Results of a Randomized Hail Suppression Experiment in Northeast Colorado. Part VIII: The Representative Draw Analysis[1]

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ABSTRACT

A detailed analysis is made of the environmental conditions existing on each of the declared hail days during the randomized seeding experiment. From the many soundings available each day, the one most representative of the near-storm environment is carefully selected. This sounding is then used to compute several parameters known to influence hailfall. It is found that two parameters, both indicative of the thermodynamic instability, have a more instable mean value on the seed days than on the control days that in one case is statistically significant at the 10% level. Correcting for this draw would result in reducing the actual ratios of seed to control hail mass found in the primary statistical evaluation of the experiment. However, the reduction would not be sufficient in relation to the very wide 90% confidence limits to affect the statistical conclusions that the ratios were not significantly different from 1.0.

An analysis of the sequences of declared hail days showed that, in spite of the careful experimental design, the random selection process produced an actual partitioning of sequence starts into seed or control such that a sequence this extreme, or more extreme, had a chance of only 3 in 100 of occurring. However, it is not likely that this unexpected draw affected the evaluation of the experiment in any significant way, since it is taken care of indirectly in the analyses of the environmental parameters.

1. Introduction

When interpreting the statistical results of a cloud seeding experiment in terms of their physical implications, the assumption is made that the only essential difference between the seeded and control experimental units is the seeding treatment itself, and that in all other respects the two sets are similar. Under normal circumstances the random selection process, when carried out over a sufficiently long series of experimental units, should produce sets of seeded and control units which have similar natural characteristics. However, this will not necessarily be the case. If, for example, the average potential for hail is very different on the seed days compared to the control days, this could influence the results in such a way as to mask any real effects due to the seeding. It is therefore usual, as an aid in interpreting the results of the NHRE randomized seeding experiment, to carry out an analysis to ascertain how well the randomization scheme used worked out in practice and whether it produced a representative draw or not. This is especially necessary in view of the fact that the experiment was terminated after only three of the planned five years.

The concept of the unrepresentative draw (although the term was not explicitly used) was introduced by Neiburger and Chin (1969) in their analysis of the Swiss Hail Suppression Experiment. In a discussion of a randomized seeding program in the Dakotas, Dennis *et al.* (1972) used the term "bad draw" in an attempt to explain part of the unexpected result. As they pointed out, "there is a possible bias pervading all cloud seeding literature, in that favorable results tend to be reported as such while unfavorable results tend to spark additional analysis." The term "bad draw" implies a bias in that it suggests attempting to find a reason why a preconceived result was not obtained. To be completely objective, the term "representative draw" should be used, and anomalies in the random selection process that could affect the outcome of the experiment in *either* direction should be investigated.

In this paper three aspects of the representative draw will be considered. First, several environmental parameters that are related to hail potential are investigated. Next, the large-scale synoptic forcing present on each of the experimental days is considered. Last, the sequences of seed and control

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days that actually resulted from the random selection process are checked for any unexpected anomalies.

2. Representative soundings

Daily estimates of parameters pertinent to storm development were obtained using a systematic approach to select a sounding considered to best represent the immediate storm environment. This selection process considered the period of convective activity, position and movement of the storms, and gave particular attention to moisture content in the lowest part of the boundary layer because of its influence on potential instability. While the selection process was going on, no reference was ever made by the analysts to sources of information on whether or not hail occurred or seeding was carried out on the days being studied.

Factors having an obvious impact on sounding representativeness are the number of sounding sites, the frequency of soundings at each site and the quality of data from individual soundings. The location of rawinsonde sites is given in Part I of this series (Foote and Knight, 1979; Fig. 1). The number of operational sites varied from year to year between 2 and 5. All stations generally obtained soundings at 90 min intervals whenever convection seemed likely or was active in the operational area.

a. The selection process

For each declared hail day the selection of a representative sounding depends on a primary data base consisting of a 500 mb chart, an hourly surface sectional analysis, and the position and tracks of radar echoes as presented in Foote *et al.* (1976). Supplementary data sources consisted of subcloud aircraft measurements and surface mesonetwork records of wind, temperature and moisture.

The initial step in the selection process was to determine the large-scale air flow patterns prevailing over northeast Colorado at the surface and aloft, based on the height contours and wind fields on 500 mb and surface sectional charts, respectively. Next, the period and position of major radar echo activity occurring over or near the seeding target area were determined, and these were compared to the location and release times of all soundings taken on the day in question. By comparing the storm's position and track to the wind in the subcloud and cloud bearing layers it was determined which soundings were best situated to characterize the environment of the moving storm, for layers both below and above cloud-base altitude. Once the sounding which was judged to be best positioned in time and space with respect to the storm was selected, a careful evaluation was made to determine whether or not its thermodynamic or wind data were in obvious error or whether the measurements were significantly perturbed by the storm itself. The latter judgment was based on comparison with the larger scale flow, other soundings lying farther from the center of convective activity and mesonetwork analyses. Possible temperature perturbations induced by the convection were cooling at the surface caused by spreading downdrafts and warming at high levels associated with the anvil blow-off from storms upstream from a particular sounding. Winds aloft were sometimes perturbed by the outflow from storms and by the blocking effect on the airflow measured by soundings taken near active convective towers. Large horizontal wind, temperature and moisture gradients sometimes dictated the consideration of more than one sounding to adequately represent the undisturbed environment at all levels in the atmosphere. This was particularly true when strong cold air advection was occurring in the middle troposphere.

A consistent result from case studies dealing with High Plains hailstorms (Marwitz, 1972a; Foote and Fankhauser, 1973; and Fankhauser, 1976) is the close agreement between the thermodynamic properties found in updrafts at cloud base and those existing in the lowest part of the surface boundary layer. Therefore, as a refinement in the sounding selection process, the thermodynamic properties of an air parcel having the mean properties of the 50 mb layer closest to the surface were compared to conditions indicated by mesonetwork stations positioned in a favorable relative low-level upwind direction from a storm and also to measurements made by aircraft flying in the inflow regions at cloud base.

