An Independent Replication of the Climax Wintertime Orographic Cloud Seeding Experiment

PAUL W. MIELKE, JR.[1], LEWIS O. GRANT[2] AND CHARLES F. CHAPPELL[3]

Colorado State University, Fort Collins

(Manuscript received 21 April 1971, in revised form 13 July 1971)

ABSTRACT

An orographic cloud seeding experiment conducted in the vicinity of Climax, Colo., has been continued for five additional wintertime periods from 1965–70. A comparison of this new independent information is made with previously discussed wintertime operations of the experiment from 1960–65. As a whole, agreement between these independent data sets is good. In particular, the agreement in temperature and wind partitions is consistent with a previously reported model which describes seeding effects under various physically defined conditions. These comparisons have been made using pooled groups of precipitation sensors having similar elevations and locations.

1. Introduction

Recently, results of the Climax wintertime orographic cloud seeding experiment have been discussed (Grant and Mielke, 1967; Grant *et al.*, 1968, 1969; Mielke *et al.*, 1970). Each of these discussions has emphasized the agreement of the empirical results with effects that would be predicted from a physical model of the cold orographic cloud system developed for the Climax area.

Early reports presented analyses based on observations from two snowfall sensors in the prime target area of the experiment. The most recent report (Mielke *et al.*, 1970) expanded the scope of the analysis to a much broader area using precipitation data collected from 65 sensors in the experimental area to show the elevation and spatial variation in the seeding effects. These reports have all been confined to data obtained during operational wintertime periods from 1960 into 1965.

The Climax wintertime orographic cloud seeding experiment has now continued for almost five additional operational wintertime periods from 1965 through 31 January 1970 with no basic alteration in the previous experimental design. The objective of the present discussion is to compare the results of the 1965–70 wintertime periods with the corresponding results of the 1960–65 wintertime periods.

The design of the Climax experiment has previously been reported (Grant and Mielke, 1967; Mielke *et al.*, 1970). This involves randomized seeding restricted only to the extent that large blocks (20–40) have the same number of non-seeded and seeded experimental units. The experimental unit is a 24-hr interval. Observations of precipitation were obtained from the previously mentioned 65 sensors located in the experimental area. The precipitation and other physical observations are made on both non-seeded and seeded experimental units.

[1] Statistics Department.
[2] Atmospheric Science Department.
[3] Utah Water Research Laboratory, Utah State University, Logan.

2. Statistical procedures

The statistical tests used to analyze the 1960–65 and the 1965–70 precipitation data are the 2-sample Wilcoxon and 2-sample sum-of-squared ranks tests. These tests have recently been discussed with respect to evaluating weather modification experiments (Grant and Mielke, 1967; Duran and Mielke, 1968; Mielke, 1967; Mielke *et al.*, 1970).

In order to give a comprehensive comparison of the two sets of wintertime periods, the 65 precipitation sensors, recently described individually by Mielke *et al.* (1970), have been reduced to 12 pooled groups of precipitation sensors having similar elevations and locations. These 12 pooled groups are defined by their respective locations on Fremont, Hoosier and Vail Passes, where the observations were made. Two pooled groups and a separate independently operated recording gage are used to represent the precipitation at the top of Fremont Pass in the center of the area originally designated as the target for the seeding. The recording gage (FCRG) 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. The two pooled groups used to represent precipitation at Fremont Pass, FSG and FTG have been used previously (Mielke *et al.*, 1970).

Another sensor, designated HAO, is located within 10 yards of FCRG. The composition of the 65 precipitation sensors within each of the pooled groups is given in the following list.

1. FCRG (Fremont Pass recording gage): FCRG
2. FSG (Fremont Pass—pooled group no. 1): FCRG, HAO
3. FTG (Fremont Pass—pooled group no. 2): FCRG, HAO, 7,8,9,11,12,13,14
4. FS (Fremont Pass—south side): 1,2,3,4,5,6
5. FPN (Fremont Pass—north side, upper portion): 15,16,17,18,19,20
6. FN (Fremont Pass—north side, lower portion): 20A,21,22,23,24,61
7. HS (Hoosier Pass—south side): 36,37,39,40
8. HP (Hoosier Pass): 41,42,43,44,45
9. HPN (Hoosier Pass—north side, upper portion): 46,47,48,49
10. HN (Hoosier Pass—north side, lower portion): 50,51,52,53,54
11. VP (Vail Pass): 62,62A,63,64,65,66,67
12. VPW (Vail Pass—west side, upper portion): 68,69, 70,71,72
13. VW (Vail Pass—west side, lower portion): 73,74, 75,76,77,78,79,80

The location of the 65 sensors and their organization into pooled groups is shown in Fig. 1. The observations recorded for each pooled group consist of arithmetic means of non-missing sensor observations on all 24-hr experimental units when at least half of the individual sensor observations are non-missing. The use of the pooled groups facilitates presentation of the results and allows for a more consistent representation of precipitation for a generally homogeneous exposure.

The use of pooled groups of precipitation sensors requires that each precipitation sensor of such a group is describing basically the same phenomena. This requirement was investigated with the aid of a simple multivariate statistical technique known as principal component analysis (cf. Anderson, 1958: Rao, 1965). The data utilized in applying this technique consist of all experimental units of the 1960–65 wintertime periods for which observations from all precipitation sensors of

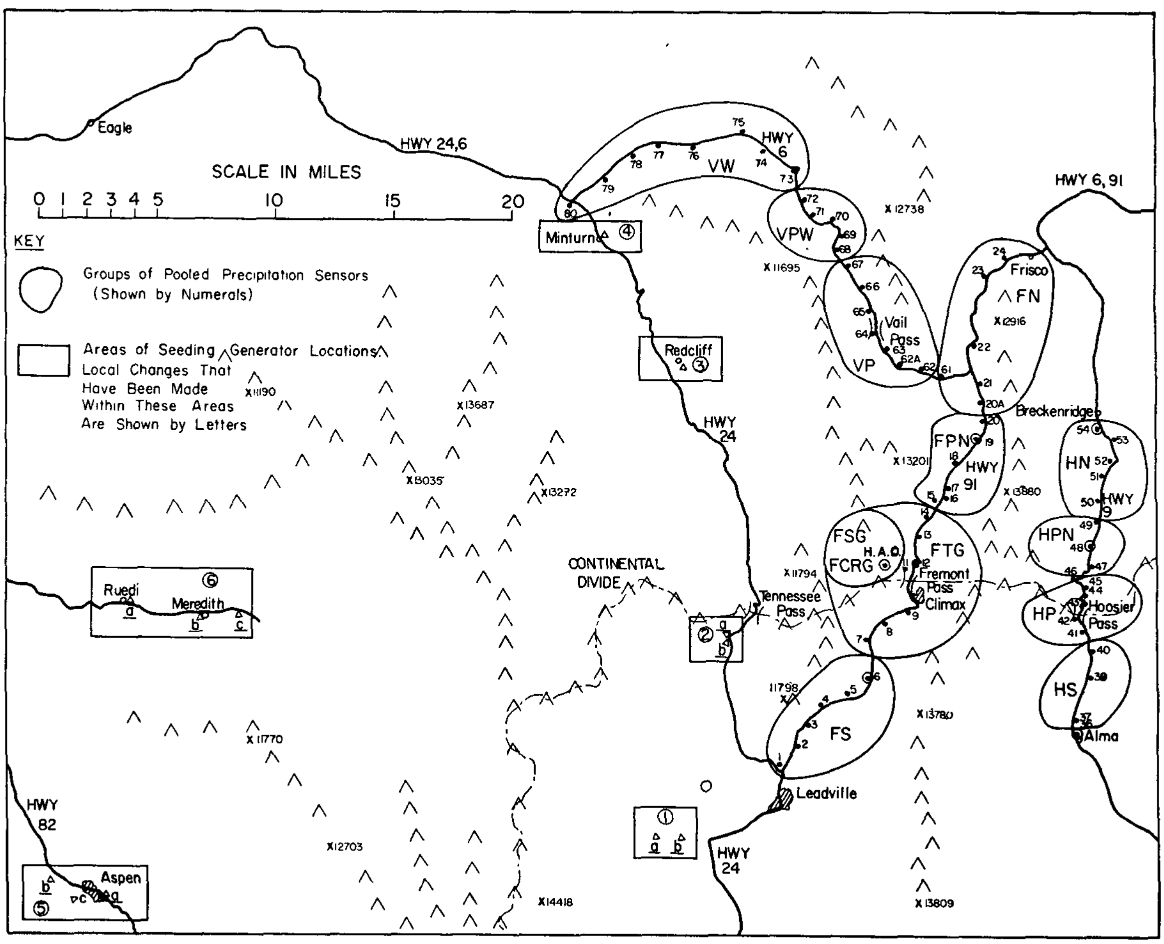

FIG. 1. Composition of pooled groups of precipitation sensors.

