A Cloud-Seeding Experiment in New England, Australia

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ABSTRACT

From 1958 to 1963 an experiment was conducted in the New England region of Australia, in which clouds were seeded with silver iodide smoke released from an aircraft. Clouds over two areas were seeded, with random choice of area. Rainfall measurements in the two areas suggest that seeding increased the rainfall during the first year, but no net changes in rainfall could be detected in subsequent years. The seeding appears to have increased the variability of rainfall.

1. Introduction

A series of experiments has been conducted in Australia to determine the amount by which seeding clouds with silver-iodide smoke, released from an aircraft, can increase precipitation in representative areas. Reports of the first two experiments, in the Snowy Mountains and in South Australia, have been published (Smith, Adderley and Walsh, 1963; Smith, Adderley and Bethwaite, 1963a). In the first, it was considered probable that cloud-seeding had caused an increase in precipitation, but the significance level was marginal. In the second, there was no evidence of a net precipitation change due to seeding.

A third experiment in this series was performed in New England, Australia, during 1958 to 1963 inclusive. The day-to-day operations have been described in six annual reports (Smith, Adderley and Bethwaite, 1963b, 1963c, 1963d, 1963e, 1963f, 1964). This paper describes the experiment and presents the general conclusions.

2. Design of experiment

The design of the experiment was very similar to that of the South Australian experiment (*loc. cit.*) and was constant throughout, except for the first year; the differences in the first year are described in Section 3. There were two areas, each of about 2000 square miles, as shown in Fig. 1. Time during the experiment was divided into periods of about 12 days, and during the whole of one period any suitable clouds over one area were seeded. Periods were arranged in pairs, and the rainfall for each period in both areas was measured. A series of random numbers (Fisher and Yeates, 1948) determined the area to be seeded during the first period of a pair; during the second period the other area was seeded. The experiment was designed to determine whether there was a difference in the relationship between north and south area rainfalls according to which area was seeded, from which inferences might be drawn as to the results of seeding.

Rainfall was measured by the Commonwealth Bureau of Meteorology, using 106 gages in the north area and 145 in the south. Their positions are shown as spots in Fig. 1. All were standard 8-inch gages read at 0900 hours local time daily. Rainfall figures quoted below are the mean of the readings of all the gauges whose records are complete for the period, usually 90 per cent to 95 per cent of the total. Daily figures are for the full 24 hours and period figures are the total of all the daily figures of the period, whether any seeding took place or not.

The cloud-seeding "period" had an arbitrary minimum length of ten days, thereafter it was changed to the next period at 0900 hours on the first day on which the Bureau of Meteorology forecast no rain in the areas. An arbitrary maximum period length of 25 days was introduced in 1959 as it was found that summer forecasts sometimes included a long series of "possible afternoon storms."

The experiment was suspended during periods of excessive rainfall; the New South Wales Department of Agriculture appointed a "Referee" who was familiar with the rainfall requirements of the areas but did not know which area was seeded at anytime. When in his opinion further rain would have been detrimental to the interests of the inhabitants he suspended the experiment. If this suspension occupied more than 5 days of any period, the period was cancelled. The experiment was also suspended in any period when no aircraft was available for more than five days, and during the wheat harvest, which usually took place between about 7 November and 7 January.

3. Differences in first year's operation

The design described in Section 2 applied during all years of the experiment except the first, when there were two differences. The choice of which area was to be seeded in any period was according to a random series, as distinct from the random pairs used subsequently. Secondly, the full network of rain gages was not ready for use until the 1959 season, so the 1958 rainfall figures are the averages of all the gages (65 in the north area and 66 in the south area) which were available. Their locations are shown as circles in Fig. 1; all were on the same sites as gages used in subsequent years. Some of them were of smaller diameter (5 inch) than the 8-inch gages used subsequently.

4. Area of operations

The two experimental areas are shown in Fig. 1 and their position in Australia in Fig. 2. They are situated about 200 miles north of Sydney and 100 miles from the sea; they lie on the western slopes of the Great Dividing Range. They are generally similar in respect of climate, topography and orography. The western side of both areas is relatively flat at an elevation of about 1500 ft while the eastern side is hilly, sloping up to the crest of the range at about 4000 ft. Most of the areas are fairly densely settled, the principal product being wheat.