It is well known that the accuracy of the humidity measurement obtained with the conventional rawinsonde package is limited to 10 to 20% of its true value (Morrissey and Brousaides, 1970). The error is always toward the low side since it is due to radiational heating of the humidity sensing element. For this reason, when discrepancies were noted between moisture data at low levels on soundings and those recorded by reliable independent sources such as aircraft and calibrated mesonetwork instruments, soundings were modified to agree with the more reliable information. On those occasions when thermodynamic data for a particular sounding were considered representative but winds were in doubt, undisturbed wind data were extracted from the nearest alternate sounding site.

In a number of cases the rawinsonde ascents, although outside of convective storms, did pass through cloud layers. This resulted in saturated conditions on some soundings which may or may not be representative of the overall ambient moisture content in the atmosphere above the convective cloud-base altitude. Due to the local variability of these middle and upper level cloud layers, little

TABLE 1. Representative sounding statistics.

				LOWEST 50-MB ANALYSIS			LIFTING CONDENSATION LEVEL (LCL)			TOP OF POSITIVE ENERGY AREA (TPEA)			WIND DATA (SURFACE-LCL)		WIND DATA (LCL-TPEA)		THERMODYNAMIC ENERGY (JOULES/G)			-5°C LEVEL		TROPOPAUSE DATA			500-MB	
DATE	STA	RELEASE TIME (MDT)	CLASSIFICATION CODE	θ(°K)	θ_e(°K)	r(G/KG)	P(MB)	T(°C)	z(M)	P(MP)	T(°C)	z(M)	MEAN VECTOR $\bar{V}$(M S^{-1})	SHEAR VECTOR V_S(10^{-3} s^{-1})	$\bar{V}$	V_S	POSITIVE	NEGATIVE	NET	P(MB)	z(M)	P(MB)	T(°C)	z(M)	T(°C)	STABILITY INDEX
5/26/72	STK	1650	I	308.3	328.0	6.4	665	1.2	3550	248	-53.4	10710	142/6.4	2.0 (295)	247/6.2	2.7 (240)	0.35	- .01	0.34	579	4660	193	-63.2	12280	-15.0	-2.7
6/02/72	GRO	1350	I	315.8	346.3	9.7	658	7.1	3660	169	-65.1	13300	032/2.7	2.1 (268)	293/8.4	1.4 (298)	2.16	0	2.16	492	5970	173	-65.1	13140	- 9.9	-5.6
6/03/72	STK	1650	I	313.7	336.8	7.3	637	2.6	3920	221	-54.8	11600	167/4.3	1.0 (216)	247/8.9	2.6 (285)	0.62	0	0.62	535	5310	163	-70.3	13470	-10.8	-2.7
6/09/72	KMB	1658	I	313.1	337.6	7.8	652	3.8	3690	270	-42.0	10290	111/3.3	1.7 (188)	174/4.9	0.6 (209)	0.15	-0.7	0.08	531	5330	184	-62.8	12760	- 9.1	-1.3
6/10/72	4FM	1656	II	312.5	339.5	8.7	672	5.7	3480	216	-54.4	11760	142/6.5	1.5 (325)	243/7.5	1.5 (191)	0.63	0	0.63	522	5490	162	-66.0	13550	- 9.1	-2.1
6/15/72	KMB	1351	I	312.1	334.6	7.1	647	2.5	3810	265	-45.0	10370	198/5.7	3.9 (259)	269/9.9	2.3 (319)	0.63	0	0.63	546	5150	200	-55.7	12200	-12.8	-3.6
6/16/72	4FM	1358	I	309.5	339.4	9.7	718	8.4	2940	237	-49.0	11170	080/4.8	4.7 (213)	251/5.3	1.1 (288)	0.70	-0.11	0.59	523	5490	225	-50.9	11500	-10.2	-3.1
6/17/72	STK	1650	II	312.5	341.7	9.4	684	7.1	3300	230	-49.0	11340	176/3.9	1.7 (290)	251/11.0	3.2 (262)	0.96	0	0.96	512	5600	206	-54.5	12060	-10.8	-4.6
6/21/72	KMB	1539	II	310.0	340.7	10.0	717	8.7	2890	221	-52.3	11520	190/11.2	14.1 (230)	279/27.5	6.5 (300)	1.31	-0.16	1.15	517	5520	185	-58.0	12650	-11.8	-5.2