a specific group in question are non-missing. If there are n precipitation sensors comprising a group and t experimental units with no missing observations, then principal component analysis essentially transforms the t sets of observations from each of the n precipitation sensors into t sets of n orthogonal linear functions of the n precipitation sensor observations. The n orthogonal linear functions are constructed such that one linear function (termed the first principal component) accounts for a maximal amount of the total variation, another orthogonal linear function (termed the second principal component) accounts for a maximal amount of the remaining variation given the first principal component, and so forth until n such ordered orthogonal linear functions are constructed. These n orthogonal linear functions are termed the n principal components and they jointly account for the total variation in question. In each analysis of the 12 pooled groups, the first principal component is merely the mean of the precipitation sensor observations in question. The proportion of total variation attributed to the first principal component together with the number of experimental units available for principal component analysis of each group are as follows:

FSG(0.967,183)	FTG(0.968,93)	FS(0.957,143)
FPN(0.966,110)	FN(0.928,101)	HS(0.962,120)
HP(0.958,106)	HPN(0.957,123)	HN(0.955,134)
VP(0.962,139)	VPW(0.966,165)	VW(0.945,152)

It can be seen from these results that the composition of the 65 precipitation sensors into 12 pooled groups appears to have removed little of the basic information contained in this experiment.

3. Empirical Results

Results presented at the Fifth Berkeley Symposium on Mathematical Statistics and Probability in December 1965 showed the importance of cloud top temperatures on seeding effects (Grant and Mielke, 1967). The importance of cloud top temperature and vertical velocity of the airstream in determining the weather modification potential of the orographic cloud was described in a physical model of orographic cloud and precipitation processes; the parameters have formed the basis for previous meteorological partitionings (Grant and Mielke, 1967; Grant *et al.*, 1968, 1969; Mielke *et al.*, 1970). The observations for the 12 pooled groups presented in this paper are consequently considered in terms of these meteorological parameters and for partitions shown by the model to be important. Observations of cloud top temperature and vertical air motion are difficult and expensive to obtain and were not made on a routine basis during the experiment. Meteorological partitionings according to the 700-mb equivalent potential temperature (Table 1) and 500-mb temperature (Table 2) are used in this paper as indices of the cloud temperatures. Average cloud tops during winter are near 500 mb in the Climax area although values considerably lower or higher frequently occur. The 700-mb equivalent potential temperature provides an index of the temperature structure and moisture content of the air mass in which the orographic cloud is forming. This inclusion of moisture in the index refines the temperature characterizations since a number of experimental units in all partitions had zero precipitation due to the absence of moisture for adequate cloud formation.

TABLE 1. Statistical description of precipitation data for sensor groups in terms of total sample and 700-mb equivalent potential temperatures.

Sensor group and elevation (ft)	Total sample		Equivalent potential temperature partitions 308–325K		295–307K		281–294K	
Climax I	(131,120)		(41,33)		(69,64)		(21,23)	
Climax IIA	(190,182)		(60,66)		(97,82)		(33,34)	
Climax IIB	(139,147)		(54,59)		(78,64)		(17,24)	
I	113(35)	99(31)	36(11)	29(8)	63(20)	52(16)	14(4)	18(7)
FCRG	0.162	1.11	0.141	1.81	0.174	0.95	0.161	0.61
11,104	0.60	0.77	1.46	1.80	0.08	0.02	−1.16	−1.33
IIA	171(60)	162(50)	55(31)	59(18)	88(24)	77(28)	28(5)	26(4)
	0.112	1.13	0.093	1.62	0.115	1.01	0.137	0.72
	1.12	1.15	2.76	2.55	−0.80	−0.48	−0.23	−0.50
IIB	136(57)	131(45)	51(30)	52(16)	73(23)	61(25)	12(4)	18(4)
	0.080	1.45	0.078	1.81	0.086	1.19	0.055	1.69
	2.03	2.25	3.00	2.87	−0.54	−0.13	1.18	1.20
I	128(27)	118(28)	41(12)	33(10)	66(15)	62(16)	21(0)	23(2)
FSG	0.158	1.09	0.127	1.77	0.174	0.96	0.166	0.66
11;104	0.37	0.65	1.12	1.52	0.01	0.05	−1.79	−1.81
IIA	187(57)	180(49)	59(28)	66(18)	96(24)	80(27)	32(5)	34(4)
	0.112	1.13	0.097	1.56	0.117	1.01	0.125	0.77
	1.00	1.09	2.62	2.43	−0.94	−0.55	−0.33	−0.52

Table 1.—(*Continued*)

Sensor group and elevation (ft)	Total sample		Equivalent potential temperature partitions 308–325K		295–307K		281–294K	
IIB	146(54) 0.083 1.82	145(45) 1.39 2.06	53(27) 0.081 2.96	59(16) 1.76 2.79	77(23) 0.088 −0.72	62(25) 1.16 −0.26	16(4) 0.062 0.57	24(4) 1.28 0.61
I FTG 11,003	111(27) 0.152 0.40	108(27) 1.06 0.65	32(12) 0.130 1.15	29(10) 1.68 1.39	62(15) 0.163 0.17	58(15) 0.95 0.27	17(0) 0.151 −1.76	21(2) 0.67 −1.78
IIA	170(53) 0.098 1.29	172(46) 1.18 1.36	55(27) 0.100 2.31	64(18) 1.43 2.07	86(21) 0.097 −0.69	77(25) 1.07 −0.31	29(5) 0.099 0.52	31(3) 0.93 0.27
IIB	133(50) 0.077 1.93	138(42) 1.40 2.12	49(26) 0.085 2.66	57(16) 1.60 2.43	69(20) 0.076 −0.46	59(23) 1.23 0.01	15(4) 0.053 0.90	22(3) 1.36 0.85
I FS 10,137	109(38) 0.099 0.03	102(36) 1.02 0.22	33(16) 0.098 1.28	28(11) 1.57 1.41	59(19) 0.101 −0.30	55(19) 0.89 −0.20	17(3) 0.098 −1.60	19(6) 0.59 −1.54
IIA	174(59) 0.065 1.01	172(50) 1.10 0.99	55(28) 0.073 1.89	64(18) 1.21 1.57	89(26) 0.058 −0.62	76(29) 1.13 −0.22	30(5) 0.076 0.22	32(3) 0.76 −0.19
IIB	135(55) 0.047 1.85	138(43) 1.40 1.89	49(27) 0.059 2.23	57(16) 1.39 1.93	71(24) 0.039 −0.18	59(24) 1.54 0.23	15(4) 0.050 0.64	22(3) 0.86 0.37
I FPN 10,450	102(38) 0.132 0.48	96(35) 1.08 0.68	31(16) 0.114 1.24	26(11) 1.70 1.39	53(19) 0.146 0.13	50(18) 0.93 0.21	18(3) 0.123 −1.22	20(6) 0.79 −1.04
IIA	170(54) 0.097 0.77	171(48) 1.09 0.78	55(27) 0.092 2.31	63(18) 1.50 2.14	86(23) 0.097 −0.84	77(26) 0.92 −0.65	29(4) 0.106 −0.72	31(4) 0.74 −0.80
IIB	131(51) 0.070 1.79	137(44) 1.41 1.96	49(26) 0.077 2.68	56(16) 1.70 2.49	68(22) 0.069 −0.42	59(24) 1.18 −0.10	14(3) 0.052 0.13	22(4) 1.24 0.28
I FN 9,610	97(37) 0.140 0.15	97(35) 0.99 0.00	29(16) 0.111 1.11	24(11) 1.65 1.23	56(18) 0.159 −0.41	55(18) 0.86 −0.60	12(3) 0.120 −0.77	18(6) 0.75 −0.84
IIA	167(55) 0.082 0.96	170(52) 1.19 1.10	55(28) 0.078 2.39	63(19) 1.64 2.22	83(22) 0.083 −0.66	77(29) 1.04 −0.28	29(5) 0.091 −0.86	30(4) 0.75 −0.89
IIB	129(52) 0.063 1.96	137(46) 1.49 2.13	49(27) 0.066 2.82	56(16) 1.81 2.59	66(21) 0.065 −0.30	59(26) 1.26 0.17	14(4) 0.044 0.10	22(4) 1.39 0.15
I HS 10,660	82(39) 0.086 −0.79	75(38) 0.71 −0.97	28(15) 0.077 0.34	18(9) 1.01 0.35	47(20) 0.089 −1.11	45(24) 0.65 −1.17	7(4) 0.097 −0.18	12(5) 0.45 −0.51
IIA	90(30) 0.087 0.91	102(31) 1.17 0.95	25(12) 0.061 2.37	36(8) 1.98 2.27	51(15) 0.098 −0.72	48(19) 0.94 −0.55	14(3) 0.096 0.33	18(4) 0.97 0.30
IIB	65(26) 0.063 1.61	85(29) 1.63 1.90	22(12) 0.045 2.64	31(7) 2.69 2.62	37(13) 0.073 −0.13	40(18) 1.30 0.24	6(1) 0.064 0.17	14(4) 1.27 0.41
I HP 11,230	81(34) 0.139 0.11	78(33) 0.95 −0.05	30(14) 0.132 0.78	21(9) 1.38 0.92	42(17) 0.146 −0.42	43(19) 0.82 −0.65	9(3) 0.126 −0.48	14(5) 0.73 −0.73

