A Cloud-Seeding Experiment in Tasmania

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ABSTRACT

A cloud-seeding experiment was conducted in Tasmania using a target area and three control areas. Seeding was on a random basis using silver-iodide smoke released from an aircraft. Evidence is presented that seeding increased rainfall in the eastern half of the target area during autumn.

1. Introduction

An experiment was conducted in Tasmania from 1964 to 1970 inclusive, the main purpose being to investigate the amount by which seeding clouds with silver-iodide smoke released from aircraft could increase precipitation in a catchment area. Here we give a brief description of the experiment and the main results. The raw data may be found in annual reports (Smith and Adderley, 1967, 1969a,b, 1971). A full description has been published as an institutional report (Smith *et al.*, 1977) and a description with preliminary results was given by Smith *et al.* (1971). The experiment was performed by CSIRO and jointly sponsored by CSIRO and the Hydro-Electric Commission of Tasmania.

2. Description of experiment

Randomized on/off seeding took place over a single target area. This was on a plateau at about 1000 m altitude[1] with a few 1500 m mountains in the western parts. There were three control areas where clouds were not seeded. The areas are shown in Fig. 1.

Time during the experiment was divided into periods of 10–18 days with the period changes occurring on days when the Bureau of Meteorology forecast fine weather. Consecutive periods were arranged in pairs such that during the whole of one period of each pair, selected on a random basis, clouds over or approaching a target area were seeded whenever they were suitable. During the other period of the pair no seeding was carried out.

Rainfall data for all areas for each period and for each day were provided by the Bureau, none of whose officers knew the seeding sequence. A network of 54 daily-read gages was used; the locations of the gages are indicated in Fig. 1.

Before the experiment began the following decisions were made:

1) The main analysis would be based on a comparison of the target area rainfall in seeded periods with an estimate of the rain that would have occurred in the same area and periods if the seeding had had no effect, the estimate being based on target and control area rainfalls during the (randomized) seeded and unseeded periods.[2]

2) Results were to be analyzed separately for the four seasons, a period pair being allocated, e.g., to spring if its second period began in September, October or November.

3) Results were to be analyzed separately for the east and west halves of the target area. (The western half is

[1] All altitudes are above mean sea level.

[2] All the rain in a "seeded" period (except as noted in Section 2d) was counted toward the period total even if it fell on a day when no seeding took place. The crews of the seeding aircraft knew whether a given day fell in a seeded or unseeded period. In principle they could have used this knowledge to produce a dilution of results, e.g., by not seeding when clouds were suitable and should have been seeded. However, we cannot think of any way by which the crew could have used this knowledge to provide a positive bias to the results of analysis of period rainfalls.

If analysis of daily rainfalls is attempted, of course, bias of various kinds is possible. Therefore such analyses are relegated in this report to subsidiary status, as in Section 10d, where they are used mainly in an attempt to elucidate how the effects of seeding depend on the conditions.

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appreciably more mountainous and is usually upwind.)

4) Provision was made to exclude from the analysis rainfall on days when the aircraft was not available or the crew were ill, or when (by objective criterion) either the wind speed at cloud height or the rainfall gradient between control areas was excessive. The details of these provisions and the numbers of days excluded are given in Smith *et al.* (1977). A summary of the results if rainfall on these days is not omitted is given in the Appendix.

The original experiment design included the north and south control areas: the northwest control area was added after the first two years' operation. This was done because it was found that rainfall in new gages in the western parts of the target area was not as well-correlated with that in the original two control areas as had been hoped.

In previous cloud-seeding experiments in Australia, results appeared to deteriorate in successive experimental years (Bowen, 1966; Smith, 1967). In the hope of investigating this effect and perhaps of evading its consequences, seeding operations in Tasmania were conducted in alternate years only. The "on" and "off" years were only approximately of one year's duration to give varying dates of starting and stopping.

3. Climate

Rain in the experimental areas is mostly associated with cold fronts and westerly stream weather when depressions move eastward to the south of Tasmania. Occasionally a depression passes over or to the north of Tasmania, bringing heavy rain with east winds. Rain falls in all seasons with a small maximum in winter: the mean annual rainfall in the target area varies from 750 mm in the east to 2300 mm in the west. Clouds are of varying and often mixed types but stratiform clouds tend to predominate in the autumn and winter and cumuliform clouds in the summer. The 0°C level on days with clouds suitable for seeding is ~1200 m in winter and 3000 m in summer.

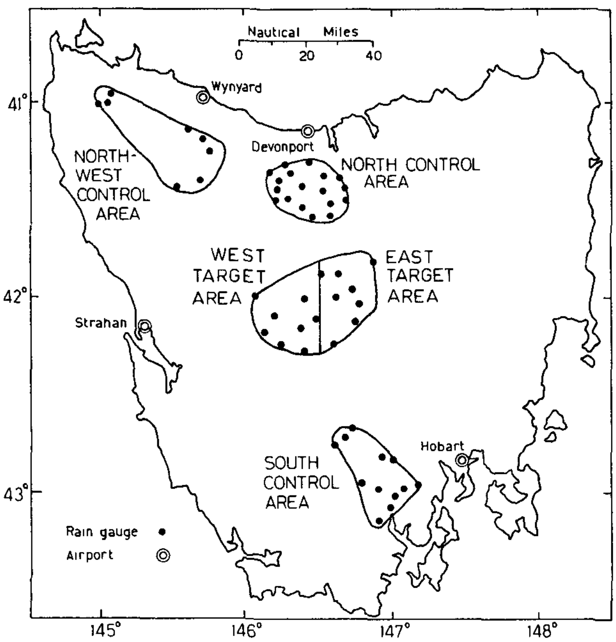


Fig. 1. Experimental areas.

4. Aircraft and seeding equipment

During 1964 and 1966 a Cessna 310B aircraft with one crew was used. In 1968 and 1970 there were two crews and the aircraft was a De Havilland (Canada) Twin Otter.

An acetone solution of silver iodide and sodium iodide was burnt in two ice nucleus generators on the aircraft's wings, each producing 10^{14} nuclei per second active at $-20°C$, 10^{13} at $-14°C$ and 10^{11} at $-10°C$ (Smith *et al.*, 1966).

