Reply

ARTHUR L. RANGNO AND PETER V. HOBBS

Cloud and Aersol Research Group, Department of Atmospheric Sciences, University of Washington, Seattle, Washington

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1. Background

We welcome Ruben Gabriel's and Paul Mielke's comments on our studies of the Climax cloud seeding experiments. These experiments, which were carried out on winter storms in the Colorado Rockies, are important in the history of cloud seeding because they are one of just a very few demonstrations that appeared to provide both strong physical arguments and statistical evidence that under certain conditions the artificial seedings of clouds can increase precipitation. Even today, the Climax experiments are often quoted as evidence for the efficacy of cloud seeding (e.g., Reynolds 1988; Cotton and Pielke 1992; Young 1993), despite the fact that we have shown that many of the physical arguments and the statistical results presented by the Climax experimenters[1] to support a seeding effect are faulty (Hobbs and Rangno 1979; Hobbs 1980; Rangno and Hobbs 1987, 1993).

Before responding to Gabriel's and Mielke's comments, we will summarize some of the background information relevant to the present discussion. For more details, the reader is referred to our earlier papers on this subject (loc. cit.).

The physical arguments proposed by the Climax experimenters to support the view that there is a potential for precipitation enhancement by cloud seeding in the Colorado Rockies were as follows:

- At cloud-top temperatures $\geq -20°C$, natural ice particle concentrations often fall below those required for precipitation (Grant 1968, 1986; Chappell et al. 1971).
- Assuming that 500-mb temperatures are representative of cloud-top temperatures, it was concluded that the latter are often $\geq -20°C$ and, therefore, artificial seeding should initiate precipitation in these situations (Chappell et al. 1971). In statistical analyses of the effects of cloud seeding by the Climax experimenters it was also assumed that 500-mb temperatures can be used as a surrogate for cloud-top temperatures (Grant and Mielke 1967; Mielke et al. 1981).
- Daily precipitation amounts in the Rockies decrease markedly as 500-mb temperatures increase above about $-20°C$. This was attributed to decreasing concentrations of natural ice nuclei with increasing cloud-top temperature (Chappell 1970; Grant et al. 1971; Grant and Kahan 1974).

In contrast to these conclusions, Hobbs and Rangno (1979) pointed out the following facts:

- Measurements over the Rockies show that ice particle concentrations in clouds frequently bear little relationship to cloud-top temperature or ice nucleus measurements, and ice particle concentrations are often high even at temperatures $\geq -20°C$ (e.g., Marwitz et al. 1976).
- There is no evidence to support the contention that 500-mb temperatures are a good measure of cloud-top temperatures over the Rockies. [In fact, Cooper and Marwitz (1980) found that the lowest cloud-top temperatures were often encountered at the highest 500-mb temperatures and the highest cloud-top temperatures at the lowest 500-mb temperatures.]
- The conclusion by the Climax experimenters that daily precipitation amounts decrease as 500-mb temperatures increase above $-20°C$ was based on the control days of the Climax experiments (Chappell 1970; Grant et al. 1971). Analysis of station data for the period 1947–75 shows that the average daily precipitation increases, or remains constant, as 500-mb temperatures increase above $-20°C$. Hence, the control days of both Climax experiments are highly anomalous relative to the climatology of the region.

Turning now to the statistical results of the Climax experiments, Rangno and Hobbs (1987) pointed out that there are significant differences between the precipitation amounts used by the Climax experimenters and the Department of Commerce's published data for the independently maintained key target gauge at Cli-

[1] As in our previous publications on this subject, we will refer to the many authors of the papers and reports on the Climax experiments that have emanated from Colorado State University (CSU) as the "Climax experimenters."

Corresponding author address: Prof. Peter V. Hobbs, Department of Atmospheric Sciences, AK-40, University of Washington, Seattle, WA 98195.

max 2 NW. Using the Department of Commerce's data, Rangno and Hobbs found that neither Climax I nor II exhibited statistically significant increases in precipitation due to seeding when 500-mb temperatures were $\geq -20°C$. We also found that many of the 500-mb temperature and 700-mb wind assignments used by the Climax experimenters were incorrect.