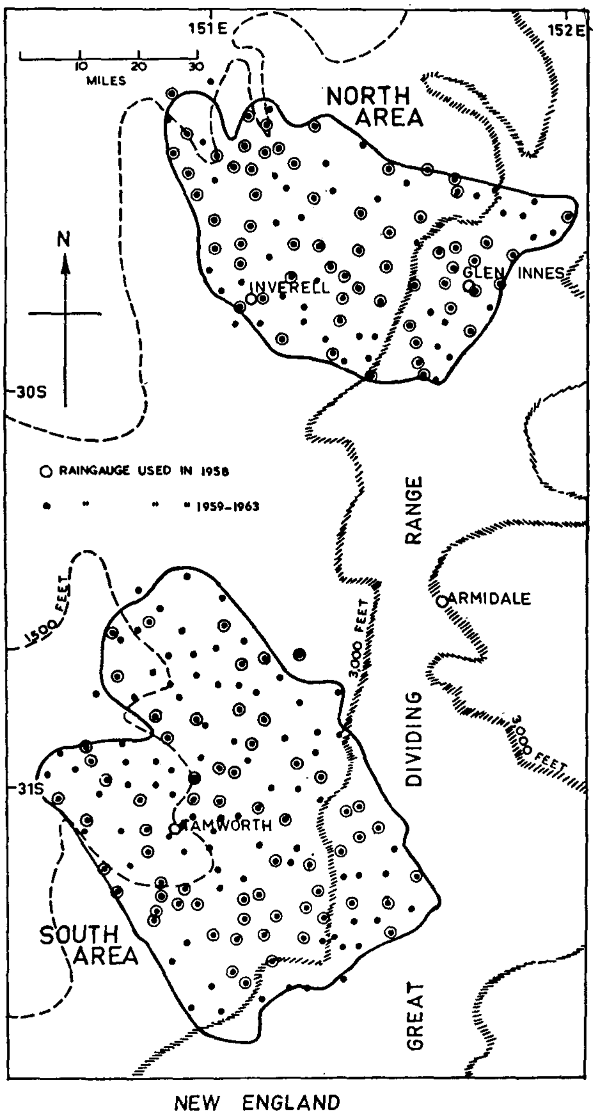

FIG. 1. The experimental areas.

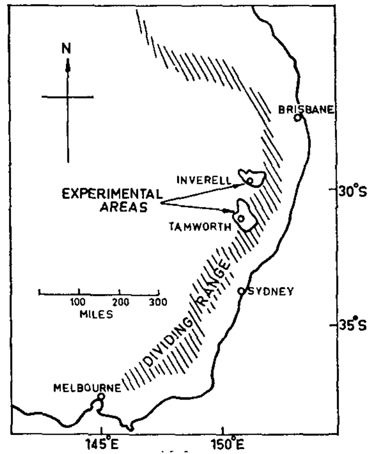

FIG. 2. Location of the areas.

5. Climate

The average annual rainfall in the western parts of the experimental areas is about 25 inches, with one and one half inches and four rain days per month in winter and two inches and seven rain days per month in summer. In the higher ground in the eastern parts of the areas the equivalent figures are 35 inches, two inches, six days, four inches and 10 rain days, respectively. There is very little snow. The limited pluviograph data available suggests that rainfall has a pronounced maximum in the afternoon and early evening, particularly with the heavier falls.

High pressure systems pass from west to east with a period of about six days, their centers passing to the north of the areas on the average in winter and to the south in summer. Low pressure systems also pass from west to east, usually to the south of the experimental areas, their longitudes being between those of the highs. Cold fronts often extend northwards and northwestwards from the lows.

In wintertime much of the rainfall of the area is associated with the cold fronts when reinforced by orographic uplift. In summer, instability showers form in north-westerly airstreams, often preceding the arrival of a front.

Occasional tropical depressions may occur at any time of year, being most frequent in autumn. They usually arrive from the north, bringing heavy rain from stratiform clouds, often with easterly winds.

6. Equipment

For most of the time a single aircraft was employed, two being used for short periods when available. They included a Beechcraft Twin Bonanza from 1959 to 1963, a Cessna 310 in 1958, and for brief periods an Avro Anson and a Lockheed Hudson. All had full radio and navigation equipment and all but the Anson were equipped for flying at night and in cloud. Silver iodide smoke was generated by burners on the aircraft's wings. The equipment and its performance have been described by Smith *et al.* (1958); the ice-nucleus output per burner is 3×10^{13} per sec active at −17C and 1.5×10^{11} per sec active at −10C, the number of effective nuclei decreasing by a factor of 10 in 40 to 60 min on exposure to daylight. During 1959 a slightly different type of burner was used; the ice nucleus output being sensibly the same.

7. Operational procedure

The operational procedure was similar to that used in the experiments in the Snowy Mountains and South Australia. When suitable clouds appeared over or approached the target area for the period, the objective was to seed as high a proportion of them as was possible for one aircraft and one crew, with occasional assistance from a back-up aircraft or crew when available.

Clouds were regarded as suitable for seeding if their tops contained supercooled water at a temperature below −5C, and they were deep, durable and compact, without much included clear air space, and with a life exceeding 30 min. In case of doubt as to the suitability of clouds they were seeded.

Cumulus clouds were usually seeded at base, wherever they occurred in a seeding area, derived from the target area by allowing for the wind drift of the clouds between seeding and the rain reaching the ground. The time interval used was 30 minutes, plus one minute per thousand feet terrain clearance of the bases. Stratiform clouds were usually seeded by making repeated passes, at about the −5C level, along a seeding track about 50 miles long oriented across wind and displaced upwind from the target area using a time interval of 45 min plus $1\frac{1}{2}$ min for each 1000 ft terrain clearance. Sometimes the aircraft could not reach the −5C level when seeding stratiform clouds; for each 1000 ft below the −5C level at which seeding took place the time interval was increased by 15 min.

8. Weather conditions encountered

Rainfall in the experimental areas during the operational time of January to October varied from 17 inches in 1958 to 25 in 1963. Historical records are only available for a few gages, but judging by these the 1958 rainfall was slightly below average while the 1963 rainfall was near the upper quartile.

Some statistics relevant to the clouds in the target area on seeded days are presented in Table 1. The seeded days were divided into three categories, cumulus, stratiform and indeterminate, according to the predominent type of cloud which was seeded. Cloud top and base

TABLE 1. New England: cloud characteristics on seeded days.

