The Cloud Seeding Temperature Window

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ABSTRACT

The greatest potential for seeding with artificial ice nuclei to augment precipitation should occur with cloud summit temperatures in the range from about −10C to about −25C. This is the temperature region where there may be a deficiency of natural ice-forming nuclei. This cloud-top temperature range therefore constitutes a "temperature window" for seeding effectiveness. This article considers the results from a number of cloud seeding experiments reported in the literature with respect to this temperature window. The analysis of seven randomized experiments and references to four other experiments indicates that there is a window in the cloud-top temperature range for which precipitation increases are indicated. This extends from about −10C to about −24C for seeding conducted in the modes employed on these projects. At the coldest cloud-top temperatures, generally less than about −30C, decreases in precipitation are indicated. There are variations among the samples which appear to be explainable in terms of differences in the degree of convection present, the seeding methods used, or in the type of nucleant employed. No evidence is presented to show that the temperature window concept applies where there are strong dynamic effects, either natural or due to seeding, such as those in relatively large and isolated cumuli.

1. Introduction

Observational evidence of the control of cloud-top temperature on the effectiveness of cloud seeding to augment precipitation has been presented by several investigators. Grant and Mielke (1967) have shown that the cloud-top temperature, as represented by the 500-mb temperature, clearly delineates differing degrees of effectiveness for seeding to augment precipitation from the orographic clouds near Climax, Colo. When the 500-mb temperature was −20C or warmer, the indicated effect from seeding was positive. When the temperature was colder than −20C, there was little effect, or it was negative. Subsequently, Rhea *et al.* (1969), Smith (1970) and Elliott *et al.* (1971) have also described variations of seeding effects with cloud-top temperature.

Several investigators (Ludlam, 1955; Grant *et al.*, 1968; Chappell, 1970) have shown that optimal concentrations of ice crystals in orographic clouds should be about 10–50 per liter. Natural ice nuclei for the formation of primary ice crystals are typically activated in these concentrations at temperatures around −24 to −26C. At colder temperatures concentrations of natural ice nuclei are nearly always sufficient to produce enough ice crystals to consume all liquid cloud water for the diffusional growth of ice crystals. This assumes crystal settling from cloud top at speeds exceeding updraft speed, or a cloud mixing process by which the ice crystals can be distributed to the lower, warmer portion of the cloud, since the coldest cloud temperature normally occurs at cloud top. This is a reasonable assumption for stratified and many orographic clouds and at least some convective clouds. For convective clouds a redistribution process for ice crystals from the upper to lower cloud levels is very complex and in many convective clouds probably does not occur. A cloud-top temperature of around −24C, however, should constitute a "cold side" limit for a requirement for additional ice nuclei for many clouds. When the entire cloud is warmer than about −24C, the concentrations of natural ice nuclei activated can be below optimal values for full utilization of cloud condensate for the formation of precipitation. The precipitation efficiency in these clouds might be enhanced by additional ice nuclei supplied by cloud seeding.

At considerably warmer temperatures many clouds are too warm throughout for the formation of significant amounts of precipitation from the "ice" process. The natural concentrations of primary ice nuclei effective at temperatures of −5 to −10C are very low, generally well less than 0.01 per liter of air. A need for seeding frequently exists in these clouds but they are near the "warm side" threshold for seeding even by artificial ice nuclei such as silver iodide. While nuclei effective at these warmer temperatures can be artificially produced, their numbers are 10^3 to 10^6 per gram less than at −20C. In addition, the slower diffusional growth rate of ice at warmer temperatures (still <0C) constitutes another restriction on the formation of precipitation from an ice process. The combination of lowered net effectiveness of the seeding materials and the slower ice diffusional growth thus sets a "warm side" limit

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for the effectiveness of seeding even though temperatures are still below freezing.

It is apparent from these considerations that clouds with summit temperatures in the range from about −10C to about −25C which permit a redistribution of ice crystals from the colder to warmer elevations should have the greatest potential for seeding with artificial ice nuclei to augment precipitation. The cloud-top temperature from about −10C to −25C therefore constitutes a "temperature window" for seeding effectiveness for these types of clouds. This article considers the results from a number of cloud seeding experiments reported in the literature with respect to this temperature window. Few experiments have been conducted where cloud-top temperatures were well distributed throughout the entire temperature window. The results of any given experiment can consequently lead to only partial understanding of the role played by cloud-top temperature on the efficacy of cloud seeding. By considering a number of different experiments, seeding results over the whole temperature range becomes possible. The purpose of this analysis is not to verify seeding effects statistically, but to evaluate and emphasize the importance of cloud temperature on seeding effectiveness.

