

A Reevaluation of the Climax Cloud Seeding Experiments Using NOAA Published Data

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ABSTRACT

Some significant differences exist between the precipitation amounts for Climax 2NW (a station situated near the center of the target area in the Climax I and Climax II cloud seeding experiments) that have been used in previous analyses of the Climax experiments and NOAA published values for this station. Some of the interpolated 500 mb temperature assignments used in previous analyses also differ in category (i.e., $\geq -20^{\circ}\text{C}$ or $< -20^{\circ}\text{C}$) from those derived from NOAA sounding data.

Using the NOAA data for precipitation at Climax 2NW, and the same control stations and series of statistical tests (which, in order of increased sophistication, are the seed/no-seed single, double and covariate ratios) used by the Climax Experimenters, the following results are obtained for interpolated 500 mb temperatures $\geq -20^{\circ}\text{C}$ at Climax 2NW. For the exploratory Climax I experiments: seed/no-seed single, double and covariate ratios of 1.65, 1.14 and 1.25, respectively (compared to seed/no-seed single and double ratios of 2.17 and 1.32 for Climax 2NW and a seed/no-seed covariate ratio of 1.34 for the "target group mean" precipitation reported by the Climax Experimenters). For the confirmatory Climax II experiment: seed/no-seed single, double and covariate ratios of 0.90, 1.04 and 0.90, respectively (compared to seed/no-seed single and double ratios of 1.24 and 1.17 for Climax 2NW and a seed/no-seed covariate ratio of 1.27 for the "target group mean" precipitation reported by the Climax Experimenters).

We conclude that the Climax II experiment failed to confirm that precipitation can be increased by artificial seeding in the Colorado Rockies.

1. Introduction

Climax I and Climax II were an important series of experiments carried out in the Colorado Rockies to explore the effects on precipitation of ground-based seeding with silver iodide (Grant and Mielke, 1967; Grant et al., 1969; Mielke et al., 1971). Both experiments were randomized statistically, but Climax I was considered an exploratory experiment and Climax II a confirmatory experiment (Mielke et al., 1981). Initial statistical analyses by Grant et al. (1969), Mielke et al. (1970) and Mielke et al. (1971) indicated that when interpolated 500 mb temperatures were $\geq -20^{\circ}\text{C}$ the average precipitation at Climax 2NW (U.S. Weather Bureau Precipitation Station Number 05-1660, which was located near the center of the seeded target area) on the seeded days exceeded that on the control days by $>100\%$ in Climax I and by $\sim 24\%$ in Climax II. However, subsequent analyses (Mielke et al., 1981) which attempted to take into account a regional bias in precipitation that favored seeded days (Mielke, 1979), showed that when interpolated 500 mb temperatures were $\geq -20^{\circ}\text{C}$ the precipitation at Climax 2NW was 32% greater on seeded days than on control days in Climax I and 17% greater in Climax II.

Since these statistical results appeared to be explainable on physical grounds (e.g., see Grant and Mielke, 1967; Mielke et al., 1971), the Climax experiments have

often been considered as one of the few cloud seeding experiments to have demonstrated that precipitation on the ground can be increased by cloud seeding (e.g., see National Academy of Sciences, 1973; Warner 1973). However, in a previous paper (Hobbs and Rangno, 1979) we pointed out that the cornerstones of the physical arguments that were presented to explain the apparent increases in precipitation due to seeding in the Climax experiments do not stand up to scrutiny.

In the present paper, we consider the data used in the statistical analyses of the Climax I and II experiments. We show that there are a number of differences between the precipitation amounts at Climax 2NW that have been used by the Climax Experimenters (i.e., Grant, Mielke and their co-workers) and those officially documented by the National Oceanic and Atmospheric Administration (NOAA). In addition, there are some differences in the interpolated 500 mb temperatures used by the Climax Experimenters and those we have derived from NOAA sounding data. The NOAA published data is used to reevaluate, by means of the same statistical techniques used by the Climax Experimenters, the apparent effects of seeding on precipitation at Climax 2NW in the Climax I and Climax II experiments. The results obtained differ significantly from those reported by the Climax Experimenters.

TABLE 1. Experimental days in the Climax I experiment for which interpolated 500 mb temperature at Climax 2NW derived from the NOAA publication *Northern Hemispheric Data Tabulations* (NHDT) results in a change in the 500 mb temperature category ($< -20^{\circ}\text{C}$ or $\geq -20^{\circ}\text{C}$) from that given by the Climax Experimenters.

