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RANDOMIZED CLOUD SEEDING AT GUTIAN, FUJIAN, CHINA

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Abstract. To increase rainfall over the watershed of Gutian reservoir, halfway from Shanghai to Canton and 100 km inland from Taiwan strait, metaldehyde and silver iodide were injected by rocket into clouds during three seasons, April-June 1975, 1977, and 1981. Randomization provided 50 seeded and 51 unseeded three-hour cases, indicating a 20% increase (significant at 5% level) in mean rainfall over the 1500 km^2 target, mostly in frontal situations. Fourth-root transformations provided adequate transformation to normality of the three-hour rainfall totals. Residual variances of regressions of seeded and unseeded cases differed markedly, requiring special analyses. Contrary to previous assumptions, seeding effects were not proportional to control area rainfall, and regression intercepts were not zero.

1. INTRODUCTION

From April to June of 1975, 1977, and 1978, a series of randomized cloud seeding experiments was conducted over the Gutian (Kutien) reservoir in the coastal mountains of Fujian (Fuchien) province, about 100 km inland from Taiwan (Formosa) Strait, almost midway between Shanghai and Guangzhou (Kuangchou, Canton) (Fig. 1). (Throughout this report, place names are in Pinyin, the new official Chinese transliteration system, with the older Wade-Giles and other forms in parentheses on first usage. Personal names are in western style, family name last. -- Ed.)

For 15 years up to 1974, the mean water storage at the end of June in Gutian reservoir had been only 65% of capacity, insufficient for hydro-electric generation. A research program was organized by Mr. Yuen-yun Sue, Director of the Institute of Meteorology, Weather Bureau, Fujian Province, to study synoptic situations suitable for cloud seeding to increase rainfall over the reservoir's watershed, and to estimate the area possibly affected by such seeding.

Long-term mean monthly rainfall in April, May, and June at Gutian is 218 mm on an average of 22 rainy days per month. The chief precipitation in late spring is from frontal cyclones with stratiform and cumuliform clouds. Cloud tops usually are higher than 5,000 m, with the upper parts generally supercooled. Thus a cold cloud seeding technique was adopted for the rain stimulation experiment, using metaldahyde (C_2H_4O or ("MA") and silver iodide (AgI).

Small rockets, made in Fujian (Inst. of Met., 1975), each carrying 100 g of MA or 5 g of AgI, could be shot to heights of 2.6 to 4.0 km, according to rocket type. The operation site, on Mt. Shita 32 km NW of Gutian, was about 1.6 km MSL, so seeding agents could be sent as high as 4.2 to 5.6 km MSL. During the experimental period the 0 C level over Fuzhow (Fuchou or Fuchow) is about 4.4 to 5.2 km, so that the MA or AgI usually was released near the 0 C level and carried by updrafts to the supercooled regions of the cloud. On the 29 cases using MA, average dose was 3,295 g; for the 21 uses of AgI, average dose was 213 g. Laboratory experiments (Inst. of Met., 1977) showed the nucleation efficiencies and average numbers of activated nuclei given in Table 1.