5. Operational procedures

The objective during seeded periods was to seed as high a proportion as possible of the suitable clouds which occurred over the target area in daylight. Clouds were regarded as suitable if their tops contained supercooled water at a temperature of $-5°C$ or colder for stratiform clouds and $-10°C$ or colder for cumuliform clouds, and if they were deep, compact, without excessive included clear-air spaces, and with tops vertically above their bases. In case of doubt as to whether the clouds met the specification, they were to be seeded, even if already raining.

A secondary objective of the air crew in both seeded and unseeded periods was to observe and report the cloud conditions in the target and one or more control areas.

Whenever forecasts or local reports indicated that suitable clouds might exist in the target area a flight was made to enable the crew to assess the clouds' suitability. If the clouds met the requirements, cumulus clouds were supposed to be seeded at their bases if they were accessible. However, the bases were often on the hills, in which case they were mostly seeded at heights of 2000–3000 m. Stratiform clouds were seeded at or above the $-5°C$ level. Clouds were seeded upwind from the target to allow for wind drift in the expected time for precipitation to develop and fall, allowing 30 min for cumulus and 45 min for stratiform clouds, based on previous experiments on individual clouds (Warner and Twomey, 1956; Bethwaite *et al.*, 1966).

If the target area was upwind from any control area, as indicated by winds measured in the seeding aircraft, clouds were not seeded while this condition prevailed. Days when this occurred were included in the analysis. This, of course, may have diluted the results but cannot have introduced a positive bias.

TABLE 1. Period rainfalls (mm).

Period no.	S/U	T	TE	TW	NC	SC	NWC
			1964			Autumn	
1	S	63.5	42.9	94.7	41.9	45.7	84.6
2	U	19.3	18.8	19.8	27.7	20.1	40.4
			1964			Winter	
3	S	21.1	20.6	21.8	60.7	9.1	52.3
4	U	42.4	36.6	51.1	75.2	32.3	102.9
5	S	84.6	63.0	117.1	105.7	54.9	152.4
6	U	37.1	21.3	60.7	70.1	22.1	105.9
7	U	19.6	9.4	34.8	27.4	21.6	87.6
8	S	14.7	9.4	21.3	6.6	11.9	22.9
			1964			Spring	
9	U	45.0	33.8	58.7	64.3	27.4	92.7
10	S	110.5	85.9	141.2	70.1	78.7	128.5
11	S	25.4	17.5	37.1	27.2	16.3	49.5
12	U	50.0	36.1	70.9	36.1	27.4	31.0
13	S	17.3	11.2	26.7	6.1	11.2	23.9
14	U	24.4	19.3	31.5	17.8	17.0	23.9
			1964			Summer	
15	S	40.4	28.7	57.9	24.6	42.2	56.1
16	U	29.5	22.4	40.1	26.9	28.7	37.1
			1966			Summer	
45	S	9.1	4.3	14.0	3.3	6.9	8.9
46	U	13.5	6.4	19.6	2.5	7.6	8.6
47	U	29.0	19.8	36.8	9.7	14.7	17.0
48	S	9.4	10.2	8.6	11.4	10.9	11.2
			1966			Autumn	
49	S	16.8	13.2	20.1	10.7	11.9	13.5
50	U	60.7	69.3	53.1	56.9	102.1	64.0
51	U	43.9	22.9	62.2	13.2	33.5	55.4
52	S	53.6	41.1	64.5	23.9	40.4	43.9
53	U	39.6	23.6	53.6	30.2	21.6	58.7
54	S	25.4	16.0	33.3	19.3	18.0	32.5
			1966			Winter	
55	S	21.6	10.7	31.2	3.3	15.0	23.1
56	U	13.5	16.3	10.9	38.1	6.1	29.2
57	U	13.0	7.6	17.5	26.2	5.6	47.8
58	S	28.4	22.4	33.5	47.5	14.7	75.4
59	U	25.9	19.3	31.8	47.0	34.5	55.1
60	S	28.2	31.8	25.4	51.8	18.0	56.4
61	U	26.2	27.4	25.1	36.6	25.4	41.7
62	S	23.9	28.2	20.3	37.1	37.6	10.2
			1966			Spring	
63	S	75.2	87.1	64.8	129.0	45.0	106.7
64	U	12.2	13.7	10.9	16.8	18.5	23.1
65	S	10.7	9.9	11.2	12.4	14.0	13.0
66	U	73.2	64.3	80.8	83.1	68.1	91.4
67	U	21.6	20.6	22.6	33.8	10.9	55.4
68	S	21.1	9.9	31.0	6.4	11.7	22.6
			1966			Summer	
69	S	26.9	21.8	31.5	17.5	12.4	17.5
70	U	56.6	54.9	58.2	53.8	24.1	46.2
			1968			Spring	
95	U	49.3	43.2	55.4	36.8	37.3	55.9
96	S	40.9	31.0	50.8	54.1	28.7	59.2
97	S	3.6	1.8	5.6	.5	2.0	6.1
98	U	19.8	12.4	27.2	9.1	22.1	14.5
99	U	31.0	18.0	43.9	18.3	25.1	24.9
100	S	65.0	42.4	87.9	25.9	48.0	62.7
			1968			Summer	
101	U	29.2	18.5	38.4	4.6	36.1	18.0
102	S	62.5	45.5	79.5	46.5	46.2	79.0
103	U	15.7	4.8	26.7	2.0	10.2	14.5
104	S	1.8	0.0	3.8	0.0	1.0	1.0
			1968			Summer	
105	S	17.0	11.2	22.6	21.1	9.7	17.8
106	U	18.5	7.9	29.2	.3	11.2	16.8
107	S	23.4	24.4	22.4	67.3	21.6	37.6
108	U	28.4	26.4	30.5	32.3	35.3	30.5
			1968			Autumn	
109	S	1.3	1.3	1.5	0.3	5.8	2.5
110	U	3.0	1.0	5.1	8.9	19.1	5.1
111	S	60.5	46.5	74.4	45.7	41.1	76.7
112	U	56.1	56.9	55.1	112.8	26.7	91.2
113	S	82.5	63.5	101.3	72.1	62.0	113.8
114	U	35.8	27.9	43.4	52.1	33.0	102.6
115	S	72.4	46.5	98.3	76.5	42.2	115.8
116	U	55.9	35.8	75.9	65.5	30.7	100.3
			1968			Winter	
117	U	26.7	18.8	34.5	56.4	15.5	68.1
118	S	58.9	27.7	90.4	1.8	57.4	52.8
119	S	27.7	20.1	36.3	41.1	29.5	72.9
120	U	138.9	103.1	170.4	110.2	83.6	162.6
121	U	13.5	10.2	16.3	26.2	14.7	45.0
122	S	33.8	19.3	46.5	38.1	10.4	65.0
			1968			Spring	
123	S	67.1	38.9	91.9	38.6	41.1	72.6
124	U	45.7	14.2	73.2	9.4	31.8	44.2
125	U	67.3	44.2	87.6	54.4	25.4	111.5
126	S	60.7	40.4	81.0	59.9	38.9	77.0
127	U	84.6	48.5	120.4	43.4	51.6	82.3
128	S	93.0	53.1	132.8	53.8	70.4	112.8
			1968			Summer	
129	U	72.1	40.4	99.6	35.1	53.6	76.5
130	S	36.6	16.8	56.4	5.3	35.8	20.3
131	U	14.0	17.3	10.7	12.2	15.0	17.3
132	S	19.1	11.7	27.4	.3	16.5	12.2
133	S	10.4	5.6	15.7	3.8	3.3	10.7
134	U	35.3	28.2	43.2	33.5	14.5	39.1
135	S	38.1	44.7	30.2	57.4	26.4	32.3
136	U	131.6	130.0	133.4	151.1	100.8	136.4
			1970			Autumn	
171	U	9.7	3.0	15.2	4.8	7.1	17.8
172	S	13.2	9.4	16.5	7.9	5.8	21.1
173	S	99.8	126.2	77.0	36.6	79.8	21.8
174	U	27.4	14.5	38.9	7.6	18.3	35.1
175	S	8.9	3.3	13.7	2.8	3.6	14.7
176	U	93.0	62.7	119.4	93.0	46.7	136.1
177	U	43.4	25.7	58.9	29.0	20.6	53.1
178	S	21.8	14.0	28.7	33.0	8.6	62.2
			1970			Winter	
179	S	10.7	6.1	15.5	1.3	9.7	22.9
180	U	43.7	59.9	29.2	46.7	43.9	59.2
181	S	86.1	59.7	109.0	107.7	42.4	139.2
182	U	84.6	56.6	109.2	50.5	48.3	93.2
183	U	53.6	29.5	77.7	62.0	38.6	101.9
184	S	64.3	41.4	84.1	56.1	59.9	82.5
185	S	55.6	27.4	80.5	20.3	57.2	70.9
186	U	154.4	152.4	156.2	239.3	91.4	199.1
			1970			Spring	
187	S	125.5	67.8	176.0	69.6	77.0	162.3
188	U	6.4	9.1	3.8	0.0	4.8	1.5
189	S	25.9	14.7	35.8	24.4	16.3	31.5
190	U	62.5	34.5	87.1	35.1	47.2	73.9
191	S	36.1	29.7	41.9	31.0	57.9	40.1
192	U	54.4	60.2	49.3	62.5	62.7	60.7
193	S	1.3	.5	2.0	1.3	.5	2.3
194	U	39.1	23.4	53.1	15.5	22.1	34.3

