CLOUD SEEDING EXPERIMENTAL PROGRAM IN RHODESIA: 1974-75

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ABSTRACT

Using randomized instructions, isolated cumulus clouds were either left alone or seeded near cloud top from an aircraft fitted to fire pyrotechnic cartridges. The rain falling from both seeded and untreated clouds was measured at cloud base using a rain water collector. Seeded clouds with tops warmer than about $-10^{o}C$ gave much the same rain as similiar non-seeded clouds. With colder clouds, however, the average rainfall was greater on seeded than on non-seeded occasions. When rain falling earlier than 40 minutes after the start of the experiment was excluded from the calculations, then the apparent bias in favour of the seeded clouds in the two-season period 1973-74-75 was significant at the 10% level.

Again excluding early rain, the six heaviest falls all came from seeded clouds; the probability that this was pure chance is less than 0.04. However, there were also several seeded clouds which failed to rain.

INTRODUCTION

The 1974-75 experimental program was the logical continuation of the previous year's program, when single cumulus clouds reaching to at least the $-10^{o}C$ level were seeded from near cloud-top level using silver iodide pyrotechnic cartridges. These experiments and their results have been described by McNaughton, (1975).

The next question to be investigated was whether clouds whose tops fell short of the $-10^{o}C$ level could still respond to seeding. Therefore the experimental procedure for the 1974-75 season was precisely as before except that clouds were selected when their top temperatures were between $-10^{o}C$ and $-5^{o}C$. The decision to seed or leave alone was again determined on a randomized basis.

There was also a subsidiary program in 1974-75. When "warm" clouds did not offer, experiments continued on clouds with tops colder than $-10^{o}C$ in order to accumulate more experience of these so-called "cold" clouds which are the main source of additional rainfall.

EXPERIMENTAL PROCEDURE

Isolated solid-looking cumuliform clouds with a sharp and well-defined cloud-top outline were selected from the aircraft flying at about 21,000 feet asl. The cloud-top height and temperature were measured or estimated, and an envelope was opened containing an instruction either to seed the cloud or to leave it alone. Seeding penetrations were usually carred out 1,000-2,000 feet below cloud top, and pyrotechnic cartridges were fired as soon as updraughts were encountered.

The aircraft then descended to about 2,000 feet below cloud base in order to measure the rain using the rain collector, which consisted of a forward-pointing funnel leading into a separating chamber inside the aircraft. Measuring flights were carried out until the cloud stopped raining, with notes being made on the duration of each pass through the rain and on the quantity of water collected. The rain collector has been described in detail in an earlier paper (McNaughton, 1973), and is illustrated in Figures 1 and 2.

Graphs were plotted of the variation in time of the dimensions of the shower and of the rate of rainfall. The area under this second graph gave the total rain yield from the cloud. At the end of the season all clouds were ranked in order of their rainfall so that the relative positions of seeded and non-seeded clouds could be examined. The procedure was similar to that used in Australia and described by Bethwaite _et al_, (1966).

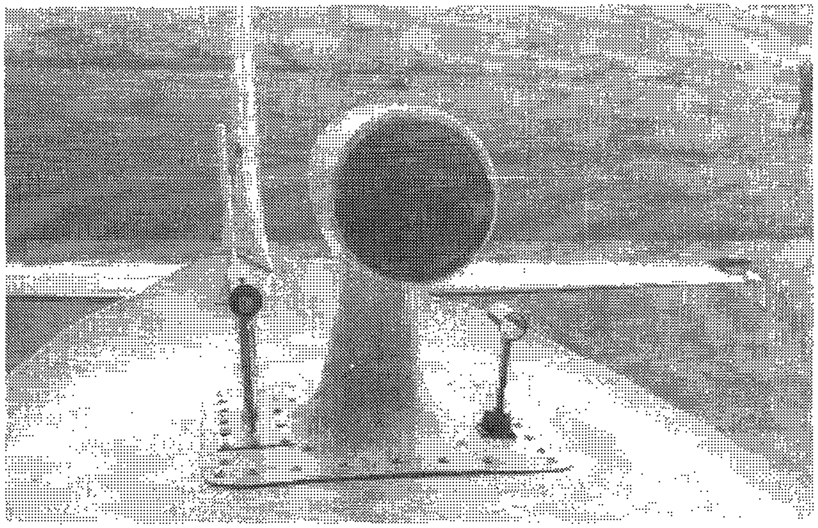
During the first half of November a second aircraft was usually available for experimental work, having been detached from the national operation. This aircraft observed changes in cloud-top height and appearance while the first aircraft was measuring the rain beneath the cloud.

