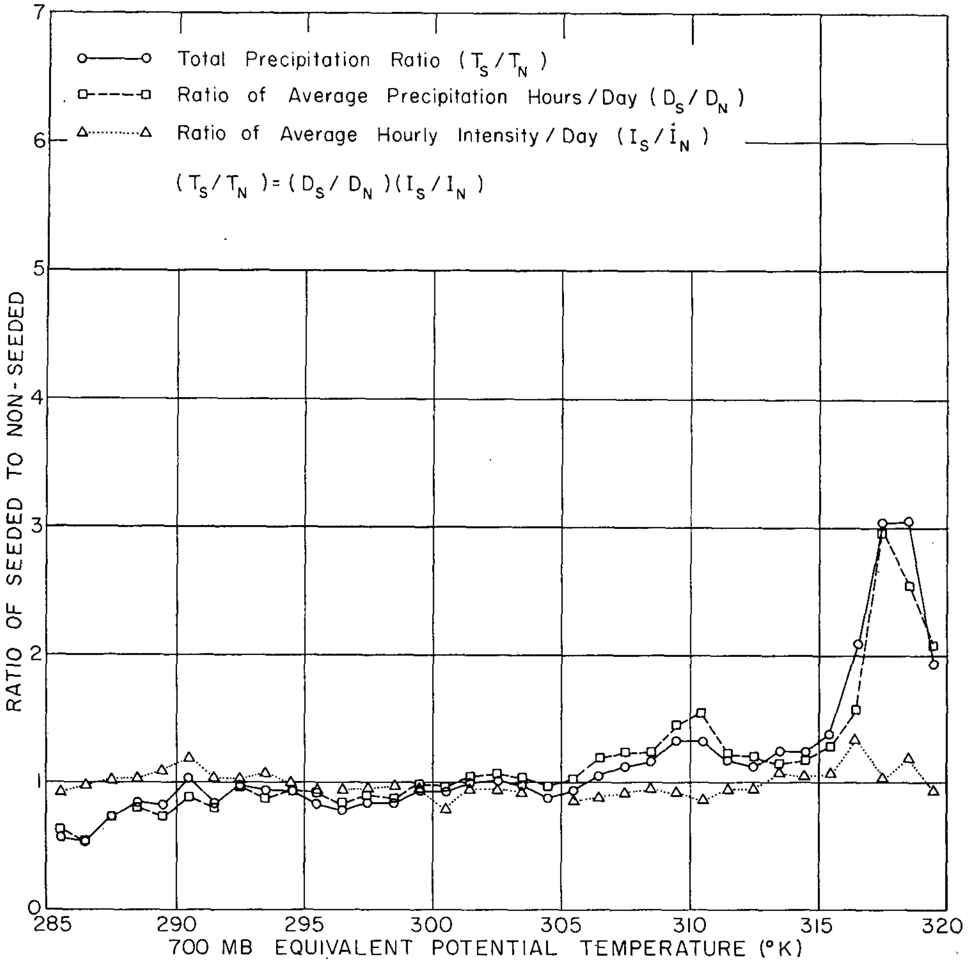

FIG. 1. Seeded to non-seeded ratios of total precipitation change, precipitation duration change, and precipitation intensity change as a function of 700-mb equivalent potential temperature. Plotted values are computed using a running mean over a 5K temperature interval. Precipitation data were measured at the High Altitude Observatory during experimental days of the total Climax sample (623 days).

5. Precipitation duration

In order to establish the importance of this precipitation duration effect, seeded and non-seeded distributions of positive and zero precipitation hours during experimental days were compared. Table 1 shows these distributions when 700-mb equivalent potential temperatures were 315–320K. The null hypothesis associated with Table 1 is that the proportion of zero precipitation hours is independent of seeding. The alternative hypothesis for Table 1 is that seeding reduces the proportion of zero precipitation hours. Under the null hypothesis the distribution of the test statistic, say T, is chi-square with one degree of freedom. The observed value of the Table 1 chi-square test statistic, say T_0, has an associated p value (probability of observing a value of T more extreme than T_0 under the null hypothesis) which suggests that some positive precipitation hours on seeded days would be zero without seeding. It can also be demonstrated that seeding probably produces a decrease in the number of precipitation hours for the cold and relatively dry cloud systems. This may be seen in Table 2. The null hypothesis associated with Table 2 is the same as for Table 1. However, the alternative hypothesis for Table 2 is that seeding increases the number of zero precipitation hours. The observed value of the Table 2 chi-square test statistic suggests that some zero precipitation hours on seeded days would be positive without seeding.