6. Operation

a. Continuity

The operational years had actual durations as follows:

1964 13 May 1964–23 December 1964
1966 29 December 1965–21 December 1966
1968 14 September 1967–26 February 1969
1970 19 February 1970–7 December 1970.

During these periods the operation was continuous except that a total of 191 days were cancelled (and the rainfall on those days was excluded from analysis) for reasons specified in the design of the experiment.

b. Cloud conditions

Suitable clouds were seeded for 361 h on 202 days out of 1216 operational (i.e., uncancelled) days. Clouds were predominantly cumuliform on 48 of the seeded days, statiform on 69 and mixed on 85.

In addition, clouds were observed to be suitable on 211 days during unseeded periods. On 31 days in seeded periods, clouds were observed to be suitable but were not seeded because the wind was blowing from the target toward a control area, and on 3 days clouds were seeded but the days were subsequently cancelled because of excessive rainfall gradients.

Most of the seeding was carried out in cloud at a temperature of about −8°C. Airframe icing was usual and often severe; it occurred for about three-quarters of the seeding time.

The instructions to air crews were the same throughout; nevertheless, the seeding time per year progressively increased. In the four operational years it was 24, 30, 181 and 128 h (or 3.2, 2.5, 10.7 and 14.2 h seeding per month). The increase probably reflected the increasing skill of crews in this difficult area, and the provision of a better aircraft, as well as changes in the incidence of suitable clouds; however, as the cloud suitability was assessed from the seeding aircraft it is difficult to determine the relative influence of these factors.

c. Rainfall conditions

Rainfall during three of the four operational years was above normal, especially in the target area. This is shown in the following table giving the rainfall for the part of the year during which the experiment was conducted as a percentage of the mean value for the same part of the year for 1954 to 1963, when there was no seeding. "Control" refers to the mean rainfall in the north and south control areas.

Year	Target area	Control
1964	142%	127%
1966	95%	93%
1968	140%	129%
1970	137%	115%

7. Period rainfalls

Rainfalls (mm) for each period of 10–18 days are given in Table 1. Areas are indicated as follows: target area T, western half of target area TW, eastern half of target area TE, north control area NC, south control area SC and northwest control area NWC. The column headed S/U indicates whether each period was seeded or unseeded. There were 12, 14, 16 and 12 period pairs in autumn, winter, spring and summer.

8. Rainfall totals

Rainfall totals for each area for the four operational years are given in Table 2 for the seeded and unseeded periods.

The totals are subdivided by seasons, but they do not reflect the relative rainfall in the seasons because the operational years contained about 3 autumns, 4 winters, 4.5 springs and 3.5 summers.

9. Statistical analysis

The main objectives of the analysis were to investigate whether cloud seeding had any effect on the period rainfall in the target area, and if so to estimate the magnitude of the effect. Two approaches were made, a simple double-ratio analysis, such as has been used in previous Australian experiments, and a regression analysis. The null hypothesis in both cases was that seeding had no effect on period rainfalls. The regression analysis also enables an approach to be made to other questions such as the variation of the results with the average meteorological conditions in a seeded period.

a. Double-ratio analysis

The results of this type of experiment can be presented in the form of a double-ratio (DR) such as T/C (seeded)/T/C (unseeded), i.e., the ratio of the rainfall in a target area to that in a control area during seeded periods divided by the similar ratio during unseeded periods. The expected value of the DR is close to 1.00 if seeding has no effect. In an experiment of

TABLE 2. Rainfall totals (mm).