2. Precipitation and cloud-top temperature relationship

Seven experimental projects have been specifically considered to compare the precipitation on seeded days with that on not-seeded days as a function of estimated cloud-top temperatures (shown as precipitation-temperature, or *P-T* curves). The experiments were primarily for orographic "type" clouds, and all employed randomization to determine which experimental units would be seeded and which would be left unseeded for control. The geographical areas where these experiments were conducted have a widely varying range of cloud-top temperature relative to the temperature window. Large numbers of events are generally available for the respective experiments to minimize errors for individual events for which cloud-top temperatures undoubtedly varied considerably, both above and below the estimated value. The following is a brief discussion of the respective experiments.

a. The wintertime Climax experiments

The Climax experiments were conducted near Climax, Colo., by Colorado State University. Climax is located in the central Colorado Rockies at an elevation of 11,300 ft MSL and was designated as the center of the area to be seeded. The seeding generators were located on the upwind mountain slopes at distances of 8–40 mi and at elevations from 8000–10000 ft MSL. The experimental unit was 24 hr and randomization was used in determining the days to be seeded. A network of six generators utilized an AgI-NaI-acetone solution and each generator consumed about 20 gm of AgI per hour when operated. The number and location of specific generators to be used during each operation was controlled by wind conditions. Normally, two or three generators were used during a seeding experiment. The generators were tested at the Colorado State University Cloud Simulation Laboratory (Grant *et al.*, 1967) and produce about 4×10^{15} ice nuclei per gram of AgI active at −20C, 7×10^{14} per gram active at −15C, and 4×10^{13} per gram active at −10C. Laboratory tests have shown these generators to be ineffective at temperatures warmer than about −8C, but wintertime clouds with cloud tops this warm are extremely rare in the central Colorado Rockies.

Analyses of the Climax experiments have emphasized parallel physical and statistical evaluations. The original experiment (Climax I) was carried out from 1960 until the spring of 1965. The preliminary findings were reported in December 1965 (Grant and Mielke, 1967). An independent replication of the experiment (Climax II) was carried out from 1965 to the spring of 1970. The details of these experiments and many of the experimental results have been previously reported (Grant and Mielke, 1967; Grant *et al.*, 1968, 1969, 1971; Mielke *et al.*, 1970, 1971; Chappell *et al.*, 1971).

Cloud-top temperatures are not available for each case during the Climax experiments. Furman (1967), using radar and other visual and aircraft observations, has shown that the 500-mb level is close to the mean elevation of the wintertime orographic cloud tops near Climax. Furman found that the most frequent range of the tops of the orographic clouds was from 16,000 to 21,000 feet MSL, with an occasional extreme top reaching to 27,000 ft. The study by Furman, and further investigations by Chappell (1970), show that the best estimate of the mean orographic cloud-top elevation in the Climax area is at about 460 mb. Consequently, 460-mb temperatures have been used in this study to represent cloud-top temperatures. Undoubtedly, this pressure height is not representative of cloud-top temperatures over many other mountain barriers.

The precipitation during the Climax experiments was observed over a dense network of precipitation gauges located at about 1-mi intervals over Fremont, Hoosier and Vail Passes. For this paper, the average precipitation for two stations with the most complete data record (the Climax recording gauge and Climax Snowboard—both located at the High Altitude Observatory near the center of the target) have been used to represent the precipitation for the seeded and not-seeded days. It has been shown (Grant *et al.*, 1969; Mielke *et al.*, 1972) that these stations can reasonably represent the precipitation in the seeded target area. Previously reported analyses have shown the same basic relationships between cloud temperatures and precipitation for all precipitation stations and groups

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of stations in the climax network (Mielke *et al.*, 1970, 1971).

The comparison of the precipitation on seeded and on not-seeded days as a function of estimated cloud top temperature for the Climax I and Climax II experiments is shown in Tables 1 and 2, respectively. The precipitation values represent the average precipitation of all experimental cases for 5C intervals centered at the indicated temperature. The number of seed and not-seed cases, respectively, which were available to determine the precipitation averages, are shown in parentheses. The last column shows the ratio of precipitation on the seeded days to that on the not-seeded days. The seed/no seed precipitation ratios are plotted as a function of the estimated cloud-top temperature in curves 1 and 2 of Fig. 1.

It can readily be observed from Tables 1 and 2 and Fig. 1 that the ratio of precipitation on the seeded and not-seeded days does not vary greatly from 1.0 at temperatures colder than about −23C for the Climax I experiment or colder than about −22C for Climax II. There is an indication of somewhat higher ratios for several degrees centered around −30C for the Climax II experiment. There is also some suggestion that seeded precipitation tends to become less than the not-seeded precipitation at the coldest temperature. At temperatures of >24C or >23C, respectively, for Climax I and Climax II, the precipitation on the seeded days is markedly greater as cloud-top temperatures increase to about −19C. The sample size becomes small at still warmer temperatures.

The data from both the Climax I and Climax II

TABLE I. Climax I (1960–65) average precipitation as a function of estimated cloud-top temperature (460-mb temperature) for seeded and not-seeded experimental cases. Values of precipitation are given for 5C moving means centered at the indicated cloud-top temperature. Numbers of cases are shown in parentheses.