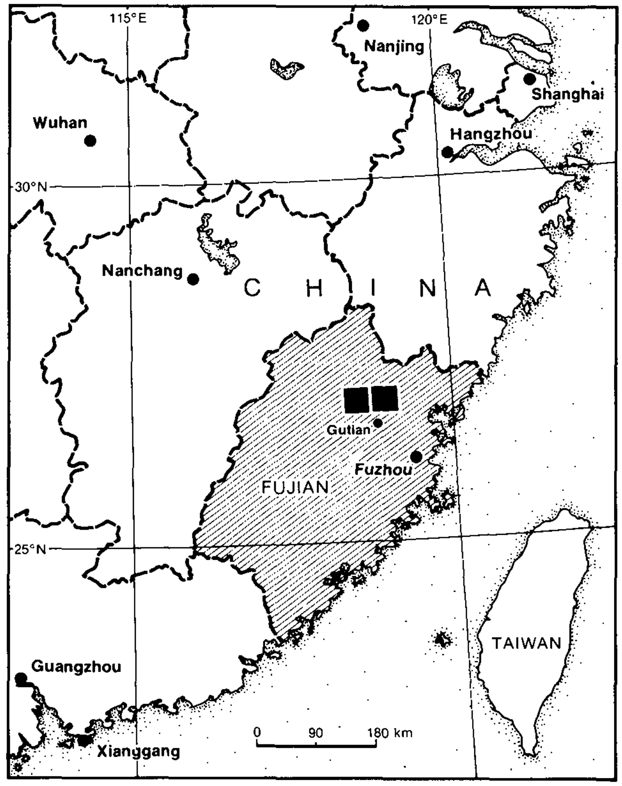

Fig. 1. Location of target (right) and control (left) areas, each about 1500 km^2 (39 km square), in northern Fujian Province, China, of 1975-1978 April-June randomized cloud seeding experiment.

TABLE 1.

Nucleation efficiencies and number of activated nuclei

	Temperature, C	Efficiency per gram	Number of activated nuclei
MA	-10 to -15	10^{10} to 5×10^{10}	3.3×10^{13} to 1.7×10^{14}
AgI	-12 to -13.5	10^{11} to 10^{12}	2.2×10^{13} to 2.2×10^{14}

2. EXPERIMENTAL DESIGN

To evaluate objectively the effects of cloud seeding, a randomized program was adopted (Weather Bureau, 1979), using regressions of precipitation in a specified target area on that in a control area. When a synoptic situation suitable for seeding appeared, whether or not the target area would actually be seeded was decided by a randomized procedure. The control area was never seeded. Separate regressions were constructed predicting rainfall in the target area from that in the control area for seeded and unseeded cases. The difference between the two regressions showed whether the seeding had any effect. This design avoids use of historical rainfall data. The randomized procedure gave a firm foundation for the assumption of similarity between the synoptic situations of the seeded and control cases, thereby increasing the efficiency of the test of seeding effect.

The target area was a rectangle of about 1500 km^2 over the Gutian reservoir watershed (Fig. 2). Winds at the 500 mb level blow from WSW 82%, 83%, and 69% of the time in April, May, and June, respectively, and the main precipitating systems move from west to east at about 20 km/h, drifting across the target in about two hours. Thus a three-hour period was adopted as the experimental unit, assuming that a seeding agent produced during one experimental period would not last into the next one, and no sequential contamination was likely.

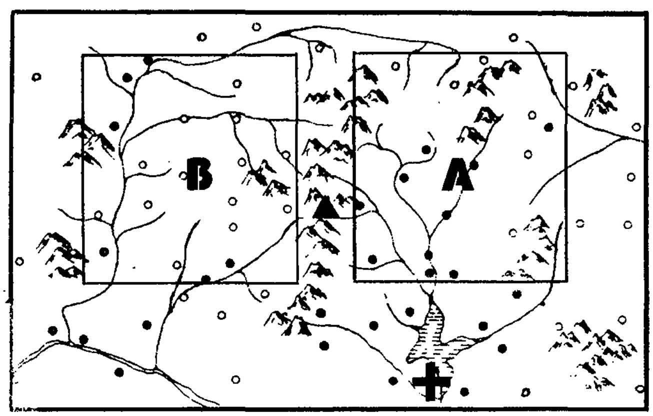

Figure 2. Raingages (solid circle = recording, open circle = ordinary), locations of rocket launch site on Mt. Shita (solid triangle) and of radar on Mt. Turtle at Gutian (cross), and drainage and topography of target (right) and control (left) areas, separated by 11-km buffer strip.

The control area was another 1500 km^2 rectangle west (upwind) of the target, topographically similar, separated from it by a buffer zone 11-km wide containing Mt. Shita, on the watershed between the two areas.