6/22/72	GRO	1550	II	313.5	339.7	8.4	657	4.9	3650	245	-46.5	10950	189/4.5	5.3 (305)	273/21.5	5.4 (282)	0.48	-0.10	0.38	521	5510	178	-57.2	13040	- 9.8	-2.9
6/23/72	KMB	1525	I	313.8	337.2	7.4	638	2.8	3880	281	-39.7	10000	184/3.5	3.7 (257)	242/23.4	5.1 (248)	0.39	-0.05	0.34	533	5320	181	-55.4	12900	-10.7	-2.7
6/26/72	KMB	1351	I	310.7	331.6	6.7	651	1.6	3710	286	-42.2	9790	221/7.0	6.3 (272)	258/19.6	3.5 (270)	0.35	-0.02	0.33	561	4890	212	-50.8	11780	-13.9	-3.3
6/27/72	STK	1050	II	310.8	337.2	8.5	686	5.8	3300	216	-55.9	11650	259/5.0	4.4 (320)	279/27.1	3.7 (269)	1.29	0	1.29	533	5300	220	-56.0	11530	-14.2	-6.2
7/06/72	STK	1400	I	313.1	337.7	7.8	651	3.8	3750	224	-53.6	11510	113/3.2	2.9 (257)	295/18.1	2.0 (312)	0.93	-0.05	0.88	531	5380	188	-58.3	12610	-12.1	-4.3
7/07/72	STK	1651	III	312.5	343.1	9.8	691	8.0	3270	173	-65.4	13110	---	---	---	---	1.85	-0.13	1.72	506	5760	178	-66.3	12950	-11.7	-6.1
	4FM	1720	IV	---	---	---	---	---	---	---	---	---	106/3.6	1.1 (127)	290/18.7	3.4 (293)	---	---	---	---	---	---	---	---	---	---
7/10/72	4FM	1417	I	317.6	339.0	6.7	593	0.3	4520	250	-45.8	10880	076/1.0	3.2 (017)	274/14.1	3.8 (267)	0.36	0	0.36	524	5500	171	-65.7	13250	- 8.1	-0.9
7/11/72	STK	1651	I	316.6	344.6	8.8	638	5.3	3960	238	-45.2	11190	006/3.2	2.1 (317)	281/12.2	3.4 (283)	1.26	-0.03	1.23	500	5900	209	-51.5	12050	-11.0	-6.0
7/22/72	STK	1521	II	315.3	337.3	6.9	616	1.3	4230	300	-35.7	9600	195/2.8	3.5 (259)	245/24.3	7.6 (234)	0.47	-0.08	0.39	532	5390	144	-69.3	14360	-11.1	-3.2
7/24/72	KMB	1537	I	315.8	344.0	8.9	646	5.6	3840	233	-47.0	11390	159/7.2	2.4 (278)	247/17.6	4.0 (243)	0.70	-0.03	0.67	502	5860	135	-67.0	14830	- 9.0	-3.8
7/25/72	4FM	1653	I	315.3	348.6	10.6	676	8.7	3450	217	-48.6	11900	053/2.3	5.3 (318)	249/16.6	3.3 (233)	0.77	-0.09	0.68	483	6150	132	-67.6	15030	- 7.2	-3.7
7/26/72	4FM	1655	II	315.3	344.2	9.2	654	6.1	3750	259	-40.5	10700	122/5.6	1.7 (240)	257/15.9	3.0 (241)	0.64	-0.04	0.60	502	5870	188	-55.6	12800	- 8.9	-3.7
7/27/72	KMB	1351	I	312.8	339.9	8.7	670	5.7	3540	259	-43.0	10650	310/3.4	4.8 (307)	271/21.8	3.3 (250)	0.30	-0.05	0.25	520	5570	200	-55.3	12350	- 7.5	-0.7
5/21/73	4FM	1520	II	308.2	330.9	7.4	688	3.8	3200	242	-52.9	10800	058/4.5	3.9 (248)	245/20.2	3.1 (220)	0.84	-0.03	0.81	564	4800	201	-61.3	11970	-14.7	-3.9
6/28/73	4FM	1320	I	314.3	345.6	10.0	677	7.9	3440	204	-54.3	12260	132/4.3	1.8 (247)	281/16.6	3.1 (281)	0.92	-0.10	0.82	495	5950	208	-54.3	12110	- 7.5	-2.9
7/08/73	STK	1620	I	315.9	350.4	11.0	676	9.3	3490	193	-54.6	12670	174/7.0	1.7 (351)	265/12.7	2.2 (261)	1.33	-0.02	1.31	476	6310	166	-59.7	13620	- 7.1	-4.3
7/09/73	STK	1630	II	315.6	343.8	9.0	649	5.7	3840	229	-48.3	11550	040/8.4	3.8 (010)	337/9.3	3.1 (226)	0.70	-0.10	0.60	503	5880	157	-62.9	13940	- 8.5	-3.2
7/21/73	KMB	1620	I	308.9	345.5	11.8	756	12.0	2470	209	-52.6	11970	146/4.8	4.8 (292)	236/16.8	2.1 (232)	1.53	-0.04	1.49	496	5880	201	-53.7	12220	-10.7	-6.0
7/28/73	SNY	1320	I	313.6	336.0	7.1	634	2.1	4000	257	-46.1	10690	213/3.2	3.2 (321)	238/6.9	1.2 (197)	0.15	-0.05	0.10	539	5300	183	-62.5	12840	-10.1	-1.6