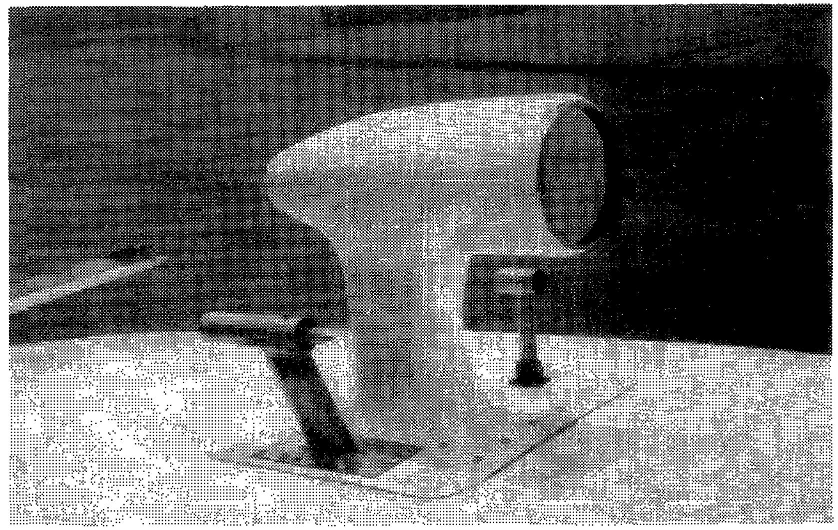
RESULTS OF EXPERIMENTS

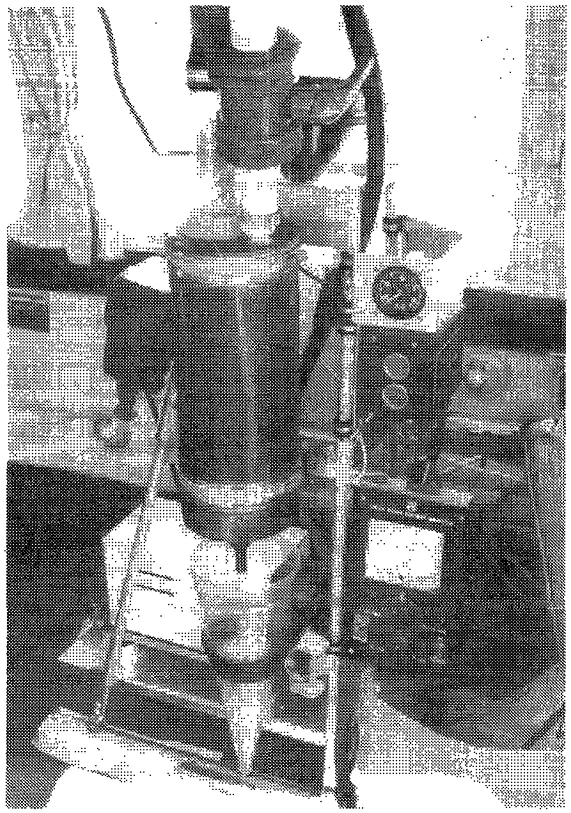
Table I gives the data from all randomized experiments in chronological order. It lists the clouds belonging to the main program with tops in the -5°C to -10°C range; it also lists the balance of subsidiary clouds with tops colder than -10°C forming an extension of the group investigated in the previous year. For each cloud, regardless of whether seeded or left alone, the total rainfall produced is given for periods commencing 10, 20, 30, 40 and 50 minutes after the time of the first pass through the cloud top until the cessation of rain.

(1) The Effect of Seeding Cloud Tops in the -5°C to -10°C Range

Seventeen randomized clouds with tops warmer than -10°C were investigated. One of these, on 30th January, grew beyond the -10°C level quite soon after seeding, and therefore had to be included in the "cold" category. Of the remaining 16, seven were seeded and nine were left