The target area already had 15 to 17 raingages, the control area 16 to 18. For the experiment, additional raingages were places in both area, making a total of 81 to 93, some of them recording. The ordinary gages were read every three hours. Isohyetal maps based on the raingage readings were drawn and mean area rainfall obtained by integrator. For the 51 unseeded units during the three years, the correlation between average areal precipitation in target and control areas was 0.8245. (The 95% confidence interval, determined from Fisher's z-prime transformation, for a correlation of 0.82 based on 51 pairs extends from 0.70 to 0.90 -- Ed.)

Suitability of synoptic conditions for seeding was determined mainly from weather predictions, radar observations, and radiosonde data. When a precipitating system was predicted, the type 711 radar on Mt. Turtle at Gutian began to watch the clouds over the experimental region.

Half an hour before a three-hour experimental unit would begin, if stratiform cloud tops in the two areas were higher than 5,000 m or cumuliform tops higher than 5,500 m, and would probably remain or develop during the period, and the wind direction at the 500 mb level was from 217^{o} to 290^{o}, then the period was declared experimental and a randomized decision made whether seeding should begin.

In this way, during the three years 101 experimental units were selected:

	Seeded	Control	Total
Stratiform	29	30	59
Cumuliform	21	21	42
Total	50	51	101

In addition to this cloud-type stratification, experimental units were classified synoptically into prefrontal, frontal, postfrontal, and high pressure situations.

TABLE 2.

Goodness of fit and area correlations of various transformations

Transformation exponent:	none	1/2	1/3	1/4	1/5	log
Goodness of fit, $1 - K(y_0)$:	0.0041	0.4578	0.7442	0.9373	0.9430	0.5537
Area correlation coefficient:	0.6676	0.7754	0.8102	0.8245	0.8358	0.8435

3. STATISTICAL OPERATIONS

Because the statistical distribution of the three-hour rainfall totals was quite skewed and thus markedly different from that of the normal distribution, on which the usual statistical procedures are based, transformations were needed. Logarithmic and square, cube, fourth, and fifth root transformations were compared to a normal distribution by the Kolmogorov-Smirnov test (Table 2).

The logarithmic transformation yielded the strongest correlation between the average rainfalls in the two areas, but a poor fit to normality. Both the fourth and fifth root transformations gave distributions very close to normal, with goodness of fit of 0.94 and correlation greater than 0.82 between transformed rainfall amounts in the two areas. For all comparisons, therefore the fourth root of the 3-hour precipitation totals was used.

The general multiple event regression procedures for cloud seeding evaluation developed by Thom (1957) assume equality of variances of the seeded and control samples. Tests of the residual variance in regression analysis (Table 3) showed that such equality may be acceptable for rain from stratiform clouds but not from cumuliform clouds or for the entire sample including both types. Consequently, a two-sample regression analysis for unequal variances was developed (Yeh and Fan, 1981) for use here.

TABLE 3. Residual variances in regressions.

	n_s	S^2_{sr}	n_c	S^2_{cr}	F	Signif.
Stratiform	29	0.0307	30	0.0274	1.1204	>0.05
Cumuliform	21	0.0308	21	0.0705	2.2890	>0.05
Total	50	0.0270	51	0.0447	1.6556	>0.05

In the randomized cloud seeding experiment with control areas, the regression equations for areally-average rainfall are

$$\hat{Y}_j = a_j + b_j X$$

where $\hat{Y}$ is the regression estimate of target area rainfall, X is the observed control area rainfall, and $j = s$ for seeded 3-hour units, $j = c$ for control units. The corresponding linear normal regression models are

$$Y_j = \alpha_j + \beta_j X + e_j .$$

The residuals e_j are normally distributed with zero means and possibly unequal variances σ^2_s and σ^2_c. These can be estimated from the sample residual variances

$$S^2_{jr} = \sum_{i=1}^{n_j} (Y_{ji} - \hat{Y}_{ji})^2 / (n_j - 2)$$

For a test of the null hypothesis of equality of the means of the regression-computed target rainfalls for the seeded and unseeded units, a student's t test can be used. For it, the sample residual variances must be adjusted to obtain the pooled standard deviation:

$$Q^2_j = S^2_{jr} \left[\frac{1}{n_j} + (X - \bar{X}_j)^2 / \sum_{n_j} (X_i - X_j)^2 \right]$$

In the denominator of the t-statistic,

$$Z_{\hat{y}} = (\hat{Y}_s - \hat{Y}_c) \quad (Q^2_s + Q^2_c)^{-1/2}$$

The adjusted residual variances also appear in the expression for the degrees of freedom of the t-statistic for the unequal variance case. When $S^2_{sr} = S^2_{cr}$, the simpler multiple event test of Thom (1957) is used.