Season	TW	TE	NC	SC	NWC
Autumn					
Seeded	624	424	371	365	603
Unseeded	601	362	502	379	760
Winter					
Seeded	733	388	579	428	899
Unseeded	825	568	912	484	1199
Spring					
Seeded	1018	542	610	558	971
Unseeded	876	496	536	500	821
Summer					
Seeded	370	225	259	233	305
Unseeded	566	377	364	352	458

TABLE 3. Tests of significance of seeding effect.

		Regression analysis						
		No transformation			Cube-root transformation			
Season	Double-ratio analysis	F-test	F-test with pooled residuals	Permutation test	F-test	F-test with pooled residuals	Permutation test
Autumn							
TW	0.06	0.04	<0.01	0.04	0.17	0.03	0.05
TE	0.01	<0.01		0.07	0.02		0.12
Winter							
TW	0.2	0.25	0.08	0.19	0.17	0.05	0.08
TE	0.6	0.47		0.38	0.35		0.34
Spring							
TW	0.5	0.98	0.98	0.96	0.20	0.42	0.20
TE	0.6	0.98		0.96	0.91		0.95
Summer							
TW	0.5	0.80	0.93	0.64	0.83	0.76	0.76
TE	0.98	0.04		0.02	0.10		0.12

Note: F-test with pooled residuals is not valid for TE.

sufficient length the DR provides an estimate of the factor by which the mean rainfall has been increased by seeding: the DR is positively biased but empirical studies show that in this experiment the bias for a season is less than 2%. The DR will underestimate increases due to seeding if they persist into unseeded periods. Significance levels have been calculated for each DR by a permutation test using 4000 different re-randomizations. These significance levels are given as column 1 of Table 3.

Double ratios for target east were based on $\frac{1}{2}$(NC+SC) as originally intended, and for target west on $\frac{1}{2}$(NWC+SC) using the better correlations thus made available. It would of course be possible to undertake more complex analyses of the same general type. For example, the three control areas could be used simultaneously, thus improving correlations further and making some allowance for the effects of rainfall gradients. However, this is done better by the regression analysis presented below. The simple double ratio is used because it is traditional.

b. *Regression analysis*

1) THE MODEL

For each period, estimates of the target rainfall were provided by linear regression on the three control rainfalls and on four seeding variates, for comparison with the measured target rainfall. The model used was as follows:

$$\mathrm{XT}=b+d_1\mathrm{PC1}+d_2\mathrm{PC2}+d_3\mathrm{PC3}+e_0s+e_1s\mathrm{PC1}+e_2s\mathrm{PC2}+e_3s\mathrm{PC3},$$

where XT is the estimated target rain and b a block constant which has a separate value for each period pair. The next three terms allow for natural rainfall relationships between the target rainfall and the principal components of the control rainfalls (numerical values of which are similar to those of the space mean control rainfall and two rainfall gradients between areas). The last four terms allow for seeding effects which may vary with control rainfalls: s is a seeding indicator which has a value of 0.5 in each seeded period and -0.5 in each unseeded period. The coefficients, of course, have different values for the four seasons and the east and west halves of the target area.

We did not know in advance how the seeding effect would vary with control rainfall. This relatively complicated model was chosen because it was flexible enough for a range of possible effects.

2) SIGNIFICANCE TESTING

The null hypothesis is that seeding had no effect on period rainfalls, i.e., the four regression coefficients e_0–e_3 are all zero. The residual sum of squares (RSS) from the regression equation was compared with that from a simpler model omitting the last four terms which refer to seeding effects. The significance of the improvement of RSS made by including the four seeding terms was estimated in the usual way from the F-distribution. (This was done both using the residuals for the season concerned, and in the case of target west using pooled residuals over the four seasons, a procedure shown by Bartlett's test to be appropriate for this area but not for target east.)

This F-test is valid subject to various assumptions being met, e.g., homoscedasticity and normality of residuals. There were too few degrees of freedom for error (5, 7, 9 and 5 in autumn, winter, spring and summer, respectively) to enable these assumptions to be checked adequately, so the significance of the observed F-ratio was also tested by a permutation test, in which the regression analysis was repeated 1000 times, each time with a new random series and each leading to a new ratio of the two RSS.

Significance tests based on the F-ratio for this versatile model are appropriate for a wide range of types of seeding effect, but at some sacrifice of sensitivity. A test appropriate to a specific type of effect (e.g., multiplicative) might have been more sensitive, but only if the effect proved to be of the type assumed. We preferred the tests described above because they allowed for the possibility that seeding effects might vary with the control rainfalls in ways which we could not anticipate.

3) Transformations

The period rainfalls have a skew distribution which can be approximately normalized by something between a square-root and cube-root transformation. In this type of analysis, transformations are customarily selected for the purpose of improving the validity of the assumptions on which the F-test is based, e.g., homoscedasticity of residuals. However, as mentioned above, we cannot adequately check these assumptions (and so select the best transformation) since we have insufficient degrees of freedom for this purpose: there are not enough estimated residuals and these are far from independent of each other. The analysis was therefore performed with cube-root and square-root transformations and with no transformation. Results were very similar for all three, and those for the cube root and untransformed analyses are presented.

The model has the same mathematical form for the transformed and untransformed analysis but, of course, the meanings of the individual terms differ in detail. In the case of the transformed analysis, back-transforming is needed in order to present the results in terms of rainfall: bias correction was performed by the method of Neyman and Scott (1960).

c. Results

1) Significance

Significance levels are presented in Table 3. Those for target east in autumn are grouped around 0.02; those for target west in autumn and for target east in summer around 0.04, and those for target west in winter around 0.01.

2) The size and nature of the effect

In analyzing the results of cloud-seeding experiments it is customary to assume the nature of the effect of seeding and then to calculate its magnitude. The usual assumption has been that the effect is multiplicative and the results are accordingly expressed as, for example, a 20% increase over the rain that would have fallen naturally. Alternatively, the effect may be assumed to be additive, in which case the result is expressed as, e.g., a 2 mm rainfall increase per seeded day.

Table 4. Estimates of seeding effect.

