Results of a Randomized Hail Suppression Experiment in Northeast Colorado. Part IV: Analysis of Radar Data for Seeding Effect and Correlation with Hailfall[1]

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ABSTRACT

Radar data collected during the seeding experiment of the National Hail Research Experiment are used in a search for possible effects of seeding. Two types of variables, denoted by P and Q, are defined as daily integrals of reflectivity and areas of reflectivity above a given threshold. These and other radar variables are examined for correlation with hailfall at the ground and for seeding effect. Though several variables are closely associated with the occurrence of hail in the network, according to the present sample, none is highly correlated with the amount of hail. A method for measuring hailfall by radar recently used in Switzerland with apparently good results was not successful when applied to the Colorado area.

Ten radar variables were tested for seeding effect by comparing their values on seed and control days. Both the Student's t-test and the Wilcoxon-Mann-Whitney test were employed and gave comparable results. No variables tested showed a difference between seed and control days that was significant at the 10% level. An examination of regressions developed between two adjacent areas (one of which was expected to be much more strongly affected by seeding than the other) also failed to detect a statistically significant difference between seed and control days.

1. Introduction

The results of the seeding experiment have been evaluated in the previous two papers in terms of precipitation measured by a network of ground instruments (Crow *et al.*, 1979a, 1979b). In the present paper we employ various quantities derived from S-band radar observations of the storm as alternative measures of response to seeding.

There are two ways in which results from such a study can be interpreted. If radar-measured variables are found to be highly correlated with hailfall, then deduced changes in radar returns following seeding might be interpretable as hail suppression (or augmentation) effects. A variety of studies have attempted to document such a correlation (e.g., Geotis, 1963; Rinehart and Staggs, 1968; Barge, 1974; Eccles, 1976; Waldvogel *et al.*, 1978; Dye and Martner, 1978). If strong correlations are not found between radar measurements and hail at the ground, however, a search for seeding effects in the radar observations is still of interest; our current state of knowledge is such that solid evidence for any effect of seeding would be a valuable contribution, even if such effects could not be uniquely interpreted in microphysical terms. In this respect, it is worth noting that the Soviets have reported striking changes in reflectivity structure of hailstorms following seeding (Sulakvelidze *et al.*, 1967; Kartsivadze, 1968), but such changes have not been apparent in studies of Alberta storms (Summers and Renick, 1971; Inkster, 1977). Such contradictions are not an uncommon feature of the hail suppression literature. In this paper we examine the radar variables both for correlation with surface-measured hail and for possible seeding effects independent of the surface measurements.

2. The data

The measurements used in the present investigation were made with the CP-2 S-band radar located at the Grover, Colorado, field site (Foote and Knight, 1979). The data were processed on site with two different systems, each of which produced digital magnetic tapes of averaged radar reflectivity factors throughout periods of storm activity. Details of the radar, and the calibration and recording procedures are given by Foote *et al.* (1976). For the first five sample days in 1972 the CP-2 data were not recoverable because of recording problems. These days are excluded from the analyses presented in this paper.

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TABLE 1. Listing of daily values for various quantities. The units of the Q-integrals are $u = 10^8$ mm^6 m^{-3} km^2 s^{-1}. H_{max} is the maximum echo-top height observed in the area; $\bar{H}_{max}$ is the average of the five highest echo tops recorded in the target area.

	TARGET AREA											80-KM BY 80-KM AREA					
DATE	P_{45} (10^3 km^2 s)	r_{45} (km)	τ_{45} (s)	P_{55} (10^2 km^2 s)	r_{55} (km)	τ_{55} (s)	Q_{45} (u)	Q_{55} (u)	LOG Z_{MAX} (dBZ)	H_{MAX} (km MSL)	$\bar{H}_{MAX}$ (km MSL)	P_{45} (10^3 km^2 s)	P_{55} (10^2 km^2 s)	Q_{45} (u)	Q_{55} (u)	LOG Z_{MAX} (dBZ)	H_{MAX} (km MSL)
6-16-72	0	0	0	0	0	0	0	0	-	-	-	13.6	4.1	14.2	1.6	54	10.2
6-22-72	19.9	1.76	2040	0	0	0	11.4	0	54	12.9	11.3	408.3	99.4	367.6	55.6	63	13.3
6-27-72	64.7	2.04	4940	13.5	0.70	870	54.6	6.2	59	12.4	10.8	158.6	176.6	243.9	118.1	63	13.7
7-06-72	815.1	6.04	7110	811.4	2.90	3979	1380.9	707.4	67	14.1	13.6	1891.6	2099.4	3268.7	1694.0	68	14.3
7-11-72	242.3	3.43	6560	121.4	1.51	1700	271.0	62.0	64	11.6	10.9	588.6	621.8	1162.0	656.7	67	11.6
7-22-72	557.9	4.80	7700	1844.3	3.46	4900	2536.3	2095.2	70	11.8	10.9	1755.9	3183.7	4640.5	3194.7	70	11.8
7-25-72	112.0	2.64	5130	96.4	1.12	2450	152.4	67.4	66	11.9	10.6	877.6	1470.8	1935.6	1211.4	69	13.0
7-27-72	1232.0	6.93	8170	2172.6	3.62	5290	2887.0	1848.1	67	14.0+	13.5	2978.9	5448.1	7148.4	4634.2	69	14.0+
5-21-73	411.8	6.34	3260	829.8	3.23	2538	1131.0	807.0	68	12.3	11.2	997.0	2156.3	2880.9	2105.4	70	12.3
7-09-73	299.7	3.13	9740	38.9	0.81	1874	234.7	19.4	68	12.5	11.1	1382.5	1040.7	1788.1	744.7	68	13.3
7-21-73	210.5	4.77	2950	35.7	0.80	1794	183.1	14.1	57	13.7	13.1	625.2	60.8	468.8	27.8	61	13.7
7-28-73	136.0	2.56	6630	13.7	0.54	1472	98.2	6.8	60	12.7	12.5	304.2	152.5	321.1	108.0	63	12.7
5-19-74	18.1	1.39	2990	0	0	0	11.2	0	43	11.0	10.7	92.6	0	54.6	0	51	11.3
6-04-74	0	0	0	0	0	0	0	0	44	8.5	8.1	9.4	0	5.2	0	52	10.5
6-07-74	0	0	0	0	0	0	0	0	44	6.5	5.9	0.05	0	0.02	0	46	6.9
6-10-74	0.4	0.58	380	0	0	0	0.2	0	50	7.1	6.5	7.1	0	3.7	0	50	7.4
6-13-74	0.3	0.50	380	0	0	0	0.1	0	47	11.6	10.1	3.5	0	1.8	0	52	11.6
6-17-74	82.9	2.89	3160	53.2	1.01	1640	98.5	32.0	64	13.4	13.0	250.4	175.2	298.5	103.4	64	13.4
6-19-74	0	0	0	0	0	0	0	0	44	8.9	8.2	0.1	0	0.04	0	46	9.9
6-26-74	49.0	1.75	5080	9.8	0.92	370	37.8	4.4	58	12.2	11.6	136.5	66.0	136.9	32.7	61	12.2
7-07-74	10.6	1.01	3330	0	0	0	5.2	0	51	8.4	8.1	57.5	1.2	37.1	0.4	55	10.9
7-11-74	0	0	0	0	0	0	0	0	40	10.1	9.3	88.1	222.3	290.5	218.6	70	12.5
7-17-74	0.1	0.25	510	0	0	0	0.06	0	49	11.7	10.0	10.5	9.6	11.7	2.3	60	11.9
7-24-74	103.2	2.45	5490	147.8	1.53	2020	179.0	82.7	63	13.7	12.5	966.5	936.9	1347.9	556.1	64	15.7
7-26-74	0.2	0.51	250	0	0	0	0.05	0	46	11.3	9.3	203.2	183.8	300.9	136.9	66	14.0
7-29-74	0	0	0	0	0	0	0	0	-	7.7	7.4	112.5	84.6	151.2	56.5	64	11.0
8-04-74	249.5	3.81	5470	172.6	1.45	2590	298.6	101.0	57	11.7	11.2	698.2	647.1	943.1	371.3	67	11.9
8-09-74	249.7	3.40	6900	142.6	1.53	1940	278.9	67.9	61	12.5	11.2	1053.7	882.0	1474.4	603.6	69	13.2