		1958			1959			1960			1961			1962			1963			1958 to 1963		
		C	S	I	C	S	I	C	S	I	C	S	I	C	S	I	C	S	I	C	S	I
Top temperature (deg C)	Median	−12	−10	−7	−13	−11	−9	−13	−10	−8	−10	−7	−6	−11	−10	−9	−9	−9	−4	−11	−10	−7
	Quartiles	−6, −15	−6, −11	−6, −10	−8, −16	−10, −14	−7, −13	−8, −16	−8, −14	−6, −10	−6, −13	−6, −10	−4, −8	−8, −18	−7, −15	−5, −17	−2, −14	−6, −13	−4, −6	−7, −15	−7, −13	−6, −10
Top height (1000 ft)	Median	17	14	14	15	14	15	18	14	13	15	13	12	16	16	14	16	17	13	16	14	14
	Quartiles	12, 20	13, 15	12, 16	14, 18	12, 16	13, 17	14, 20	13, 15	9, 15	12, 18	12, 16	11, 14	13, 18	14, 18	12, 17	13, 18	15, 18	12, 14	13, 18	13, 16	11, 15
Base temperature (deg C)	Median	7	−1	7	11	−1	8	8	−3	3	6	−1	4	9	−1	6	12	6	8	9	−1	5
	Quartiles	12, 4	3, −3	10, 3	16, 3	1, −4	10, −2	12, 5	1, −7	8, 0	11, 5	7, −3	7, 3	14, 6	1, −3	8, 2	14, 10	8, 3	13, 4	13, 6	3, −3	10, 2
Base height (1000 ft)	Median	7	8	6	6	8	6	7	10	6	7	8	6	6	9	7	6	9	7	6	9	6
	Quartiles	5, 8	7, 10	5, 7	5, 7	5, 9	4, 8	6, 7	6, 12	4, 7	6, 8	6, 9	5, 8	5, 7	8, 12	6, 7	5, 7	7, 10	6, 8	5, 7	7, 11	5, 7
No. of seeded days		33	16	22	38	15	11	27	13	34	31	7	19	32	11	11	23	5	5	184	67	102
No. of hours seeded		77	41	56	96	54	38	83	25	105	56	25	37	56	23	23	27	14	7	395	182	266

C = Cumulus, S = Stratiform, I = Indeterminate.

TABLE 2. Cloud top temperatures on seeded days, by season (deg C).

		Spring SON	Summer DJF	Autumn MAM	Winter JJA
C	Median	−13	−10	−10	−11
	Quartiles	− 9 −15	− 4 −17	− 5 −14	− 8 −17
S	Median	−12	− 5	− 8	−11
	Quartiles	− 7 −14	− 5 − 6	− 5 −11	− 7 −15
I	Median	− 9	− 5	− 7	− 8
	Quartiles	− 8 −12	− 2 − 7	− 5 − 9	− 6 −12

heights and temperatures were measured by aircraft soundings in the seeded area; sometimes the aircraft could not reach cloud top in which case the height was estimated (with confirmation from commercial aircraft when available) and the temperature extrapolated from the sounding at 2C decrease per 1000 ft. The cloud top height is sometimes given in the original flight reports as "greater than" a certain height, usually when the aircraft climbed in stratiform clouds without reaching the top. In these cases the cloud tops have been assumed to be 2000 ft higher and 5C cooler than the given value, and are so recorded in Table 1. For this reason some of the heights of the tops of stratiform clouds may be underestimated. Sometimes there were two or more layers of stratiform cloud, the upper layer being seeded. In this case the figures quoted in Table 1 for the height and temperature of the bases refer to an arbitrary height such that a single continuous layer extending from the actual top to the quoted base would have a volume equal to that actually present. This was intended to allow for growth or reduced evaporation of drops due to the lower cloud layer. The same data, in respect of cloud top temperature only, are given in Table 2 separated by the season, with December, January and February counting as summer, etc.

The most common suitable clouds encountered were diurnal cumuli, usually reaching their maximum development about 1400–1500 hours. Stratiform clouds, and cumulo-nimbus associated with cold fronts, occurred at any time of day. Nighttime cumulo-nimbi were not seeded; nighttime stratiform clouds were sometimes seeded, 5% of the total seeding time occurring at night. In the authors opinion, possibly 50% of the available diurnal cumuli would have been seeded, but the fraction of other types of cloud which was seeded would have been less.

9. Period rainfall and seeding figures

Data for each cloud-seeding "period" (Section 2) are given in Tables 3 to 8, one table for each year of the experiment. The columns display the period number, the dates of beginning and end of the period, the seeding time and the average rainfall in both areas. No seeding

TABLE 3. Period data 1958.