Season	Double ratio	From regression analysis* μ	λ
Autumn			
TE	1.40	1.30	1
TW	1.23	1.09	10
Winter			
TW	1.13	0.74	19
Summer			
TE	0.88	0.89	−1

* Values of combined multiplicative effect μ and additive effect λ are means of those for untransformed and cube-root-transformed analyses. λ is in millimeters per seeded period.

One estimate of the multiplicative type is the double ratio. Values of double ratio for the target-season combinations mentioned in the previous section are given in column 1 of Table 4.

The regression analysis enables us to avoid choosing between a multiplicative or an additive effect; instead, we can ask the data to indicate whether the effect is additive or multiplicative, or a combination of the two. The analysis provides, for each seeded period, an estimate XTu of the rain that would have fallen in the target area if the seeding had no effect. These estimates can be plotted as abscissas against the measured target rainfalls Ts as ordinates, and a line fitted to the points. A smoothed estimate of the seeded rainfall XTs for any natural rainfall XTu is then given by

$$XTs=\lambda+\mu XTu.$$

If seeding had no effect, λ should be near zero and μ should be near 1.0. With a multiplicative increase, λ should still be near zero but μ should exceed 1.0. An additive increase would be indicated if μ was near 1.0 but λ exceeded zero. (In other words, if there is no effect the line fitted to the points should pass near the origin at 45°. A multiplicative increase should tilt it up, and an additive increase should move it up without tilting it.)

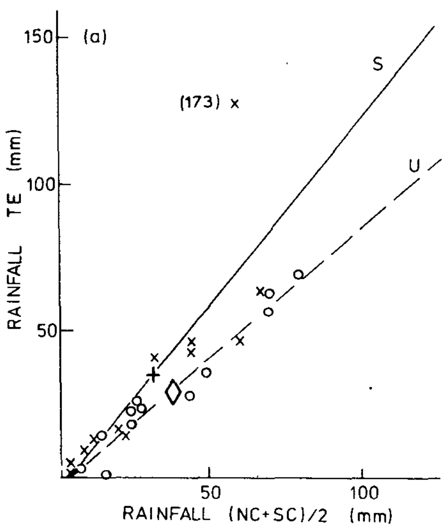
Values of μ and λ, giving a combined multiplicative and additive representation of the effects of seeding, are given in Table 4. There was little difference between the values on the transformed and untransformed basis so the mean of the two is given.

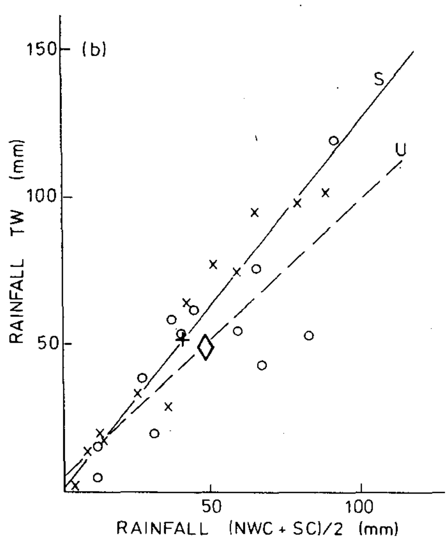
For target east in autumn, μ is 1.30 and λ is close to zero, i.e., the effect of seeding is estimated as a roughly multiplicative increase of ~30%. In target west the effect is estimated as a multiplicative increase of 9% together with an additive increase of 10 mm per period.

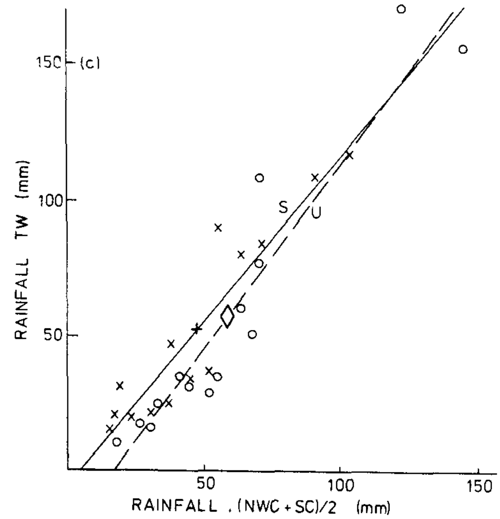
For target west in winter, if the effect is real it is estimated by the μ, λ representation as a 19 mm increase in dry periods decreasing to zero as the expected value rises to 75 mm. If the effect for target east in summer is real, a roughly multiplicative decrease of about 12% is indicated.

10. Supporting evidence

In the target/season combinations noted in Section 9c1 there were differences between the seeded and unseeded period rainfalls. The significance calculations indicate (Table 3) that even for the "best" of these (target east in autumn) there was one chance in 50 of such a large difference occurring if seeding had no effect. We must consider whether to accept that the difference was indeed caused by the seeding. Ideally we should be assisted by auxiliary statistics, showing, for example, the conditions in which the seeding effects occurred, together with results of measurements of the physical processes by which the release of ice nuclei leads to rain falling in the target area. Unfortunately, in this experiment (the design of which was finalized in 1964) provision was not made for extensive physical and meteorological measurements, and the means to make them were not available at that time. (In particular, we had no instrumented aircraft capable of flying safely in icing clouds over the rugged terrain of the target area.) However, there is some auxiliary statistical information which is examined below.







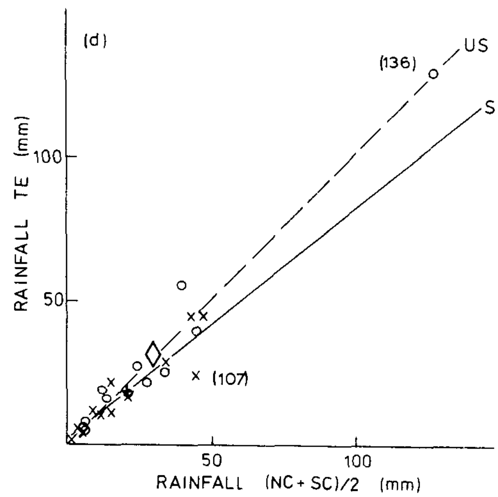


FIG. 2. Scatter diagrams of target and control period rainfalls: (a) target east, autumn; (b) target west, autumn; (c) target west, winter; (d) target east, summer. (O) seeded; (X) unseeded; (+) mean seeded; (◇) mean unseeded.

a. Scatter diagrams

Scatter diagrams of target and control rainfalls appear as Figs. 2a–2d, using controls as described in Section 9a.