CONTROL DAYS

TABLE 1. (*Continued*)

		TARGET AREA											80-KM BY 80-KM AREA					
	DATE	P_{45} (10^3 km^2 s)	r_{45} (km)	τ_{45} (s)	P_{55} (10^2 km^2 s)	r_{55} (km)	τ_{55} (s)	Q_{45} (10^8 u)	Q_{55} (10^8 u)	LOG Z_{MAX} (dBZ)	H_{MAX} (km MSL)	$\bar{H}_{MAX}$ (km MSL)	P_{45} (10^3 km^2 s)	P_{55} (10^2 km^2 s)	Q_{45} (10^8 u)	Q_{55} (10^8 u)	LOG Z_{MAX} (dBZ)	H_{MAX} (km MSL)
	6-15-72	199.8	2.41	11,000	150.9	1.27	2970	236.8	71.9	60	11.5	10.0	876.1	284.6	767.3	136.9	62	11.5
	6-17-72	405.6	4.41	6630	314.2	1.67	3590	460.7	151.9	61	12.6	11.7	1707.0	1501.6	2212.6	797.3	64	14.5
	6-21-72	0	0	0	0	0	0	0	0	41	0	0	497.4	1361.0	2771.3	2375.2	72	13.0
	6-23-72	740.3	7.06	4730	726.5	2.47	3790	1099.9	450.1	65	13.9	12.5	1952.5	1761.7	2794.1	1120.6	65	13.9
	6-26-72	89.1	3.10	2950	32.4	1.02	990	83.0	17.0	60	10.1	9.6	190.3	38.7	157.4	19.7	60	10.3
	7-07-72	1233.3	7.88	6320	2498.0	4.19	4520	3351.7	2295.3	71	15.8+	15.0+	2619.2	4437.4	6079.2	3836.4	71	15.8+
	7-10-72	241.0	3.58	5990	108.1	1.34	1920	242.5	54.4	64	12.6	11.7	1250.5	714.9	1361.4	386.4	65	12.6
	7-24-72	1019.5	4.73	14,520	636.7	1.67	7260	1275.2	517.8	68	12.8	12.2	3503.0	4321.2	6372.9	3683.7	68	13.9
	7-26-72	821.3	6.57	6070	624.8	2.33	3650	1060.2	395.4	66	11.1	10.4	1638.5	984.4	1906.0	609.1	67	12.8
SEED DAYS	6-28-73	169.6	2.98	6070	15.3	0.79	780	97.1	5.5	56	13.9	13.0	319.3	40.2	200.6	17.0	58	13.9
	7-08-73	6.8	1.07	1890	0	0	0	4.1	0	51	11.5	11.1	435.0	312.6	505.2	182.3	63	13.0
	5-17-74	10.4	1.54	1390	0	0	0	5.7	0	53	10.0	9.5	116.5	64.0	122.2	34.6	60	12.0
	5-25-74	1.7	1.32	310	0	0	0	1.1	0	47	10.5	9.0	52.1	1.0	33.1	0.4	56	10.5
	5-27-74	8.1	1.28	1560	0.7	0.47	100*	4.7	0.2	55	10.4	9.0	136.7	160.6	243.7	139.1	68	11.8
	6-09-74	0	0	0	0	0	0	0	0	36	5.6	5.6	5.8	0	2.9	0	50	8.8
	6-16-74	0.5	0.73	300	0	0	0	0.2	0	46	12.4	10.4	13.0	0.8	8.4	0.3	56	12.4
	6-18-74	2.9	0.80	1440	0	0	0	1.8	0	51	10.1	8.4	20.3	1.4	15.1	1.0	58	10.7
	7-08-74	114.7	3.30	3360	80.8	1.79	800	134.3	36.9	59	10.8	9.8	256.1	107.9	248.2	49.0	59	13.0
	7-10-74	455.5	5.16	5450	275.9	1.95	2300	526.8	150.4	62	12.1	11.0	1133.8	701.0	1311.9	379.0	64	12.1
	7-12-74	234.7	4.37	3910	13.4	0.72	830	164.0	5.2	57	12.4	12.0	1054.9	435.0	993.2	218.5	63	13.6
	7-14-74	101.2	2.80	4090	23.8	0.83	1000	93.6	10.3	60	12.7	12.2	405.8	228.1	453.3	133.9	64	13.4
	7-21-74	53.7	1.97	4380	35.5	0.81	1730	63.2	18.6	60	13.6	12.1	374.9	473.2	758.0	467.9	69	14.8
	7-28-74	182.5	3.34	5200	436.3	1.68	4950	537.7	384.8	67	12.7	12.4	361.4	561.7	749.4	448.8	67	13.0
	8-07-74	1321.7	4.97	17,020	3958.2	3.27	11,750	5934.3	4931.3	71	15.0	14.3	5461.1	16,573.6	21,972.8	17,791.4	71	15.2

*ESTIMATED

Concise summaries of the radar observations on each of the 57 days included in the statistical experiment have been given by Foote *et al.* (1976). These include tabulations of the characteristics of individual cells, such as their size and lifetime, along with cell tracks, typical PPI's and envelopes of radar reflectivity.

For the purposes of this investigation we have sought to characterize the convective activity over a region in terms of two integrals:

$$P = \int S_Z dt,$$

$$Q = \iint Z dA dt.$$

Here S_Z is the area of a given reflectivity contour (inside some prescribed geographical area) at a given time t, Z is the radar reflectivity factor, dA is an element of area, and the integrals are evaluated in finite-difference form using values available at each range gate and azimuth (~1 km spacing between data points) for each low-level scan (between 1° and 2° elevation, with time resolution of usually 2–4 min though somewhat longer in 1972). It is expected that such integrals will be better measures of storm severity over a period of time, such as the hail day, than instantaneous intensities alone. For example, if the reflectivity factor were proportional to hail rate, then the quantity Q would be proportional to the amount of hail that fell in the area during the day. Recent studies have shown that, at least in Switzerland, integrals of both types are correlated with surface hailfall (Waldvogel *et al.*, 1978).

Several different values of P and Q have been computed for each of the 52 sample days for which data from the Grover radar were available. We denote by P_{45} and P_{55} the time integrals of the areas of the 45 and 55 dBZ contours, respectively, and by Q_{45} and Q_{55} the Q integrals including only reflectivities > 45 and 55 dBZ, respectively. Values of each of these integrals are presented in Table 1 for two areas and times: 1) the target area for the seeding experiment during the period from hail day declaration until 2030 MDT, and 2) a square 80 km on a side surrounding and including the target, and for the total period for which radar observations were available, commonly encompassing all the significant convection on a day, including that after daylight hours. The maximum reflectivity measured in the two areas and the maximum height of the 30 dBZ echo, H_{max}, are also indicated. The figures in the second column of the echo-top summaries are the average of the five highest tops ($\bar{H}_{max}$) measured in the target area during the day. These values are more stable estimates of the maximum storm echo top and hence better estimates of maximum intensity of convection on a day.

The P integrals can be represented as an average storm size multiplied by the storm duration. If τ_Z is the duration of a reflectivity level Z within the target area, then an equivalent radius r_Z can be defined as:

$$r_Z = \left(\frac{P_Z}{\pi \tau_Z}\right)^{1/2}.$$

Since τ_Z and r_Z might individually be sensitive to seeding, these parameters are also included in Table 1 but only for the target area.

It might be anticipated that since the various quantities in Table 1 are all derived from a common data base, there would be strong intercorrelations among them. We consider this now because it will allow us to eliminate from later consideration a few variables that essentially duplicate one another.

Table 2 shows an array of correlation coefficients computed for a number of variables and their logarithms for control days and for the 80 km × 80 km area. The large area is used here because of the expectation that the sample distributions of quantities measured over this area will more nearly represent the distribution of the underlying population than would measurements over the smaller target area. (In fact, the relative dispersions are smaller in every case for distributions defined over the 80 km × 80 km area than those defined over the target area.)

All of the correlation coefficients except the first one for H_{max} are significantly different from zero if the variables are normally distributed, the 5% points for sample sizes 28 and 22 being 0.374 and 0.423. Since substantial disagreement with normality and lognormality is found in Section 4a, the Spearman rank correlation coefficient, which is independent of the distribution shape, was calculated in three cases also, as shown in Table 2. In each case it falls between the other two (product moment) correlation coefficients and is significant, so the distribution shape is not crucial in Table 2.