4. CLOUD SEEDING EFFECTS

Results of the cloud seeding were examined through comparisons of the fourth roots of the average precipitation in the target and control areas, stratified by cloud type, synoptic situation, and rainfall amount in the control area. In addition, results were examined for individual target raingages, and differences sought between the MA and AgI treatments.

The mean increase in target rainfall, overall, was 20.3%, significant at the 0.05 level in a one-sided test; the corresponding absolute increment was 1.11 mm/3h (Fig. 3). By cloud type, mean inrement of rainfall from stratiform clouds was 21.7%, from cumuliform clouds 17.5%, each corresponding to absolute increments of about 1 mm/3h, but none of these was significant at the 5% level (Table 4).

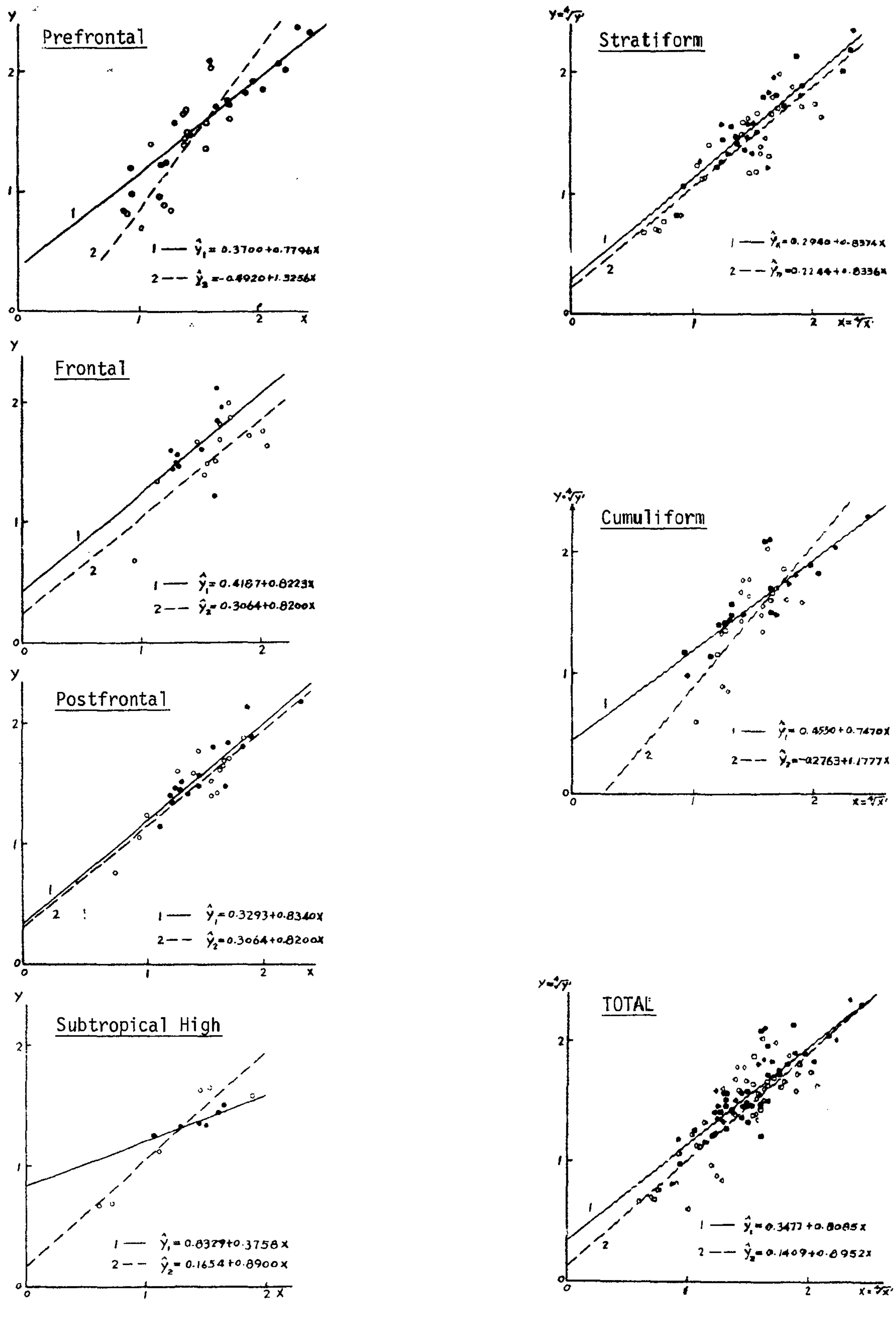

Figure 3. Target-control regressions of fourth roots of areal precipitation for seeded (dots) and control (circles) units, by cloud-type and synoptic stratifications.

1: Seeded 2: Control

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TABLE 4.

Correlations, regression parameters, and significance levels of regression comparisons of the fourth root of seeded (S) and control (C) rainfall, under two different stratifications

		BY CLOUD TYPES		STRATIFIED BY SYNOPTIC SITUATIONS				
		Strati-form	Cumuli-form	Pre-front	Front	Post-front	Subtrop. High	TOTAL
Numbers of 3-hour Units	S	29	21	18	10	16	6	50
	C	30	21	15	13	14	* 8	51
	T	59	42	33	23	30	14	101
Correlations of Areal Precipitation	S	0.8633	0.8667	0.8830	0.5210	0.9169	0.9059	0.8771
	C	0.9011	0.7138	0.7708	0.8282	0.8794	0.9372	0.8245
Regression Constants, α	S	0.2948	0.4550	0.3770	0.4187	0.3293	0.8327	0.3477
	C	0.2244	0.2763	0.4920	0.2501	0.3064	0.1654	0.1409