Estimated cloud-top temperature (°C)	Average precipitation Seed (inches)	Average precipitation Not-seeded (inches)	Precipitation ratio Seed/No seed*
−17	0.025 (2)	0.043 (3)	—
−18	0.017 (3)	0.077 (8)	—
−19	0.235 (8)	0.067 (12)	—
−20	0.174 (14)	0.070 (16)	2.491
−21	0.169 (17)	0.067 (22)	2.535
−22	0.165 (20)	0.093 (31)	1.767
−23	0.192 (32)	0.102 (33)	1.885
−24	0.161 (33)	0.147 (36)	1.098
−25	0.168 (42)	0.166 (46)	1.011
−26	0.181 (50)	0.175 (52)	1.036
−27	0.196 (54)	0.180 (54)	1.088
−28	0.188 (53)	0.190 (56)	0.989
−29	0.182 (52)	0.181 (50)	1.009
−30	0.193 (41)	0.177 (41)	1.091
−31	0.177 (35)	0.200 (35)	0.884
−32	0.161 (32)	0.214 (29)	0.752
−33	0.156 (24)	0.202 (25)	0.775
−34	0.161 (22)	0.196 (27)	0.821
−35	0.154 (19)	0.193 (23)	0.800
−36	0.157 (16)	0.184 (18)	0.853

* Lack of entry indicates sample too small to be significant.

TABLE 2. As in Table 1 except for Climax II (1965–70).

Estimated cloud-top temperature (°C)	Average precipitation Seed (inches)	Average precipitation Not-seeded (inches)	Precipitation ratio Seed/No seed*
−17	0.046 (8)	0.030 (7)	—
−18	0.092 (12)	0.016 (13)	5.73
−19	0.105 (17)	0.014 (19)	7.65
−20	0.094 (21)	0.035 (28)	2.67
−21	0.097 (33)	0.043 (42)	2.24
−22	0.102 (47)	0.070 (48)	1.47
−23	0.111 (61)	0.102 (55)	1.09
−24	0.105 (71)	0.119 (67)	0.89
−25	0.124 (89)	0.120 (75)	1.03
−26	0.133 (88)	0.137 (65)	0.97
−27	0.164 (80)	0.134 (74)	1.08
−28	0.140 (70)	0.124 (73)	1.13
−29	0.149 (60)	0.113 (68)	1.32
−30	0.148 (45)	0.121 (59)	1.22
−31	0.142 (39)	0.123 (55)	1.15
−32	0.130 (34)	0.115 (43)	1.13
−33	0.141 (31)	0.131 (39)	1.08
−34	0.139 (29)	0.155 (30)	0.89
−35	0.131 (22)	0.153 (24)	0.86
−36	0.116 (17)	0.165 (19)	0.70

* Lack of entry indicates sample too small to be significant.

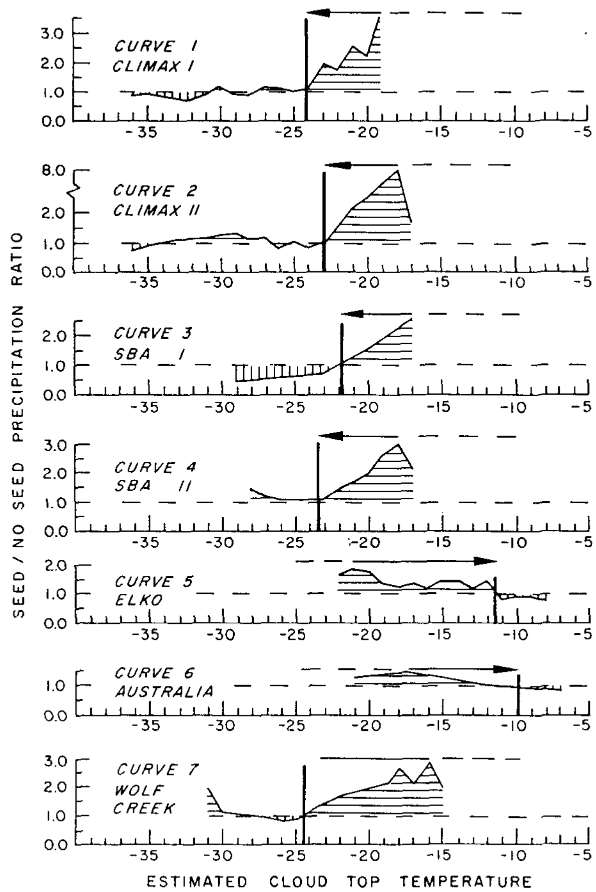

FIG. 1. Comparative seed/no seed precipitation ratios as related to estimated cloud-top temperatures for seven seeding experiments.

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TABLE 3. As in Tables 1 and 2 except for the combined climax sample (1960–70) using a 3C moving mean.