TABLE 1. (*Continued*)

				LOWEST 50-MB ANALYSIS			LIFTING CONDENSATION LEVEL (LCL)			TOP OF POSITIVE ENERGY AREA (TPEA)			WIND DATA (SURFACE-LCL)		(LCL-TPEA)		THERMODYNAMIC ENERGY (JOULES/G)			-5°C LEVEL		TROPOPAUSE DATA			500-MB	
DATE	STA	RELEASE TIME (MDT)	CLASSIFICATION CODE	θ(°K)	θ_e(°K)	r(G/KG)	P(MB)	T(°C)	z(M)	P(MB)	T(°C)	z(M)	MEAN VECTOR V(M S^{-1})	SHEAR VECTOR V_s(10^{-3} s^{-1})	$\bar{V}$	V_s	POSITIVE	NEGATIVE	NET	P(MB)	z(M)	P(MB)	T(°C)	z(M)	T(°C)	STABILITY INDEX
5/17/74	GRO	1325	II	302.3	329.4	9.0	781	8.5	2160	262	-48.9	10300	130/10.6	15.2 (147)	229/16.9	4.0 (247)	0.32	-0.14	0.18	572	4690	190	-61.4	12350	-13.1	-1.6
5/19/74	GRO	1330	IV	---	---	---	---	---	---	---	---	---	189/13.5	3.9 (227)	208/33.8	3.3 (195)	---	---	---	---	---	---	---	---	---	---
	STK	1625	III	317.6	337.7	6.3	585	-0.8	4540	217	-55.3	11640	---	---	---	---	0.78	-0.06	0.72	531	5310	206	-57.4	11960	-10.3	-2.5
5/25/74	GRO	0728	II	308.9	327.0	5.8	648	-0.3	3780	240	-56.1	10910	242/2.8	3.7 (335)	351/12.5	2.0 (357)	0.65	-0.01	0.64	584	4600	219	-59.7	11470	-16.5	-3.8
5/27/74	STK	1325	II	315.7	340.1	7.7	627	3.1	4040	185	-63.5	12690	227/2.3	1.9 (266)	267/16.6	2.1 (254)	1.35	0	1.35	519	5530	180	-63.9	12840	-10.2	-3.5
6/04/74	STK	1625	I	315.9	334.4	5.8	587	-1.8	4540	197	-63.2	12230	208/5.8	1.5 (217)	268/9.4	2.2 (311)	0.73	-0.03	0.70	546	5110	197	-63.2	12220	-11.5	-2.3
6/07/74	GRO	1320	II	304.8	316.7	3.8	627	-6.5	3880	424	-27.9	6820	212/7.8	3.8 (272)	277/8.1	1.5 (334)	0.05	-0.01	0.04	644	3670	286	-50.1	9520	-18.9	-0.6
6/09/74	STK	1635	II	304.3	321.3	5.5	682	-0.4	3310	413	-26.6	7110	331/12.1	6.1 (327)	322/20.2	3.7 (349)	0.20	0	0.20	617	4100	260	-47.9	10310	-17.5	-1.8
6/10/74	STK	1625	II	306.8	326.4	6.4	680	1.6	3370	403	-24.9	7400	286/1.9	5.1 (280)	299/20.0	3.1 (310)	0.05	-0.03	0.02	587	4540	210	-59.7	11790	-13.5	-0.5
6/13/74	STK	1625	II	314.9	333.1	5.7	593	-2.0	4520	283	-41.9	9960	297/4.0	5.2 (320)	331/21.3	1.9 (016)	0.28	-0.08	0.20	553	5070	210	-56.9	11910	-11.2	-1.4
6/16/74	STK	1625	I	312.7	334.7	7.0	639	2.0	3900	293	-38.8	9750	262/2.1	3.7 (323)	317/16.1	2.7 (280)	0.16	-0.23	-0.07	545	5180	240	-48.7	11090	- 9.9	-0.8
6/17/74	STK	1845	I	315.7	341.0	8.0	629	3.4	4010	204	-57.1	12150	324/3.0	5.0 (338)	312/25.6	3.6 (273)	0.74	-0.11	0.63	515	5600	205	-57.5	12110	- 9.1	-2.7
6/18/74	STK	1325	II	317.7	336.5	5.8	576	-1.9	4750	258	-45.5	10630	293/7.0	1.9 (300)	293/11.4	1.1 (302)	0.35	-0.01	0.34	536	5310	210	-53.5	11970	- 8.9	-0.7
6/19/74	STK	1500	I	320.8	342.0	6.5	564	-0.7	4970	261	-41.2	10660	206/5.3	1.3 (226)	272/11.4	3.0 (300)	0.34	-0.12	0.22	511	5760	124	-67.8	15420	- 7.2	-1.2
6/26/74	STK	1635	I	318.6	340.7	6.8	588	0.5	4620	322	-29.5	9170	180/1.2	4.6 (335)	290/8.0	1.4 (277)	0.22	-0.19	0.03	517	5640	124	-69.3	15360	- 7.5	-1.0
7/07/74	STK	1335	II	317.0	341.5	7.7	615	2.7	4220	265	-40.6	10490	206/1.7	0.6 (189)	223/14.6	3.3 (247)	0.47	-0.05	0.42	513	5670	129	-67.1	15120	- 8.5	-2.3
7/08/74	STK	1635	II	318.1	346.0	8.7	624	4.8	4120	222	-48.7	11700	154/2.8	0.2 (070)	226/13.7	2.4 (227)	0.82	0	0.82	494	5970	140	-65.4	14610	- 8.4	-3.9
7/10/74	STK	1500	II	317.6	346.2	9.0	632	5.4	3990	220	-48.9	11760	146/4.5	2.4 (269)	240/13.2	1.6 (250)	0.50	-0.08	0.42	493	5980	142	-66.7	14540	- 6.5	-2.2
7/11/74	STK	1630	I	319.2	344.2	7.8	599	2.6	4450	250	-42.7	10960	103/4.8	2.0 (232)	228/14.4	3.7 (211)	0.41	-0.01	0.40	502	5870	156	-63.8	13970	- 5.8	-0.7
7/12/74	STK	1625	II	319.4	349.1	9.3	621	5.6	4220	223	-46.5	11800	147/7.3	0.8 (273)	216/9.6	2.3 (215)	0.62	-0.01	0.61	481	6250	150	-62.9	14330	- 6.8	-3.5
7/14/74	GRO	1320	II	316.2	343.4	8.6	638	4.9	4020	186	-61.3	12890	082/7.1	1.0 (098)	144/1.8	1.7 (234)	0.73	-0.01	0.72	505	5870	177	-62.4	13180	- 9.6	-4.2
7/17/74	STK	1625	I	317.5	345.4	8.8	630	5.0	4080	210	-52.5	12150	194/5.5	2.0 (225)	210/3.9	0.9 (064)	0.44	-0.12	0.32	496	6000	150	-65.1	14260	- 6.4	-1.8
7/21/74	STK	1325	I	313.6	343.9	9.7	679	7.5	3480	234	-46.9	11430	026/8.0	0.7 (289)	233/5.6	0.8 (224)	0.54	-0.09	0.45	503	5900	174	-62.4	13280	- 7.4	-2.2
7/24/74	GRO	1620	II	314.8	345.9	9.9	667	7.2	3630	189	-58.4	12760	050/1.7	2.9 (280)	277/16.5	1.9 (258)	1.21	0	1.21	494	6030	173	-61.5	13320	- 7.4	-2.9
7/26/74	STK	1625	I	319.1	339.2	6.2	572	-1.2	4880	275	-39.9	10320	211/2.6	1.5 (307)	291/10.5	2.9 (296)	0.26	-0.05	0.21	524	5580	170	-62.1	13420	- 6.8	0.4
7/28/74	STK	1335	I	314.3	340.1	8.2	648	4.5	3870	235	-49.0	11340	083/6.3	1.3 (139)	293/9.4	3.0 (292)	0.65	-0.08	0.57	520	5650	165	-62.3	13580	- 9.6	-2.8
7/29/74	STK	1625	II	311.5	337.8	8.4	676	5.4	3500	292	-37.0	9820	177/1.9	2.0 (026)	326/8.6	2.6 (299)	0.47	-0.01	0.46	530	5440	179	-56.6	13060	- 9.2	-1.5
8/04/74	STK	1325	II	313.9	336.8	7.3	634	2.4	4000	253	-46.4	10750	183/4.0	2.8 (316)	286/8.4	1.6 (283)	0.70	0	0.70	535	5360	156	-60.3	13850	-11.4	-3.3
8/07/74	STK	1625	II	314.2	342.0	8.8	659	5.7	3620	219	-52.1	11640	130/2.6	2.5 (276)	248/7.9	0.6 (208)	1.22	0	1.22	511	5630	188	-59.3	12610	-11.4	-5.3
8/09/74	STK	1800	I	305.9	335.0	9.6	754	9.0	2500	282	-40.9	9940	149/8.4	5.4 (189)	241/9.1	2.2 (306)	0.42	-0.08	0.34	543	5140	194	-60.7	12370	-11.0	-2.1

could be done to ensure that observed moisture conditions aloft were a valid representation of environmental conditions. A detailed discussion of the meteorological situation and sounding selection for each declared hail day is available in Fankhauser *et al.* (1976).