TABLE 1.—(*Continued*)

Sensor group and elevation (ft)	Total sample		Equivalent potential temperature partitions 308–325K		295–307K		281–294K	
IIA	106(25)	114(27)	26(11)	44(7)	59(11)	49(16)	21(3)	21(4)
	0 127	1.13	0.090	1.78	0.143	0.97	0.130	0.97
	0.81	1.01	2.36	2.19	−0.65	−0.28	0.05	0.08
IIB	74(21)	93(25)	23(11)	39(6)	44(9)	39(15)	7(1)	15(4)
	0.098	1.41	0.072	2.13	0.116	1.15	0.075	1.57
	1.43	1.80	2.57	2.37	−0.53	0.05	0.92	1.27
I	93(34)	85(33)	30(14)	22(9)	52(18)	49(19)	11(2)	14(5)
HPN	0.141	0.91	0.122	1.54	0 152	0.76	0.147	0.61
10,415	−0.43	−0.58	0.90	1.04	−0.76	−1.03	−1.72	−1.65
IIA	107(26)	116(27)	26(11)	42(7)	61(11)	52(16)	20(4)	22(4)
	0.131	1.13	0.097	1.77	0.138	0.98	0.153	0.84
	0.72	0.78	2.17	1.87	−0.57	−0.19	−0.52	−0.78
IIB	76(21)	94(25)	23(11)	37(6)	46(9)	42(15)	7(1)	15(4)
	0.104	1.38	0.083	1.98	0.117	1.12	0.091	1.42
	1.29	1.62	2.38	2.05	−0.46	0.15	0.53	0.82
I	87(35)	84(33)	26(14)	21(9)	50(18)	49(19)	11(3)	14(5)
HN	0.119	1.02	0.108	1.68	0.125	0.88	0.118	0.56
9,750	0.06	0.02	1.05	1.11	−0.29	−0.34	−1.20	−1.42
IIA	106(25)	115(26)	28(11)	43(7)	59(11)	51(15)	19(3)	21(4)
	0.132	1.07	0.097	1.78	0.145	0.91	0.146	0.68
	0.21	0.37	2.22	2.06	−0.93	−0.53	−1.33	−1.62
IIB	75(21)	94(24)	25(11)	38(6)	44(9)	41(14)	6(1)	15(4)
	0.109	1.27	0.086	1 88	0.124	1.07	0.089	1.01
	0.82	1.16	2.24	2.02	−0.49	0.15	−0.51	−0.53
I	96(34)	98(31)	29(15)	22(8)	54(16)	56(16)	13(3)	20(7)
VP	0.178	1.11	0.136	1.47	0.196	1.13	0.200	0.63
10,329	0.91	0.90	1.24	1.22	0.89	0.97	−1.29	−1.40
IIA	136(31)	129(30)	37(12)	40(7)	72(13)	59(18)	27(6)	30(5)
	0.162	1.02	0.162	1.45	0.167	0.90	0.148	0.67
	0.11	0.18	1.88	1.62	−0.90	−0.52	−0.75	−1.09
IIB	104(29)	99(24)	33(12)	35(5)	58(13)	43(14)	13(4)	21(5)
	0.125	1.30	0.133	1.68	0.135	1.11	0.063	1.38
	1.59	1.76	2.54	2.22	−0.02	0.43	0.63	0.67
I	99(34)	96(32)	30(15)	21(8)	56(16)	55(17)	13(3)	20(7)
VPW	0.177	1.09	0.165	1.25	0.182	1.17	0.181	0.65
9,426	0.48	0.57	0.73	0.65	0.60	0.80	−1.27	−1.29
IIA	136(31)	131(30)	35(12)	40(7)	73(13)	60(18)	28(6)	31(5)
	0.168	1.02	0.189	1.30	0.166	0.92	0.147	0.77
	−0.01	−0.04	1.40	1.04	−1.08	−0.67	−0.23	−0.50
IIB	103(29)	101(24)	31(12)	35(5)	59(13)	44(14)	13(4)	22(5)
	0.134	1.27	0.162	1.46	0.138	1.11	0.054	1.94
	1.36	1.39	2.04	1.57	−0.33	0.16	1.34	1.45
I	97(37)	92(36)	30(15)	20(7)	55(19)	55(21)	12(3)	17(8)
VW	0.114	1.10	0.108	1.40	0.120	1.13	0.103	0.60
8,196	0.25	0.34	1.00	0.98	0.19	0.29	−1.28	−1.17
IIA	127(34)	127(33)	33(14)	42(9)	70(14)	58(18)	24(6)	27(6)
	0.114	0.99	0.139	1.14	0.109	0.94	0.095	0.70
	0.07	0.02	1.22	0.85	−0.75	−0.46	−0.52	−0.77
IIB	95(32)	98(27)	30(14)	37(7)	55(14)	42(14)	10(4)	19(6)
	0.089	1.22	0.116	1.30	0.083	1.14	0.037	1.52
	1.10	1.04	1.75	1.36	−0.28	−0.01	0.84	0.94

TABLE 2. Statistical description of precipitation data for sensor groups in terms of 500-mb temperatures.

Sensor group and elevation (ft)	Temperature partitions −20 to −11C		−26 to −21C		−39 to −27C	
Climax I Climax IIA Climax IIB	(42,35) (68,73) (60,62)		(58,58) (86,75) (68,63)		(32,27) (36,34) (21,22)	
I FCRG 11,104	37(16) 0.099 1.32	29(12) 2.17 1.69	52(16) 0.190 0.10	49(12) 0.92 −0.11	24(3) 0.197 −1.59	21(7) 0.71 −1.44
IIA	64(39) 0.085 1.35	68(34) 1.24 1.35	76(18) 0.116 0.89	65(12) 1.21 0.91	31(3) 0.157 −0.10	29(4) 0.92 −0.14
IIB	57(37) 0.057 1.81	57(29) 1.72 1.91	63(17) 0.096 0.92	56(12) 1.35 1.11	16(3) 0.099 0.92	18(4) 1.32 0.93
I FSG 11,104	41(16) 0.096 0.82	35(15) 1.85 1.21	55(11) 0.188 0.16	56(11) 0.97 0.07	32(0) 0.187 −1.74	27(2) 0.78 −1.44
IIA	67(37) 0.085 1.34	73(33) 1.28 1.34	84(17) 0.119 0.76	73(12) 1.15 0.85	36(3) 0.146 −0.23	34(4) 0.95 −0.10
IIB	59(35) 0.060 1.82	62(29) 1.74 1.93	66(16) 0.098 0.74	61(12) 1.28 0.91	21(3) 0.099 0.62	22(4) 1.18 0.81
I FTG 11,003	31(16) 0.085 1.12	32(15) 1.93 1.36	52(11) 0.180 0.42	51(10) 0.99 0.34	28(0) 0.173 −1.94	25(2) 0.72 −1.57
IIA	60(34) 0.078 1.14	70(32) 1.29 1.08	79(16) 0.109 0.99	70(11) 1.18 0.98	31(3) 0.111 0.65	32(3) 1.12 0.71
IIB	53(32) 0.065 1.53	59(28) 1.51 1.54	62(15) 0.090 1.02	58(11) 1.33 1.19	18(3) 0.068 1.33	21(3) 1.53 1.52
I FS 10,137	32(21) 0.064 1.30	30(16) 1.78 1.39	49(15) 0.111 0.15	47(14) 0.97 0.23	28(2) 0.119 −2.33	25(6) 0.61 −2.13
IIA	62(34) 0.060 0.58	69(33) 1.00 0.45	79(21) 0.065 1.52	70(12) 1.31 1.56	33(4) 0.076 0.06	33(5) 0.92 0.03
IIB	54(32) 0.044 1.20	59(28) 1.13 1.11	62(19) 0.051 1.47	58(12) 1.57 1.64	19(4) 0.048 1.01	21(3) 1.20 0.81
I FPN 10,450	29(21) 0.077 1.57	30(16) 1.95 1.57	47(15) 0.159 0.41	43(13) 0.99 0.44	26(2) 0.145 −1.46	23(6) 0.76 −1.08
IIA	61(35) 0.082 1.01	69(32) 1.17 0.98	77(17) 0.101 0.89	70(12) 1.17 0.91	32(2) 0.115 −0.50	32(4) 0.85 −0.47
IIB	53(33) 0.058 1.53	58(28) 1.59 1.52	60(16) 0.083 1.21	58(12) 1.34 1.36	18(2) 0.065 0.48	21(4) 1.26 0.71
I FN 9,610	31(21) 0.082 1.01	28(16) 1.61 1.07	43(14) 0.172 0.06	48(13) 0.93 −0.32	23(2) 0.157 −1.86	21(6) 0.64 −1.75
IIA	59(36) 0.065 1.25	69(34) 1.34 1.16	77(16) 0.088 1.02	70(13) 1.30 1.22	31(3) 0.102 −0.36	31(5) 0.85 −0.24