Date	Interpolated 500 mb temperature used by the Climax Experimenters* (C°)	Interpolated 500 mb temperature derived from NHDT (C°)	Precipitation at Climax 2NW from NOAA hourly precipitation data (in hundredths of an inch)
(a) Control days			
29 March 1960	-25	-20	53 [†]
2 April 1961	-16	-21	1 [†]
2 February 1965	-20	-23	0 [†]
22 March 1965	-21	-20	0
28 March 1965	-21	-20	19 [†]
30 March 1965	-20	-21	0 [†]
(b) Seeded days			
14 March 1960	-20	-23	55 [†]
3 March 1961	-21	-20	16
14 April 1961	-20	-27	46 [†]
22 December 1961	-20	-27	18 [†]
26 December 1961	-22	-19	2 [†]
26 February 1963	-18	-21	0
25 December 1964	-23	-19	52

* These data are on a magnetic tape generated by the Climax Experimenters, which is on file with the Division of Atmospheric Resources Research, Bureau of Reclamation, Denver, CO 80225-0007.

[†] For these cases the interpolated 500 mb temperature category used by the Climax Experimenters supports the hypothesis that the seed/no-seed single ratio is greater than unity (i.e., precipitation was greater on seeded days than on control days) when the 500 mb temperature was $\geq -20^{\circ}\text{C}$, whereas the 500 mb temperature category derived from the NHDT data refutes this hypothesis.

2. Comparisons of interpolated 500 mb temperature data

The apparent effects of seeding on precipitation in the Climax experiments have been stratified by 500 mb temperature by the Climax Experimenters (e.g., Grant and Mielke, 1967; Mielke et al., 1981). The 500 mb temperatures at Climax 2NW were estimated by interpolating data originating from the NOAA rawinsonde launch sites at Grand Junction and Denver, Colorado, with the temperatures weighted by the distance of the launch site from Climax 2NW (Mielke et al., 1981). The method of assigning these interpolated temperatures to the experimental days on which precipitation fell at Climax 2NW has been described by Fritsch (see Grant et al., 1974). For those experimental days on which precipitation fell, we have used the same methods for deriving and assigning interpolated 500 mb temperatures to Climax 2NW as those described by Mielke et al. (1981) and Fritsch, and we have used the 500 mb temperature data for Grand Junction and Denver listed in the NOAA publication *Daily Series, Synoptic Weather Maps, Part II, Northern Hemisphere Data Tabulations* (NHDT).¹ An illustration of the application of this method may be found in Rangno

(1979). The method of assigning interpolated 500 mb temperatures to those experimental days without precipitation has not been described by the Climax Experimenters. We have assigned these latter temperatures using a similar method to that described by Fritsch for days with precipitation, except that an average has been taken of the two interpolated NHDT 500 mb temperatures that fell within each experimental day.

Differences exist between the interpolated 500 mb temperatures used by the Climax Experimenters and those derived by us using the NHDT data. These differences are listed in Tables 1 and 2 for those cases in which our derived values for the interpolated 500 mb temperature for Climax 2NW results in a different temperature category (i.e., $\geq -20^{\circ}\text{C}$ or $< -20^{\circ}\text{C}$) from that given by the Climax Experimenters.

In the case of Climax I, there are 13 days for which the interpolated 500 mb temperature category used by the Climax Experimenters differs from that we obtained using the NHDT data (Table 1). In nine of these cases, the category used by the Climax Experimenters support the hypothesis that the seed/no-seed single ratio is greater than unity (i.e., precipitation was greater on seeded days than on the control days) when the 500 mb temperature was $\geq -20^{\circ}\text{C}$.

For Climax II there are 16 days where the interpolated 500 mb temperature category used by the Climax Experimenters differs from those we derived from the NHDT data. Of these 16 days, 13 of the temperature

¹ The NHDT are available from the National Climatic Center, Asheville, NC 28801.

TABLE 2. As in Table 1, but for Climax II.