TABLE 1. Contingency table showing seeded and non-seeded distributions of positive and zero precipitation hours for the total Climax sample (623 days) when 700-mb equivalent potential temperatures were 315–320K.

	Seeded	Non-seeded
Positive precipitation hours	106	45
Zero precipitation hours	299	465
$T_0=49.3$		
p value <0.001		

Fig. 2 shows the average number of precipitation hours per experimental day for seeded and non-seeded conditions as a function of the 700-mb equivalent potential temperature.

It is seen that, in general, precipitation duration for seeded and non-seeded conditions is about equal in the intermediate range of cloud temperatures. However, precipitation duration for seeded conditions falls off as cloud temperatures become colder, while precipitation duration for non-seeded conditions decreases as cloud temperatures become warmer.

Consider the null hypothesis that the average number of precipitation hours on seeded experimental days ($D_s=6.28$ hr) and non-seeded experimental days ($D_n=2.12$ hr) are the same when equivalent potential temperatures were 315–320K. The p value associated with Student's t test for this situation is 0.03.

Similarly, consider the null hypothesis that the average number of precipitation hours per experimental day for seeded conditions ($D_s=3.53$ hr) and non-seeded conditions ($D_n=6.54$ hr) are the same when 700-mb equivalent potential temperatures were 284–289K. The p value associated with Student's t test for this case is 0.16.

6. Precipitation intensity

It may be noted that the intensity change computed here compares the average hourly precipitation intensity for seeded conditions with that for non-seeded conditions. The average hourly precipitation intensity for favorable seeding conditions includes those hours when snow would have occurred naturally, plus additional hours of precipitation that arise from the seeding. This analysis, therefore, does not measure exactly the intensity change that would result from seeding natural snowfall hours only. However, seeded and non-seeded distributions of hourly *positive* precipitation intensities suggest that the additional hours of precipitation, produced by seeding the warmer cloud systems, are distributed similarly among the hourly intensity classes as natural precipitation hours. Consider only the hourly frequency data of Table 3 having positive intensities. The p value associated with the chi-square test for homogeneity with three degrees of freedom for comparing seeded and non-seeded frequencies is about 0.90. This suggests that the proportion of seeded and non-seeded frequencies in question are in agreement. The intensity change computed in Table 3, therefore, should approximate closely the intensity change to be expected when seeding natural snowfall hours only.

Table 2. Contingency table showing seeded and non-seeded distributions of precipitation hours for the total Climax sample (623 days) when 700-mb equivalent potential temperatures were 284–289K.

	Seeded	Non-seeded
Positive precipitation hours	51	73
Zero precipitation hours	296	195
$T_0=14.8$		
p value= <0.005		