Regression Coeff., β	S	0.8374	0.7470	0.7796	0.8340	0.8340	0.3758	0.8085
	C	0.8376	1.1777	1.3256	0.8260	0.8260	0.8900	0.8952
Increment Estimates	mm/3 h	1.14	1.01	-0.79	0.72	0.72	- 0.72	1.11
	%	21.4	17.5	-9.4	11.8	11.8	-17.0	20.3
Approx. Levels of Significance	α_1	0.063	0.225	0.250	0.213	0.213	0.250	0.050
	α_2	0.100	0.200	0.250	0.200	0.200	0.200	0.050

α_1 is from the multiple event test, α_2 from two-sample regression test, both one sided.
* one control case not classified synoptically.

More interesting results came from the synoptic stratification: seeding effects were significant only for frontal weather, where the mean increment was 70.6%, or 2.82 mm/3h, with less than 5% probability of being due to chance (Table 4). Effects under prefrontal, postfrontal, and high pressure conditions were not significant.

Effects of rainfall intensity on the experiment were studied by stratifying all experimental data of seeded and unseeded units according to rain intensity in the control area (Fig. 4). The relative increments ranged from 12 to 81%, but decreased with increasing control area rainfall, while absolute additions increased, from 0.44 to 1.14 mm/3h. For all cases, seeding effects were significant at the 5% level when control area rainfall was between 5.80 and 10.50 mm/3h, not significant at lesser or greater intensities (Table 5). Stratiform clouds provided the largest increases (about 22%) when control area rainfall was around 2 mm/3h, cumuliform clouds (up to 67%) when control area rainfall was only about 1 mm/3h. Absolute increments from stratiform clouds were significant when control area rainfall was between 2.86 and 5.80 mm/3h, from cumuliform clouds only when it was less than 2.86 mm/3h.