In our latest studies of the Climax experiments (Rangno and Hobbs 1993) we found the following:

- In Climax I, cloud seeding had no apparent effect on precipitation after the control stations were selected (halfway through the experiment).
- Evidence of a faulty execution of the randomization scheme, which contributed to misleading results in both Climax I and II.
- It was unlikely that the artificial seeding agent released from the ground could have reached clouds in the target area under the conditions for which the greatest apparent seeding effect was reported by the Climax experimenters (viz., southwesterly flow and 500-mb temperatures $\geq -20°C$).

We now turn to the specific comments of Gabriel (1995) and Mielke (1995).

2. Responses to Gabriel's comments

If there were a movie version of the intriguing Climax experiments, it should be patterned after Akira Kurosawa's *Rashomon*; certainly, everyone who studies this fascinating experiment sees something different (including the Climax experimenters at various times—Table 1).

Gabriel (hereafter G) begins by asking three important questions. Were the selections of experimental units and allocations of seeding treatment unbiased in the Climax experiments? Were the Climax hypotheses formulated independently of the data? Were the tests of statistical significance of the Climax data properly applied in view of the many hypotheses that could have been suggested by the data? These questions are addressed to the Climax experimenters, rather than to us. We join G in encouraging candid answers, particularly in view of the fact that the Climax experimenters have not responded to any of our previous criticisms of their experiments.

Gabriel asks why we are concerned with the fact that 6 and 7 December 1966 were excluded from the Climax II experiments. In the Climax experiments, experimental days were declared by the United States Weather Bureau (USWB); the only requirement for an experimental day was a USWB forecast of a chance of measurable precipitation at Leadville, Colorado. These forecasts were relayed to CSU personnel; if a chance of measurable precipitation was forecast, CSU personnel were to draw a random seed/no-seed decision (e.g., Grant and Mielke 1967; Mielke et al. 1981). The Climax statistical design required that a random seed/no-seed decision be drawn for every experimental day. On both the 6 and 7 December 1966 the USWB forecast heavy precipitation for all the mountainous regions of Colorado, including Leadville; they were, therefore, official experimental days for Climax II. However, a random seed/no-seed decision was not

TABLE 1. Some statements by the Climax experimenters on various aspects of the Climax experiments.

Reference	Statement
(a) Relationship Between 500-mb Temperatures and Cloud-Top Temperatures	
Grant and Mielke (1967)	"500 mb is consistently near cloud top level and the 500 mb temperature is considered as representative of cloud top temperature."
Mielke (1979)	"Thus (in retrospect), considering the extreme short-period variability of cloud and moisture conditions found in the CRBPP, the upper air data for the Climax experiments could not reliably index the detailed character of the cloud conditions on which the (Climax) physical seeding hypotheses were based."
Mielke et al. (1981)	"The 500 mb temperature represents the temperature near the tops of the orographic, or blanket portions of the clouds over the mountains."
(b) Degree of Correlation between Precipitation in the Target Area and the Eight Control Stations used by the Climax Experimenters	
Grant and Mielke (1967)	"well correlated"
Mielke et al. (1970)	"poorly correlated"
Mielke et al. (1981)	"excellent covariates"
(c) The "Independence" of the Precipitation Data at Climax 2 NW	
Mielke et al. (1971)	"The recording gauge (FCRG—Climax 2 NW) is shown separately since these data were independently collected by an agency not associated with the Colorado State University program. Specifically, FCRG is the U.S. Weather Bureau Station No. 05-1660 at Climax, Colo."
Mielke et al. (1981)	". . . (the) results of this reanalysis is based strictly on data associated with CRG (Climax 2 NW) are presented separately in the Appendix, since these results involve data which were independently collected by the N.W.S., an agency not associated with the Colorado State University program."
Mielke (1995)	"It was necessary (for CSU personnel) to take the data from the raw output of CRG [the Climax 2 NW recording gauge] since it would have taken a number of years before the 'official' USWB (data) would be available from Asheville, North Carolina."

drawn by CSU on either of these two days (although they were drawn the day before and the day after). Therefore, the statistical design of the Climax experiments was not rigorously implemented. As we have discussed (Rangno and Hobbs 1993), had the 6 and 7 December 1966 been included in the randomized draws, they could have changed the statistical results of Climax II and drastically altered the average daily precipitation on control days. Apparently, there were other experimental days on which random seed/no-seed decisions were not made (see Mielke's comments). We join G in urging the Climax experimenters to describe fully and specifically how decisions were made to refrain from drawing random decisions on official experimental days.