TABLE 2.—(*Continued*)

Sensor group and elevation (ft)	Temperature partitions −20 to −11C		−26 to −21C		−39 to −27C	
IIB	52(34) 0.052 1.72	58(29) 1.59 1.68	60(15) 0.073 1.21	58(13) 1.50 1.47	17(3) 0.061 0.60	21(4) 1.34 0.80
I HS 10,660	25(20) 0.041 1.00	21(14) 1.20 0.98	41(15) 0.093 −0.96	39(19) 0.73 −0.89	16(4) 0.134 −1.74	15(5) 0.41 −2.08
IIA	27(10) 0.070 0.70	31(10) 1.31 0.72	44(16) 0.088 0.85	50(16) 1.25 0.89	19(4) 0.109 −0.30	21(5) 0.90 −0.45
IIB	22(10) 0.040 1.22	26(9) 2.20 1.36	33(13) 0.069 1.17	43(16) 1.67 1.49	10(3) 0.092 −0.16	16(4) 0.98 −0.31
I HP 11,230	27(18) 0.079 0.78	23(14) 1.74 0.92	38(14) 0.164 −0.26	36(14) 0.80 −0.52	16(2) 0.179 −1.21	19(5) 0.69 −1.47
IIA	28(9) 0.114 0.84	36(9) 1.28 0.81	51(12) 0.124 0.75	54(13) 1.16 0.96	27(4) 0.147 −0.31	24(5) 0.97 −0.28
IIB	22(9) 0.071 1.50	31(8) 1.92 1.47	39(9) 0.103 0.72	46(13) 1.37 1.21	13(3) 0.130 0.02	16(4) 1.06 −0.00
I HPN 10,415	27(18) 0.078 0.66	23(14) 1.63 0.75	45(15) 0.161 −0.20	42(14) 0.85 −0.46	21(1) 0.181 −1.97	20(5) 0.65 −1.88
IIA	30(9) 0.105 1.02	35(9) 1.50 1.09	51(12) 0.131 0.65	55(13) 1.12 0.77	26(5) 0.160 −0.92	26(5) 0.84 −0.98
IIB	24(9) 0.079 1.46	30(8) 1.91 1.52	39(9) 0.111 0.63	47(13) 1.27 1.03	13(3) 0.128 −0.13	17(4) 1.06 −0.02
I HN 9,750	23(18) 0.064 1.11	22(14) 1.83 1.10	43(15) 0.126 0.28	42(14) 0.99 0.21	21(2) 0.163 −1.62	20(5) 0.70 −1.51
IIA	29(9) 0.102 1.12	36(9) 1.48 1.22	51(12) 0.138 −0.05	55(12) 1.00 0.09	26(4) 0.155 −0.85	24(5) 0.88 −0.84
IIB	23(9) 0.076 1.61	31(8) 1.89 1.67	39(9) 0.124 −0.04	47(12) 1.08 0.35	13(3) 0.119 −0.18	16(4) 1.13 −0.06
I VP 10,329	28(18) 0.105 1.21	24(11) 1.38 1.14	45(14) 0.196 1.12	50(14) 1.21 1.10	23(2) 0.234 −1.41	24(6) 0.71 −1.30
IIA	41(18) 0.148 0.75	38(15) 1.22 0.77	61(8) 0.168 0.29	61(11) 1.05 0.50	34(5) 0.169 −1.23	30(4) 0.72 −1.33
IIB	37(18) 0.112 1.58	29(10) 1.56 1.58	47(6) 0.144 0.55	51(11) 1.18 1.01	20(5) 0.107 0.41	19(3) 1.16 0.32
I VPW 9,426	29(18) 0.124 0.52	23(12) 1.18 0.45	46(14) 0.188 0.84	49(14) 1.22 0.87	24(2) 0.219 −1.53	24(6) 0.72 −1.28
IIA	39(18) 0.156 0.50	39(15) 1.16 0.40	63(8) 0.172 0.14	61(11) 1.06 0.38	34(5) 0.175 −0.74	31(4) 0.79 −0.88

TABLE 2.—(*Continued*)

Sensor group and elevation (ft)	−20 to −11C		Temperature partitions −26 to −21C		−39 to −27C	
IIB	35(18) 0.130 1.22	30(10) 1.37 1.01	48(6) 0.147 0.28	51(11) 1.18 0.74	20(5) 0.112 1.07	20(3) 1.37 1.05
I VW 8,196	29(18) 0.083 0.50	22(12) 1.25 0.49	45(17) 0.118 0.92	48(16) 1.31 0.92	23(2) 0.146 −1.86	22(8) 0.58 −1.60
IIA	37(19) 0.113 0.43	39(16) 1.05 0.28	58(9) 0.118 0.53	58(12) 1.04 0.60	32(6) 0.108 −0.77	30(5) 0.82 −0.83
IIB	33(19) 0.093 1.14	30(11) 1.20 0.90	44(7) 0.093 0.41	49(12) 1.23 0.70	18(6) 0.068 0.72	19(4) 1.24 0.60

Meteorological partitionings according to the direction (Table 3) and velocity (Table 4) of air flow relative to the orographic barrier are used as an index of the vertical lifting due to orography.

Evaluation summaries for the independent temporal periods are presented separately in Tables 1–4. Each evaluation summary presented in each of the tables consists of a format given by

$$\begin{array}{ll} z_1(z_2)z_3(z_4) & \\ z_5 & z_6 \\ z_7 & z_8 \end{array}$$

where

z_1 is the number of observed non-seeded experimental units,

z_2 is the number of experimental units of z_1 with zero precipitation,

z_3 is the number of observed seeded experimental units,

z_4 is the number of experimental units of z_3 with zero precipitation,

z_5 is the mean precipitation amount (inches of water per experimental unit) for the z_1 experimental units,

z_6 is the mean precipitation amount (inches of water per experimental unit) for the z_3 experimental units divided by z_5,

z_7 is the normalized tie-adjusted Wilcoxon test comparing the z_3 experimental units with the z_1 experimental units, and

z_8 is the normalized tie-adjusted sum-of-squared ranks test comparing the z_3 experimental units with the z_1 experimental units.

If, in fact, precipitation is increased or decreased by seeding under a given set of conditions, it would be expected that 1) z_6 be greater or less than one, respectively, and 2) z_7 and z_8 be greater or less than zero, respectively. The elevation recorded in Tables 1–4 for each pooled group is simply the average elevation of the individual sensors comprising each pooled group.