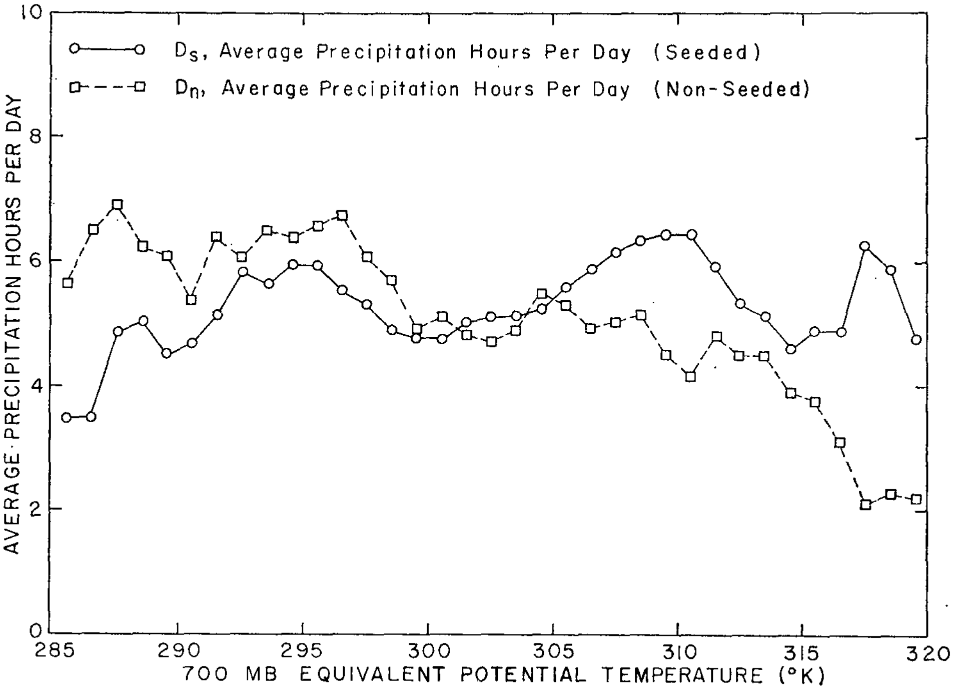

Fig. 2. Average daily precipitation duration for Climax experimental days as a function of 700-mb equivalent potential temperature. Plotted values are computed using a running mean over a 5K temperature interval. Precipitation data were measured at the High Altitude Observatory during experimental days of the total Climax sample (623 days).

TABLE 3. Seeded and non-seeded distributions of hourly precipitation intensities (inches) for the total Climax sample (623 days) when 700-mb equivalent potential temperatures were 315–320K.

Hourly precipitation intensity	Seeded	Non-seeded
0	299	465
0.01	43	19
0.02	29	11
0.03 and 0.04	15	8
0.05–0.19	19	7

Average hourly precipitation intensity (seeded) = 0.0283 inch
Average hourly precipitation intensity (unseeded) = 0.0277 inch
$I_s/I_n = 1.019$

7. Summary and conclusions

This investigation into the nature of the seeding effect indicates that seeding influences the duration of precipitation more than its intensity. The dominant effect of seeding warmer cloud systems was to bring about a precipitation release during many hours when it would not have occurred naturally. A smaller beneficial effect was to increase precipitation rates during snowfall hours. Evidence presented also suggests that seeding suppressed precipitation during some hours for the very cold cloud systems.

The pronouned effect of seeding upon precipitation duration for the warmer cloud systems suggests a threshold of cloud microstability exists in cold orographic clouds that must be overcome before precipitation occurs. The natural supply of ice crystals is generally sufficient to overcome this threshold for the colder cloud systems. However, this is frequently not the case for the warmer cloud systems, and for these conditions seeding appears successful in overcoming cloud microstability for many additional hours.

The results also indicate that overseeding of the coldest cloud systems was present and is mainly a duration phenomena as suggested by theory.

The relatively small contribution to total precipitation change by the precipitation intensity change component suggests that the efficiency of the natural precipitation process is relatively high during precipitation occurrence, once the stable cloud microstructure has been disrupted. The major inefficiency of the natural cold orographic cloud system lies mainly in the lack of securing a precipitation release at all.

These findings have important implications in the design of experimental and operational cloud seeding programs. As the experimental sampling period becomes a fraction of the average precipitation episode and seeding efforts become biased toward natural precipitation hours only, the actual weather modification potential present and available will not be realized in the experiment or operation. It appears that real emphasis should be placed on *cloud* seeding, rather than on *precipitation* seeding.

The cold orographic cloud observed in the vicinity of Climax, Colo., is for the most part a stable cloud system. The results and conclusions set forth here should therefore be applied only to similar type clouds. The seeding of warmer and more moist cloud systems, or those with more vertical convection, may bring about different results due to the increasing probability of dynamic effects, largely absent in the Climax cloud.

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