In Rangno and Hobbs (1987, 1993) we discussed the temperature and wind *partitioning* (rather than *criteria*) used by the Climax experimenters. We found that the Climax experimenters had made many misassignments of 500-mb temperatures and 700-mb winds. In Climax II, for example, 12 out of the 16 misassignments of 500-mb temperatures were such as to favor a positive effect of seeding on precipitation for 500-mb temperatures $\geq -20°C$. These misassignments contributed to the erroneous precipitation climatology based on control days of the Climax experiments [see Fig. 3 in Rangno and Hobbs (1993)].

We do not question that increases in precipitation due to the seeding of clouds with top temperatures $\geq -20°C$ might well have been hypothesized by the Climax experimenters prior to the initiation of the statistical experiments. (Indeed, this was a basic tenet of the cloud physics community prior to the discovery of unexpected high concentrations of ice in natural clouds at temperatures much higher than $-20°C$.) What we do question is the assumption of the Climax experimenters that cloud-top temperatures in the Rockies are reliably indexed by 500-mb temperatures [see Fig. 4 in Rangno and Hobbs (1993)]. Therefore, even if there were a good correlation between 500-mb temperatures and a seeding effect (and we do not think there is), this would not confirm any hypothesis concerning cloud-top temperatures and seeding effects.

Concerning the choice of control stations, one should be skeptical of statistical analyses of any cloud seeding experiments that are based on relatively few control stations chosen *after* the statistical experiment has begun, particularly when the data are not synchronized with the experiment day, which was the case for the Climax experiments (Rhea 1983).

Finally, G raises some issues concerning our criticisms of the interpretations of the Climax results. In our view, the demonstration of an effect of artificial seeding on precipitation requires both good statistical evidence and sound physical linkages between the artificial seeding and the affected precipitation. The results of the Climax experiments, as presented by the Climax experimenters, appeared to satisfy both requirements. However, our reanalysis of the Climax experiments shows that there was no statistically significant evidence for increases in precipitation due to seeding. In fact, once the control stations were specified, the statistical results showed virtually no effect of seeding on precipitation for *seven seasons* at the key gauge in the center of the target area! This could have been due to faulty execution and/or a null effect of the seeding on precipitation. We have pointed out several deficiencies in the execution of the Climax experiments. However, we have also pointed out that there was no reason to expect that glaciogenic seeding should increase precipitation in the Rockies, as hypothesized by the Climax experimenters, since the natural clouds already have ample ice particles for the efficient release of precipitation. In terms of G's simile, the disappointment at Columbus' failure to reach Asia was more than offset when the reason was understood (i.e., another continent stood in the way!).

3. Responses to Mielke's comments

We thank Mielke (hereafter M) for providing previously unavailable information on the Climax experiments. Our responses to his remarks are grouped under the same headings that he uses.

a. Randomization

We do not question the *design* of the randomization scheme for the Climax experiments, but we are critical of the way it was *implemented.* Mielke states that the experiments could not have been biased because the experimental days (i.e., the days for which random seed/no-seed decisions should have been made) were chosen by the USWB. This statement would be correct if a random seed/no-seed decision had been made for every experimental day (as the statistical design required) and had the USWB been in charge of drawing the random seed/no-seed decisions. In fact, CSU personnel were responsible for drawing these decisions (Grant and Mielke 1967; Mielke et al. 1981). As we have seen, experimental days were declared for which random seed/no-seed decisions were not drawn by the Climax experimenters; this compromised the statistical results of the Climax experiments.