Date	Interpolated 500 mb temperature used by the Climax Experimenters* (C°)	Interpolated 500 mb temperature derived from NHDT (C°)	Precipitation at Climax 2NW from NOAA hourly precipitation data (in hundredths of an inch)
(a) Control days			
19 January 1967	-20	-23	0†
7 December 1967	-20	-21	0†
30 January 1968	-19	-21	0†
26 January 1970	-20	-21	0†
(b) Seeded days			
14 January 1967	-19	-23	37†
4 November 1967	-21	-20	0†
23 November 1967	-20	-21	40†
30 November 1967	-22	-20	0†
22 December 1967	-18	-26	0
11 January 1968	-19	-25	10
24 November 1968	-20	-22	0
27 January 1969	-18	-21	47†
26 February 1969	-22	-18	0†
8 April 1969	-22	-20	10†
16 April 1969	-20	-21	15†
28 January 1970	-20	-28	60†

* These data are on a magnetic tape generated by the Climax Experimenters, which is on file with the Division of Atmospheric Resources Research, Bureau of Reclamation, Denver, CO 80225-0007.

† For these cases the interpolated 500 mb temperature category used by the Climax Experimenters supports the hypothesis that the seed/no-seed single ratio is greater than unity (i.e., precipitation was greater on seeded days than on control days) when the 500 mb temperature was $\geq -20^{\circ}\text{C}$, whereas the 500 mb temperature category derived from the NHDT data refutes this hypothesis.

category assignments used by the Climax Experimenters support the hypothesis that seeding increased precipitation when the 500 mb temperature was $\geq -20^{\circ}\text{C}$ (Table 2).

3. Comparisons of precipitation data

During the Climax experiments, the Climax 2NW precipitation gage was maintained by the University of Colorado's High Altitude Observatory, a group not affiliated with the Climax cloud seeding experiments. The Climax Experimenters state that they used precipitation measurements from the Climax 2NW gage in analyzing both the Climax I and II experiments (e.g., Mielke et al., 1970, 1971, 1981). However, comparisons of the data they used with the official records for Climax 2NW, contained in the NOAA publication entitled *Hourly Precipitation Data (HPD)*,² reveal a number of differences, particularly for Climax II.

Listed in Table 3 are those cases for Climax I for which our values of the interpolated 500 mb temperatures at Climax 2NW were $\geq -20^{\circ}\text{C}$ and the precipitation amounts for Climax 2NW used by the Climax Experimenters differ from the amounts listed in the HPD.

Out of the total sample of two hundred and fifty-one daily precipitation amounts for Climax 2NW in the Climax I experiment, only six (two for control days and four for seeded days) used by the Climax Experimenters differ from those in the HPD. Four of these days (30 March, 6 April, 7 April and 8 April 1963) were in a period when the recording gage at Climax 2NW was out of service, but the nonrecording 24-h precipitation gage at this site showed no precipitation on each of these days (see NOAA publication *Climatological Data, Colorado* under relevant dates). The Climax Experimenters list the precipitation for these six days as "missing." In five out of these six cases, listing the precipitation as missing favors the hypothesis that precipitation was greater on the seeded days than on the control days for 500 mb temperatures $\geq -20^{\circ}\text{C}$.

In the case of Climax II, the differences between the precipitation values at Climax 2NW used by the Climax Experimenters and the values in the HPD are far more numerous and significant (Table 4). Out of the 40 entries in Table 4 where a value can be assigned to the difference between the precipitation amounts used by the Climax Experimenters and that listed in the HPD, 39 were assigned to the same interpolated 500 mb temperature category by the Climax Experimenters and by us. For 30 out of these 39 cases, the precipitation amounts used by the Climax Experimenters favor the hypothesis that precipitation on the seeded days was

² The HPD for Colorado is available from the National Climatic Center, Asheville, NC 28801.

TABLE 3. Comparison of precipitation amounts (in hundredths of an inch) for Climax 2NW used by the Climax Experimenters in their analyses of the Climax I experiment and those contained in the NOAA publication *Hourly Precipitation Data (HPD)*. Only those days are listed for which the interpolated 500 mb temperatures at Climax 2NW which we have derived are $\geq -20^{\circ}\text{C}$.

Date	Precipitation amount used by the Climax Experimenters*	Precipitation amount in HPD
(a) Control days		
7 April 1963	NR [†]	0
15 January 1965	NR	15
(b) Seeded days		
30 March 1963	NR	0
6 April 1963	NR	0
8 April 1963	NR	0
14 January 1965	NR	0

* These data are a magnetic tape generated by the Climax Experimenters, which is on file with the Division of Atmospheric Resources Research, Bureau of Reclamation, Denver, CO 80225-0007.

[†] Missing

greater than that on the control days for 500 mb temperatures $\geq -20^{\circ}\text{C}$. This was because either the precipitation amounts on the control days used by the Climax Experimenters were lower than the HPD values or because the precipitation amounts on the seeded days used by the Climax Experimenters were greater than the HPD values.