Estimated cloud-top temperature (°C)	Average precipitation Seed (inches)	Average precipitation Not-seeded (inches)	Precipitation ratio Seed/No seed*
−17	0.050 (4)	0.039 (7)	—
−18	0.042 (10)	0.036 (9)	—
−19	0.089 (13)	0.040 (20)	2.20
−20	0.165 (21)	0.033 (25)	5.05
−21	0.148 (27)	0.051 (35)	2.90
−22	0.131 (39)	0.054 (50)	2.40
−23	0.094 (52)	0.096 (57)	0.97
−24	0.136 (71)	0.120 (64)	1.13
−25	0.136 (75)	0.168 (64)	0.81
−26	0.153 (91)	0.158 (77)	0.97
−27	0.154 (84)	0.148 (79)	1.04
−28	0.174 (82)	0.145 (82)	1.20
−29	0.181 (63)	0.150 (72)	1.21
−30	0.161 (49)	0.146 (65)	1.10
−31	0.146 (43)	0.141 (49)	1.04
−32	0.138 (35)	0.144 (40)	0.96
−33	0.152 (36)	0.177 (36)	0.86
−34	0.155 (32)	0.181 (36)	0.86
−35	0.143 (26)	0.178 (32)	0.80
−36	0.141 (18)	0.162 (24)	0.87
−37	0.092 (13)	0.158 (13)	0.58

* Lack of entry indicates sample too small to be significant.

experiments have also been combined to maximize the sample size for considering the control of cloud-top temperature of seeding effects in more detail and are shown in Table 3 and Fig. 2. In this combined sample the precipitation value represents the average precipitation of all experimental cases for a 3C interval centered at the indicated temperature. This shows a clear peak in the seed/no seeded precipitation ratio near −20C and the rapid lowering of the ratio at temperatures <−22C. The secondary and smaller apparent increase in the precipitation advantage for the seeded days when estimated cloud-top temperatures are near −29C may or may not reflect a chance occurrence. If it is, in effect, from seeding (the sample size is large), it may have resulted from a positive buoyancy enhancement gained from seeding selected convective elements in some of the more complex orographic cloud systems.

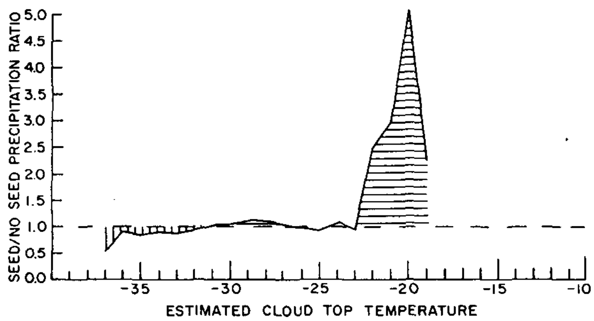

FIG. 2. Seed/no seed precipitation ratio as related to estimated cloud-top temperature for the combined Climax I and Climax II samples. Values of precipitation are given for 3C moving means centered at indicated cloud-top temperature.

The substantial advantages observed for the warmer seeded cases are consistent with changes expected from physical considerations. It has been shown (Grant *et al.*, 1968, 1971; Chappell, 1970) that the natural concentrations of ice crystals in the orographic clouds over the Climax area are generally insufficient to utilize all of the cloud condensate available before re-evaporation of the condensate takes place to the lee side of the Rocky Mountains when cloud-top temperatures are warmer than about −20C to −25C. Conversely, it has also been shown that at colder temperatures the concentrations of natural ice crystals are nearly always sufficient. Thus, at Climax the cold side of the temperature window for cloud seeding is well defined. The warm side of the window cannot be clearly identified from the Climax experiments since all cloud top temperatures are considerably colder than the expected warm side temperature threshold.

b. Santa Barbara I

The Santa Barbara I project was conducted over the mountainous country of Santa Barbara County, California, during the January–April season during the period 1957–59. The seeding was conducted continuously during randomly selected 12-hr blocks within storms. A widespread network of about 30 AgI-NaI-acetone type generators, each emitting 6 gm hr^{-1} of AgI, was used for the seeding, and a widespread network of recording gauges was used for the evaluation of results. The particular group of generators operated at a given time was determined on the basis of wind flow.

The bulk of the precipitation fell from winter type convective clouds embedded in a stratiform deck and arranged in bands moving in from the Pacific Ocean. The bands passed through the target area every 3–4 hr and had point durations ranging from one-half hour up to one or two hours. An orographic component of precipitation also occurred over most of the target area. Aerological and other evidence indicated cloud tops during active precipitation averaged 18,000 ft during most of the heavy precipitation and this has been used as the key temperature level.