We are troubled to learn from M that Climax II was sometimes "shut down" by commercial seeding; this introduces another source of nonrandomized decisions into the Climax experiments (e.g., Chappell 1970).

b. Target data

Mielke states that the need for timely reporting in the Climax experiments led to the decision to analyze *raw output data* from the USWB Station 05-1660 (i.e., Climax 2 NW). Specifically, M states: "it would have taken a number of years before the 'official' USWB (now National Weather Service) data would be avail-

able from Asheville, North Carolina." In fact, at that time, the publication, *Hourly Precipitation Data, Colorado* (HPD), to which M refers, appeared within six months of the data being collected. More importantly, the Climax experimenters should have stated in their papers that the data they used for the key target station, Climax 2NW, were not *official*, independent data. Instead, they emphasized repeatedly the opposite (see Table 1c).

Mielke questions our reliance on the official HPD precipitation data (from Asheville) in analyzing the Climax experiments. He notes that some of the data for Climax 2 NW were missing from the HPD. Is M suggesting that the seeding effect claimed by the Climax experimenters for Climax II is confined to the relatively small amount of data missing in the HPD that can be obtained only from the Climax experimenters?

It should be noted also that there are important differences between the precipitation amounts used by the Climax experimenters and the HPD (Rangno and Hobbs 1987) and these differences are not random. Thirty-two out of the 43 differences in precipitation amounts in Climax II generated by the Climax experimenters were such as to favor a positive seeding effect (for 500-mb temperature $\geq -20°C$). The probability that these differences were due to chance is less than one in a thousand!

Further, missing data for the Climax 2 NW recording gauge in the official HPD record during the Climax experiments are almost entirely confined to the Climax II experiment. Was this due to a priori handling of these recording charts by CSU personnel?

c. Control data

Mielke implies that the eight control stations, which he chose halfway through Climax I, would have been the same had they been chosen prior to the experiment. He describes the locations of these control stations as "southwest, west, and northwest of the target." In fact, three of the eight control stations (Winter Park, Grand Lake 6 SSW, and Fraser) are northeast of and, therefore, often *downwind* of Climax 2 NW, which was the center of the target area for seeding [see Fig. 1 in Mielke et al. (1981) and also (Rangno and Hobbs 1993)]. It is difficult to understand why these stations were chosen as controls. Nor does M explain why the Climax experimenters did not choose control stations that were synchronized with Climax 2 NW, since when this is done the apparent effects of seeding on precipitation in Climax I and II are reduced to insignificance (Rhea 1983).

How does M explain the dramatic reduction in the apparent effects of seeding on precipitation (from a large positive to a weak negative effect) following the declaration of the eight control stations [see Fig. 1 in Rangno and Hobbs (1993)]?

Table 2 shows the stepwise regression results for these eight stations for the Climax I experiment at the time they were selected. It can be seen that only one station, Winter Park, provides significant "power," while six of the eight stations provide less than 2% of the explained variance. Despite this, the contribution of each station to the control precipitation was weighted only by the precipitation of the station and not by its contribution to the explained variance. There are many stations in western Colorado that could have been chosen with similar or better predictive power than those used by the Climax experimenters, and various possible choices would have led to quite different results for the effects of seeding.

TABLE 2. Stepwise multiple correlation coefficients and variances for precipitation at Climax 2 NW and the eight control stations chosen by the Climax experimenters (From Grant et al. 1969).

	Multiple correlation	Total variance explained	Increment of explained variance
Winter Park	0.7332	0.5375	0.5375
Aspen	0.7962	0.6282	0.0907
Crested Butte	0.8019	0.6430	0.0147
Eagle	0.8043	0.6469	0.0039
Grand Lake 6SSW	0.8060	0.6496	0.0027
Shoshone	0.8070	0.6513	0.0017
Fraser	0.8074	0.6518	0.0006
Marvine Ranch	0.8077	0.6523	0.0005

d. Partitions

Mielke states that the partitioning for 500-mb temperatures and wind directions used by the Climax experimenters were not driven by "target response variables" (i.e., by precipitation in the target area). We do not question the partitioning *categories*. Rather, in attempting to replicate the results of the Climax experiments from the Department of Commerce's published data, using the method of the Climax experimenters, we discovered that many of the values used by the Climax experimenters for 500-mb temperatures and 700-mb wind directions were incorrect (Rangno and Hobbs 1987).