b. Sounding classification

The foregoing considerations led to the development of four different classes of representative sounding:

CLASS I: includes the cases where a single sounding most appropriately defines both the thermodynamic and wind conditions in the environment at all levels for the case under consideration.

CLASS II: includes soundings that 1) have been modified to eliminate obvious errors, 2) have been adjusted to agree with reliable independent data or 3) represent cases where data from more than one sounding have been combined to produce a more appropriate environmental state.

CLASS III: includes soundings that may be considered representative of the environmental temperature and humidity, but wind data were either in serious error, missing or locally disturbed at some upper level.

CLASS IV: includes soundings that have been used to provide wind data to supplement temperature and humidity conditions on Class III soundings.

c. Sounding statistics

Full details of the representative soundings selected for each of the declared hail days are tabulated and plotted in Fankhauser *et al.* (1976). Selected parameters, required in this and another paper in the series, are presented in Table 1, which includes the following information:

1) Sounding site and release time.
2) Sounding classification.
3) Potential temperature (θ), equivalent potential temperature (θ_e), and mixing ratio (r) based on the average temperature (T) and dew-point temperature (T_d) in the 50 mb layer overlying the surface.
4) Pressure, temperature and height at the lifting condensation level (LCL) for the air parcel having properties in (3).
5) Pressure, temperature and height at the top of the positive energy area (Z_e), *viz*, that level where the pseudo-adiabat passing through the LCL intercepts the environmental temperature profile at the top of the positive energy area on a thermodynamic diagram.
6) Mean wind ($\bar{V}$) and the shear vectors (V_s) in two layers: from the surface to the LCL and from the LCL to Z_e (shear vector orientation shown in parentheses).
7) Positive, negative and net energy for a lifted parcel having thermodynamic properties defined in (3).
8) Pressure and height where the lifted parcel has a temperature of −5°C.
9) Pressure, temperature and height of the tropopause.
10) The 500-mb temperature and the stability index (SI) based on the pseudo-adiabatic ascent of the parcel defined in (3).

d. Discussion

Based on research results quoted earlier, the LCL data can be considered to be a reasonably accurate representation of actual conditions at cloud base. In some cases direct observations by aircraft verify the correspondence between the LCL as defined here and the cloud-base conditions actually observed. For many days, however, no direct cloud base measurements exist.

With somewhat less confidence the parcel equilibrium level TPEA at the top of the positive energy area may be used as a measure of storm tops. The frequency of direct measurement here was even lower, but a comparison with the five highest echo tops observed on a given day showed that the TPEA was a reasonably reliable indicator of average storm top conditions.

When using the data in Table 1 it is important to recognize that the given low-level moisture content and associated difficulties in its measurement, influence nearly all of the tabulated parameters. In addition to having a dominant effect on static stability, the low-level moisture has a direct influence on kinematic parameters, since mean wind and shear vectors are computed through layers with boundaries at the LCL. Although considerable effort was made to arrive at the most reliable moisture conditions using all of the available independent data, it is still possible that in some cases the tabulated values do not adequately represent the environment of the storms.

3. Environmental parameters and hail potential

An important factor that could influence the outcome of the experiment is the distribution of ''hail potential'' as determined, for example, from environmental precursors. Since there is a very large day-to-day variation of hail potential in northeast Colorado, a large number of experimental units is required before the average values of the hail potential on the sets of seed and control days are essentially equal. The data from the 3-year experiment have been analyzed to see how well, in fact, the average hail potential on the seeded and control days matched up.

TABLE 2. Tests of statistical significance for the difference between the mean value of selected environmental parameters on seed and control days.

			Seed days		Control days		Two-tailed significance	
Parameter	Linear correlation coefficient with observed hail mass	Units	Mean	SD	Mean	SD	t-test	WMW* rank test
Stability index	−0.29	°C	−3.25	1.45	−2.51	1.65	0.08	0.03
Net energy	0.28	J g^{-1}	0.73	0.49	0.53	0.40	0.15**	0.16
Cloud-base temperature†	0.26	°C	4.57	3.11	3.36	3.86	0.21	
Surface mixing ratio	0.19	g kg^{-1}	8.30	1.49	7.83	1.63	0.23	
Wind shear through cloud	0.006	s^{-1}	2.73	1.32	2.72	1.39	0.98	

* WMW = Wilcoxon Mann-Whitney.
** Based on the logarithms of the energy.
† Determined by lifted condensation level.

The problem of finding covariates having a sufficiently high correlation with hailfall to be useful as predictors is a difficult one so that, even after some 30 years of effort, it is still far from being solved. Some success has been achieved in forecasting the occurrence or non-occurrence of hail and also, when occurring, its maximum size (Foster and Bates, 1956; Longley and Thompson, 1965; Renick and Maxwell, 1977). However, no work has been done to date on relating amount of hail, in terms of area covered or total hail mass (the hail precipitation rate integrated over time and area, i.e., the total mass of hail which fell from a storm) to environmental parameters. Yet it is precisely this latter response variable that forms the basis of the primary statistical analyses of the seeding experiment. Several environmental parameters, known from previous work to be related to convective storm intensity or type, were checked for their correlation with total hail mass. The linear correlations (r) were determined for the 30 control days only, and are shown in Table 2 for the few parameters that had the highest correlation. All confirm our expectation as to sign, but none are significantly different from zero. A fifth parameter, wind shear through the cloud depth is shown also, even though r is essentially zero, since several workers (e.g., Chisholm, 1973; Marwitz 1972a) have shown this to be related to the structure and kinematic behavior of storms. Further, Marwitz (1972b) and Foote and Fankhauser (1973) have shown a relationship between the precipitation efficiency (ratio of rainout to water vapor inflow) and the vertical wind shear for High Plains convective storms.