In all synoptic classes, relative increments declined with increasing control area rainfall, but were significant at the 5% level only when control area prefrontal rain was around 1 mm/3h, frontal rain from 4.50 to 5.66 m/3h, when relative increases were as much as 70% and absolute additions 2.82 to 3.04 mm/3h. No significant increases were obtained in postfrontal or subtropical high pressure conditions, the latter partly because only 14 cases were so classified.

For the first two years of the experiment, double-ratio analysis had been used (Weather Bureau, etc., 1979). This assumes that rainfall at a single target station is proportional to mean control area rainfall, and with no regression intercept; neither assumption seemed acceptable. Thus, the two-sample regression method was adopted for comparing separately each target station rainfall with control area averages. Correlations between individual target gages and control area averages (Fig. 5) differed significantly (1% level) from zero for all stations in the stratiform cases but, for cumuliform cases at only two stations, both in the southwest corner of the target. Thus both regression analysis and double-ratio tests for single-station rainfall from cumulus clouds gave meaningless results over most of the target area.

Two-sample regressions for single-station rainfall in all cases indicated increments of more than 20% over an area some 20 km wide and 10 to 50 km downwind of Mt. Shita (Fig. 6). At most stations in this swath, effects were significant at the 5% level. For stratiform clouds, the area of effect, in which about half the stations showed increases significant at the 5% level, was similar, about 20 km wide and 15 to 50 km long. No significant differences in the effects of metaldehyde (29 cases) and silver iodiee (21 cases) were shown by analysis of varience (Table 6) for all cases; the F values were only about a quarter as large

TABLE 5.

Seeding effects indicated by two-sample regression analyses for two cloud and four synoptic stratifications, and various control area rainfall rates

CATEGORY	Control Area Rain		Target Area Increment			Significance Tests		
seed/not	mm/3 h	4th rt	$y_s - y_c$	mm/3 h	%	z_y	y	α
Stratiform 29 / 30	0.41	0.80	0.0732	0.24	38.42	0.7738	48.26	0.20
	1.00	1.00	0.0742	0.39	31.14	1.0000	48.58	0.10
	2.86	1.30	0.0753	0.73	25.09	1.4756	51.58	0.08
	5.06	1.50	0.0761	1.05	22.29	1.6616	54.78	0.05
	5.80	1.55	0.0763	1.15	21.67	1.6269	55.00	0.06
	10.50	1.80	0.0872	1.67	18.90	1.4730	54.76	0.20
Sumuliform 21 / 21	0.41	0.80	0.3867	1.03	524.42	1.8609	25.97	0.05
	1.00	1.00	0.3006	1.43	216.28	1.9282	27.01	0.05
	2.86	1.30	0.1714	1.66	66.89	1.9280	31.16	0.05
	5.06	1.50	0.0852	1.23	24.90	1.2171	33.03	0.20
	5.77	1.55	0.0638	1.01	17.52	0.8849	32.23	0.20
	10.50	1.80	-0.0440	-1.06	-9.21	-0.3950	26.44	>0.25
Prefrontal 18 / 15	0.41	0.80	0.4252	0.87	833.41	2.0296	20.70	0.05
	1.00	1.00	0.3160	1.26	261.67	2.0533	23.07	0.025
	2.86	1.30	0.1522	1.37	59.39	1.6140	27.56	0.10
	5.06	1.50	0.0430	0.60	12.00	0.4410	22.88	>0.25
	7.50	1.66	-0.0407	-0.79	-9.45	-0.3349	17.94	>0.25
	10.50	1.80	-0.1208	-2.98	-23.17	-0.7522	16.16	0.25
Frontal 10 / 13	0.41	0.80	0.1869	0.72	114.48	0.5308	11.16	>0.25
	1.00	1.00	0.1915	1.16	95.51	0.7448	11.88	0.25
	2.86	1.30	0.1984	2.14	77.28	1.5133	15.18	0.10
	4.50	1.46	0.2020	2.82	70.58	2.0508	16.61	0.05
	5.06	1.50	0.2030	3.04	68.94	2.0402	15.72	0.05
	10.50	1.80	0.2098	4.86	59.73	1.0938	10.02	0.20
Postfrontal 16 / 14	0.41	0.80	0.0341	0.13	14.93	0.2842	24.69	>0.25
	1.00	1.00	0.0369	0.22	13.76	0.4024	24.80	0.25
	2.86	1.30	0.0411	0.44	12.53	0.7148	24.70	0.25
	5.06	1.50	0.0439	0.66	11.93	0.8608	22.63	0.20
	5.63	1.54	0.0445	0.72	11.84	0.8558	22.34	0.20
	10.50	1.80	0.0481	1.13	11.24	0.6671	20.78	>0.25
Subtropical High 6 / 8	0.41	0.80	0.2557	1.06	178.08	2.5698	9.87	0.025
	1.00	1.00	0.1529	0.89	71.78	2.0066	9.55	0.05
	2.86	1.30	-0.0015	-0.01	-0.45	-0.0250	7.42	>0.025
	4.12	1.43	-0.0655	-0.72	-17.06	-1.0234	6.92	0.20
	5.06	1.50	-0.1043	-1.27	-25.04	-1.4900	7.03	0.10
	10.50	1.80	-0.2587	-4.58	-46.89	-2.5239	7.71	0.025
T O T A L 50 / 51	0.41	0.80	0.1376	0.44	81.38	1.6801	94.76	0.05
	1.00	1.00	0.1201	0.63	55.05	1.8766	95.81	0.05
	2.86	1.30	0.0941	0.93	32.12	2.2193	96.03	0.025
	5.06	1.50	0.0768	1.08	22.37	1.9845	93.63	0.025
	5.79	1.55	0.0723	1.11	20.29	1.8682	87.84	0.05
	10.50	1.80	0.0507	1.14	12.07	0.9584	82.56	0.20