The best correlation shown is between $\log P_{45}$ and $\log Q_{45}$ ($r = 0.993$). A scatter diagram including values for all 52 sample days is shown in Fig. 1 (correlation coefficient 0.989). The linear regression of $\log Q_{45}$ on $\log P_{45}$ converts to the relation $Q_{45} = 0.50\, P_{45}^{1.16}$ (units given in Table 1). The correlation between $\log P_{55}$ and $\log Q_{55}$ is also high, being 0.996. These results suggest that it should make little difference whether the P's or the Q's are used to look for seeding effects, and in a later section we consider only one of these. Though $\log P_{45}$ and $\log P_{55}$ are also highly correlated ($r = 0.88$), one can devise a plausible physical argument for why P_{55} might be more sensitive to seeding than P_{45} if a reduction in the maximum size of hail is actually occurring. Such an argument involves the strong dependence of reflectivity on hail size, assuming the contributions to

Z from rain are not dominant. Thus, we examine both quantities for seeding effect.

The variables r and τ tend to be well correlated with P, as expected, but less well with each other. The variables $H_{\max}$ and $Z_{\max}$, which are extremes of instantaneous measurements, are moderately well correlated with the time-integrated quantities, $Z_{\max}$ more than $H_{\max}$.

3. Radar measurements and surface hail

Probably the biggest problem in measuring hail with radar is the unknown contribution of rain to the total reflectivity. Since the reflectivity from rain alone can often exceed, for example, 55 dBZ in heavy showers, a possible relationship between a parameter such as P_{55} and hail at the ground must be established empirically. In this section we first consider the association of radar-derived variables with the occurrence of hail in the surface network, and then examine the utility of these variables as quantitative predictors of hail amount.

a. Radar variables and the occurrence of hail at the surface

We first consider the association of P_{55} with the occurrence of surface hail (as distinct from the amount of hail) by comparing the presence or absence of hail anywhere in the target area as detected by hail/rain separators (from the tabulations of Crow *et al.*, 1979a) with the presence or absence of values of P_{55} greater than zero (from Table 1). The number of occurrences for all the combinations is shown in Table 3 for the seed and control days separately. The tabulation shows that using P_{55} as an indicator of the presence or absence of hail would have been correct on 25 out of 28 days, or 89% of the time on control days, and 88% of the time on seed days. The question of whether such an extreme 2 × 2 contingency table (or one more extreme) could have occurred by chance can be answered by consulting Table 46 (critical values of Fisher's exact test) of Odeh *et al.* (1977). Both tables show association at the 1% significance level.

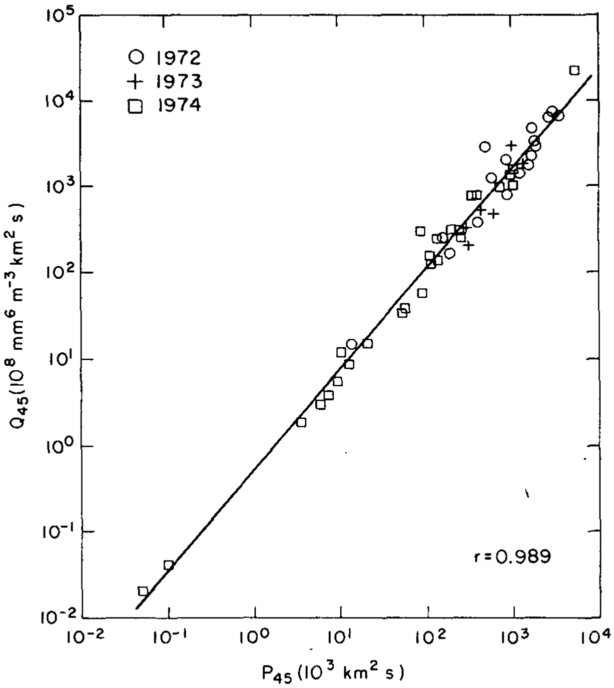

FIG. 1. Scatter diagram of Q_{45} vs P_{45} for the 80 km × 80 km area including all 52 seed and control samples for which radar data were available. The regression line and correlation coefficient (based on the logarithms of the quantities) are indicated.

TABLE 2. Correlation coefficients between radar variables defined over the 80 km by 80 km area for control days. Twenty-eight days are included in the calculation except for the quantity $\log P_{55}$, where because of six zero-values, only 22 days are included. Correlations both between the variables indicated (lin) and their logarithms to base 10 (log) are shown. In three cases, denoted by an asterisk, the Spearman rank correlation coefficient is shown.

	P_{45}		r_{45}		$H_{\max}$	
	lin	log	lin	log	lin	log
P_{55}						
lin	0.94		0.73		0.35	
log		0.88		0.79		0.54
Q_{45}						
lin	0.96		0.77		0.38	
log		0.99		0.94		0.78
r_{45}						
lin	0.83	0.92*			0.64	
log		0.94				0.74
τ_{45}						
lin	0.70	0.80*	0.52	0.65*	0.59	
log		0.92		0.74		0.73
log ($Z_{\max}$)						
lin	0.62	0.88	0.71	0.82	0.73	0.73
log		0.89		0.82		0.75
$H_{\max}$						
lin	0.50		0.64			
log		0.78		0.74		

Waldvogel and Federer (1976) emphasized a threshold of P_{55} = 6000 km^2 s^{-1} as an indicator of hail on the ground. A tabulation using this threshold is shown in Table 4. With the present data set the predictive skill is actually less than in Table 3, being correct on 36 out of 52 occasions, or only 67% of the time if seed and control days are combined. In fact, the association on control days is not significant.

A similar contingency table is given in Table 5 for two different thresholds of P_{45}. Since the predictive capability is similar for both seed and control days, the two sets of days are combined here. Though the presence of nonzero values of P_{45} does not predict hailfall as well as do nonzero values of P_{55}, the

TABLE 3. Numbers of days in various categories. M is the total hail mass in the target area.

	Control days		Seed days	
	$P_{55} = 0$	$P_{55} > 0$	$P_{55} = 0$	$P_{55} > 0$
$M = 0$	12	2	6	2
$M > 0$	1	13	1	15

TABLE 5. Numbers of days in various categories. The seed and control samples have been combined.

	$P_{45} = 0$	$P_{45} > 0$	$P_{45} < 10^4$ km^2 s^{-1}	$P_{45} \geq 10^4$ km s^{-1}
$M = 0$	8	14	16	6
$M > 0$	0	30	1	29
	38/52 = 0.73		45/52 = 0.87	

"skill" of P_{45} is comparable to that of P_{55} if a small threshold value is used.

Since the condition $P_{55} > 0$ implies that the maximum reflectivity in the target area Z_{max} is greater than 55 dBZ, evidently this threshold in reflectivity is also a good indicator of hail in northeast Colorado (46 out of 52 predictions correct if all days are combined). The dependence of the estimated probability (relative frequency) of hail in the target area on the maximum reflectivity in the target is shown in Fig. 2. There is a dramatic increase in the probability of hail as Z_{max} increases from 50 to over 55 dBZ; some hail was present on 28 out of 32 occasions (88%) when Z_{max} was above 55 dBZ, and no hail was recorded on any of the days for which the maximum reflectivity was <50 dBZ.

It must be remembered that what is being compared here is maximum reflectivity anywhere in the target area with the occurrence of hail anywhere in the target area. If the comparison is made instead between the presence of hail at a given position in the network and reflectivity measured at low elevation angles over that position, then the hail probability curve will not rise so sharply, nor will such high probabilities (relative frequencies) be achieved, at least as judged by data from northeast Colorado (Dye and Martner, 1978).

A similar plot is shown in Fig. 3 using maximum echo-top height, $\bar{H}_{max}$ (average of the five largest top heights recorded), as the predictor. A marked increase in hail probability occurs with echo tops in the range 9–11 km, in general agreement with the results of Douglas (1963). If we use 11 km as a threshold for predicting hail, we obtain the results shown in Table 6. In this case, the occurrence of hail is correctly predicted on 39 out of 50 occasions or 78% of the time. One can get a slightly better "predictor" of hail in the sample by using Z_{max} and $\bar{H}_{max}$ jointly. Thus, on the 23 occasions for which both Z_{max} and $\bar{H}_{max}$ exceeded their respective thresholds, hail was reported on 22 occasions or 96% of the time. Of the 18 days in the experiment for which neither threshold was exceeded, hail fell on only two days.