For target east in autumn there is a clear separation between the seeded and unseeded points both for wet and dry periods. No obvious imbalances due to unfortunate randomization appear. Impressions tend to be dominated by one period (173) but even if this is disregarded, the separation of points is still reasonably apparent.

For target west in autumn, rainfalls are more scattered in unseeded periods than in seeded periods. It is difficult to see how seeding could have caused such an effect.

For target west in winter, there is no evidence of separation between seeded and unseeded rainfalls in wet periods, but for periods with $\lesssim 70$ mm control rainfall the separation is clear.

For target east in summer, there was one exceptionally wet unseeded period (No. 136). In the rest of the periods the rainfall was relatively light and the difference between seeded and unseeded periods appears to derive mainly from one seeded period (No. 107).

b. Exceptional periods

1) In period 173 (autumn) Fig. 2a suggests a rainfall increase in target east. Rainfalls were TE 126, TW 77, NC 37, SC 80, NWC 22 mm. (For notation see Section 7.) Most of the rain was associated with a depression which passed west to east along the Bass Strait north of Tasmania. Deep stratiform clouds approached from the east. Seeding took place for 3 h 35 min at 4600 m, -8°C, in conditions of heavy airframe icing, indicating abundant supercooled water. The cloud top was not observed but was believed to be several degrees colder than -8°C. These are the circumstances in which seeding is thought to be effective, suggesting that an increase of rain could have been caused in target east.

2) In period 107 (summer) Fig. 2d suggests a rainfall decrease in target east. Rainfalls were TE 24, TW 22, NC 67, SC 22, NWC 38 mm. Almost all the rain fell on one day. Over and upwind from the target area there was altostratus cloud with base 3700–4300 m, about 0°C, tops 4900–6400 m, -10°C. It was marginally suitable for seeding in parts and was seeded for 36 and 40 min on two flights. It was not thought likely to contribute much rain, being mostly too shallow. Clouds over the north and northwest controls were not observed but were believed to be similar to those over the target area when the aircraft was flying. An occluded front lay east to west a few miles north of the north coast: it was not observed but is thought likely to have been associated with cumulonimbus clouds which could have drifted into the north and northwest control areas during the night. It is difficult to believe that seeding thin, high-based clouds could have caused a substantial rainfall reduction in target east.

TABLE 5. Rainfall data (mm) on seeded days and on days in unseeded periods when suitable conditions were observed.*

Cloud type	TE autumn	TW autumn	TW winter	TE summer
All clouds				
Rainfall totals				
Target seeded	316	438	477	157
Target unseeded	249	410	663	332
Control seeded	252	319	347	158
Control unseeded	284	333	580	309
Double ratio	1.43	1.11	1.20	0.92
Cumulus				
Rainfall totals				
Target seeded	26	58	151	52
Target unseeded	57	88	201	45
Control seeded	24	44	102	33
Control unseeded	66	86	133	29
Double ratio	1.26	1.28	0.98	1.02
Stratiform				
Rainfall totals				
Target seeded	141	148	145	19
Target unseeded	127	180	218	213
Control seeded	90	98	115	14
Control unseeded	139	151	264	213
Double Ratio	1.71	1.26	1.52	
Mixed				
Rainfall totals				
Target seeded	149	232	181	86
Target unseeded	65	142	244	74
Control seeded	138	177	130	111
Control unseeded	79	96	183	67
Double ratio	1.32	0.88	1.04	0.70

* Control for target east is ½(NC+SC) and for target west ½(NWC+SC).

TABLE 6. Numbers of seeded days and of days in unseeded periods when suitable conditions were observed.

Cloud type	TE autumn	TW autumn	TW winter	TE summer
All clouds				
Seeded	41	41	58	27
Unseeded	48	48	66	41
Cumulus				
Seeded	7	7	11	6
Unseeded	11	11	16	9
Stratiform				
Seeded	14	14	24	7
Unseeded	18	18	27	17
Mixed				
Seeded	20	20	23	14
Unseeded	19	19	23	15

c. Daily rainfalls

The main results of the experiment, presented above, are based on measurements of rain for each period of 10–18 days' duration. Rainfall measurements were made for each day, and on each "suitable" day (i.e., seeded days and days in unseeded periods when suitable clouds were observed) the flight crews reported on the clouds they observed. These reports can be used for stratification of the daily data. The daily rainfall data are not of the same quality as those for periods, e.g., because 2-day totals were sometimes given. Further, the use of daily

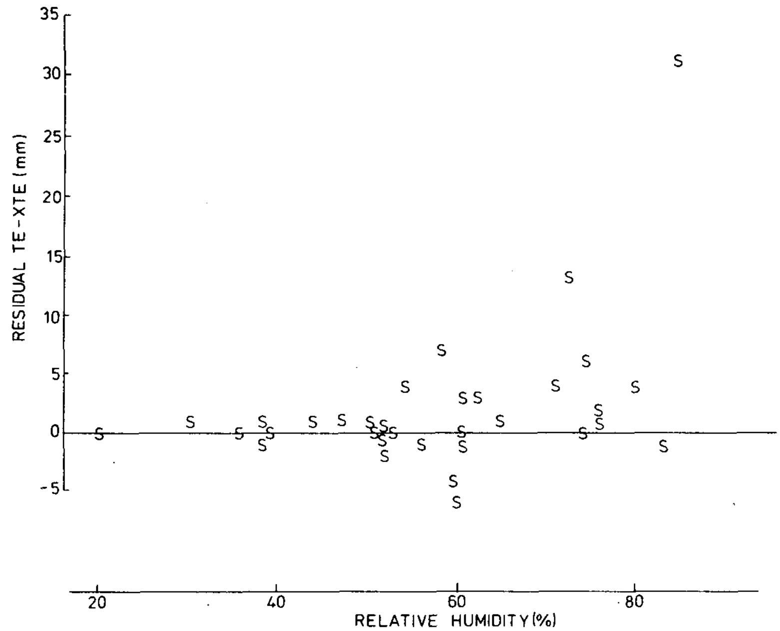


FIG. 3. Sample plot of estimated seeding effect for the day against a measure of ambient conditions (in this case relative humidity between the 0 and −10°C levels).

data is open to the possibility of bias. (The operating crews were trained to use the same criteria in seeded and in unseeded periods for declaring a day suitable and for describing the clouds encountered, but at least in principle it is possible that they used different criteria. Such behavior, of course, would have no effect on analysis by the period.) Nevertheless, if the effects of seeding are real and they occur mostly on the same day, one might expect that estimates of the effects based on rainfalls for "suitable" days would be greater than those based on period rainfalls.