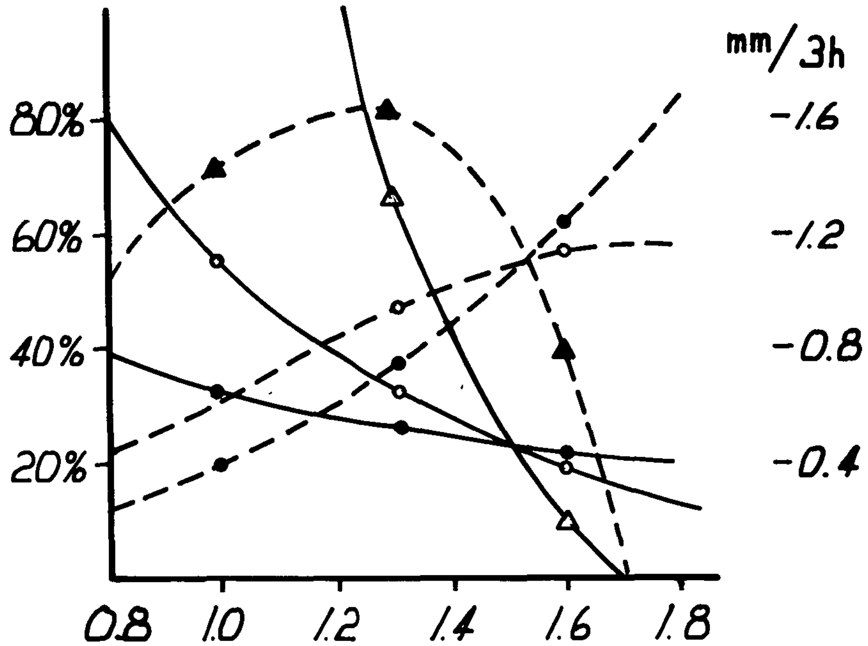
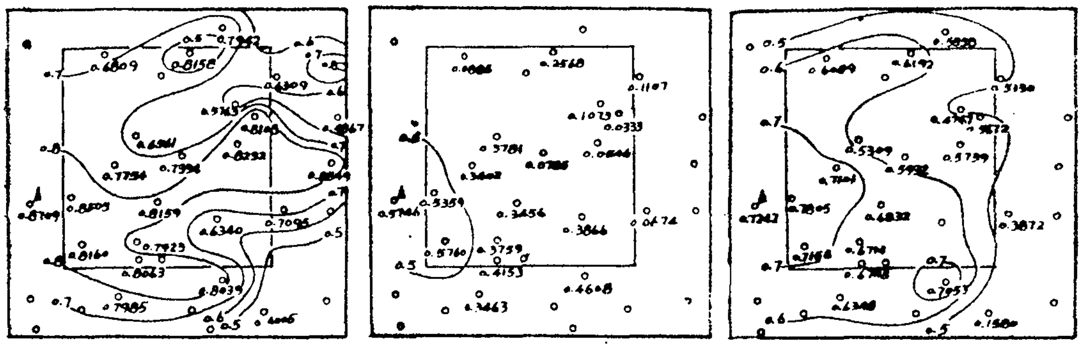
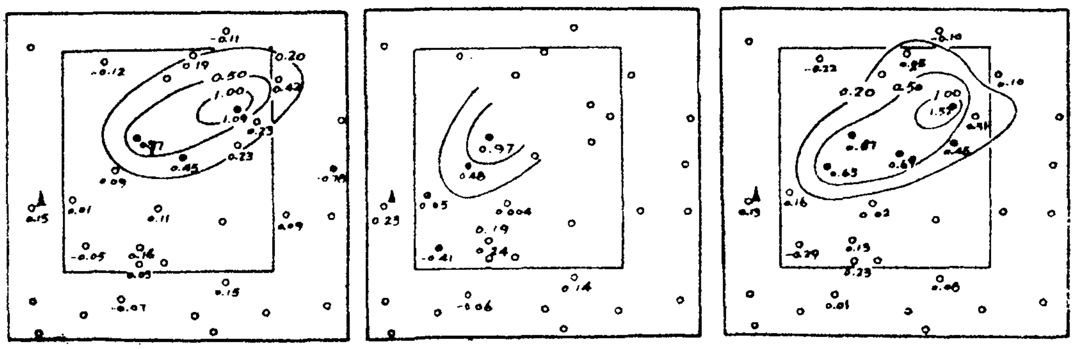