TABLE 4. Association of hail with $P_{55} \geq 6000$ km^2 s^{-1}. M is the total hail mass in the target area.

	Control days		Seed days	
	$P_{55} < 6000$ km^2 s^{-1}	$P_{55} \geq 6000$ km^2 s^{-1}	$P_{55} < 6000$ km^2 s^{-1}	$P_{55} \geq 6000$ km^2 s^{-1}
$M = 0$	12	2	7	1
$M > 0$	7	7	6	10

In summary, there are a number of radar parameters that are closely associated with the occurrence of hail in the Colorado target area. These parameters tend to be strongly correlated with one another, so that the various results are not independent.

b. *Radar variables and the magnitude of surface hailfall*

If one turns now to the problem of predicting the amount of hail, rather than just the occurrence of hail, none of the parameters considered above does as well. Correlation coefficients between the logarithms of nonzero separator hail mass in the target area, $\log M$, and various logarithmic radar variables for the target area are shown in Table 7. For the control days no parameter is well correlated with $\log M$, the largest coefficient (0.57) being attained by $\log r_{45}$. The quantity $\log P_{55}$, which one might expect to be the best predictor of hail mass among the variables in Table 7, has the correlation coefficient only 0.20 with $\log M$. The sample size of 14 for nonzero hail days is rather small (13 for the variables involving the 55 dBZ level), and the two-sided 5% point of the correlation coefficient is 0.532 for normal distributions, so not more than one of these control day coefficients is significant.

For the seed days the correlation coefficients are higher, ranging narrowly from 0.50 to 0.67 for the eight radar variables considered. However, again the sample size is small (15 or 16) and the 5% point of the coefficient is 0.514 or 0.497, the 1% point 0.661 or 0.641. Furthermore, the radar variables are intercorrelated (as shown in Table 2), so we do not have independent items of information here. The correlation of these radar variables with hail mass is positive, not surprisingly, but not large.

Waldvogel *et al.* (1978) found correlation coefficients of 0.7 to 0.8 between the daily kinetic energy of hailfall derived from individual hailpads and a radar-derived measure of kinetic energy (the latter proportional to the Q integrals except that the power of Z is slightly different from unity, 0.840). One

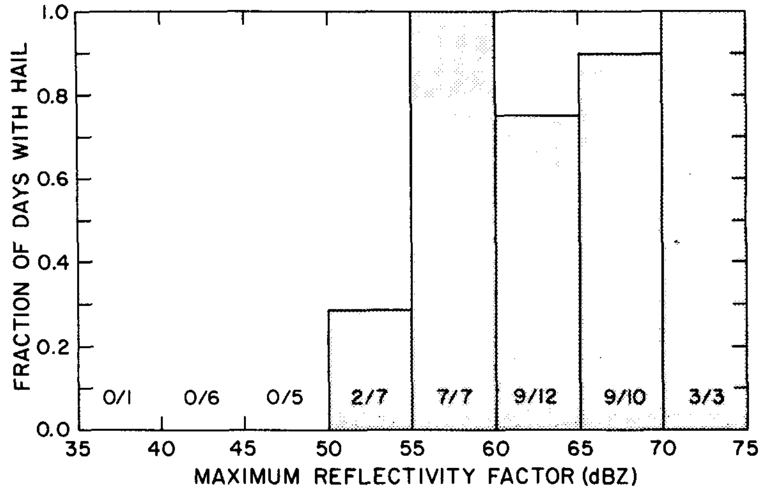

FIG. 2. Fraction of the days with measured hailfall in the target area as a function of the maximum reflectivity observed at low-elevation angles (1–2°) over the target area. Both seed and control days are included. The actual fractions are indicated at the bottom of the figure.

would expect that integration over a larger area would increase the correlation and, indeed, Waldvogel *et al.* obtain such a result when four neighboring pads are combined. Of perhaps greater interest, though, than correlation coefficients is the accuracy of radar estimates of hailfall[2] over a large area, termed a global estimate by Waldvogel *et al.* These authors show results for six hail days. On those days the radar estimates are within 30% of the global kinetic energy estimated from a hailpad network (of ~700 km^2). Such results are striking indeed.

The results of calculations similar to those of Waldvogel *et al.* (1978) are shown in Table 8. Columns 2, 3 and 4 show the integrated hail mass M for the separator network, and the values of Q_{45} and Q_{55} computed for the target area on those control days that had a nonzero hailfall. The following two columns are the ratio $k_Z = Q_Z/M$. The fact that k tends to be much larger than 1.0 is not important, since the Q integrals are only proportional to the hail mass (or kinetic energy) and the proportionality constant from the semi-empirical development of Waldvogel *et al.* has not been included here. The wide range of k-ratios, however, is important to notice. In particular, the ratio of radar estimate to ground measurement on 22 July 1972 is 55 to thousands of times larger than on the other days. If the Q's are to be good predictors of M, then the range of variation of the ratios k must be small. This range can be seen more easily by dividing by the mean of the ratios k, so that the average of the adjusted values k', becomes the desired value, 1.0. Waldvogel *et al.* also show that by normalizing in this way, uncertainties in the absolute radar calibration and scattering laws for hail tend to be removed. This is also a convenient empirical way of partially accounting for the fact that only a fraction of the

[2] Little distinction need be made between measuring/predicting hail mass over an area and the kinetic energy of hailfall over an area (derived from the size spectrum and the theoretical *vertical* speed). According to Crow *et al.* (1979a) the quantities are very highly correlated ($r = 0.997$).

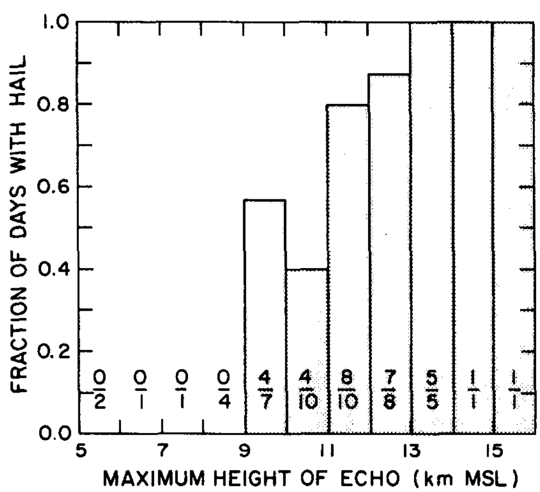

FIG. 3. As in Fig. 2 except as a function of $\bar{H}_{max}$, the average of the five highest echo-top heights recorded over the target area. Both seed and control days are included.

TABLE 6. Occurrences of hail for two categories of $\bar{H}_{max}$, the average of the five largest echo-top heights.

	$\bar{H}_{max} < 11$ km	$\bar{H}_{max} \geq 11$ km
$M = 0$	17	3
$M > 0$	8	22

TABLE 7. Correlation coefficients between nonzero separator hail mass, M, and other radar variables (when nonzero also) over the target area. The numbers of pairs are shown in parentheses.

	Log$M$	
	Control days	Seed days
$\log P_{55}$	0.20 (13)	0.63 (15)
$\log r_{55}$	0.22 (13)	0.60 (15)
$\log \tau_{55}$	0.12 (13)	0.52 (15)
$\log P_{45}$	0.42 (14)	0.67 (16)
$\log r_{45}$	0.57 (14)	0.61 (16)
$\log \tau_{45}$	−0.19 (14)	0.62 (16)
$\bar{H}_{max}$	0.17 (14)	0.67 (16)
$\log Z_{max}$	0.11 (14)	0.60 (16)

backscattered power is due to hail and a fraction results from rain. The final two columns in Table 8 show k'_{45} and k'_{55} computed after eliminating the outlier values from 22 July 1972 (and for k'_{55} the zero value from 19 May 1974). In contrast to the results of Waldvogel *et al.*, in which all estimates k' are within 30% of the value 1.0, only 4 out of the 13 estimates k'_{45} are within 50% of the desired value, and only 1 out of the 13 estimates k'_{55} is within 50%. If 22 July 1972 is included in the sample then in no case is the estimate within 50% of the desired value. It might be mentioned here that there is no particular reason to discount the measurements on 22 July 1972. In spite of displaying relatively strong reflectivities, the storm on this day produced small amounts of hail for reasons thought to be related to weak instability and observed weak updrafts [for further discussion of this case see Foote and Fankhauser (1973), Musil *et al.* (1973) and Foote and Mohr (1979)].