Period	Area seeded	Date Started	Date Stopped	Seeding time (hr, min)	Average rainfall (inches) N. area	Average rainfall (inches) S. area
1	N	13 Feb.	23 Feb.	4.35	1.08	1.54
2	N	24 Feb.	13 Mar.	22.42	2.88	1.23
3	S	14 Mar.	23 Mar.	8.10	0.07	0.03
4	N	24 Mar.	4 Apr.	4.25	0.37	0.05
5	S	5 Apr.	16 Apr.	13.50	0.39	0.52
6	N	17 Apr.	27 Apr.	13.25	0.32	0.04
7	S	28 Apr.	7 May	4.07	0.03	0.17
8	S	8 May	18 May	11.24	2.05	2.56
9	N	19 May	28 May	0.00	0.04	0.00
10	N	29 May	11 Jun.	11.21	0.60	0.25
11	N	12 Jun.	22 Jun.	1.10	0.07	0.09
12	S	23 Jun.	2 Jul.	15.50	1.07	1.62
13	S	15 Jul.	24 Jul.	5.50	0.80	0.61
14	N	25 Jul.	8 Aug.	1.15	0.73	0.77
15	S	9 Aug.	19 Aug.	6.20	0.49	1.32
16	S	20 Aug.	29 Aug.	15.14	0.75	0.72
17	N	30 Aug.	8 Sept.	1.30	1.50	1.86
18	N	9 Sept.	18 Sept.	4.35	1.59	0.68
19	S	19 Sept.	28 Sept.	7.05	1.42	1.37
20	N	29 Sept.	8 Oct.	7.45	0.78	0.82
21	S	13 Oct.	22 Oct.	5.55	0.76	0.89
22	S	23 Oct.	2 Nov.	7.40	0.07	0.29

TABLE 4. Period data 1959.

Period	Area seeded	Date Started	Date Stopped	Seeding time (hr, min)	Average rainfall (inches) N. area	Average rainfall (inches) S. area
23	N	18 Jan.	30 Jan.	0.00	2.400	1.040
24	S	31 Jan.	18 Feb.	17.05	2.910	4.035
25	N	19 Feb.	9 Mar.	8.55	1.833	2.309
26	S	10 Mar.	6 Apr.	21.45	4.254	2.663
27	S	7 Apr.	20 Apr.	0.00	0.318	0.257
28	N	21 Apr.	3 May	0.00	0.200	0.023
29	N	4 May	13 May	0.00	0.001	0.010
30	S	14 May	24 May	6.20	1.582	1.119
31	N	25 May	4 June	0.00	0.015	0.021
32	S	5 June	14 June	1.40	0.052	0.128
33	N	15 June	24 June	0.00	0.028	0.127
34	S	25 June	5 July	10.45	0.547	0.577
35	S	6 July	26 July	31.30	3.066	2.399
36	N	27 July	5 Aug.	2.45	0.143	0.121
37	N	6 Aug.	19 Aug.	0.35	0.001	0.190
38	S	20 Aug.	1 Sept.	0.00	0.065	0.017
39	N	2 Sept.	22 Sept.	25.30	1.929	1.817
40	S	23 Sept.	6 Oct.	21.50	1.317	1.367
41	S	7 Oct.	22 Oct.	20.15	1.194	1.414
42	N	23 Oct.	5 Nov.	18.55	2.572	1.346

occurred in some periods when no suitable clouds were encountered.

In 1958, the first period started on 13 February, being delayed by administrative reasons. In the period 3 July to 14 July no aircraft was available; period 13 started on 15 July which complied with the requirements for a period change date (Section 2).

In 1959, period 23 was cancelled by the Referee (Section 2) as the areas were too wet, and period 27 because the aircraft was unserviceable.

In 1962, the start was delayed to 19 January and the experiment was suspended for 29 to 31 October by the Referee due to excessive rainfall, but no period was cancelled.

Table 5. Period data 1960.

Period	Area seeded	Date Started	Date Stopped	Seeding time (hr, min)	Average rainfall (inches) N. area	Average rainfall (inches) S. area
43	N	7 Jan.	17 Jan.	0.00	0.004	0.099
44	S	18 Jan.	27 Jan.	29.35	1.848	1.831
45	S	28 Jan.	7 Feb.	12.15	1.376	0.600
46	N	8 Feb.	2 Mar.	17.00	2.274	1.789
47	S	3 Mar.	16 Mar.	19.00	0.695	0.535
48	N	17 Mar.	27 Mar.	4.05	0.043	0.181
49	S	28 Mar.	6 Apr.	9.05	0.700	0.812
50	N	7 Apr.	17 Apr.	6.40	0.253	0.494
51	S	18 Apr.	27 Apr.	6.15	0.348	1.192
52	N	28 Apr.	8 May	6.25	1.254	0.896
53	N	9 May	20 May	5.20	1.403	0.920
54	S	21 May	31 May	1.10	0.181	0.314
55	S	1 June	10 June	0.00	0.113	0.035
56	N	11 June	23 June	6.30	0.993	0.779
57	S	24 June	5 July	10.45	1.124	1.198
58	N	6 July	15 July	7.10	1.031	1.654
59	N	16 July	25 July	5.10	0.593	0.660
60	S	26 July	4 Aug.	15.05	1.715	1.867
61	S	5 Aug.	14 Aug.	8.30	0.020	0.168
62	N	15 Aug.	24 Aug.	1.25	0.033	0.187
63	N	25 Aug.	4 Sept.	0.00	0.003	0.010
64	S	5 Sept.	26 Sept.	15.25	1.771	2.226
65	N	27 Sept.	12 Oct.	0.55	0.082	0.085
66	S	13 Oct.	27 Oct.	20.50	1.800	2.125
67	S	28 Oct.	6 Nov.	4.00	0.222	0.366

Table 6. Period data 1961.