Values of r between 0.2 and 0.3 mean that only four to 9% of the variance of the observed hail mass can be accounted for by the environmental parameters shown. Such predictors of total hail mass would thus not be very efficient in day-to-day forecasting or in reducing the uncertainties in the experiment. However, there is a slight trend indicated here suggesting that if the average values of these four parameters were substantially different on the seed days compared to the control days, then this could have resulted in a substantially different amount of total hail mass falling on the set of days selected for seeding even in the absence of seeding.

The mean value and standard deviation for each of the five parameters were calculated using the daily values from Table 1 for the samples of 27 seed days and 30 control days. Note that in all cases, except for the wind shear, the difference is in the direction of indicating higher hail potential on the seed days. In some cases, the difference is quite substantial.

The statistical significance of these differences was checked in two ways. Frequency distributions of the parameters visually indicated that they were approximately normally distributed except for the net energy. In this latter case the logarithm of the energy was indicated to be normally distributed. Therefore it was possible to apply the Student's t-test to these differences, and the results are shown in the eighth column of Table 2. It can be seen that only in one case was the difference between the mean values on the seed and control days significant at the 10% or higher level. For the first two listed parameters another check was made on the significance using the Wilcoxon Mann-Whitney rank test. The results are interesting because they show that in spite of the careful experimental design the random draw of seed and control days produced a tendency in some of the environmental conditions towards producing greater hail potential on the seed days that in the case of the stability index had less than a one in ten chance of occurring naturally. *Regardless of whether these differences were statistically significant or not, it is their physical significance that is important.* The differences are substantial, they actually occurred and the question is whether they were sufficient to alter the outcome of the experiment. This will now be investigated by considering two of the parameters in more detail.

SEED	STABILITY INDEX (°C)	CONTROL
	+0.0	4
9	-0.0	5 6 7 7
8 8 7 6	-1.0	0 2 3 4 5 6 8
9 8 7 7 2 2 1	-2.0	1 3 3 5 7 7 9 9
9 8 8 7 6 5 5 3	-3.0	1 2 2 3 7 9
6 3 2	-4.0	3
6 3 2	-5.0	
1	-6.0	0 0 2

SEED: MEAN=-3.25, MEDIAN=-3.5

CONTROL: MEAN=-2.51, MEDIAN=-2.4

FIG. 1. Stem-and-leaf plot of the Showalter Stability Index for each of the seed and control days.

a. The stability index

The index used here, the Lifted Index, is similar to the Showalter (1953) Index except that, as explained in Section 2, the average properties of the lowest 50 mb of the atmosphere are used instead of those at 850 mb. The distribution of seed and control days is shown in a stem-and-leaf plot in Fig. 1. Note that increasing negative values of the index indicate increasing instability, and Showalter found a good relationship between such an index and the severity of convective activity reported in the Midwest United States. Fig. 1 shows that there is a tendency for the control sample to contain more of the low instability days and for the seed sample to contain more of the high instability days. The Wilcoxon Mann-Whitney rank test shows that there is a probability of only 0.03 of such a difference in the distributions or of one more extreme occurring by chance. An estimate of what this difference implies in terms of hail size can be made using the results of Fawbush and Miller (1953) who found a good relationship between maximum reported hail size ($d_{\max}$) in inches on a storm day and the Showalter Index (SI) that can be expressed in the form $d_{\max} = -\mathrm{SI}/2$. For the mean values of the Lifted Index given in Table 2 this implies that the expected mean maximum hail diameter on seed days was 4.13 cm and on control days 3.18 cm, a difference of 0.95 cm.

TABLE 3. Rating of large-scale forcing mechanism. Horizontal lines separate sequences of haildays and isolated haildays.

1 = Weak 2 = Moderate 3 = Strong

Day	Category	Seed/ Control	Day	Category	Seed/ Control
5-26-72	3	S	5-17-74	2	S
6-2-72 6-3-72	1 2	S C	5-19-74	2	C
6-9-72 6-10-72	2 3	C S	5-25-74	1	S
6-15-72 6-16-72 6-17-72	2 2 3	S C S	5-27-74	1	S
6-21-72 6-22-72 6-23-72	3 3 3	S C S	6-4-74	1	C
6-26-72 6-27-72	2 2	S C	6-7-74	1	C
7-6-72 7-7-72	2 3	C S	6-9-74 6-10-74	1 2	S C
7-10-72 7-11-72	2 3	S C	6-13-74	2	C
7-22-72	2	C	6-16-74 6-17-74 6-18-74 6-19-74	2 2 1 2	S C S C
7-24-72 7-25-72 7-26-72 7-27-72	2 3 3 2	S C S C	6-26-74	2	C
5-21-73	3	C	7-7-74 7-8-74	2 2	C S
6-28-73	3	S	7-10-74 7-11-74 7-12-74	3 2 2	S C S
7-8-73 7-9-73	2 3	S C	7-14-74	2	S
7-21-73	3	C	7-17-74	2	C
7-28-73	2	C	7-21-74	2	S
			7-24-74	3	C
			7-26-74	2	C
			7-28-74 7-29-74	3 2	S C
			8-4-74	2	C
			8-7-74	3	S
			8-9-74	3	C

Note: only the first days of sequences were randomly selected and appear to give a reasonable split with a total of 19S selections and 17C selections. All sequences show the automatic alternation of S and C days.

b. Net energy and a simple one-dimensional model

The stability index uses data from only two levels of the environmental sounding. A more complete measure of the convective potential can be obtained by using the whole sounding to compute the net energy available. Table 2 shows that the average net energy is 38% higher on seed days than on control days. However, both these parameters are only measures of the maximum convective potential that could be realized in the area for which the sounding is representative. This area would usually be much larger than the experimental target area itself and in some cases no storms would occur in the target area even though high potential existed. The important consideration is thus the intensity of the actual convective activity realized over the target area each day. This is discussed by Foote and Mohr (1979) who use a technique for "tuning" a simple one-dimensional model using the observed cloud tops to estimate the maximum vertical velocity ($W_{\max}$) realized over the target area. The true maximum updraft speed determines the largest hailstone which can be supported within a storm. There is a long noted tendency for large hailstones to be associated with large hailfalls (in terms of hailfall area and total amount of hail produced). In a way $W_{\max}$ is the most meaningful measure to consider in the representative draw analysis since it is to a large extent a function of the first few parameters in Table 2 and combines and integrates them into one measure of the intensity of convective activity that is *actually realized* in the target area.