In Table 4, there are six precipitation values listed as "missing" by the Climax Experimenters for which values appear in the HPD. Also, in 12 cases the Climax Experimenters list precipitation amounts on days for which the HPD shows the values to be "missing."

4. Impact on the results of the Climax experiments

We now compare statistical analyses of the effects of seeding in the Climax experiments using the NOAA published data with the statistical analyses that have been reported by the Climax Experimenters. The target we will consider is the Climax 2NW station which, as previously mentioned, was situated near the center of the Climax target area for seeding.³ The precipitation amounts that we use for the control area are the same as those used by Mielke et al. (1981). We confine our attention to those cases where the interpolated 500 mb temperature at Climax 2NW (derived by the respective investigators) was $\geq -20^{\circ}\text{C}$, since it is for this temperature category that the Climax Experimenters have reported significant effects of seeding on precipitation.

Following Mielke et al. (1970, 1971), we first use the seed/no-seed single ratio, which is defined as the av-

erage precipitation amount at the target on seeded days divided by the average precipitation amount at the target on control days. The results are shown in Table 5. Using the NOAA published values for precipitation at Climax 2NW, and those cases for which the interpolated 500 mb temperature that we have derived for Climax 2NW is $\geq -20^{\circ}\text{C}$, we obtain seed/no-seed single ratios at this station of 1.65 for Climax I (compared to 2.17 given by Mielke et al., 1970) and 0.90 for Climax II (compared to 1.24 given by Mielke et al., 1971).

During both Climax I and II, the seed/no-seed single ratio exhibited high values *outside* of the target area (Mielke, 1979). Mielke et al. (1981) attempted to take this regional-wide meteorological "bias" into account through the use of control stations and the seed/no-seed double ratio test. The seed/no-seed double ratio is defined as the ratio of the average precipitation amount at a target on seeded days to that on control days divided by the ratio of the average precipitation amount in a control area on seeded days to that on control days. The values for the seed/no-seed double ratio obtained by Mielke et al. (1981) for Climax 2NW, and for their interpolated 500 mb temperatures $\geq -20^{\circ}\text{C}$, were 1.32 for Climax I and 1.17 for Climax II (Table 6). The same procedure applied to the NOAA published values for precipitation at Climax 2NW, and for interpolated 500 mb temperatures $\geq -20^{\circ}\text{C}$ that we have derived, yields quite different values (Table 6). In this case, the seed/no-seed double ratio for Climax I is 1.14 and that for Climax II is 1.04.

Mielke and Medina (1983) described a statistical procedure that employs a seed/no-seed covariate ratio for estimating treatment-induced effects. This procedure is designed to allow for uncontrolled natural variability, for disproportionate allocation of nontreated and treated experimental units; it moderates the effects of individual values, and it accounts for differential treatment effects. Mielke and Medina applied this pro-

³ In addition to Climax 2NW, Mielke et al. (1970, 1971, 1981) consider the "target group mean" (TGM) precipitation, which was defined as the average precipitation amount for eight snowboards situated within the Climax target area. Since these snowboards were maintained by the Climax Experimenters, and data from them cannot be verified from an independent source, we will not use the TGM.

TABLE 4. As in Table 3 except for the Climax II experiment.

Date	Precipitation amount used by the Climax Experimenters* (Column 1)	Precipitation amount in HPD (Column 2)	Column 1 - Column 2†
(a) Control days			
11 April 1966	19	21	-2
23 April 1966	48	57	-9
27 April 1966	16	20	-4
30 November 1966	NR‡	13	—
5 January 1967	1	4	-3
22 January 1967	0	3	-3
27 January 1967	13	17	-4
10 February 1967	13	NR	—
19 March 1967	13	NR	—
12 April 1967	0	4	-4
14 April 1967	105	NR	—
10 November 1967	5	6	-1
11 December 1967	5	4	1
24 February 1968	32	NR	—
13 April 1968	22	NR	—
6 May 1968	7	8	-1
10 May 1968	18	17	1
14 May 1968	2	10	-8
19 November 1968	18	19	-1
20 November 1968	0	2	-2
26 December 1968	12	NR	—
15 January 1969	7	9	-2
26 January 1969	87	88	-1
12 December 1969	22	19	3
22 December 1969	NR	40	—
26 December 1969	26	24	2
16 January 1970	3	0	3
(b) Seeded days			
19 April 1966	41	33	8
4 December 1966	NR	11	—
15 January 1967	20	17	3
16 January 1967	NR	8	—
31 January 1967	24	27	-3
18 March 1967	26	NR	—
25 March 1967	8	0	8
17 April 1967	28	NR	—
5 May 1967	5	1	4
6 May 1967	35	18	17
2 November 1967	20	26	-6
20 November 1967	18	7	11
25 November 1967	NR	20	—
30 November 1967§	3	0	3
20 February 1968	5	1	4
21 February 1968	62	NR	—
25 February 1968	13	NR	—
7 March 1968	0	NR	—
2 April 1968	7	NR	—
17 April 1968	NR	13§	—
7 May 1968	31	28	3
13 May 1968	4	0	4
1 November 1968	2	1	1
4 December 1968	2	0	2
1 January 1969	4	5	-1
21 January 1969	9	0	9
13 April 1969	21	60	-39
21 December 1969	23	22	1
24 December 1969	72	66	6
10 January 1970	10	9	1
22 January 1970	21	12	9