Period	Area seeded	Date Started	Date Stopped	Seeding time (hr, min)	Average rainfall (inches) N. area	Average rainfall (inches) S. area
68	N	5 Jan.	18 Jan.	1.55	0.572	0.147
69	S	19 Jan.	12 Feb.	13.25	1.628	1.173
70	N	13 Feb.	1 Mar.	20.10	2.434	3.574
71	S	2 Mar.	14 Mar.	3.45	1.297	0.550
72	N	15 Mar.	2 Apr.	6.15	0.637	1.279
73	N	3 Apr.	13 Apr.	1.05	0.176	0.206
74	S	14 Apr.	24 Apr.	4.40	0.733	1.110
75	N	25 Apr.	4 May	3.35	0.146	0.611
76	S	5 May	14 May	0.20	0.005	0.020
77	S	15 May	24 May	0.00	0.004	0.003
78	N	25 May	7 June	14.30	2.028	0.583
79	N	8 June	19 June	0.00	0.094	0.282
80	S	20 June	29 June	0.00	0.018	0.096
81	S	30 June	9 July	2.40	0.416	0.723
82	N	10 July	19 July	0.00	0.000	0.002
83	N	20 July	30 July	6.40	1.959	1.397
84	S	31 July	14 Aug.	5.35	1.279	0.840
85	N	15 Aug.	27 Aug.	6.20	0.851	2.123
86	S	28 Aug.	6 Sept.	2.20	0.191	0.177
87	S	7 Sept.	17 Sept.	2.27	0.435	0.401
88	N	18 Sept.	27 Sept.	3.40	0.187	0.121
89	S	28 Sept.	11 Oct.	5.30	0.566	0.526
90	N	12 Oct.	25 Oct.	7.40	1.652	2.215
91	S	26 Oct.	6 Nov.	5.45	0.564	0.851

Table 7. Period data 1962.

Period	Area seeded	Date Started	Date Stopped	Seeding time (hr, min)	Average rainfall (inches) N. area	Average rainfall (inches) S. area
92	N	19 Jan.	2 Feb.	5.15	1.903	1.827
93	N	3 Feb.	13 Feb.	4.30	1.645	1.726
94	S	14 Feb.	25 Feb.	6.57	1.368	1.516
95	N	26 Feb.	16 Mar.	13.05	2.676	1.069
96	S	17 Mar.	30 Mar.	0.50	0.458	0.383
97	N	31 Mar.	13 Apr.	7.50	1.538	1.734
98	S	14 Apr.	23 Apr.	1.55	0.060	0.055
99	N	24 Apr.	3 May	1.00	0.004	0.087
100	S	4 May	13 May	1.30	0.162	1.261
101	S	14 May	24 May	2.48	0.181	0.256
102	N	25 May	3 June	4.10	1.507	1.202
103	S	4 June	13 June	0.00	0.058	0.023
104	N	14 June	24 June	0.00	0.000	0.010
105	S	25 June	4 July	0.00	0.015	0.029
106	N	5 July	15 July	4.55	1.949	0.451
107	N	16 July	25 July	1.50	1.214	0.827
108	S	26 July	15 Aug.	19.50	1.629	1.598
109	S	16 Aug.	26 Aug.	6.25	0.819	1.083
110	N	27 Aug.	6 Sept.	0.00	0.000	0.000
111	N	7 Sept.	17 Sept.	5.40	1.002	0.758
112	S	18 Sept.	28 Sept.	6.27	1.259	1.081
113	S	29 Sept.	8 Oct.	0.00	0.150	0.046
114	N	9 Oct.	22 Oct.	3.30	1.480	3.461
115	S	23 Oct.	1 Nov.	3.50	0.725	1.541

Table 8. Period data 1963.

Period	Area seeded	Date Started	Date Stopped	Seeding time (hr, min)	Average rainfall (inches) N. area	Average rainfall (inches) S. area
116	N	14 Jan.	4 Feb.	4.05	1.485	2.901
117	N	5 Feb.	15 Feb.	1.05	0.086	0.187
118	S	16 Feb.	25 Feb.	0.00	0.565	0.297
119	S	26 Feb.	22 Mar.	15.10	2.277	1.600
120	N	23 Mar.	1 Apr.	3.20	2.299	2.957
121	N	2 Apr.	12 Apr.	1.10	0.392	0.814
122	S	13 Apr.	23 Apr.	0.20	0.107	0.025
123	N	24 Apr.	18 May	4.15	6.044	6.689
124	S	22 July	31 July	0.50	0.273	0.269
125	S	1 Aug.	12 Aug.	0.00	0.013	0.072
126	N	13 Aug.	25 Aug.	4.45	1.803	2.085
127	N	26 Aug.	5 Sept.	0.40	1.435	1.370
128	S	6 Sept.	15 Sept.	0.40	0.002	0.034
129	N	16 Sept.	1 Oct.	1.20	1.173	1.348
130	S	2 Oct.	11 Oct.	0.00	0.007	0.068
131	S	12 Oct.	1 Nov.	12.40	1.031	1.838
132	N	2 Nov.	7 Nov.	1.40	0.301	0.332

In 1963, the experiment was suspended by the Referee from 8 May to 22 July due to a prolonged period of excessive rainfall, and period 123 was cancelled.

10. Displays of period rainfall figures

The period rainfall figures for the two areas are plotted in Figs. 3 and 4, respectively, for 1958 (random choice of area) and for 1959–1963 (random pairs of periods). North-seeded periods are shown as circles and south-seeded periods as crosses. A square-root scale is used.

In Fig. 3 the north-seeded and south-seeded period points are well separated in the way one would expect if seeding caused an increase in rainfall. No such separation appears in Fig. 4.