A similar result is obtained if one considers the 15 seed days with non-zero hailfall. In that case, 1 of 16 estimates, k'_{45}, is within 50% of the value 1.0, and 3 of 16 estimates, k'_{55}, are within 50%.

Though this method has worked well for a small sample of hailstorms in Switzerland, it evidently has not yielded good results from the present data set collected in Colorado. There are several possible explanations for this, including errors in the hail and radar measurements, a subject we now consider. The accuracy of the total hail mass M has been discussed by Crow *et al.* (1979a). By comparing totals derived from two different types of instruments, and using different methods of integrating point measurements to get the total over an area, these authors conclude that the rms errors in M are about 80%. Indicated in another way, the correlation coefficient between log$M$ and log of mass derived from hail *pads* over all nonzero days is 0.78, whereas that between log$M$ and $\log Q_{55}$ is 0.45, which accounts for only one-third of the variance accounted for with the 0.78 figure.

The accuracy of the integral Q depends primarily on the radar calibration, and to an extent also on the time resolution (time between successive scans); with the digital data available, the integration scheme is itself quite accurate. Foote and Knight (1979) discuss errors that existed in reflectivity measurements during the field seasons of 1972 and 1973. These errors have been evaluated by Rinehart (1978) and are corrected in the present data. One calibration has been applied to all the days in 1972. Given the observed changes in daily calibration during the summers of 1974 and 1976, one may expect the error on a given day in 1972 to be as much as 3 to 4 dB, but more typically in the 2 dB range. In 1973 and 1974 the reflectivities are expected to be within ±2 dB.

The time between successive radar scans at low elevation angle was 2 to 3 min in 1973 and 1974, although in 1972 intervals of 2 to 5 min were more common, with occasional intervals as long as 10 min. Given the smoothness and continuity of the data, as shown for example in curves of $A_{55}(t)$ (Foote

TABLE 8. Estimation of hail mass, M, in the target area on control days using Q_{45} and Q_{55} (units of Q are 10^8 mm^6 m^{-3} km^2 s^{-1}). The quantity k is equal to Q/M, and $k' = k/\bar{k}$, see text; n is the number of hail separators reporting hail.

Day	M (10^7 kg)	n	Q_{45}	Q_{55}	k_{45}	k_{55}	k'_{45}	k'_{55}
6-27-72	2.92	11	54.6	6.2	18.7	2.1	0.2	0.06
7-06-72	6.45	28	1380.9	707.4	214.1	109.7	2.4	2.9
7-22-72	0.19	5	2536.3	2095.2	13,349.0	11,027.4	—	—
7-27-72	11.99	24	2887.0	1848.1	240.8	154.1	2.7	4.1
5-21-73	106.38	59	1131.0	807.0	10.6	7.6	0.1	0.2
7-09-73	1.83	11	234.7	19.4	128.2	10.6	1.4	0.3
7-21-73	42.89	68	183.1	14.1	4.3	0.3	0.05	0.01
7-28-73	0.75	5	98.2	6.8	130.9	9.1	1.5	0.2
5-19-74	0.53	1	11.2	0	21.1	0	0.2	—
6-17-74	0.77	4	98.5	32.0	127.9	41.6	1.4	1.1
6-26-74	1.64	3	37.8	4.4	23.0	2.7	0.3	0.07
7-24-74	0.90	3	179.0	82.7	198.9	91.9	2.2	2.5
8-04-74	6.53	15	298.6	101.0	45.7	15.5	0.5	0.4
8-09-74	29.32	16	278.9	67.9	9.5	2.3	0.1	0.06

et al., 1976) the error introduced by the finite time resolution is probably within the range associated with the radar calibration.

Since the rms deviations for k'_{45} and k'_{55} from Table 8 are 7 and 9 dB respectively (rms values of 10 logk'), measurement errors do not seem to be a reasonable explanation for the discrepancies noted between M and Q. The calculations summarized in Table 8 have also been repeated using estimates of hail mass M from the hailpad network, rather than the separator network (Crow *et al.*, 1979a). The values of k' that result from using this independent assessment of M are similar to those shown in Table 8.

If instead of using the full set of control days on which hail was measured, one restricts attention to the eight cases for which 10 or more separators measured hail, arguing that a representative value of M is not obtained in the other cases, there is again no improvement in the agreement between M and Q, the rms values for 10 logk'_{55} increasing to 10 dB. Similarly, there is no significant improvement if only the five days for which $n \geq 10$ in 1973 and 1974 are considered, arguing that errors in the radar data are potentially worse in 1972.

A possibly important difference in the calculation made here and by Waldvogel *et al.* (1978) is that, whereas the hailfalls (M) in Table 8 vary over some three orders of magnitude, those of Waldvogel *et al.* vary by a factor of only 4. To see the effect of this difference the calculations presented here have been repeated including only those days (three control and five seed days) that are within the same range of intensity as the days studied by Waldvogel *et al.* The intensities have been judged by adjusting the Swiss values of global kinetic energy to a network the size of the NHRE target area, and then converting from kinetic energy to hail mass by using the empirical relationship derived from the NHRE hailpad data (Crow *et al.*, 1979a). It happens that the eight storm days thus included are the eight days from the NHRE experiment with the heaviest hailfalls. The results of the calculations on this set of days is that only two of the eight values of k'_{45} are within 50% of the desired 1.0, and only one of the eight values of k'_{55} is within 50% of this value. Thus there is no improvement in the result by considering only days in the range of intensity studied by Waldvogel *et al.*

Although the experimental uncertainties in M and Q are far from negligible, the conclusion still seems warranted that hailfall amounts in Colorado are not well predicted by S-band radar measurements. It is likely that the major problem is the unknown contribution of rain to the reflectivity. If hail dominated the reflectivity, one would expect much better agreement between M and Q, as discussed by Waldvogel *et al.* Since virtually all rain from the clouds considered here is thought to result from melting ice particles (e.g., Dye *et al.*, 1974), the degree of melting before the precipitation reaches the ground must be an important complicating factor in attempting to measure hail from these storms with a single-wavelength radar system.

4. Seeding effects on variables derived from radar measurements

We turn now to the matter of seeding effects by treating the radar-derived quantities as possible response variables. Given the low correlations noted in the previous section, such an analysis cannot be easily interpreted in terms of hail suppression, but is important nevertheless in its own right. It would be of great interest to establish firmly that any hailstorm observable was sensitive to seeding.

a. Distribution of the variables

The entire distributions of the daily values of all variables are of interest, since it is possible that seeding might affect the distributions in some way not easily summarized, as, for example, by mean values. However, in the small sample sizes available here it is unlikely that complex effects could be detected, and the principal purpose in examining the form of the distribution is to determine appropriate statistical tests for the average change due to seeding. As examples, Figs. 4–8 present histograms of maximum reflectivity, maximum echo-top height, P_{45}, echo duration τ_{45} and equivalent radius r_{45} for the 80 km × 80 km area.