A digest of the data derived from daily rainfall measurements appears as Table 5. We present rainfall totals in the various categories, together with "results" in the simple form of double ratios, using controls as in Section 9a. (The numbers of days involved are shown in Table 6.)

The first section of Table 5 is for all suitable days, when the rainfall totals are about two-thirds of those quoted in Table 2 for all days of the experiment. Daily double ratios exceed those for the period data (Table 4) for target east in autumn and for target west in winter but not for target west in autumn nor for target east in summer.

Each suitable day was classified as cumulus, stratiform or mixed, according to the cloud type from which it was judged that most of the rain fell. Data for these three types of day are presented in Table 5. Rain totals in all categories are reasonably balanced as between seeded and unseeded days except for stratiform clouds in summer, when almost all the rain fell on unseeded days and no double ratio is shown. In other seasons results with stratiform clouds are good. We cannot tell what the effect would have been if more stratiform clouds had been seeded in summer.

For target west in autumn and for target east in summer, the negative results with mixed clouds are unexpected and do not appear consistent with those for cumuliform and for stratiform clouds separately. For target east in autumn and for target west in winter, results appear consistent in this respect.

d. Rainfalls on individual days

If seeding affects rainfall, one might expect that a series of plots of some measure of seeding effect for the day against various measures of meteorological conditions would reveal the circumstances in which seeding is most (or least) effective. Although the possibility of bias in daily data should be remembered, a clear and physically acceptable pattern emerging would nevertheless tend to support the statistical result in suggesting that there was a real effect.

For each target/season combination, the target rainfalls on suitable days in unseeded periods were regressed against the three control rainfalls, and the residuals of the target rainfalls on seeded days from this regression estimated the seeding effect. These residuals were plotted against the following quantities, values for which have been given in the annual reports [except for the last four categories which will be presented separately in an institutional report (Smith *et al.*, in preparation)]:

- The estimated value of target rainfall based on the unseeded regression

- Rainfall gradients between control areas (north/south and northwest/north)
- Height of freezing level relative to a normal value for the time of year
- Wind direction and speed at cloud height
- Cloud-top height and temperature
- Cloud-base height and temperature
- Showalter stability index
- Lapse rate −20 to −10°C, 10 to 0°C, 950 mb to 0°C
- Relative humidity −20 to −10°C, 10 to 0°C, 950 mb to 0°C
- Surface pressure.

A sample plot appears as Fig. 3, which suggests that seeding increases rain on days with high relative humidity between the 0 and −10°C levels. The rest of the plots will also be presented in the institutional report; they are also available on application to the authors. Too much should not be expected of these plots since values of all these quantities often change during the day, and attributing a representative value to a quantity which was only observed for part of the time is a very subjective process. Further, a few of the plots could be expected to show "apparent effects" due to chance processes even if seeding had no effect.

A preliminary inspection showed that recognizable patterns appeared on plots for days with stratiform clouds and similar patterns on days with mixed clouds, but there were no recognizable patterns on days with cumulus clouds. The following observations apply to days with stratiform or mixed clouds taken together.

1) RANDOMIZATION BALANCE

The randomization worked well in autumn, giving well-balanced seeded and unseeded samples in all respects examined. In winter this balance was not as good in two respects. First, there were nine suitable days when the wind at cloud height had an easterly component; all occurred in unseeded periods. We have no indications as to the effects of seeding on easterly days in winter. Second, there were six values of the expected daily rainfall in target east in winter greater than 15 mm; they all occurred in unseeded periods (two of them had east winds). Target west rainfalls in winter were quite well balanced in this respect. Finally, in summer the target east rainfalls were not well balanced since most stratiform clouds were not seeded.

TABLE 7. Credibility indications.

	TE autumn	TW autumn	TW winter	TE summer
Significance level	0.02	0.04	0.1	0.04
Scatter diagrams	+	−	+	−
Exceptional periods	+			−
Double ratios for suitable days	+	−	+	−
Consistency of daily results	+	−	+	−
Randomization balance	+	+	−	−
Conditions for success	+		+	−
Authors' opinion: should null hypothesis be rejected?	Yes	Possibly	Probably	No

Symbols: (+) Evidence increases authors' inclination to reject null hypothesis. (−) Evidence reduces authors' inclination to reject null hypothesis. No symbol, evidence has no effect.

2) TARGET EAST IN AUTUMN

The residual plots strongly suggest that seeding was most effective when natural rainfall was moderate or high, when the cloud-top height was greater than about 3000 or 4000 m, and with a warm, moist, unstable northwesterly air stream (perhaps also with easterly winds, but there were very few occasions). These indications are consistent with seeding having increased rainfall from deep prefrontal stratiform clouds.

3) TARGET WEST IN AUTUMN

The plots suggested (though not as clearly as in the previous case) that rain increases were associated with cold, southwest air streams.

4) TARGET WEST IN WINTER

The plots clearly suggested that rainfall increases were associated with natural rainfall $\lesssim 10$ mm day^{-1}, with cloud-top heights less than 3000 or 4000 m, cloud-top temperatures not below −14°C, with relative humidity high up to the −10°C level but low above it, and with cold southwest winds. This is consistent with seeding having increased rain from the relatively shallow stratiform or stratocumulus layers characteristic of postfrontal conditions. There were nine suitable days with east winds but they were all in unseeded periods so no indications were given.

5) TARGET EAST IN SUMMER

No indications whatever could be seen in the residual plots.

11. Authors reactions to evidence

The first purpose of presenting the evidence in the previous sections is to provide a basis for deciding whether or not to reject the null hypothesis, i.e., to accept that seeding had an effect on period rainfalls. The authors' reactions to this evidence are as follows.

The significance levels of around 0.02 for target east in autumn, 0.04 for target west in autumn and for target east in summer, and 0.1 for target west in winter suggest that seeding had some effect. However, we have subdivided the data into eight categories (for the four seasons and the eastern and western halves of the target area). Traces of significance might be expected to appear in some target/season combinations even if seeding had no effect, and allowance should be made accordingly when interpreting the observed significance

TABLE 8. Effect of omitting rain on cancelled days.