The difference between the period rainfall in the seeded area and that in the unseeded area is displayed in Fig. 5, for each year of the experiment. It has an expected value near zero if seeding has no effect, as the two areas had about the same total rainfall during the experiment. The mean value of the difference varied

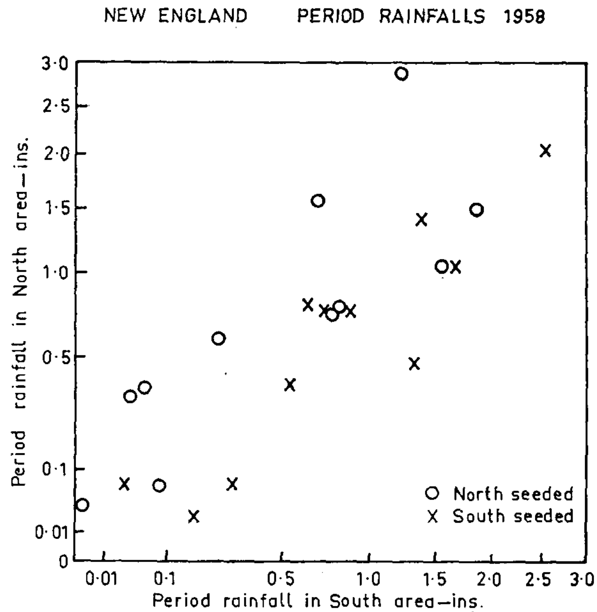

FIG. 3. Period rainfalls, 1958.

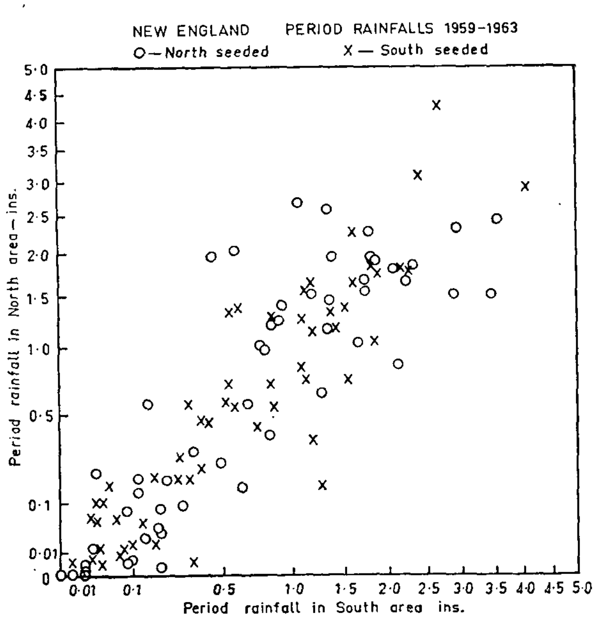

FIG. 4. Period rainfalls, 1959–1963.

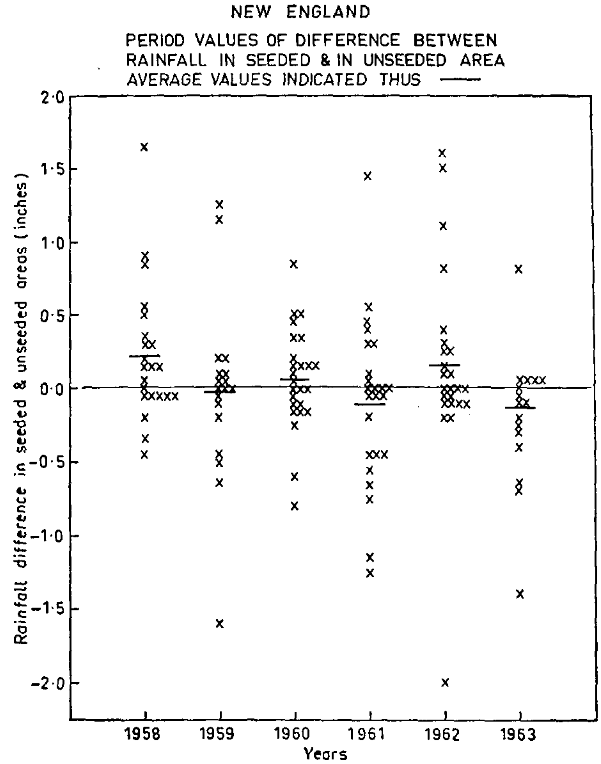

FIG. 5. Period values of difference between rainfall in seeded and in unseeded area.

from year to year, being high in 1958 and 1962 and low in 1961 and 1963.

11. Rainfall totals and ratios

Rainfall totals are presented in Table 9, for each year of the experiment and for the six years combined. The first four lines display the totals for the two areas in north-seeded and south-seeded periods. These totals do not include periods 23 and 27 and 123 during which the experiment was suspended (Section 9). In individual years the totals are sometimes markedly different in north-seeded and south-seeded periods, but no important difference appears in the six-year totals.

In line 5 of Table 9 is displayed the double ratio

$$N_n/S_n/N_s/S_s,$$

i.e., the ratio of the rainfall in the north area to that in the south area during north-seeded periods, divided by the similar ratio during south-seeded periods. The expected value of this double ratio if seeding has no effect is unity. The overall value observed was 1.08 which is consistent with a small increase due to seeding. The annual value of this double ratio fluctuated, being high in 1958 and 1962 and low in 1961 and 1963, with a tendency to decrease with time.