Figure 4. Increments (relative, %, solid, and absolute, mm/3 hrs, dashed) in seeding stratiform (dots), cumuliform (triangles), and all cloud types (circles) in target area as function of control area precipitation.



Stratiform Cumuliform Total

Figure 5. Correlation coefficients between individual station rainfalls in target area and mean rainfall in control area, for cloud type stratification.



Stratiform Cumuliform Total

Figure 6. Seeding effects (relative increments) of individual stations in target area. Solid circles significant at 5% level, open circles not.

as the critical values.

5. SUMMARY AND CONCLUSIONS

Detailed examination of the 50 seeded and 51 unseeded cases during three seasons leads to seven conclusions:

a. Fourth-root and fifth-root transformations of 3-hour rainfall amounts provide acceptable normality; goodness of fit reached 0.94 and correlation between fourth-root amounts in target and control areas exceeded 0.82.

b. Residual variances of regressions for seeded and unseeded samples, separately, differed significantly, so that unequal variances were considered in the regression analyses.

c. Mean target rainfall was increased by about 20.3% by seeding, with one-sided significance of about 5%.

d. Frontal conditions, with an increase of 70.8% (significant at the 5% level) were most favorable for rainfall increase; other synoptic conditions showed little or no significant increases.

e. Relative seeding effects were greatest when control area rain was light, and were generally insignificant when control area rain exceeded 3 mm/3h. Absolute amounts, however, increased with control area rainfall, less for cumuliform and prefrontal rain than otherwise. Thus, seeding effects apparently were neither constant not proportional to natural rainfall, as others have supposed (Biondini, 1976; Scott, 1973).

f. The area in which rainfall increases exceeded 20% was about 20 km wide and 20 to 50 km long, downwind from the rocket release site.

g. Although ten times as much metaldehyde as silver iodide was used, no significant differences in effects was found.

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