The values of $W_{\max}$ were calculated for each experimental day and then treated in exactly the same way as the other parameters in Table 2. The linear correlation coefficient between $W_{\max}$ and total hail mass for the control days is 0.27 (0.36 if the logarithm of hail mass is used); the correlation is weak, but does show a trend for increasing hail mass with increasing convective intensity as discussed by Foote and Mohr (1979). The mean value of $W_{\max}$ for the control days is 17.0 m s^{-1} and for the seed days 18.6 m s^{-1}. The difference of 1.6 m s^{-1} is not statistically significant, though the question of statistical significance is not the important one here. The difference actually did occur, and is in the direction to suggest that more hail would have fallen on the seed days even in the absence of seeding. The question of how much more hail would have been expected cannot be answered accurately by this analysis because $W_{\max}$ is not a very strong predictor of hail amount. Simple linear regression of hail mass on $W_{\max}$ indicates that the observed natural excess in the mean value of $W_{\max}$ on seed days over that on control days is about right to explain the observed greater amount of hail on seed days, without a seeding effect having occurred. However, little confidence can be placed on this result.

4. The synoptic-scale forcing

The variables just discussed are all "static" parameters and do not take account of various dynamical mechanisms for initiating and maintaining convection. To obtain some subjective estimates of the synoptic-scale influences on convection, three meteorologists on the NHRE staff independently judged the large-scale features of each of the hail days by reviewing the daily meteorological summaries (Fankhauser *et al.*, 1976). One of the three categories of synoptic-scale forcing was assigned to each day (1 = weak, 2 = moderate, 3 = strong) after weighing upper-level influences (presence of strong baroclinic zones, horizontal divergence, strong winds, cold air advection) and lower level influences (organized low-level easterlies, surface convergence and frontal zones, abundant low-level moisture). The three independent assessments were then averaged and rounded off (this actually amounts to discarding the discordant value in this case) to obtain a single rating for each day. The individual values actually agreed quite well. In 72% of the cases the judgements of all three meteorologists agreed. In 28% of the cases one individual would disagree by one category from the other two. In no circumstance did one individual assign a day to Category 3 and other individuals assign it to Category 1. The categories assigned to each day are shown in Table 3.

These ratings were then averaged for the seed and control days in each year and the results are shown in Table 4. Note that there appears to be a substantial difference in the average large-scale forcing between years. The low value in 1974 can be explained in terms of the inadvertent lower threshold used for declaration of hail days in that year (Foote and Knight, 1979) leading to the inclusion of more days with lower "hail potential" in that sample. This effect also shows up in the rainfall distribution for 1974 (Crow *et al.*, 1979).

For all years combined, there was no difference in the average value of this parameter, indicating that large-scale forcing on seed and control days was comparable.

This subjective analysis was confirmed by an objective technique developed more recently in a continuing search for useful predictors of hail in northeast Colorado. One such predictor called the DIVSUM developed by Modahl (1977) combines the difference between the maximum divergence aloft and the divergence at 850 mb with the surface mixing ratio, and thus in a sense combines some of the essential elements in the vertical motion and moisture fields on the synoptic scale. A variation of this parameter using the more representative mixing ratio in the lowest 50 mb, rather than at the surface, denoted by DIVLAM (*div*ergence plus *la*yer *m*oisture), was calculated for each day. The mean values of DIVLAM corresponding to each category of synoptic-scale forcing were found to be as follows:

	Mean value of DIVLAM (10^{-6} s^{-1} + g kg^{-1})
Weak synoptic forcing (Category 1)	15.63
Moderate synoptic forcing (Category 2)	19.91
Strong synoptic forcing (Category 3)	21.11

TABLE 4. Average value of the large-scale synoptic forcing for seed and control days classified by year.

	1972	1973	1974	All years
Seed	2.5	2.5	1.9	2.2
Control	2.3	2.8	2.0	2.2
Both categories	2.4	2.7	2.0	2.2

The increasing mean values of DIVLAM for increasing categories of the synoptic-scale forcing thus adds credence to the subjective assessments.

A frequency distribution of the values of DIVLAM for the seed and control days is shown in Fig. 2. The distributions are essentially identical and show that there was an even draw in the selection of seed and control days in terms of this parameter in a way that would not influence the outcome of the experiment.

5. The distribution of hail sequences

Because of a suspected serial correlation between hail that falls on consecutive days (Lovell, 1972) and also since hail often occurs in northeast Colorado in runs of several consecutive days, a special feature was built into the randomization scheme (Foote and Knight, 1979). Briefly, this scheme dictated that when declared hail days occurred as isolated events (i.e., were not preceded by a declared hail day) then the choice of seed or control days was completely random. On the other hand, when a declared hail day followed a declared hail day, then the choice of seed or control was not random, but was automatically the opposite of the choice for the preceding day. Thus, by ensuring that consecutive hail days were never given the same treatment, it was hoped to take advantage of this serial correlation in the analysis. The scheme also implied that the seed or control decision on only the first day of any sequence was randomized, so that over a long enough period of time there should be approximately the same number of seed and control starts to each sequence. An analysis was carried out to determine how the random selection scheme worked out in practice for the limited sample. The actual distribution of single events and sequences was obtained from the listing of declared hail days given by Crow *et al.* (1979) and can be seen in Table 3.