The distributions of maximum reflectivity (actually log$Z$) and maximum echo top (Figs. 4 and 5) have a central mode and appear conceivably consistent with a normal form, but the other distributions appear J-shaped or more nearly consistent with a lognormal form. To justify applying the Student's t-test for difference in the means, the distributions of seed and control values and their logarithms were tested for normality using the test of Shapiro and Wilk (1965) and excluding the few zero values in Table 1. The resulting sample significance levels are given in Table 9. Of the nine variables considered, only three (H_{max}, τ_{45} and r_{45}) are consistent with normality for both the seed and control days, and only three (P_{55}, r_{45}, r_{55}) are also consistent with lognormality (with zero lefthand boundary). The high incidence of rejection of lognormality is surprising in view of the small sample sizes and the general consistency with lognormality found for surface hail variables in Part II (Crow *et al.*, 1979a).

b. Tests for seeding effect

Although the Student's t-test of the difference of the two mean values is not highly sensitive to departures from normality, it is seen above that its

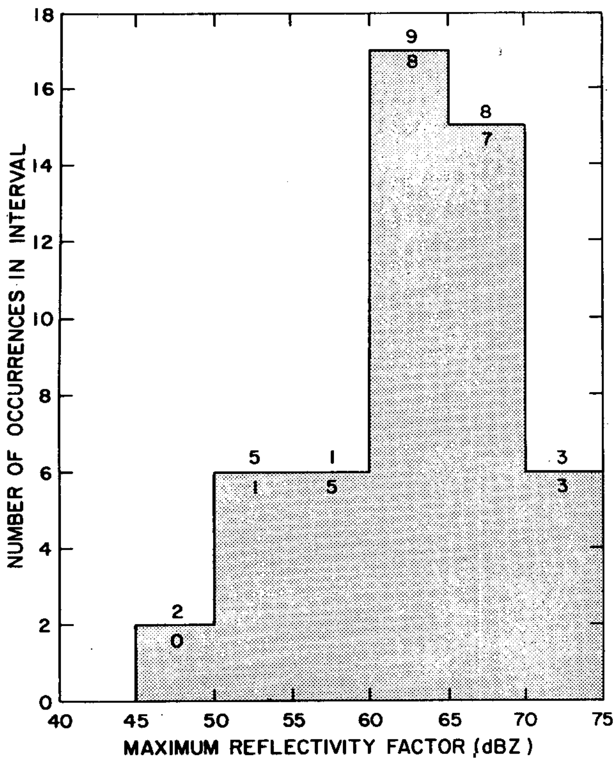

FIG. 4. Frequency distribution of maximum reflectivity in the 80 km × 80 km area for seed and control days combined. The numbers above the line are for control days, and the numbers below the line are for seed days.

application to at least five of the eight variables (or their logarithms) to test for seeding effect is questionable. A more appropriate test is the Wilcoxon-Mann-Whitney (WMW) test, which requires no assumptions about the form of distribution, is a generally quite powerful test of shift, and has the advantage of being applicable to the full samples including zeros, which are excluded if logarithms are taken to achieve at least approximate normality. Two-tailed sample significance levels from both the t test and the WMW test are shown in Table 10.

No variable tested shows a significant difference between seed and control samples at the 10% level (two-sided). This result is true no matter which test is used, and, in fact, the WMW results follow those of the t test fairly closely. When the zero values of variables are included in the WMW test (results shown in parentheses) the significance levels are somewhat smaller, reflecting the higher proportion of zeros on control days than on seed days, though no significance level is $<12\%$.

It may be questioned why there is no significant seeding effect shown when Table 9 shows several instances of a seed day distribution consistent with normality or lognormality and the corresponding control day distribution not so. The answer could be twofold: 1) Two random samples could be consistent with each other (to the extent shown by the appropriate statistical test), and still only one of them could be consistent with a theoretical shape;

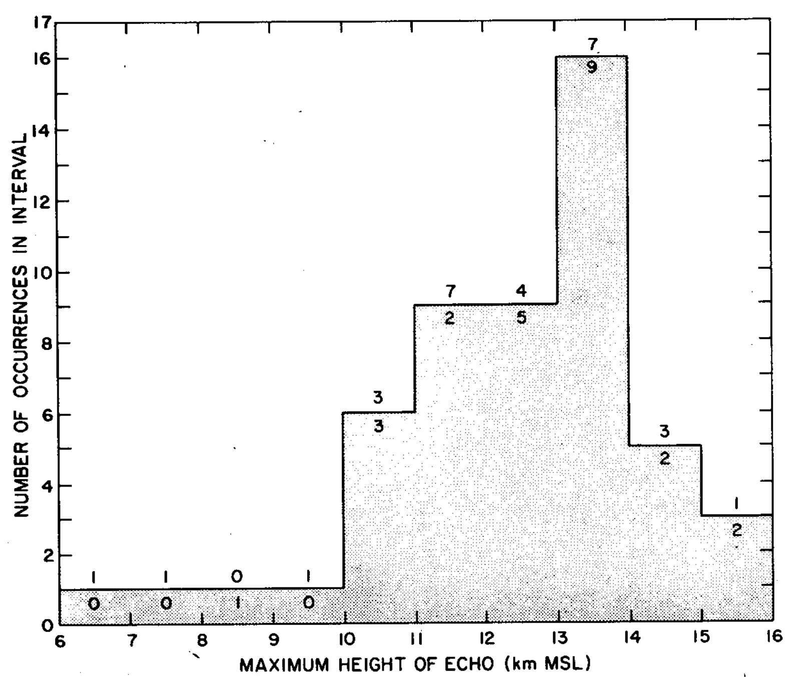

FIG. 5. Frequency distribution of maximum echo-top height as in Fig. 4.

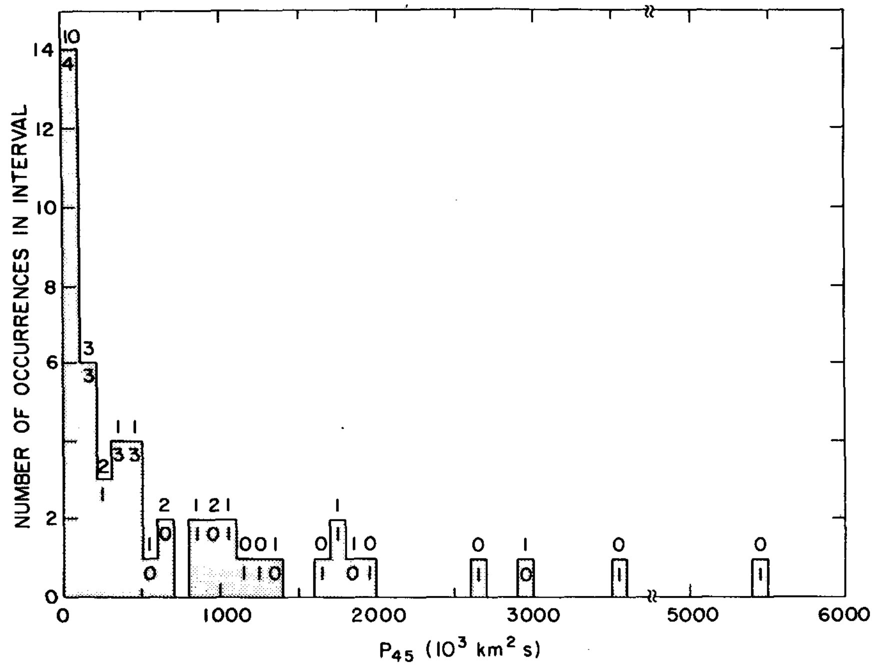

FIG. 6. As in Fig. 4 except frequency distribution of P_{45}.

2) the seed and control distributions could differ in some respects other than mean value, such as shape or dispersion. To test the latter, the Kolmogorov-Smirnov two-sample test (Kim and Jennrich, 1970) was applied to the seed and control samples of Z_{max}, $\bar{H}_{max}$, Q_{45} and τ_{45} for the 80 km × 80-km area (that area over which the variables were computed for testing distribution shape in Table 9). In no case did the seed and control sample turn out to be significantly different from each other even at the 10% significance level. In other words, the results obtained are all of the type 1.

The variables examined in Table 10 were originally

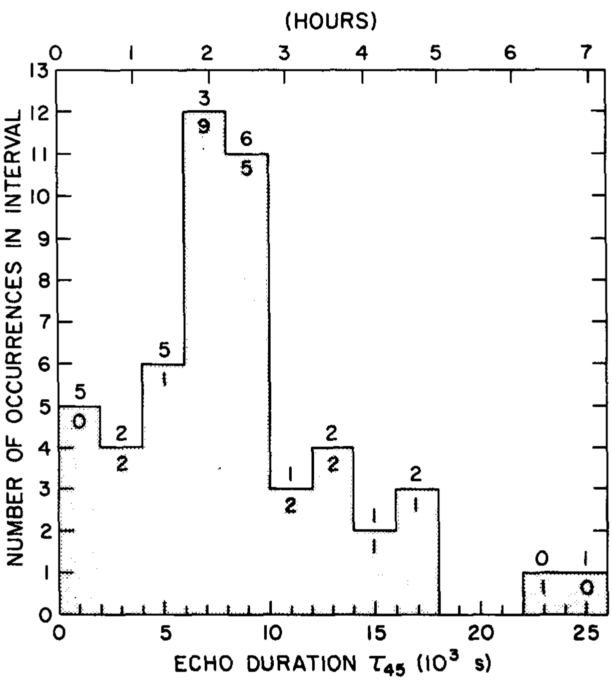

FIG. 7. As in Fig. 4 except frequency distribution of echo duration τ_{45}.