12. Statistical analysis

The first year's operations differed from those of subsequent years, in that a different randomization scheme was used (Section 3) and the rainfall figures were based on a different network of raingages. It is not therefore possible to apply statistical tests to the pooled data as they are not homogeneous. The rainfall figures for the first and subsequent years have therefore been analysed separately and the results combined. Two one-sided tests were applied to the null hypothesis that cloud-seeding caused no increase in the rainfall.

A random-sampling test on cumulative sums of period rainfalls (Adderley, 1961) was applied, 10,000 samples

TABLE 9. Rainfall totals (inches) and ratios.

		1958	1959	1960	1961	1962	1963	1958–1963
North-seeded	North area	9.95	6.72	7.97	10.74	14.92	8.97	59.27
	South area	7.33	5.96	7.75	12.54	13.15	11.99	58.73
South-seeded	North area	7.90	14.99	11.91	7.14	6.88	4.28	53.09
	South area	10.09	13.72	13.27	6.47	8.87	4.20	56.62
$N_n/S_n/N_s/S_s$		1.74	1.03	1.14	0.78	1.46	0.74	1.08

being taken on an electronic computor. The significance level for 1958 was 0.01, that for the five subsequent years was 0.54 and the combined significance level was between 0.02 and 0.05. An alternative approach to this analysis is to consider each year's results separately; the significance levels for the six years (taking 1000 samples for each) are then 0.01, 0.48, 0.24, 0.78, 0.18, 0.75 and the combined significance level is between 0.10 and 0.20.

A regression analysis was applied to the 1958 figures with square-root transformation, giving a significance level of 0.01. For the subsequent years using random pairs of periods, the "cross-difference" $(N_a+S_b-N_b-S_a)$ was used as a test variate, where N and S represent the period rainfalls in the north and south areas, and a and b indicate the first and second period of a pair. A t-test was applied to the difference of means of the cross-differences, separated in groups in which the north-seeded period came first or second, for all years of the experiment except the first, giving a significance level of 0.45. This combined with the regression analysis for 1958, gave a significance level of 0.02 to 0.05. Alternatively, these tests for the six years separately gave significance levels of 0.01, 0.42, 0.18, 0.78, 0.28 and 0.82 and a combined significance level between 0.1 and 0.2.

13. Primary result

The primary result of the experiment is that over the whole six years there was a small difference, at a low significance level, between the rainfall balance in the two areas in north-seeded and in south-seeded periods. However during the first year there was a substantial difference at a high significance level.

14. Primary conclusion

The primary result can be interpreted in two ways. If the results of all six years of the experiment are considered together, they suggest that seeding caused a small increase in the mean rainfall, but they do not provide acceptable proof. However, if the results of each year's experimenting are considered separately they lead to the conclusion that cloud-seeding caused an increase in the mean rainfall in the first year but no significant change thereafter. In the opinion of the authors the data do not justify a definite judgement between these two possibilities.

15. Stream flow

The irregular shapes of the two areas (Fig. 1) were so chosen that each formed a river catchment, the runoff from which was monitored by two stream gages at the north-west extremities of the areas. Period stream-flow figures were computed for each area, arbitrarily allowing one day time-lag between rainfall and gage reading. Results were similar to those for rainfall; in 1958 the double ratio was 2.06, the significance level, computed by regression analysis with logarithmic transformation, being 0.01. In subsequent years there were no significant effects. These results lead to the same conclusions as those from rainfall.

16. Auxiliary analyses

The rainfall figures have been analysed in various ways which were not envisaged in the original design. These *post hoc* analyses cannot modify the main conclusions but they may be used as the basis for predictions which can be tested in future experiments. The following aspects of the data were investigated.

Rainfall correlations. Correlation coefficients were calculated between the means of the monthly readings of five raingages in each area, omitting November, December and January (during which, or much of which, the experiment was usually suspended—Sections 2 and 9). For six consecutive six-year periods preceding the experiment the values were 0.74, 0.73, 0.81, 0.77, 0.79 and 0.81. Using the monthly readings of the same gages during the six years of the experiment, again omitting November, December and January, the coefficient was 0.72. Using monthly readings of the full network of 145 and 106 gages (except for 1958 when 65 and 66 gages were used—Section 3), the coefficient was 0.78. Using the period rainfall totals with the full gage network the coefficient was 0.80.

The correlation using five gages during the experiment was lower than in any historical period investigated, suggesting either that the weather in the experimental years was unusual or that the seeding had reduced the correlation.

The correlation coefficient between the seeding period rainfalls exceeded that derived from monthly readings of the same raingages. This probably reflects the method of changing periods during fine weather (Section 2).

Variability in period rainfall relationship between areas. Figs. 3 and 4 are plots of the period rainfalls in the north area against those in the south area. The scatter in these plots during north-seeded periods appears to exceed that during south-seeded periods.

An F-test was applied to the differences in variance of $(\sqrt{N_n}-\sqrt{S_n})$ and $(\sqrt{N_s}-\sqrt{S_s})$ where N and S are the period rainfalls in the north and south areas, and n and s denote north-seeded and south-seeded. The significance level of the difference was 0.01. A similar effect was observed in the South Australian experiment (*loc. cit.*) the significance level being 0.02.