Only the first days of each sequence were selected at random, and were evenly distributed with 19 selected as seed and 17 as control. However, there is a strong preponderance (11 cases out of 14) of runs of two or more consecutive declared hail days that began with a seed day. The single events and sequences were sorted into seed and control starts and the results are presented in the form of a contingency table as shown in Table 5. The hypothesis of equal partitioning of the start of sequences between seed and control days was tested using the chi-square test. From Table 5, $\chi^2 = 4.5$, which with one degree of freedom gives a probability of 0.03. Fisher's exact test for two by two contingency tables gives a probability less than 0.05 (see Table 46 in Odeh *et al.*, 1977). In other words, in spite of the careful experimental design, the random selection process or an unknown experimental bias produced an actual partitioning of sequence starts into seed or control such that one this extreme (or more extreme) had a chance of only 3 in 100 of occurring. One can only imagine personal bias entering the experiment through the hail-day declaration procedures. Sequences were started by declaring a day following a hailday to be a hailday. The hailday declarations have been critically reviewed by Sanborn *et al.* (1976). Recorded radar data and atmospheric soundings were examined to determine

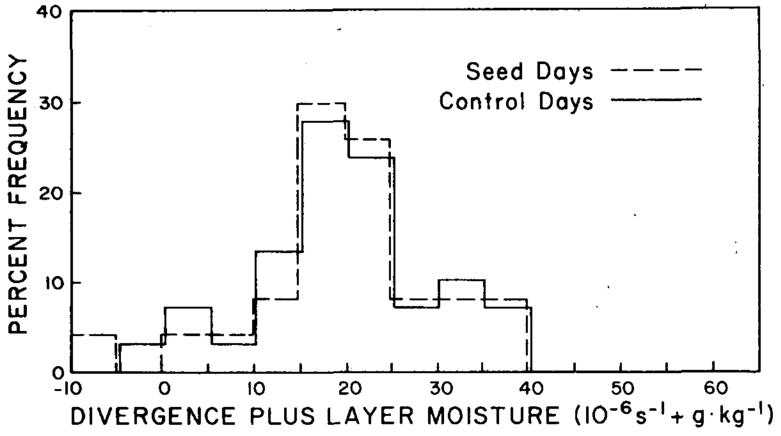

FIG. 2. Frequency distributions, for seed and control days, of the DIVLAM parameter produced by adding the surface layer mixing ratio to the difference between the maximum divergence aloft and the divergence at 850 mb.

TABLE 5. Contingency table generated by sorting the single declared hail days and sequences of declared hail days into seed and control starts.

	Seed start	Control start
Single event	8	14
Sequences	11	3

the exact moment when the hailday criteria were met, for comparison with time at which a hailday was actually declared. Only one hail-day declaration which occurred on the second day of a sequence was found questionable, the other 13 such days being found to have been properly designated according to the definitions of the experimental design. One of five third-day-of-sequence cases was declared 6 min late and one of two fourth-day-of-sequence cases was in error. Thus, there is no indication of bias in the process.

It is not immediately obvious whether such a draw has any real physical significance that could have an impact on the outcome of the experiment or whether it is just an interesting quirk of the random draw. In order to investigate this, the average value of one of the environmental parameters, net energy (E), was computed for the isolated days and for each of the sequence days, and the results are shown in Table 6. The largest average value of E occurs on the second day of a sequence, but the differences in E indicated in Table 6 are rather small and are statistically not significant at the 10% level.

An interesting feature is the total observed hail mass shown in the last line of Table 6. The 22 isolated hail days accounted for 72% of the total hail mass that fell during the 57 experimental days. While the experimental design attempted to use a presumed serial correlation between hail amounts on consecutive hail days, this really was a misdirected emphasis. A more recent analysis by Crow *et al.* (1979) has shown that any serial correlation is weak and of no practical significance.

6. Summary and conclusions

The representative draw analysis shows that there was a higher "hail potential," in terms of greater instability, on seed days than on control days. The modified Showalter Index showed a difference that was significant at better than the 10% level. Using empirical relations developed in the Great Plains the difference would indicate the mean maximum hailstone size to be expected on seed days would be almost 1.0 cm greater than on control days. While such a relationship may not necessarily be valid in the High Plains, it would still suggest a substantial difference between seed and control days.

A more quantitative approach using a simple one-dimensional cloud model showed that the additional instability would lead to more vigorous updrafts and to slightly higher predicted hail mass on seed days compared to control days.

Other environmental parameters such as wind shear through the cloud depth and the large-scale synoptic-forcing mechanisms which are more likely to affect the type and persistence of the storms, once formed, did not show any difference between the seed and control days.

An interesting result was that, although the random draw process resulted in a roughly equal number of seed and control days, the distribution of these among single days and sequences of hail days was very uneven. In fact, the actual partitioning that resulted during the experiment, or one more extreme, only had a chance of 3 in 100 of occurring. The direct impact, if any, of such a draw on the results of the experiment cannot be determined, but according to Crow *et al.* (1979) gives little cause for concern.

Finally, it is difficult to evaluate in a precise, quantitative way how the draw may have affected the outcome of the experiment. Qualitatively, it would be in the direction of decreasing the values of the seed to control ratios for hail mass given by Crow *et al.* (1979) in his Table 8. Correcting for the effect of the draw may be sufficient to change the value of the seed to control ratio to less than 1.0. However, it would not likely change the ratio sufficiently in relation to the very wide 90% confidence limits to affect the statistical conclusion that the ratios were not significantly different from 1.0.

Acknowledgments. The authors wish to thank C. Mohr for assistance in preparing the data shown

TABLE 6. Average net energy on the isolated declared hail days and the various days within sequences.

		Sequence days			
	Isolated days	First	Second	Third	Fourth
Mean net energy (J gm^{-1})	0.59	0.65	0.72	0.57	0.24
Number of seed days	8	11	3	5	0
Number of control days	14	3	11	0	2
Total observed hail mass (10^7 kg)	316.32	122.80			

in Tables 1 and 2, respectively, and C. Wade for assisting in the judgement of the synoptic-scale forcing in Section 4. E. L. Crow provided valuable advice on many of the statistical aspects of this paper.

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