Table 4 lists the precipitation figures upon which the curve 3 in Fig. 1 is based. The basic data employed are listed by Neyman *et al.* (1960) for all of Santa Barbara County. The curves refer to the complete seeded and not-seeded samples from Santa Barbara County without reference to any seeding in Ventura County to the east, which was included as part of the overall project during the last two years. Precipitation was averaged over the entire county for 25 seeded and 26 not-seeded cases. Averages were computed by 2.5–3.0C steps. The peak in the not-seeded precipitation is at −26C and in the seeded precipitation at −17.5C. A "seeding window" is suggested for a temperature region extending from some value warmer than −15C to somewhat less than −20C. At temperatures colder

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than this a reduction in precipitation with seeding is strongly suggested.

c. Santa Barbara II

The Santa Barbara II randomized project (1967–70) was conducted over the mountainous portions of Santa Barbara County during the November–April winter seasons of the years 1967–68 through 1969–70 (Elliott *et al.*, 1971). The seeding was carried out only during the passage of convection bands through the test area. The bands were detected and tracked by telemetered rain gauges and weather radar as they moved eastward over an upwind control area. The seeding decision was made just before the band entered the test area. The source of artificial nucleant was an LM-83 pyrotechnic flare (St. Amand *et al.*, 1970) employed at a single site on a 3500-ft mountain ridge lying inland from the Pacific Ocean. The seeding flare emitted about 400 grams of AgI smoke in a period of 3 min. Flares were ignited every 15 min during the band passage.

Specially collected aerological and radar top data indicated that the average top of convection within the bands averaged 20,000 ft and this has been used as the key temperature level. In particular, soundings were launched from Santa Barbara Airport so as to penetrate almost every convection band passing into the test area. The curves are based upon precipitation data for a 10-station average in the primary target area. This set of 10 stations was chosen so as to cover approximately the same area highlighted by the highest gage density in the SBA I project. There were 43 seeded and 41 not-seeded bands and moving 5C means were computed at 1C steps.

Table 5 lists the precipitation figures upon which curve 4 of Fig. 1 is based. The peak for not-seeded precipitation is at −27C. The seeded curve shows two peaks: a major one at −18C, and a minor one at the same temperature as that for the not-seeded curve at around −27C. The curves suggest a seeding window similar in general to that for Santa Barbara I. However, there is no appearance of overseeding at temperatures <-22C, but rather a change in the seeded curve to a condition paralleling closely the not-seeded curve. In this colder region the excess of seeded over not-seeded precipitation may not be significant.

Convection certainly complicates the picture and reduces somewhat the relative importance of the cloud-top temperature as a useful parameter. The convection effect is dominant in both Santa Barbara I and II. Application of a numerical convection model containing ice crystal cloud microphysics shows that, when typical soundings are used, the model does predict some cloud-top rise due to seeding produced buoyancy enhancement. This amounts to 2000–3000 ft in the average case, enough to be of some importance in the generation of precipitation. Santa Barbara II also has the complicating factor of a different nucleant from Santa Barbara I and Climax. The model was capable

TABLE 4. Santa Barbara I (1957–59) average precipitation as a function of estimated cloud-top temperatures for seeded and not-seeded cases. Values of precipitation for moving means of two temperature steps of 2.5–3C are centered on the indicated cloud-top temperature. Numbers of cases are shown in parentheses.

Cloud-top temperature (°C)	Seeded precipitation (inches per 12 hr)	Not-seeded precipitation (inches per 12 hr)	Precipitation ratio Seed/No seed*
−15	0.697 (8)	—	—
−17.5	0.795 (10)	0.315 (8)	2.52
−20	0.773 (9)	0.500 (11)	1.55
−23	0.342 (11)	0.543 (12)	0.63
−26	0.201 (9)	0.584 (10)	0.36
−29	0.184 (6)	0.394 (6)	0.47
−33	—	0.113 (4)	—

* Lack of entry indicates sample too small to be significant.

of discriminating between the effects of different nuclei types and dosage rates. The higher outputs of effective nuclei at colder temperatures when the AgI-NaI complex is used seems to account for the over-seeding in Santa Barbara I versus Santa Barbara II.

d. Elko

The Elko County, Nevada, randomized seeding project was carried out from 1961 through 1967 by North America Weather Consultants for the State of Nevada. Seeding was accomplished by an extensive network of ground-based AgI-NaI-acetone generators consuming 6 gm hr^{-1} of AgI. Winter storm clouds were seeded during 18-hr time blocks over a semi-orographic area lying primarily upwind of a north–south oriented mountain range in northeastern Nevada. Convection embedded within the storm clouds played a role but certainly not as much as in Santa Barbara. Two areas were involved and a crossover design was employed. A recording gauge network was maintained by the Desert Research Institute, University of Nevada, and the data obtained served as the main basis for the evalu-

TABLE 5. As in Table 4 except for Santa Barbara II (1967–70) using 5C moving means centered on the indicated cloud-top temperature.