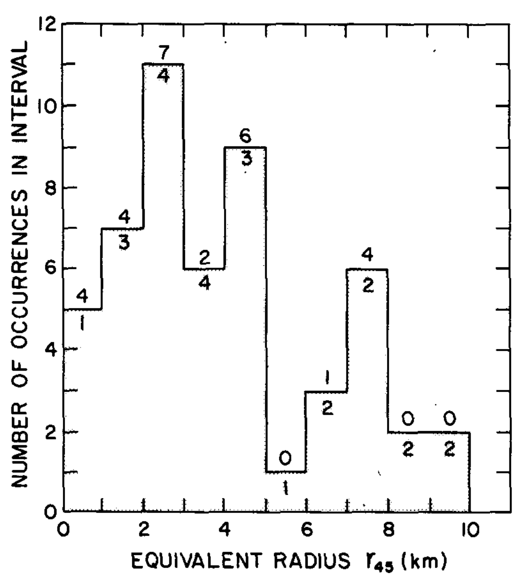

FIG. 8. As in Fig. 4 except frequency distribution of equivalent radius r_{45}.

TABLE 9. Approximate sample significance levels of Shapiro-Wilk test of normality and lognormality of daily radar variables for the 80 km by 80 km area (except for one variable also examined for the target area). The largest tabulated values indicate a closer correspondence with a normal distribution.

	Normality		Lognormality	
Variable	Seed	Control	Seed	Control
$\log Z_{max}$	67%	<1%	43%	<1%
H_{max}	87	9	39	<1
P_{45}	<1	<1	24	<1
P_{45} (target)	<1	<1	3	<1
P_{55}	<1	<1	4	22
τ_{45}	4	12	25	<1
τ_{55}	<1	<1	<1	<1
r_{45}	8	5	9	17
r_{55}	4	2	86	37

chosen because they might have some relationship to hail, although as we have seen in the previous section, the correlations are weak. We have also considered two other variables that are not obviously related to hail, but that may be sensitive to seeding. The first variable is the ratio τ_{55}/τ_{45}: the fraction of the time during which a 45 dBZ echo exists over the target that a 55 dBZ echo also exists. If seeding is successful in reducing high reflectivities, one should expect this ratio to be less on seed days than on control days. The second additional variable considered is r_{55}/r^*_{45}, where r^*_{45} is the equivalent radius of the 45 dBZ echo during the time period that the 55-dBZ echo is present. This ratio is related to the geometry of the reflectivity pattern. Once again, if seeding reduces high reflectivities, one would expect this ratio of geometric quantities to be smaller on seed days. This ratio, in fact, might be more sensitive to seeding than either r_{55} or r_{45} alone.

The Student's t-test for the difference in means has been applied to the quantities τ_{55}/τ_{45} and r_{55}/r^*_{45}. In neither case is a significant difference obtained, the two-tailed significance levels being 74 and 79%, respectively.

As a final analysis we consider the possibility that measurements in an area surrounding the target might be a useful predictor of variables in the target. Values for P_{45} and P_{55} in such a buffer area can be obtained by subtracting the values listed in Table 1 for the target area from those values listed for the 80 km × 80 km area. Since the area of the buffer is ~4800 km² (6400 km² minus 1600 km²), or approximately three times as large as the target, we normalize the variables in the buffer (e.g., $P_{45}(B)$] by dividing by three, and denote these adjusted quantities by primes [e.g., $P'_{45}(B) = P_{45}(B)/3$].

The correlation coefficient between $P_{45}(T)$, the value in the target, and $P'_{45}(B)$ for control days is 0.87 (0.84 with $n = 22$ if the logarithms of positive values are correlated, which is more appropriate to achieve normal distributions with uniform dispersion). Similar calculations for P_{55} lead to a correlation coefficient of 0.85 (0.78 for the logarithms). Clearly, there is some information in the buffer area about what happens in the target.

The usefulness of such buffer-target relationships for isolating seeding effects is complicated somewhat by the fact that some seeding was done in the buffer area. In fact, it was in this area that traveling storms were first seeded, ideally some 20 min before the storms were expected to enter the target. The purpose of this early seeding was to give the silver iodide time to work (see Foote and Knight, 1979). The amount of seeding done in the buffer, though, relative to that done in the target was small. This, coupled with the anticipated delay in the radar-detectable effect of seeding clouds dominated in their precipitation by ice processes (see Knight *et al.*, 1979), leads one to conclude that if seeding effects exist they should be much stronger in the target than in the buffer. In such a circumstance the target-buffer regression on seed days should be rather different from the regression determined for control days.

Figs. 9 and 10 show target-buffer regressions on both seed and control days for the variables $\log P_{45}$ and $\log P_{55}$. The respective regression lines are

$$P_{45}\begin{cases}\text{Seed:} & \log_{10}P_{45}(T) = -0.73 + 1.31\log_{10}P'_{45}(B), \quad r = 0.75, \quad n = 22\\ \text{Control:} & \log_{10}P_{45}(T) = -0.85 + 1.35\log_{10}P'_{45}(B), \quad r = 0.84, \quad n = 22\end{cases}$$

$$P_{55}\begin{cases}\text{Seed:} & \log_{10}P_{55}(T) = +0.70 + 0.69\log_{10}P'_{55}(B), \quad r = 0.60, \quad n = 17\\ \text{Control:} & \log_{10}P_{55}(T) = -0.08 + 0.99\log_{10}P'_{55}(B), \quad r = 0.78, \quad n = 15\end{cases}$$

The two P_{55} regressions appear to be somewhat different, but the difference is in fact far from significant; the Student's t value for testing the difference in slopes is only 0.84, and that testing the difference in mean ordinates is only 0.10. Thus neither the P_{45} nor the P_{55} target-buffer regressions show a seeding effect.

5. Summary

Many variables that might be related to hailfall have been defined and evaluated from daily radar observations for the 1972–74 NHRE randomized seeding experiment. Several of these, particularly

Table 10. Results of Student t and Wilcoxon-Mann-Whitney tests for seeding effect. All data are for the target area. Results are for nonzero daily values of each variable (prior to taking logarithms), except that results including zero values (given in parentheses) are also shown for the WMW test.

Parameter	Control		Seed		Two-tailed significance level (%)	
	Number of days	Average value	Number of days	Average value	t	WMW
$\log P_{45}$	22 (28)	1.633	22 (24)	1.941	36	45 (16)
$\log P_{55}$	15 (28)	2.079	17 (24)	2.103	94	87 (25)
$\log \tau_{45}$	22 (28)	3.489	22 (24)	3.551	66	100 (42)
$\log \tau_{55}$	15 (28)	3.290	17 (24)	3.225	75	75 (22)
$\log r_{45}$	22 (28)	0.323	22 (24)	0.447	25	35 (12)
$\log r_{55}$	15	0.146	17	0.153	94	72
$\log Z_{max}$	26	56.2	24	57.8	54	55
H_{max}	27	10.5	23	11.0	37	47

maximum reflectivity factor, echo-top height and P_{55}, are closely associated with the occurrence of hail at the surface. The value of this result, however, is diminished by the fact that the correspondence was established by comparing radar measurements with those of surface hail *anywhere in the network*, rather than by comparing maximum reflectivity, for example, with the occurrence of surface hail in the vicinity of the reflectivity maximum. If the latter procedure is followed, the correspondence is not as good (Dye and Martner, 1978).

None of the radar-derived variables is well correlated with the amount of hail. In particular, it has not been possible to duplicate the results of recent experiments using radar to measure hailfall over an area in Switzerland. The number of radar estimates of hail mass that fell within ±50% of the desired result was about what would be expected by chance, given the normalization procedure involved. Hail melting and the unknown contribution of rain to the total reflectivity are thought to be the most significant problems in applying the technique in Colorado.