	TE autumn		TW autumn		TW winter		TE summer	
Overall assessment—null hypothesis	Rejected		Possibly rejected		Probably rejected		Not rejected	
Cancelled days	Omitted	Included	Omitted	Included	Omitted	Included	Omitted	Included
Target rainfall (mm)								
Total: Seeded	424	469	624	719	733	884	225	279
Unseeded	362	423	601	688	825	1108	377	446
Double ratio	1.40	1.35	1.23	1.24	1.13	1.12	0.88	0.85
Significance level of double ratio (one-sided)	0.01	0.01	0.06	0.05	0.2	0.16	0.98	0.99

levels. The authors consider that the supporting evidence should be studied, together with the significance levels, before a conclusion is reached as to whether the null hypothesis should be rejected.

The authors' opinions of the aspects presented are displayed in Table 7. The symbols + or − indicate that the evidence increases or decreases the authors' inclination to reject the null hypothesis.

The statistical result for target east in autumn receives solid support, and the authors reject the null hypothesis that seeding had no effect. The statistical result for target east in summer receives no support whatever, and the authors find the evidence for an effect of seeding quite unconvincing.

For target west in winter, the marginal statistical results receive good support. For target west in autumn, the statistical result is better but it receives very little support. In both these cases the authors consider that while there is some evidence that seeding may have affected rainfall, a firm conclusion would not be justified until results of further experimenting become available.

12. Conclusions

1) Strong evidence is presented that seeding increased rainfall in the eastern half of the target area in autumn. Such measurements as were made suggest that the increase occurred when deep, prefrontal stratiform clouds were seeded. There is evidence that increases were also caused in the western half of the target area both in autumn and in winter, probably when shallow postfrontal stratiform clouds were seeded; however, a firm conclusion in this case would not be justified.

2) In future experiments, provision should be made for an adequate series of measurements to lend credibility to the statistical results and to determine the physical conditions in which the seeding takes place.

APPENDIX

Days Omitted from the Experiment

As mentioned in Section 2d, in certain circumstances the experiment was suspended and the rain and other data for the whole day were omitted from the results. (The decision to do this was taken before the experiment began.) Conditions leading to suspension were as follows: (i) an exceptional imbalance between the north and south control areas, the criterion being that the rain in either area was at least 25 mm more than 10 times that in the other; (ii) when the wind at cloud height, as forecast by the Bureau of Meteorology, exceeded 70 kt (36 m s^{-1}) thus making aiming difficult; and (iii) when the aircraft was unserviceable or unavailable, or when the airport was closed or the crew were ill.

In addition, after the experiment started it became clear that when only one aircrew was available a regular rest day was necessary, so for much of the 1964 and 1966 seasons the experiment was suspended on Sundays. This became unnecessary subsequently as two crews were available. On Christmas Days the experiment was suspended.

The period length (see Section 2) was based on unsuspended days, except that days were cancelled for excessive rainfall gradient between control areas [(i) above] only when the final rainfall figures became available after the end of the year's operations, and were therefore ignored in determining the period length.

The numbers of days suspended for these reasons are noted below:

Cause of suspension	Number of days 1964	1966	1968	1970	Total
Rainfall gradient	3	3	4	1	11
Forecast wind >36 m s^{-1}	6	1	1	2	10
Crew ill	4	1	3	0	8
Rest day	12	34	2	0	48
Aircraft unserviceable or unavailable	22	41	42	4	109
Airport closed	0	1	2	2	5
Total:	47	81	54	9	191

The decision to omit these days was taken before the experiment began, so if they were included the results would not be valid. Nevertheless, a check has been made as to whether omitting the rain on these days had an appreciable effect on the results of the experiment. Data appear in Table 8, for an analysis similar to that of Section 9a, for those target/season combinations where the statistical analysis showed significant or possibly significant results (Section 9c1). Cancelled days contributed about 15% of the rainfall. It makes little difference to the results whether they are included or not.

REFERENCES

Bethwaite, F. D., E. J. Smith, J. A. Warburton and K. J. Heffernan, 1966: Effects of seeding isolated cumulus clouds with silver iodide. *J. Appl. Meteor.*, **5**, 513–520.

Bowen, E. G., 1966: The effect of persistence in cloud-seeding experiments. *J. Appl. Meteor.*, **5**, 156–159.

Neyman, J., and E. L. Scott, 1960: Correction of bias introduced by a transformation of variables. *Ann. Math. Stat.*, **31**, 643–655.

Smith, E. J., 1967: Cloud-seeding experiments in Australia. *Proc. Fifth Berkeley Symp. Mathematical Statistics and Probability*, University of California Press, 161–176.

——, and E. E. Adderley, 1967: Cloud Seeding Experiment, Annual Report, Tasmania 1964. CSIRO Div. Radiophys., Rep. RPR 166, 77 pp.

——, and ——, 1969a: Cloud Seeding Experiment, Annual Report, Tasmania 1965–1966. CSIRO Div. Radiophys., Rep. RPR 168, 188 pp.

——, and ——, 1969b: Cloud Seeding Experiment, Annual Report, Tasmania 1967–1968. CSIRO Div. Radiophys., Rep. RPR 169, 102 pp.

——, and ——, 1971: Cloud Seeding Experiment, Annual Report, Tasmania 1969–1970. CSIRO Div. Radiophys., Rep. RPR 174, 55 pp.

——, ——, L. Veitch and E. Turton, 1971: A cloud-seeding experiment in Tasmania. *Preprints Int. Conf. Weather Modification*, Canberra, Amer. Meteor. Soc., 91–96.

——, J. A. Warburton, K. J. Heffernan and W. J. Thompson, 1966: Performance measurements of silver-iodide smoke generators on aircraft. *J. Appl. Meteor.*, **5**, 292–295.

——, L. G. Veitch, D. E. Shaw and A. J. Miller, 1977: A Cloud Seeding Experiment in Tasmania. Final Report—Part 1: Description and main results. CSIRO Div. Cloud Phys., Rep. No. CP 183, 134 pp.

Warner, J., and S. Twomey, 1956: The use of silver iodide for seeding individual clouds. *Tellus*, **8**, 453–459.