* These data are on a magnetic tape generated by the Climax Experimenters, which is on file with the Division of Atmospheric Resources Research, Bureau of Reclamation, Denver, CO 80225-0007.

† A positive value in this column indicates that the precipitation amount used by the Climax Experimenters favored the hypothesis that precipitation was greater on the seeded days than on control days when the 500 mb temperature is $\geq -20^{\circ}\text{C}$.

‡ Missing

§ This total is from the Climax 2NW non-recording gage (the recording gage was out of service). Use of this total is legitimate in this case because all of the precipitation fell within the 1000-0900 LST experimental day. The nonrecording gage is read at 1700 LST.

cedure to the Climax I and Climax II TGM precipitation (see footnote 3). They found that for interpolated 500 mb temperatures $\geq -20^{\circ}\text{C}$ the seed/no-seed covariate ratio was 1.34 for Climax I and 1.27 for Climax II. Application of this procedure to the NOAA published data set for Climax 2NW and for our derived interpolated 500 mb temperatures $\geq -20^{\circ}\text{C}$, yields seed/no-seed covariate ratios of 1.25 and 0.90 for Climax I and Climax II, respectively.

5. Summary and conclusions

In this paper we have shown that there are some significant differences between precipitation amounts at Climax 2NW (a station situated near the center of the target area for seeding in the Climax I and Climax II experiments) that have been used in previous statistical analyses of the Climax experiments and NOAA published values for this same station. Some of the interpolated 500 mb temperature categories (i.e., $\geq -20^{\circ}\text{C}$ or $< -20^{\circ}\text{C}$) for Climax 2NW used in previous statistical analyses also differ from those we have derived from NOAA published sounding data.

Using the NOAA published data for precipitation at Climax 2NW, the interpolated 500 mb temperature categories that we have derived, and the same series of statistical tests employed by the Climax Experimenters, the following results are obtained for increasingly refined estimates of the effects of seeding on precipitation at Climax 2NW when interpolated 500 mb temperatures were $\geq -20^{\circ}\text{C}$. For Climax I: the seed/no-seed single ratio, seed/no-seed double ratio and seed/no-seed covariate ratio were 1.65, 1.14 and 1.25, respectively. For Climax II: the seed/no-seed single ratio, seed/no-seed double ratio and seed/no-seed covariate ratio were 0.90, 1.04 and 0.90. In view of the fact that Climax II was the confirmatory experiment, we conclude that it failed to confirm that precipitation can be increased by artificial seeding in the Colorado Rockies.

TABLE 5. Comparisons of seed/no-seed single ratios at Climax 2NW for the Climax I and Climax II experiments. Results are for interpolated 500 mb temperature $\geq -20^{\circ}\text{C}$ as derived by the referenced investigators.

Data source	Seed/no-seed single ratio	Reference
(a) Climax I		
Climax Experimenters	2.17	Mielke et al. (1970)
NOAA published data	1.65	This paper
(b) Climax II		
Climax Experimenters	1.24	Mielke et al. (1971)
NOAA published data	0.90	This paper

TABLE 6. Comparisons of seed/no-seed double ratios at Climax 2NW for the Climax I and Climax II experiments. Results are for interpolated 500 mb temperatures $\geq -20^{\circ}\text{C}$, as deduced by the referenced investigators.

Data source	Seed/no-seed double ratio	Reference
(a) Climax I		
Climax Experimenters	1.32	Mielke et al. (1981)
NOAA published data	1.14	This paper
(b) Climax II		
Climax Experimenters	1.17	Mielke et al. (1981)
NOAA published data	1.04	This paper

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