Mielke states ". . . the CRG-2 (i.e., Climax 2 NW) and HAO Climax II data have been corrected." Which data have been corrected: precipitation, 500-mb temperatures, winds, or all three? And what are the results of using the correct data? Has M used the USWB *Northern Hemisphere Data Tabulations* as his source of upper-level winds and temperatures, or has he used values from the hand-drawn facsimile maps that were used previously by the Climax experimenters (e.g., Chappell 1967, 1970)?

Mielke now dismisses his previous concern (Mielke 1979) and that of Grant et al. (1979) that type I statistical errors compromised Climax I and II. Does he also dismiss his earlier conclusion that ". . . considering the extreme short-period variability of cloud and

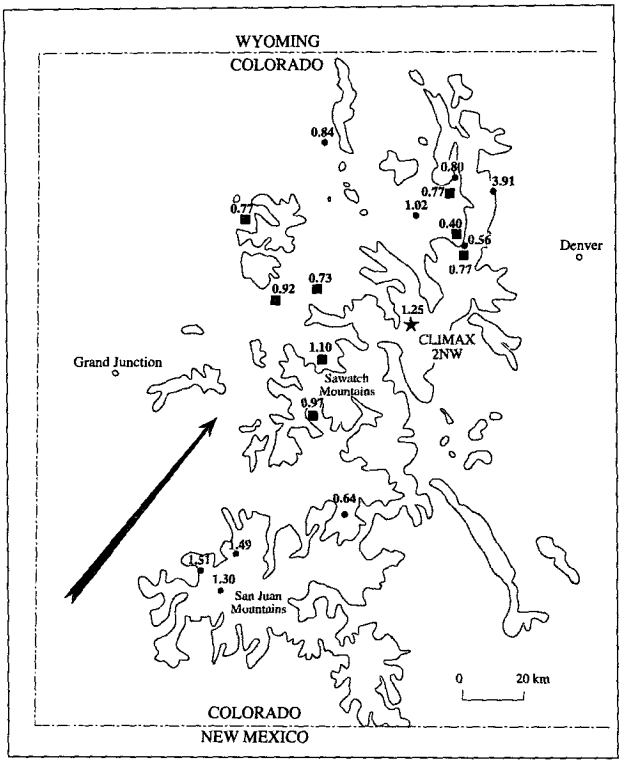

FIG. 1. Seed/no-seed ratios for the combined Climax I and II experiments when 500-mb temperatures were $\geq -20°C$ and the interpolated 700-mb winds (arrow) were from 190° clockwise through 250°. The numbers shown are based on official USWB data, and the precipitation data are synchronized to the Climax experimental days. The squares are the control stations selected by the Climax experimenters.

moisture conditions found in the Colorado River Basin Pilot Project, the upper-air data for the Climax experiments could not reliably index the detailed character of the cloud conditions on which the (Climax) physical seeding hypothesis were based" (Mielke 1979)?

The high seed/no-seed ratios surrounding Climax 2 NW (see Rhea 1983) cannot be dismissed. The high ratios at *upwind* stations were, in fact, the result of longer periods of precipitation on seeded days, just as it was for Climax 2 NW (Chappell et al. 1971).

Mielke asks why we did not test our conjectures statistically. We did (Rangno and Hobbs 1987, 1993). The result was that there was no statistically significant effect of seeding on precipitation at the center of the target area (Climax 2 NW).

e. A general appraisal

Mielke concludes by restating his belief that the Climax experiments demonstrated that artificial seeding can increase precipitation at Climax in southwesterly winds at 700 mb. Apparently, he is undaunted by the numerous problems with the execution and analyses of the experiments, which have been detailed by us. Neither, we doubt, is he deterred by the fact that stations well *upwind* of the target area for seeding (Climax 2 NW), namely, in the San Juan Mountains, show higher seed/no-seed ratios than Climax 2 NW for conditions under which the greatest seeding effects were reported by the Climax experimenters, namely, southwesterly winds at 700-mb and 500-mb temperatures $\geq -20°C$ (Fig. 1).

Despite all the evidence to the contrary, M's faith in the demonstration of increases in precipitation due to seeding in the Climax experiments remains unshaken. Others may be forgiven for being less credulous.

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