For convenience in the interpretation of the normalized test statistics z_7 and z_8, the following list of probabilities is given for the normally distributed random variable Y having mean and variance equal to zero and one, respectively.

y	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
$p(\|Y\|>y)$	1.000	0.617	0.317	0.134	0.046	0.012	0.003	<0.001

Listed below each partition's description in Tables 1–4 are the randomly allocated number of non-seeded and seeded experimental units, respectively, for the 1960–65 and 1965–70 wintertime periods. The 372 experimental units for the 1965–70 wintertime periods (designated Climax IIA) are based on the same criteria as the 251 experimental units for the 1960–65 wintertime periods (designated Climax I). These criteria were established before the experiment was begun in February of 1960 and have been restated by Mielke *et al.* (1970). On 76 of the 372 experimental units of the 1965–70 wintertime periods, the Climax experimental area was directly downwind from seeding activities at Berthoud Pass during March and April of 1966 and in the Park Range area during the four wintertime periods from 1965 into 1969. Spurious target contamination might have resulted and is suspected. Direct downwind contamination might have resulted from Berthoud Pass seeding activities during a specified experimental unit when the observed 700- or 500-mb wind direction at Climax was from 330 through 360 deg. Similarly, possible contamination might have resulted from Park Range area seeding activities during a given experimental unit when the observed 700- or 500-mb wind direction at Climax was from 290 through 360 deg. Of the 76 possibly contaminated experimental units, eight were due to Berthoud Pass seeding activities and the remaining 68 were attributed to Park Range area seeding activities. In an attempt to partially delineate this contamination problem, the remaining 296 experimental units for the

TABLE 3. Statistical description of precipitation data for sensor groups in terms of 700-mb wind directions.

Sensor group and elevation (ft)	Wind direction partitions (deg) 190–250		260–300		310–360		10–180	
Climax I Climax IIA Climax IIB	(25,26) (48,52) (45,52)		(67,56) (79,79) (68,63)		(31,26) (52,40) (28,22)		(8,12) (11,11) (8,10)	
I FCRG 11,104	20(12) 0.040 3.47	19(4) 5.43 3.64	61(17) 0.196 −0.89	49(17) 0.84 −0.83	24(4) 0.187 0.64	22(4) 1.23 0.73	8(2) 0.126 −1.53	9(6) 0.44 −1.37
IIA	43(19) 0.058 1.82	44(16) 1.94 2.06	71(26) 0.121 −0.25	72(25) 0.95 −0.24	47(13) 0.142 1.18	37(7) 1.23 1.09	10(2) 0.137 −0.12	9(2) 0.65 0.34
IIB	41(19) 0.049 2.09	44(16) 2.30 2.35	62(25) 0.100 0.40	59(22) 1.15 0.56	26(12) 0.076 1.75	20(5) 1.82 1.75	7(1) 0.096 0.18	8(2) 0.84 0.19
I FSG 11,104	25(11) 0.089 1.87	25(6) 1.94 1.90	64(11) 0.181 −1.09	56(18) 0.85 −0.81	31(4) 0.172 1.31	26(2) 1.41 1.43	8(1) 0.139 −0.79	11(2) 0.72 −0.70
IIA	47(17) 0.061 1.93	51(16) 1.93 2.24	78(25) 0.123 −0.28	79(25) 0.96 −0.21	51(13) 0.137 1.02	39(6) 1.21 0.92	11(2) 0.133 −0.20	11(2) 0.61 −0.40
IIB	44(17) 0.052 2.24	51(16) 2.27 2.57	67(24) 0.106 −0.02	63(22) 1.06 0.14	27(12) 0.074 1.92	21(5) 1.84 1.95	8(1) 0.090 0.05	10(2) 0.83 0.08
I FTG 11,003	21(11) 0.071 2.39	25(5) 2.26 2.30	57(11) 0.176 −1.13	51(18) 0.84 −0.80	25(4) 0.177 1.12	23(2) 1.28 1.17	8(1) 0.109 −1.16	9(2) 0.63 −0.91
IIA	42(17) 0.061 1.79	50(16) 1.85 2.00	71(22) 0.108 −0.14	75(24) 1.01 0.03	46(12) 0.110 1.29	38(5) 1.28 1.12	11(2) 0.125 0.50	9(1) 0.72 0.13
IIB	39(17) 0.052 2.15	50(16) 2.16 2.36	60(21) 0.094 0.16	59(21) 1.13 0.38	26(11) 0.071 1.60	21(4) 1.51 1.48	8(1) 0.085 0.89	8(1) 1.06 0.75
I FS 10,137	22(12) 0.061 1.73	25(8) 1.95 1.74	56(17) 0.122 −1.15	48(19) 0.71 −1.06	23(6) 0.094 0.78	20(3) 1.47 0.96	8(3) 0.066 −0.99	9(6) 0.71 −0.87
IIA	42(21) 0.039 2.12	50(16) 2.08 2.24	72(22) 0.066 −0.38	75(26) 0.97 −0.22	49(13) 0.080 0.91	38(7) 1.06 0.73	11(3) 0.096 −0.38	9(1) 0.44 −0.96
IIB	39(21) 0.34 2.41	50(16) 2.33 2.49	61(21) 0.053 −0.18	59(22) 1.15 −0.05	27(11) 0.045 1.63	21(4) 1.30 1.49	8(2) 0.075 0.00	8(1) 0.58 −0.44
I FPN 10,450	21(12) 0.073 1.53	21(6) 1.71 1.39	50(17) 0.161 −0.43	46(20) 0.90 −0.27	23(6) 0.138 1.10	20(3) 1.43 1.26	8(3) 0.094 −0.94	9(6) 0.66 −0.75
IIA	41(19) 0.052 1.87	50(18) 1.94 2.05	71(22) 0.102 −0.45	74(24) 0.97 −0.34	48(12) 0.119 0.59	38(5) 1.04 0.38	10(1) 0.136 −0.29	9(1) 0.71 −0.41
IIB	38(19) 0.041 2.27	50(18) 2.43 2.46	60(21) 0.089 −0.15	58(21) 1.11 −0.02	26(11) 0.065 1.44	21(4) 1.49 1.30	7(0) 0.089 −0.12	8(1) 1.13 0.05
I FN 9,610	22(12) 0.077 1.73	21(7) 1.85 1.70	48(16) 0.174 −1.15	48(19) 0.76 −1.27	20(6) 0.140 1.06	20(3) 1.30 0.85	7(3) 0.098 −0.91	8(6) 0.63 −0.78
IIA	41(19) 0.044 1.74	50(18) 2.02 1.86	70(22) 0.093 −0.13	74(27) 1.05 0.11	46(12) 0.096 0.65	37(6) 1.12 0.62	10(2) 0.105 0.33	9(1) 1.04 0.26

Table 3.—(*Continued*)