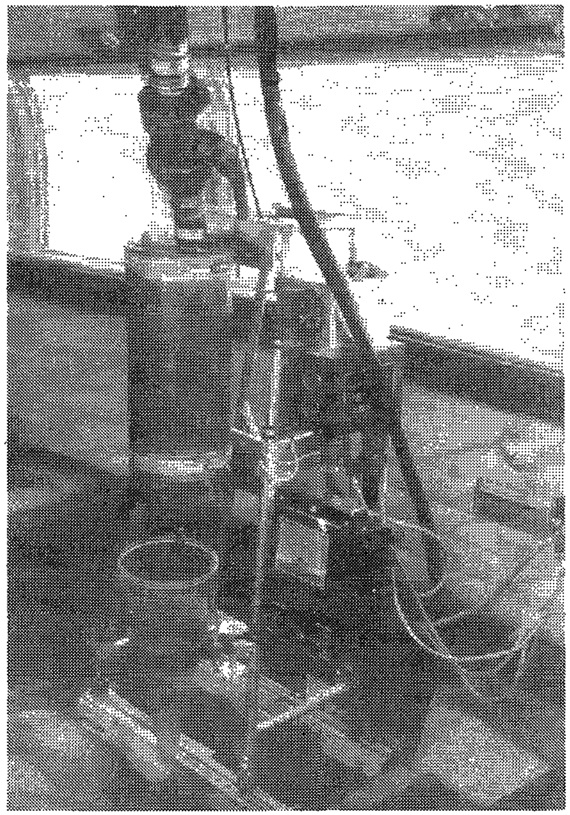


Fig. 1: (photos above, left and right) The rain water collecting funnel, flanked by a thermometer and liquid water probe.

Fig. 2: (photos left) The rain collector's separating chamber. The inlet pipe has a tap fitted; the outlet pipe next to it enables the air to escape up and out. The rain water is collected at the base of the chamber.

TABLE I

All Randomised Experimental Clouds, 1974/75

Date	Seeded or not	Seeding flight level	When selected: Cloud top FL	Temp. of top °C	Cloud Depth ft	RAIN (10^3 m^3) from x mins. after "seeding": x=10	x=20	x=30	x=40	x=50	Mins. after seeding rain ceased	Rain Duration (mins.)	Other notes
4/11/74	S	209/200	213	-16,5	9 800	Nil	Nil	Nil	Nil	Nil	-	Nil	Base rather broken.
4/11/74	S	200	205	-14	8 500	Nil	Nil	Nil	Nil	Nil	-	Nil	Top attained 21 000 ft and then collapsed.
6/11/74	S	220/210	230	-18	12 000	223,6	202,0	168,4	104,7	55,4	68	>64	Top attained 23 500 ft and glaciated. Similar clouds nearby did not glaciate, however.
12/11/74	N	-	230	-17	11 600	Trace	Trace	Nil	Nil	Nil	26	10	Good liquid water content near top,** but high cloud base.
13/11/74	S	218	235	-17,5	13 100	Trace	Trace	Trace	Nil	Nil	32	9	Multicell structure. Top attained 25 000 ft, but the body of the cloud dispersed.
18/11/74	N	-	215	-13,5	12 800	95,2	90,1	46,6	6,2	0,2	•51	36	Top grew a further 500 ft within 1 minute of selection. Multicell system with a very high liquid water content.
21/11/74	S	194	198	-11	12 300	Trace	Trace	Nil	Nil	Nil	29	6	Estimated max. cloud top about 21 000 ft, also -11 °C.
22/11/74	S	198	205	-11	12 100	555,2	491,7	351,3	190,9	110,1	69	>53	
25/11/74	S	195	198	-7,5	11 200	Nil	Nil	Nil	Nil	Nil	-	Nil	Good liquid water content. Top collapsed to 18 700 ft 8 mins. after seeding.
25/11/74	N	-	197	-7,5	11 000	Trace	Nil	Nil	Nil	Nil	19)	1	High liquid water content. Top attained 20 000 ft. Moderate shear observed.
28/11/74	N	-	190	-8	11 200	Nil	Nil	Nil	Nil	Nil	-	Nil	Top attained 19 500 ft 2 mins. after selection Base broken.
28/11/74	S	179	183	-6,5	10 300	Nil	Nil	Nil	Nil	Nil	-	Nil	Base very broken between 8 000 and 12 000 ft. Secondary cell had top at 18 500 ft.
3/12/74	S	190	196	-7,5	11 600	Nil	Nil	Nil	Nil	Nil	-	Nil	Base rather broken; some top shear.
6/12/74	N	-	202	-7,5	11 700	139,5	133,2	46,7	Nil	Nil	37	21	Top attained 20 400 ft. Cloud merged with an adjacent line in its dying moments.

** From a Johnson-Williams Liquid Water Meter, carried on the aircraft.

TABLE I (Contd.)