Cloud-top temperature (°C)	Seeded precipitation (inches per band)	Not-seeded precipitation (inches per band)	Precipitation ratio Seed/No seed*
−17	0.42 (13)	0.20 (22)	2.10
−18	0.74 (12)	0.25 (23)	2.96
−19	0.65 (24)	0.25 (21)	2.60
−20	0.49 (22)	0.26 (17)	1.88
−21	0.39 (21)	0.25 (14)	1.56
−22	0.41 (21)	0.30 (11)	1.36
−23.5	0.34 (10)	0.28 (8)	1.21
−24.5	0.40 (10)	0.35 (8)	1.14
−26	0.45 (10)	0.38 (10)	1.18
−27.5	0.62 (9)	0.49 (7)	1.26
−28.5	0.59 (7)	0.35 (5)	1.40
−31	0.37 (6)	0.22 (4)	—
−33.5	0.29 (3)	0.20 (2)	—

* Lack of entry indicates sample too small to be significant.

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TABLE 6. Elko (1961–67) average precipitation as a function of estimated cloud-top temperature for seeded and not-seeded cases. Values of precipitation for 5C moving means are centered on the indicated cloud-top temperature.

Estimated cloud-top temperature (°C)	Seeded precipitation (inches per 18 hr)	Not-seeded precipitation (inches per 18 hr)	Precipitation ratio Seed/No seed
−8	0.571 (12)	0.660 (12)	0.84
−9	0.555 (12)	0.574 (12)	0.97
−10	0.623 (13)	0.664 (13)	0.94
−11	0.546 (15)	0.626 (15)	0.87
−12	0.733 (16)	0.533 (16)	1.38
−13	0.708 (13)	0.557 (13)	1.27
−14	0.771 (11)	0.569 (11)	1.36
−15	0.731 (11)	0.545 (11)	1.34
−16	0.677 (16)	0.552 (16)	1.23
−17	0.698 (17)	0.522 (17)	1.33
−18	0.616 (18)	0.495 (18)	1.24
−19	0.796 (21)	0.597 (21)	1.33
−20	0.822 (23)	0.487 (23)	1.62
−21	0.922 (20)	0.500 (20)	1.84
−22	0.783 (17)	0.491 (17)	1.59

ation of results. Aerological analyses, pilot reports, and occasional near-by radar top data indicated average tops of the main cloud deck were about 13,000 ft MSL over the target areas and this was used as the key temperature level. The precipitation-temperature data for this experiment are shown in Table 6 and in curve 5 of Fig. 1 for the 56 cases which were seeded in one target or the other. Moving 5C averages were used at 1C steps. It is clear that we are viewing the warmer side of the seeding window. There is a peak in the seeded curve at −21C, but there is some doubt about the downturn beyond this peak, due to a paucity of data. The warm side of seeding window apparently lies at about −11C.

e. Australian experiments

A combination of three Australian randomized seeding projects, New England, Warragamba and South Australia, have been considered. These are shown in Table 7 and in curve 6 of Fig. 1. The original data were tabulated by Smith (1970) and are in 5C temperature blocks. The seeding was accomplished by airborne AgI-NaI-acetone generators. Three classes of clouds were seeded: stratiform, cumulus and mixed. Only the latter two are included in this example. The first, stratiform, was not strongly associated with significant air parcel lifting or orographic features in any of the area. The seeding was done in all seasons. Actual measurements of cloud-top temperatures were made by the seeding aircraft. Two areas were involved using a crossover type experimental design.

TABLE 7. Australian experiments average precipitation as a function of observed cloud-top temperatures for seeded and not-seeded cases. Values of precipitation using 5C means are given for the indicated cloud-top temperature range.

Cloud-top temperature (°C)	Seeded precipitation (inches per 24 hr)	Not-seeded precipitation (inches per 24 hr)	Precipitation ratio Seed/No seed
>−10	0.133 (276)	0.149 (276)	0.89
−10 to −14	0.244 (134)	0.234 (134)	1.04
−15 to −19	0.348 (91)	0.244 (91)	1.43
<−19	0.320 (60)	0.262 (60)	1.26

The *P-T* curve of Fig. 1 shows that here we are dealing with the warm side of the seeding window. The warm side is defined, within the limits possible with the 5C classes employed, at about −10C. The not seeded curve is rising at colder temperatures, and apparently has not reached its peak. The peak in the seeded curves lies between −20C and −15C.

Both the Australian and Elko data suggest a negative effect of seeding on the warm side of the window. The difference is not large and may or may not be real. If it is a seeding effect the reasons are not obvious. Several complex and interacting coalescence and ice phase processes may take place in these cases when considerable portions of the cloud are at temperatures warmer than 0C.