Of the 10 radar variables examined for responses to seeding, none showed an effect at even the 10% significance level using two statistical tests. A regression analysis involving two different areas also failed to reveal any differences between seed and control days that could be attributed to seeding. This result is consistent with that of Inkster (1977), who was unable to isolate any effects of seeding in a detailed radar study of a number of hailstorms in Alberta. If seeding does indeed lead to changes in the storm that are measurable by radar, the detection of such effects apparently requires a more

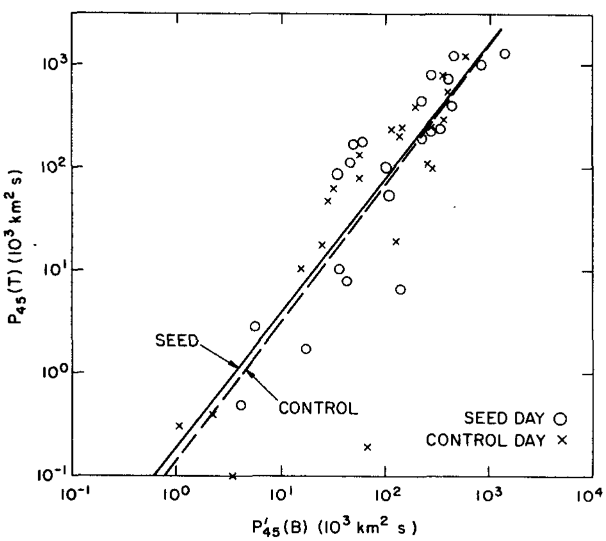

Fig. 9. Scatter diagram and regression lines for values of P_{45} in the target area versus P_{45} (adjusted) in the buffer area for seed and control days.

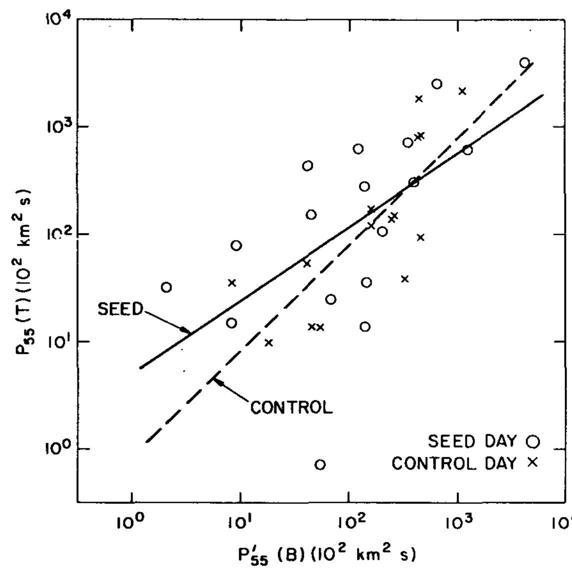

Fig. 10. Scatter diagram and regression lines for values of P_{55} in the target area versus P_{55} (adjusted) in the buffer area for seed and control days.

detailed analysis scheme than attempted either here or by Inkster, or else a greatly increased number of samples.

REFERENCES

Barge, B. L., 1974: Polarization measurements of precipitation backscatter in Alberta. *J. Rech. Atmos.*, **8**, 163–173.

Crow, E. L., A. B. Long, J. E. Dye, A. J. Heymsfield and P. W. Mielke, 1979a: Results of a randomized hail suppression experiment in northeast Colorado. Part II. Surface data base and primary statistical analysis. *J. Appl. Meteor.*, **18**, 1538–1558.

——, ——, ——, and C. W. Ulbrich, 1979b: Results of a randomized hail suppression experiment in northeast Colorado. Part III. Analysis of hailstone size distributions for seeding and yearly effects. *J. Appl. Meteor.*, **18**, 1559–1568.

Douglas, R. H., 1963: Recent hail research: A review. *Severe Local Storms, Meteor. Monogr.*, No. 27, 157–167.

Dye, J. E., C. A. Knight, V. Toutenhoofd and T. W. Cannon, 1974: The mechanism of precipitation formation in northeastern Colorado cumulus. III. Coordinated microphysical and radar observations and summary. *J. Atmos. Sci.*, **8**, 2152–2159.

——, and B. E. Martner, 1978: The relationship between radar reflectivity factor and hail at the ground for northeast Colorado thunderstorms. *J. Appl. Meteor.*, **17**, 1335–1341.

Eccles, P. J., 1976: Remote measurement of mass and kinetic energy of hail using dual-wavelength radar. *Preprints 17th Conf. Radar Meteorology,* Seattle, Amer. Meteor. Soc., 192–199.

Foote, G. B., and J. C. Fankhauser, 1973: Airflow and moisture budget beneath a northeast Colorado hailstorm. *J. Appl. Meteor.*, **12**, 1330–1353.

——, and C. A. Knight, 1979: Results of a randomized hail suppression experiment in northeast Colorado. Part I. Design and conduct of the experiment. *J. Appl. Meteor.*, **18**, 1526–1537.

——, and C. G. Mohr, 1979: Results of a randomized hail suppression experiment in northeast Colorado. Part VI. Post hoc stratification by storm intensity and type. *J. Appl. Meteor.*, **18**, 1589–1600.

——, R. C. Srivastava, J. C. Fankhauser, F. I. Harris, T. J. Kelly, R. E. Rinehart, C. G. Wade, P. J. Eccles, E. T. Garvey, M. E. Solak, R. L. Vaughan, B. E. Weiss, and R. J. Wolski, 1976: *Final Report—National Hail Research Experiment Randomized Seeding Experiment 1972–1974.* Vol. IV: *Radar Summary,* NCAR, Boulder, Colo., 326 pp. [NTIS PB266199/AS]

Geotis, S. G., 1963: Some radar measurements of hailstorms. *J. Appl. Meteor.*, **2**, 270–275.

Inkster, D. R., 1977: A radar study of seeded Alberta hailstorms. Ph.D. thesis, McGill University, 65 pp.

Kartsivadze, A. I., 1968: Modification of hail processes. Preprints *Proc. Int. Conf. Cloud Physics,* Toronto, Amer. Meteor. Soc. 778–788.

Kim, P. J., and R. I. Jennrich, 1970: Tables of the exact sampling distribution of the two-sample Kolomogorov-Smirnov criterion; D_{mn}, $m < n$. *Selected Tables in Mathematical Statistics*, Vol. I, H. L. Harter and D. B. Owen, Eds., Markham Publishing Co., 79–170.

Knight, C. A., G. B. Foote and P. W. Summers, 1979: Results of a randomized hail suppression experiment in northeast Colorado. Part IX. Overall discussion and summary in the context of physical research. *J. Appl. Meteor.*, **18**, 1629–1639.

Musil, D. J., W. R. Sand and R. A. Schleusener, 1973: Analysis of data from T-28 aircraft penetrations of a Colorado hailstorm. *J. Appl. Meteor.*, **12**, 1364–1370.

Odeh, R. E., D. B. Owen, Z. W. Birnbaum and L. Fisher, 1977: *Pocket Book of Statistical Tables*. Marcel Dekker, 166 pp.

Rinehart, R. E., 1978: On the use of ground return targets for radar reflectivity factor calibration checks. *J. Appl. Meteor.*, **17**, 1342–1350.

——, and D. W. Staggs, 1968: Use of radar to delineate surface hail areas in weather modification experiments. *Preprints Int. Conf. Weather Modification,* Toronto, Amer. Meteor. Soc., 464–473.

Shapiro, S. S., and M. B. Wilk, 1965: An analysis of variance test for normality (complete samples). *Biometrika*, **52**, 591–611.

Sulakvelidze, G. K., N. Sh. Bibilashvili and V. F. Lapcheva, 1967: *Formation of Precipitation and Modification of Hail Processes*. [Translated from Russian by Israel Program for Scientific Translations, Jerusalem, 208 pp.]

Summers, P. W., and J. H. Renick, 1971: Case studies of the physical effects of seeding hailstorms in Alberta. *Preprints Int. Conf. Weather Modification,* Canberra, Amer. Meteor. Soc., 213–218.

Waldvogel, A., and B. Federer, 1976: Large raindrops and the boundary between rain and hail. *Preprints 17th Weather Radar Conf.*, Seattle, Amer. Meteor. Soc., 167–172.

——, ——, W. Schmid and J. F. Mezeix, 1978: The kinetic energy of hailfalls. Part II: Radar and hailpads. *J. Appl. Meteor.*, **17**, 1680–1693.