Sensor group and elevation (ft)	Wind direction partitions (deg) 190–250		260–300		310–360		10–180	
IIB	38(19)	50(18)	59(21)	58(23)	25(11)	21(4)	7(1)	8(1)
	0.033	2.72	0.082	1.19	0.064	1.35	0.064	1.81
	2.25	2.43	0.10	0.36	1.53	1.33	0.64	0.82
I	20(12)	17(7)	44(20)	38(20)	13(5)	10(5)	5(2)	10(6)
HS	0.041	1.66	0.105	0.58	0.080	0.70	0.102	0.46
10,660	1.20	1.19	−1.14	−1.28	−0.55	−0.66	−1.06	−1.16
IIA	17(8)	26(11)	37(12)	42(15)	30(8)	26(2)	6(2)	8(3)
	0.041	2.58	0.079	1.04	0.105	1.20	0.179	0.65
	1.35	1.65	−0.18	−0.11	1.23	0.86	−0.26	−0.34
IIB	17(8)	26(11)	31(11)	37(14)	14(6)	15(1)	3(1)	7(3)
	0.041	2.58	0.060	1.33	0.089	1.63	0.092	1.19
	1.35	1.65	0.12	0.28	1.65	1.39	0.24	0.47
I	20(11)	17(6)	43(16)	38(18)	14(5)	12(3)	4(2)	11(6)
HP	0.069	1.86	0.176	0.73	0.130	1.43	0.115	0.72
11,230	1.54	1.55	−1.00	−1.05	1.02	0.90	−0.14	−0.21
IIA	19(8)	31(11)	45(7)	45(12)	36(8)	29(2)	6(2)	9(2)
	0.047	2.77	0.131	0.98	0.151	1.24	0.211	0.63
	1.66	2.03	−0.79	−0.46	1.51	1.27	−0.42	−0.68
IIB	19(8)	31(11)	37(6)	39(11)	15(6)	15(1)	3(1)	8(2)
	0.047	2.77	0.114	1.12	0.125	1.55	0.097	1.31
	1.66	2.03	−0.54	−0.11	1.73	1.36	0.21	0.34
I	21(11)	18(6)	49(16)	41(18)	18(5)	16(3)	5(2)	10(6)
HPN	0.064	2.01	0.178	0.66	0.136	1.35	0.120	0.74
10,415	1.77	1.83	−1.65	−1.76	0.71	0.62	−0.53	−0.49
IIA	19(8)	30(11)	47(7)	47(12)	35(9)	30(2)	6(2)	9(2)
	0.047	2.91	0.140	0.97	0.154	1.18	0.188	0.66
	1.39	1.72	−0.81	−0.44	1.21	0.74	−0.48	−0.75
IIB	19(8)	30(11)	39(6)	41(11)	15(6)	15(1)	3(1)	8(2)
	0.047	2.91	0.123	1.08	0.128	1.55	0.092	1.26
	1.39	1.72	−0.61	−0.15	1.82	1.38	0.21	0.34
I	18(11)	20(6)	48(17)	40(18)	16(5)	14(3)	5(2)	10(6)
HN	0.047	2.03	0.155	0.77	0.099	1.85	0.097	0.91
9,750	1.76	1.68	−1.05	−1.05	1.05	1.09	−0.53	−0.49
IIA	18(8)	30(10)	47(7)	47(12)	36(8)	29(2)	5(2)	9(2)
	0.059	2.16	0.144	0.95	0.147	1.16	0.190	0.64
	1.36	1.54	−0.89	−0.43	0.90	0.50	−0.20	−0.49
IIB	18(8)	30(10)	40(6)	41(11)	15(6)	15(1)	2(1)	8(2)
	0.059	2.16	0.130	1.04	0.115	1.53	0.076	1.54
	1.36	1.54	−0.58	0.02	1.69	1.33	0.53	0.54
I	19(10)	21(4)	50(15)	42(18)	20(6)	23(3)	7(3)	12(6)
VP	0.110	2.11	0.215	0.79	0.165	1.56	0.140	0.80
10,329	2.48	2.33	−1.17	−1.00	1.81	1.72	−0.27	−0.30
IIA	28(7)	30(6)	57(10)	60(19)	40(10)	32(4)	11(4)	7(1)
	0.121	1.71	0.177	0.86	0.192	0.86	0.081	1.13
	1.83	1.88	−1.04	−0.71	−0.23	−0.54	0.14	−0.12
IIB	26(7)	30(6)	47(10)	45(15)	23(9)	18(2)	8(3)	6(1)
	0.100	2.08	0.156	0.97	0.121	1.16	0.044	2.30
	2.27	2.41	−0.47	−0.14	1.19	0.87	0.59	0.58
I	19(10)	21(4)	52(15)	42(19)	21(6)	21(3)	7(3)	12(6)
VPW	0.137	1.87	0.207	0.79	0.148	1.52	0.150	0.80
9,426	2.17	2.00	−1.33	−1.07	1.35	1.28	−0.27	−0.33
IIA	28(7)	32(6)	57(10)	60(19)	40(10)	33(4)	11(4)	6(1)
	0.144	1.51	0.180	0.88	0.201	0.82	0.047	2.08
	1.15	1.14	−0.92	−0.59	−0.35	−0.69	1.12	1.07

TABLE 3.—(*Continued*)

Sensor group and elevation (ft)	Wind direction partitions (deg) 190–250		260–300		310–360		10–180	
IIB	25(7)	32(6)	47(10)	45(15)	23(9)	19(2)	8(3)	5(1)
	0.129	1.67	0.155	1.02	0.136	1.02	0.024	4.72
	1.53	1.49	−0.30	0.07	0.93	0.46	1.41	1.53
I	18(10)	20(5)	51(17)	41(20)	21(7)	20(5)	7(3)	11(6)
VW	0.083	1.90	0.128	0.81	0.112	1.52	0.099	0.69
8,196	1.83	1.67	−1.26	−1.11	0.93	0.95	−0.63	−0.71
IIA	26(8)	33(8)	51(11)	56(19)	40(10)	32(5)	10(5)	6(1)
	0.089	1.61	0.128	0.76	0.134	0.91	0.028	1.57
	1.07	1.09	−0.95	−0.80	−0.04	−0.26	1.00	0.83
IIB	25(8)	33(8)	41(11)	42(15)	22(9)	18(3)	7(4)	5(1)
	0.084	1.72	0.106	0.89	0.086	1.05	0.014	3.60
	1.26	1.30	−0.50	−0.33	0.85	0.52	1.52	1.54

1965–70 wintertime periods (designated Climax IIB) were analyzed separately.

A comparison between Climax I and Climax IIA of the distributions of experimental units among the 700-mb equivalent potential temperature partitions and the 700-mb wind direction partitions is shown in Table 5.

4. Discussion

The results of Climax IIA and Climax IIB are generally in agreement with the results of Climax I for meteorologically defined partitions. The results support expected changes predicted by a physical model of wintertime orographic precipitation processes for this area.

a. Temperature

The z_6 ratios (mean precipitation amount for seeded experimental units divided by mean precipitation amount for non-seeded experimental units) and p values (probability of having a more extreme test statistic than the observed value under the null hypothesis that seeding has no effect) of Climax IIA and Climax IIB are consistent with Climax I for the warmest temperature partitions.

As with Climax I, nearly all pooled groups of sensors of Climax IIA and Climax IIB have z_6 ratios in excess of 1.5 for the warmest 700-mb equivalent potential temperature (θ_e) partition. Two of the pooled groups of Climax IIB have z_6 ratios >2.0. One pooled group and the FCRG sensor of Climax IIA, and six pooled groups and the FCRG sensor of Climax IIB have p values <0.01. Probably due to the smaller sample sizes involved, none of the p values comprising Climax I is less than 0.01. The lower z_6 ratios and the higher p values occurred at the northwest and southwest extremes of the pooled groups where the least effective seeding coverage would be expected.

For the warmest 500-mb temperature partition, the pooled groups have z_6 ratios generally over 1.5 for Climax IIB. However, the Climax IIA pooled group z_6 ratios, while consistently greater than one, appeared affected by the previously mentioned extraneous seeding taking place upwind of the Climax experimental area. Three pooled groups of Climax IIB have p values <0.1 for the warmest 500-mb temperature partition.

Most pooled group p values of Climax I combined with Climax IIB are less than 0.01 for the warmest 700-mb θ_e partition. The combined p values are obtained from the fact that $(T_1+T_2)/\sqrt{2}$ is normally distributed with mean zero and variance one if T_1 and T_2 are independent and normally distributed with mean zero and variance one. For the warmest 500-mb temperature partition, most of the pooled group p values of Climax I combined with Climax IIB are less than 0.05.

Smaller group z_6 ratios were observed in Climax I for the middle 700-mb θ_e partition (295 to 307K) and the middle 500-mb temperature partition (−26 to −21C) than in the warmest 700-mb θ_e and 500-mb temperature partitions. Accordingly, the pooled group p values associated with the middle 700-mb θ_e and 500-mb temperature partitions of Climax I were large. Although the pooled group z_6 ratios for the middle 700-mb θ_e and 500-mb temperature partitions were somewhat larger for Climax IIA and Climax IIB than for Climax I, the pooled group p values associated with Climax IIA and Climax IIB were also large.

The coldest 700-mb θ_e and 500-mb temperature partitions of Climax IIA are in agreement with Climax I in yielding smaller amounts of precipitation on seeded experimental units than non-seeded experimental units. However, this agreement was not exhibited by Climax IIB. These coldest partitions were substantially affected by the adjustment for upwind seeding in terms of sample size. As a consequence, the contradictory results of Climax IIA and IIB are difficult to interpret. A specific difference noted between the results of Climax IIA and

TABLE 4. Statistical description of precipitation data for sensor groups in terms of 700-mb wind velocities.