f. Wolf Creek Pass

An additional randomized seeding experiment has been considered to extend the comparison of precipitation on seeded and not-seeded days through a broad range of cloud-top temperatures. This project was carried out by Colorado State University during the winter season, 1963–64, through the winter season, 1969–70. The randomization for this experiment was made for an entire winter season rather than on a daily basis. A comparison of daily values of precipitation and temperature require the assumption of no substantial difference in the distribution of daily events at the respective temperatures for the respective years. While this assumption can be questioned, the Wolf Creek results are consistent with those at Climax and show a potential for seeding at the warm temperatures on the not seeded days. All daily values of precipitation are considered as seeded for the seeded years even though seeding did not take place on some days. The inclusion of this experiment extends the available episodes into a warmer temperature regime. Based on analyses of available upper air data, 490 mb has been used as the best estimate of average cloud tops to determine cloud-top temperature. In other respects, the Wolf Creek Pass program was carried out in a manner similar to that employed in the Climax experiments. The precipitation temperature data are shown in Table 8 and the *P-T* curve is shown as curve 7 on Fig. 1. The results are similar to those at Climax. Cloud-top temperatures are more frequently warmer at Wolf Creek Pass and an important number of events occur with cloud-top temperatures in the range −14 to −20C. Similar to Climax, there appears to be a clear advantage for the seeded cases at temperatures ⩾ −24C. The advantages at warmer temperatures appear to extend to the warmest cases sampled at −14C. No general pattern

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of differences exists at colder temperatures, although at the coldest temperature there is some indication of greater precipitation on seeded days.

g. Summary of the seven seeding experiments

Fig. 1 summarizes the seeding results for the projects discussed above. These *P-T* curves are shown as a seed/no seed precipitation ratio related to temperature to emphasize the role of the one parameter—cloud-top temperature—on the apparent effectiveness of seeding. Obviously there are other geographic and storm type effects that also control the magnitude of the seeding effects. In spite of this, little or no effect from seeding is evident for clouds with coldest temperatures warmer than about −10C or colder than about −24C. In contrast, a consistent pattern of increased precipitation can be noted when cloud-top temperatures were within the "temperature window" for seeding, −10C to about −24C, with a peak advantage in the cloud-top temperature range being from about −15 to −20C.

3. Other experiments

Several other randomized experiments have been reviewed to consider the effect of cloud-top temperature on seeding effectiveness. Analyses are still in progress for certain of these projects. While sufficient data are not available in the literature for making detailed comparisons of the apparent effectiveness of seeding for these experiments, the information available does help verify the limits for the cloud seeding temperature window.

A randomized seeding experiment was carried out during the 1968–69 winter season by E.G.&G. in the Park Range of Northwestern Colorado (Rhea *et al.*, 1969). This involved seeding by aircraft for 1 hr of a 6-hr block during which intensive data collection was emphasized. Precipitation was compared for the 3-hr interval during which the first hour had been seeded (seeded sample) with the 3-hr not-seeded block. Once an experimental unit of 6 hr had been established, randomization was used to determine whether the first or last 3-hr interval should be the seeded sample. The experimental sample was divided into two categories according to cloud-top temperature categories, $\geqslant -20$C and < -20C. At Rabbit Ears Pass, near the center of the seeded area, the precipitation for the seeded cases was more than 100% greater than that for the not-seeded cases (significant at the 3% level using a non-parametric sum-of-ranks test when cloud top temperatures were warmer than −20C). A decrease of 24% was observed for the seeded cases with cloud top temperatures colder than −20C, but the difference was not statistically significant with the sample available. The results indicate that the cold side of the temperature window for the Park Range of Northwest Colorado is at around −20C.

Table 8. Wolf Creek Pass (1963–70) average precipitation as a function of estimated cloud-top temperature (490 mb) for seeded and not-seeded experimental cases. Values of precipitation are given for 3C means centered at indicated cloud-top temperature. Number of cases are shown in parentheses.

Estimated cloud-top temperature (°C)	Average precipitation Seeded (inches per day)	Average precipitation Not-seeded (inches per day)	Precipitation ratio Seed/No seed*
−14	0.472 (12)	0.006 (5)	—
−15	0.422 (15)	0.227 (13)	1.86
−16	0.410 (24)	0.147 (21)	2.78
−17	0.277 (25)	0.136 (35)	2.03
−18	0.315 (34)	0.117 (42)	2.69
−19	0.301 (42)	0.139 (55)	2.17
−20	0.309 (49)	0.157 (66)	1.97
−21	0.266 (53)	0.144 (76)	1.84
−22	0.311 (50)	0.183 (82)	1.70
−23	0.282 (57)	0.198 (78)	1.43
−24	0.272 (58)	0.218 (71)	1.25
−25	0.203 (52)	0.227 (63)	0.90
−26	0.183 (45)	0.230 (52)	0.80
−27	0.217 (38)	0.245 (43)	0.89
−28	0.203 (35)	0.199 (35)	1.02
−29	0.187 (27)	0.173 (28)	1.08
−30	0.140 (19)	0.123 (27)	1.14
−31	0.185 (14)	0.098 (19)	1.89
−32	0.213 (9)	0.119 (15)	—
−33	0.232 (6)	0.113 (10)	—

* Lack of entry indicates sample too small to be significant.