In the South Australian experiment, and in all but the first year of the New England experiment (see Fig. 4) the difference in the variability in the relationship between the north and south area rainfalls during north-seeded and south-seeded periods was not accompanied by an appreciable difference between the mean relationships. The significance level must be regarded with due reserve, as the New England experiment used random pairs of periods, and the F-test is sensitive to departures from normality. However, these results suggest that the seeding increased rainfall on some occasions and decreased it on others, the effects being different in the two areas.

Effects of season. Period rainfall figures were grouped according to the three-month season in which the period midpoints fell, counting December, January and February as "summer" etc. The total rainfalls in the two areas in north-seeded and south-seeded periods for each season are given in Table 10, together with the double ratio, as defined in Section 11. The rainfall totals do not include periods when the experiment was suspended.

There is no appreciable difference in the double ratios for autumn, winter and spring. The ratio for summer is much lower.

TABLE 10. Seasonal effects rainfall totals—inches.

	North-seeded North area	North-seeded South area	South-seeded North area	South-seeded South area	Double ratio
Summer DJF	13.31	16.10	9.70	9.45	0.81
Autumn MAM	16.15	13.83	15.58	15.18	1.14
Winter JJA	15.56	13.97	14.33	15.39	1.20
Spring SON	14.24	14.84	13.48	16.61	1.18

Note: Double ratio $N_n/S_n/N_s/S_s$ (see Section 11).

Significance calculations on these sections of the data would be of doubtful value, but in any future experiment in this area provision should be made for stratification of the data by the season.

Effects of cloud type. In order to investigate the effects of seeding clouds of different types, seeded days were classified, according to the significant type of cloud which was seeded, into three categories, cumuliform, stratiform and indeterminate. The daily rainfall in the two areas on days in each category was then examined. The original data, and the criterion used in classifying the days, have been presented in the Annual Reports (Section 1).

This analysis is subject to statistical bias, as the observations were concentrated on clouds in the seeded area on seeded days only, so any conclusions must be regarded as tentative and as requiring confirmation in future experiments.

The rainfall on seeded days was not a random sample of the total rainfall. Thus the expected value of the double ratio of rainfall on days with a given cloud category, in the absence of effects of seeding, is not necessarily unity.

TABLE 11. Rainfall totals and double ratios with various cloud types on seeded days only.

		North-seeded periods North area	North-seeded periods South area	South-seeded periods North area	South-seeded periods South area	Double ratio
Cumulus clouds	1958	2.69	1.47	0.75	1.54	3.76
	1959	3.38	2.50	3.27	4.22	1.75
	1960	1.05	0.55	2.70	3.46	2.45
	1961	1.67	2.97	2.48	2.04	0.46
	1962	3.68	2.35	1.65	1.93	1.83
	1963	2.44	2.35	2.12	2.18	1.07
	1958–1963	14.91	12.19	12.97	15.37	1.45
Stratiform clouds	1958	1.21	0.50	2.84	2.21	1.88
	1959	0.70	0.52	5.20	5.06	1.31
	1960	1.48	1.81	0.24	0.51	1.74
	1961	3.85	2.73	Nil	Nil	—
	1962	2.32	1.39	0.91	1.50	2.75
	1963	0.35	0.26	0.20	0.72	4.85
	1958–1963	9.91	7.21	9.39	10.00	1.46
Indeterminate clouds	1958	1.40	1.76	2.84	4.84	1.36
	1959	1.73	0.70	1.90	1.86	2.42
	1960	2.92	2.22	6.33	6.93	1.44
	1961	2.27	2.36	2.25	1.75	0.75
	1962	3.25	2.33	1.18	0.94	1.11
	1963	0.67	0.74	Nil	0.03	—
	1958–1963	12.24	10.11	14.50	16.35	1.37

Table 11 presents the rainfall totals and double ratios on days of the three categories. The six-year double ratio is almost the same for all categories. Double ratios cannot be calculated for stratiform clouds in 1961 and indeterminate clouds in 1963 as no rain was recorded on days thus classified in south-seeded periods. The double ratios for days classified as cumuliform and indeterminate decreased with time, while that for days classified as stratiform increased.

17. Discussion of results

From the main analysis, it appears likely that seeding increased the mean rainfall in 1958 but not thereafter. From the auxiliary analysis it appears that, all through the experiment, seeding was associated with an increase in the variability of the relationship between the period rainfalls in the two areas. The most probable explanation seems to be that seeding sometimes caused an increase in rainfall and sometimes a decrease, increases predominating in 1958 and both being evenly balanced thereafter.

It has been suggested that decreases occurred when clouds with tops warmer than -10C were seeded. (This suggestion is amplified by Bethwaite in a paper to be published at a later date). The stratification used in this analysis was on the basis of observed cloud conditions in the seeded area only. This may have introduced a bias into the results whose sense and direction we have no means of estimating. The same effect is suggested by Tables 1 and 9, the double ratio being low in 1961 and 1963, when the cloud-top temperatures were warmest, and by Tables 2 and 10, the double ratio being lowest in summer, again when the cloud tops were warmest.

Further experiments in the same region are indicated, to investigate the effects which appear to be revealed by the first experiment. They should include (a) improved seeding technique, to avoid the decreases where possible and increase the net stimulation (b) improved sensitivity, by choice of areas to improve rainfall correlations, (c) means of detecting changes in scatter of rainfall figures, (d) means of investigating the apparent deterioration of results after the first year and (e) an acceptable method of stratification of the results. An experiment incorporating these features has been started in the same region.

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