Sensor group and elevation (ft)	Wind velocity partitions ($m\ sec^{-1}$) 0–8		9–11		12–14		15–28	
Climax I	(65,52)		(29,42)		(23,13)		(14,13)	
Climax IIA	(104,90)		(43,41)		(30,34)		(13,17)	
Climax IIB	(86,74)		(31,31)		(23,29)		(9,13)	
I	53 (17)	41 (14)	28 (10)	34 (10)	19 (7)	12 (2)	13 (1)	12 (5)
FCRG	0.135	1.16	0.146	1.16	0.153	1.58	0.319	0.70
11,104	0.34	0.57	0.43	0.34	1.79	1.70	−1.42	−1.14
IIA	91 (32)	81 (30)	39 (11)	37 (11)	30 (13)	30 (3)	11 (4)	14 (6)
	0.088	0.97	0.133	1.09	0.107	1.94	0.245	0.56
	−0.10	−0.11	−0.18	−0.02	2.86	2.45	−0.60	−0.73
IIB	76 (31)	66 (27)	29 (10)	28 (9)	23 (12)	25 (3)	8 (4)	12 (6)
	0.069	1.04	0.119	1.21	0.069	3.03	0.071	1.39
	0.11	0.12	0.43	0.60	3.50	3.21	0.17	0.22
I	62 (13)	50 (13)	29 (7)	42 (9)	23 (6)	13 (1)	14 (1)	13 (5)
FSG	0.136	1.08	0.137	1.24	0.157	1.44	0.300	0.73
11,104	−0.10	0.23	0.72	0.73	1.72	1.59	−1.32	−1.00
IIA	102 (31)	88 (29)	42 (11)	41 (11)	30 (12)	34 (3)	13 (3)	17 (6)
	0.088	0.94	0.139	1.01	0.103	2.01	0.235	0.66
	−0.38	−0.38	−0.30	−0.08	3.07	2.61	−0.83	−0.86
IIB	84 (30)	72 (27)	30 (10)	31 (9)	23 (11)	29 (3)	9 (3)	13 (6)
	0.071	0.99	0.116	1.17	0.070	3.02	0.116	0.87
	−0.17	−0.14	0.34	0.52	3.74	3.39	−0.59	−0.56
I	56 (13)	46 (12)	25 (7)	39 (9)	19 (6)	11 (1)	11 (1)	12 (5)
FTG	0.129	1.07	0.142	1.13	0.153	1.52	0.284	0.64
11,003	−0.08	0.26	0.35	0.25	1.84	1.78	−1.12	−0.87
IIA	92 (30)	85 (28)	42 (10)	37 (10)	27 (10)	34 (3)	9 (3)	16 (5)
	0.082	0.93	0.126	0.98	0.096	2.02	0.144	1.03
	−0.18	−0.23	−0.43	−0.24	2.86	2.41	0.09	0.10
IIB	75 (29)	69 (26)	30 (9)	28 (8)	21 (9)	29 (3)	7 (3)	12 (5)
	0.064	1.00	0.109	1.11	0.071	2.81	0.096	1.15
	−0.05	−0.08	0.13	0.29	3.42	3.02	−0.04	−0.02
I	54 (20)	43 (19)	24 (10)	36 (11)	20 (7)	11 (1)	11 (1)	12 (5)
FS	0.082	1.02	0.084	1.22	0.116	1.16	0.192	0.68
10,137	−0.36	−0.09	−0.32	0.31	1.23	1.04	−1.02	−0.80
IIA	94 (35)	85 (31)	42 (10)	38 (11)	28 (11)	33 (3)	10 (3)	16 (5)
	0.053	0.85	0.082	0.91	0.055	2.40	0.144	0.63
	−0.12	−0.19	−0.78	−0.65	3.10	2.79	−0.16	−0.20
IIB	77 (33)	69 (27)	30 (9)	28 (8)	21 (10)	29 (3)	7 (3)	12 (5)
	0.036	0.99	0.076	1.00	0.043	3.07	0.068	0.93
	0.30	0.25	−0.28	−0.27	3.41	3.10	0.00	0.05
I	50 (20)	43 (17)	27 (10)	32 (12)	14 (7)	10 (1)	11 (1)	11 (5)
FPN	0.102	1.23	0.122	1.19	0.131	1.60	0.297	0.50
10,450	0.51	0.76	0.11	0.29	1.88	1.73	−1.59	−1.36
IIA	92 (31)	85 (29)	41 (10)	37 (11)	27 (10)	33 (3)	10 (3)	16 (5)
	0.078	0.91	0.119	0.88	0.095	1.93	0.181	0.71
	−0.33	−0.37	−0.93	−0.75	2.52	2.08	−0.19	−0.34
IIB	75 (30)	69 (27)	29 (9)	28 (9)	20 (9)	28 (3)	7 (3)	12 (5)
	0.059	1.09	0.103	1.03	0.064	2.85	0.074	1.25
	0.11	0.18	−0.28	−0.14	3.22	2.80	0.31	0.40
I	47 (19)	41 (18)	24 (10)	36 (11)	16 (7)	9 (1)	10 (1)	11 (5)
FN	0.106	1.12	0.130	1.06	0.142	1.49	0.316	0.50
9,610	0.22	0.41	0.16	−0.13	1.61	1.45	−1.60	−1.42
IIA	91 (32)	84 (31)	40 (10)	37 (12)	27 (10)	33 (4)	9 (3)	16 (5)
	0.067	1.00	0.110	0.86	0.079	2.05	0.125	1.11
	−0.28	−0.26	−0.93	−0.80	2.68	2.40	0.49	0.43

TABLE 4.—(*Continued*)

Sensor group and elevation (ft)	Wind velocity partitions (m sec^{-1}) 0–8		9–11		12–14		15–28	
IIB	74(31) 0.051 0.32	69(28) 1.22 0.37	28(9) 0.097 −0.29	28(10) 1.04 −0.19	20(9) 0.056 3.32	28(3) 2.78 2.91	7(3) 0.072 0.57	12(5) 1.55 0.66
I HS 10,660	35(18) 0.089 −1.32	36(21) 0.48 −1.60	22(10) 0.068 0.37	23(10) 1.01 0.37	16(10) 0.065 1.14	6(1) 1.03 0.74	9(1) 0.153 −1.01	10(6) 0.66 −0.57
IIA	50(21) 0.080 0.12	49(22) 1.04 0.21	22(3) 0.095 0.26	21(3) 1.18 0.38	12(5) 0.063 1.96	23(3) 2.38 1.91	6(1) 0.164 −2.20	9(3) 0.34 −2.48
IIB	36(17) 0.056 0.35	40(20) 1.44 0.61	15(3) 0.080 0.42	18(3) 1.40 0.58	11(5) 0.055 2.17	20(3) 2.84 2.14	3(1) 0.088 −0.94	7(3) 0.52 −1.14
I HP 11,230	34(17) 0.124 −0.61	35(18) 0.76 −0.88	24(9) 0.136 0.88	26(9) 1.15 0.82	15(7) 0.094 1.66	7(1) 1.80 1.51	8(1) 0.295 −1.22	10(5) 0.56 −1.08
IIA	57(20) 0.118 0.33	57(18) 0.96 0.25	25(2) 0.125 0.45	24(3) 1.23 0.62	16(2) 0.123 1.74	23(3) 1.83 2.09	8(1) 0.215 −1.38	10(3) 0.54 −1.41
IIB	41(16) 0.089 0.64	46(16) 1.17 0.72	18(2) 0.099 0.61	19(3) 1.51 0.88	10(2) 0.097 1.85	20(3) 2.31 2.07	5(1) 0.176 −0.82	8(3) 0.60 −0.76
I HPN 10,415	38(16) 0.116 −0.85	37(18) 0.77 −0.92	26(9) 0.142 0.57	28(9) 1.04 0.46	17(8) 0.106 1.73	9(1) 1.87 1.59	12(1) 0.270 −1.77	11(5) 0.58 −1.61
IIA	58(21) 0.117 0.39	59(18) 0.98 0.17	26(3) 0.141 0.10	24(3) 1.07 0.19	15(2) 0.113 1.90	23(3) 1.96 2.23	8(0) 0.227 −1.07	10(3) 0.70 −0.89
IIB	42(17) 0.093 0.79	47(16) 1.15 0.79	19(2) 0.118 0.19	19(3) 1.26 0.43	10(2) 0.094 1.81	20(3) 2.34 2.06	5(0) 0.159 −0.59	8(3) 0.94 −0.29
I HN 9,750	38(17) 0.094 −0.76	35(18) 0.77 −0.78	24(9) 0.116 0.53	29(9) 1.22 0.46	15(8) 0.096 1.99	9(1) 2.15 1.81	10(1) 0.255 −1.46	11(5) 0.58 −1.32
IIA	57(21) 0.110 0.52	59(18) 1.13 0.45	24(2) 0.163 −1.12	23(3) 0.82 −0.80	17(2) 0.128 1.75	23(2) 1.62 1.89	8(0) 0.216 −1.47	10(3) 0.55 −1.36
IIB	41(17) 0.087 0.86	48(16) 1.35 0.91	17(2) 0.146 −0.73	18(3) 0.91 −0.32	12(2) 0.110 1.68	20(2) 1.84 1.75	5(0) 0.157 −1.03	8(3) 0.71 −0.74
I VP 10,329	47(17) 0.150 0.15	41(17) 1.05 0.34	22(9) 0.177 0.96	38(9) 1.21 0.72	17(7) 0.179 1.41	11(2) 1.62 1.39	10(1) 0.316 −1.12	8(3) 0.60 −1.11
IIA	78(23) 0.116 −0.21	60(15) 1.01 −0.31	31(4) 0.219 −1.76	30(10) 0.65 −1.54	17(4) 0.186 1.40	28(3) 1.40 0.98	10(0) 0.306 −0.46	11(2) 0.81 −0.44
IIB	62(21) 0.093 0.27	46(13) 1.10 0.21	24(4) 0.197 −0.63	22(8) 0.85 −0.35	12(4) 0.130 2.42	24(1) 2.04 1.77	6(0) 0.167 −0.07	7(2) 1.19 0.14
I VPW 9,426	47(17) 0.141 0.10	39(17) 1.14 0.42	23(9) 0.190 0.54	38(9) 1.13 0.32	18(7) 0.185 1.05	11(2) 1.25 0.96	11(1) 0.292 −1.08	8(4) 0.64 −0.73