Another randomized seeding program to test the effectiveness of airborne seeding of orographic clouds has been carried out in Utah by Utah State University (Chappell, 1972; McNeil *et al.*, 1972). A 4-hr sampling unit with randomization in blocks of two was employed. When an 8-hr operational period was forecast, a randomized decision was made to seed either the first or second 4-hr block. The other 4-hr time block was left unseeded for control. Within the seeded block, actual seeding was conducted for about the first two hours. Seeding was carried out by AgI pyrotechnics (Olin R-15) mounted on an aircraft. The seeding rate averaged about 120 gm hr^{-1} and approximately 10^{14} nuclei effective at −15C were produced per gram for AgI utilized. Specified seeding tracks were followed by the aircraft according to wind conditions, and when possible, seeding was carried out at the elevation of the −5C temperature. Chappell (1972) and McNeil *et al.* (1972), based on preliminary analyses, suggest a window for precipitation enhancement from this seeding in the cloud-top temperature range from about −16 to −24C. They suggest that in the northern Utah Mountains seeding effectiveness on the warm side may be limited by ice multiplication processes and, as in other areas, by the availability of natural ice nuclei on the cold side. When the poorly understood or described "ice multiplication" effect is operative, it may control the warm side of the seeding effectiveness window. The data available in this study are not adequate to resolve this issue.

Two other randomized experiments are in the process

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of being evaluated for the effect of cloud temperature on seeding success. These include the seeding experiment of Montana State University over the Bridger Range (Super *et al.*, 1972) and the field seeding experiments of New Mexico State University over the Jemez Mountains of Northern Central New Mexico (Keys *et al.*, 1973). Supper *et al.* have emphasized that while statistical studies are still in progress ". . . preliminary analyses indicate that significant snowfall increases were obtained in at least an 83-day subset out of the 259 experimental days logged." The subset is defined by 1) a mountain-top temperature to represent the cloud temperatures for establishing the requirement for seeding, 2) a wind direction to define orographic lifting, and 3) a low-level stability to define when the atmosphere was conditionally unstable so that the seeding material would not be trapped in the cold low-level wintertime air masses. It seems clear that cloud temperature structure also plays an important role in seeding success in Montana orographic clouds. In this experiment the critical temperature for seeding effectiveness is apparently controlled by a high frequency of the seeded events when the seeding materials are restricted to the lower portions of the clouds. A better definition of seeding effectiveness for this experiment is consequently found with temperatures at near mountain-top levels. Cloud-top temperature plays a crucial role in establishing the requirement for seeding. Temperature stability in the first few thousand feet above the surface can limit the vertical transport of the seeding material so that the critical temperature for seeding effectiveness is the coldest temperature to which the seeding material rises. The problem of the transport of the seeding materials can exist in any area but is apparently accentuated in Montana due to the frequent presence of cold air trapped near the surface.

Keys *et al.* (1973) have paid specific attention to evaluating the cloud temperature control on seeding effectiveness in New Mexico. They show particularly strong advantage for the seeding cases with estimated cloud-top temperatures in the range from −10 to −18C. They found, as has been also observed at Climax (Chappell, 1970; Grant *et al.*, 1971; Mielke *et al.*, 1971), that greater statistical significance, but smaller indicated increases, resulted from using the 700-mb equivalent potential temperature to represent cloud temperatures. The use of the 700-mb equivalent potential temperature probably helps reduce the variance by grouping the experimental cases according to a temperature parameter that also reflects availability of moisture.

4. Discussion and summary

The seven examples of *P-T* curves, and a general consideration of four additional experiments, all suggest that there is a "window" in the cloud-top temperatures generally from about −10C to about −24C within which seeding, in the modes employed on these projects, has led to an increase in precipitation. At the coldest cloud-top temperatures, generally <−30C, decreases in precipitation are indicated. The samples cover a wide range of climatic zones and, with the exception of some of the Australian cases, were conducted exclusively in the winter half of the year. There are variations between examples which appear to be explainable in terms of differences in the degree of convection present, the seeding methods used, or in the type of nucleant employed. The use of seeding materials more efficient at warmer temperatures (0 to −10C) than those employed in these experiments may extend the warm side of the window to temperatures warmer than −10C. The slower growth rate of ice crystals at these warmer temperatures will probably still limit seeding effectiveness in some types of clouds.

From an operational standpoint, cloud-top temperatures, which are difficult to observe, may in some cases be reasonably estimated by sequential rawinsondes. Where high cloud decks are infrequent, satellite IR surveillance can provide valuable information over large geographical areas. K-band radar can frequently be used to monitor cloud tops and should be used more extensively. The reporting of cloud tops by commercial aircraft could prove very useful. In many cases other more readily obtained temperature information, such as 700-mb equivalent potential temperature, can be used to index cloud temperature and cloud structure.

On the basis of the foregoing it cannot be stated with any assurance that *P-T* diagrams for the summer season would show a seeding window. Complicating factors might be a highly active warm cloud coalescence mechanism, strong updrafts, and air mass structures favoring explosive cloud-top rise with seeding.

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