Table 4.—(*Continued*)

Sensor group and elevation (ft)	Wind velocity partitions (m sec^{-1}) 0–8		9–11		12–14		15–28	
IIA	78(23) 0.117 0.37	61(15) 1.04 0.21	32(4) 0.226 −2.05	30(10) 0.65 −1.80	16(4) 0.230 0.61	28(3) 1.17 0.14	10(0) 0.285 −0.46	12(2) 0.92 −0.16
IIB	62(21) 0.093 0.83	47(13) 1.17 0.79	24(4) 0.210 −1.03	22(8) 0.82 −0.77	11(4) 0.174 1.64	24(1) 1.59 1.00	6(0) 0.188 −0.52	8(2) 1.16 −0.25
I VW 8,196	47(17) 0.100 −0.38	37(16) 0.94 −0.28	22(10) 0.108 0.82	37(12) 1.41 0.71	18(8) 0.104 1.09	10(3) 1.55 1.11	10(2) 0.211 −1.42	8(5) 0.48 −1.17
IIA	73(26) 0.079 0.62	61(17) 1.07 0.42	28(4) 0.157 −1.54	28(10) 0.65 −1.38	17(4) 0.143 0.86	27(4) 1.24 0.69	9(0) 0.207 −1.33	11(2) 0.69 −0.97
IIB	57(24) 0.060 0.81	47(15) 1.14 0.60	21(4) 0.153 −0.90	21(8) 0.75 −0.75	12(4) 0.110 1.78	23(2) 1.63 1.43	5(0) 0.094 −1.22	7(2) 1.29 −0.84

IIB for the coldest partitions is that the non-seeded means for Climax IIB are roughly half the non-seeded means for Climax IIA. This difference appears related to skill in selecting operations in the Park Range Programs where an effort to concentrate primarily on the larger storms seems apparent. In contrast, the Climax experiment included all experimental units that might have any potential for precipitation. A similar suggestion of possible contamination effects is noted in Table 3 for the 700-mb wind direction partition having wind directions from 310–360 deg.

b. Wind

The 700-mb level best represents the airflow moving into the Climax experimental area where elevations range from 8000 to over 12,000 ft MSL. As a consequence, 700-mb wind directions and velocities are discussed in this paper.

The Continental Divide runs east to west across the Climax experimental area and better orographic uplifting would be expected for either northwest wind flow up the Eagle River or southwest wind flow up the East Fork of the Arkansas River. In a westerly wind flow, a good orographic fetch toward the Climax experimental area is absent since air is forced over two north-south ranges (Sawatch Range and Chicago Ridge) before reaching the primary target area. Thus, orographic considerations alone suggest that northwest and southwest flow events would favor positive seeding effects more than westerly flow events.

Wind directions most favorable to orographic lifting yielded consistently large pooled group z_6 ratios for Climax I, Climax IIA and Climax IIB. Also, the pooled group z_6 ratios of Climax I, IIA and IIB are consistently higher for the 190–250 deg wind direction partition than the 310–360 deg wind direction partition. Specifically, all pooled groups and the FCRG sensor have z_6 ratios for Climax I, IIA and IIB that are greater than 1.5 for the 190–250 deg wind direction partition. High proportions of southwest flow events occurred in the warmest 700-mb θ_e and 500-mb temperature partitions. Since southwest flow events are also associated with strong orographic lifting, these events would be expected to show the greatest positive seeding effects. The pooled group z_6 ratios of Climax IIA for the 310–360 deg wind direction partition, while consistently greater than 1.0, are less than the pooled group z_6 ratios observed for Climax IIB. As previously mentioned, this also suggests a contamination effect from upwind seeding. This problem does not arise for the 190–250 deg wind direction partition. All but three of the pooled group p values for the 190–250 deg wind direction partition of Climax I combined with Climax IIB are less than 0.01.

Similarly, 700-mb wind velocity partitions yielded results which were in agreement for Climax I, Climax IIA, Climax IIB, and physical model considerations

Table 5. Distribution of experimental units among various partitions of 700-mb equivalent potential temperature and 700-mb wind direction for Climax I (251 experimental units) and Climax IIA (372 experimental units).

700-mb equivalent potential temperature (°K)	700-mb wind direction (deg)	Climax I (proportion)	Climax IIA (proportion)
308–325		0.295	0.339
295–307		0.530	0.481
281–294		0.175	0.180
	190–250	0.203	0.269
	260–300	0.490	0.425
	310–360	0.227	0.247
	010–180	0.080	0.059

involving orographic lifting. For low 700-mb wind velocities, z_6 ratios of little consequence were observed for either Climax I, IIA or IIB. Large pooled group z_6 ratios were noted for the favorable 12–14 m sec^{-1} wind velocity partition with Climax I, IIA and IIB. For even higher 700-mb wind velocities, pooled group z_6 ratios consistently much less than 1.0 were observed for Climax I, IIA and IIB. The apparent decreases in precipitation due to seeding at the high 700-mb wind velocities are believed to be related to the too rapid transport of smaller ice crystals over the mountain barrier. When Climax I is combined with Climax IIB for the favorable 12–14 m sec^{-1} wind velocity partition, all but three of the pooled groups have p values which are less than 0.01.

5. Future studies

The two independent samples, 1960–65 and 1965–70, will be combined to provide finer meteorological partitioning than has so far been possible. In particular, analyses involving two- and three-way partitions of wind velocities, wind directions and temperatures are now underway.

Downwind effects of seeding from the Climax area are also being considered by expanding the precipitation network to include precipitation observations made by the U. S. Weather Bureau in other sections of Colorado. In addition, analyses are progressing on data resulting from a randomized seeding experiment conducted during the summer months in the Climax vicinity from June 1966 up to the present time.

Acknowledgments. This research was supported by the Atmospheric Sciences Section, National Science Foundation, under Grant GA-26401. As with many field programs, acknowledgments need to be made to the many groups and individuals who substantially assisted in the conscientious collection of data over an extended period of time. Special acknowledgment is due the Denver office of the U. S. Weather Bureau for its efforts in supplying special forecasts to define experimental days; the High Altitude Observatory of the University of Colorado and the Climax Molybdenum Company for their extensive efforts in assisting with observations in the early stages of the experiment and their continuing assistance with facilities and help in all stages of the experiment; and the many private and Colorado State University personnel who helped with the data collection and analysis.

REFERENCES

Anderson, T. W., 1958: *An Introduction to Multivariate Statistical Analysis*. New York, Wiley, 374 pp (see Chap. 11).

Duran, B. S., and P. W. Mielke, 1968: Robustness of sum of squared ranks test. *J. Amer. Statist. Assoc.*, **63**, 338–344.

Grant, L. O., and P. W. Mielke, 1967: A randomized cloud seeding experiment at Climax, Colorado, 1960–65. *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*, Vol. 5, University of California Press, 115–131.

——, C. F. Chappell and P. W. Mielke, 1968: The recognition of cloud seeding opportunity. *Preprints of Papers, Proc. First Natl. Conf. Weather Modification*, Albany, N. Y., Amer. Meteor. Soc., 372–385.

——, ——, L. W. Crow, P. W. Mielke, J. L. Rasmussen, W. E. Shobe, H. Stockwell and R. A. Wykstra, 1969: An operational adaptation program of weather modification for the Colorado River Basin. Interim Rept., Bureau of Reclamation Contract 14-06-D-6467, Colorado State University, Fort Collins, 98 pp.

Mielke, P. W., 1967: Note on some squared rank tests with existing ties. *Technometrics*, **9**, 312–314.

——, L. O. Grant and C. F. Chappell, 1970: Elevation and spatial variation effects of wintertime orographic cloud seeding. *J. Appl. Meteor.*, **9**, 476–488; Corrigendum, **10**, 842.

Rao, C. R., 1965: *Linear Statistical Inference and its Applications*. New York, Wiley, 522 pp (see 501–504).