All Randomised Experimental Clouds, 1974/75

Date	Seeded or not	Seeding flight level	When selected: Cloud Top FL	When selected: Temp. of top °C	When selected: Cloud Depth ft	RAIN (10^3 m^3) from x mins. after "seeding": x=10	x=20	x=30	x=40	x=50	Mins. after seeding rain ceased	Rain Duration (mins.)	Other notes
11/12/74	S	208	213	-11,5	12 400	3,9	3,9	3,4	0,8	Nil	45	23	Top attained 21 500 ft.
12/12/74	N	-	210	-10	13 700	74,3	42,6	0,5	Nil	Nil	31	>19	Multicell structure surrounded by layer cloud over a range of hills.
2/ 1/75	S	195	198	-9	9 800	Nil	Nil	Nil	Nil	Nil	-	Nil	Violent updraught during seeding run. Base broken.
3/ 1/75	S	201/195	206	-10,5	10,700	61,0	60,1	25,9	1,8	Nil	45	>29	
8/ 1/75	N	-	190	-8	10 700	Nil	Nil	Nil	Nil	Nil	-	Nil	Top attained 19 500 ft. Good liquid water content.
14/ 1/75	N	-	188	-7	10 800	1,1	Nil	Nil	Nil	Nil	20	>13	Good liquid water content near top; broken base. Top attained 19 200 ft.
29/ 1/75	N	-	194	-7,5	11 400	138,9	115,4	54,8	19,2	Nil	50	35	Multicell surrounded by extensive layer cloud.
30/ 1/75	S	195/200	196	-9*	10 300	17,6	4,1	0,1	Nil	Nil	32	>19	High water content near top; poor base. Top FL 207 soon after selection. A comparable unseeded cloud nearby gave similar rain.
25/ 2/75	S	198	204	-9,5	12 100	0,6	0,5	Nil	Nil	Nil	27	11	High liquid water content.
4/ 3/75	N	-	195	-9,5	11 900	15,8	1,4	Nil	Nil	Nil	22	>8	
5/ 3/75	N	-	193	-6,5	10 800	2,7	0,6	Nil	Nil	Nil	23	12	Good liquid water content near top, but base broken.
25/ 3/75	S	198	202	-9,5	10 700	Nil	Nil	Nil	Nil	Nil	-	Nil	Good liquid water content.
25/ 3/75	N	-	203	-9,5	10 800	Nil	Nil	Nil	Nil	Nil	-	Nil	Large multicell structure with high liquid water content.
27/ 3/75	S	187	190	-8,5	11 500	288,5	222,4	46,5	2,4	Nil	45	>34	Top attained 19 500 ft (-9,5°C). Situated over hills.

* This cloud top grew to -11°C soon after selection and has therefore been analysed in the "cold" category.

alone, and their average cloud depths and top temperatures when selected can be found in Table II.

TABLE II

	Depth Ft.	Top Temperature °C
7 seeded clouds	11,000	-8,3
9 non-seeded clouds	11,100	-7,9

Table III compares their rainfall yields. It will be noticed that the seeded and untreated clouds above were of similiar size and top temperature, and that there was negligible difference in their rainfalls. Many Australian, American and Israeli experiments also indicate that clouds warmer than about -10°C usually fail to give significant rain after seeding (Smith, 1967; Grant and Elliott, 1974; Gagin and Neumann, 1974).

In addition to the randomized experiments, a series of supplementary experiments was carried out for various reasons. For example it is often instructive to perform both a seeding and a non-seeding experiment on the same sortie. Sometimes, immediately after completing a randomized experiment using sealed instructions, another experiment was carried out using the opposite treatment, without opening any envelope. Most of these "pairs" consisted of "warm" clouds, and on two such occasions, 14th January and 5th March, 1975, the maximum cloud-top attained by each member of the pair (listed under "other notes" in Table IV was almost the same. It is

TABLE III

WARM CLOUD EXPERIMENTS, 1974-1975

	Rain Measurement from x Minutes After "Seeding"				
	x = 10	x = 20	x = 30	x = 40	x = 50
Average rain, seeded clouds (kilocumes)	41	32	6,6	0,3	Nil
Average rain, non-seeded clouds (kilocumes)	33	28	11,3	2,1	Nil

TABLE IV

Supplementary Experiments, 1974/75

Date	Seeded or not	Seeding flight level	When selected: Cloud Top FL	When selected: Temp of top °C	When selected: Cloud Depth ft	RAIN (10^3 m^3) from x mins. after "Seeding." x=10	x=20	x=30	x=40	x=50	Mins. after seeding rain ceased	Rain Duration (mins.)	Other notes
7/11/74	S	188	197	-11	9 200	Nil	Nil	Nil	Nil	Nil	–	Nil	Unlike other clouds nearby, this cloud glaciated (although failed to rain,) High liquid water content near cloud top.
7/11/74	S	193	200	-11,5	6 500	Nil	Nil	Nil	Nil	Nil	–	Nil	Base high and broken. Glaciation observed but no rain. High liquid water content near cloud top.
8/11/74	S	240	213	-13,5	12 300	Trace	Trace	Trace	Nil	Nil	34	4	Top collapsed, but grew again to 21 700 ft within 5 minutes.
8/11/74	S	215	230	-16	14 000	424,1	390,7	165,1	37,0	0,5	52	37	Randomised, but the main cell was too large to seed. Overall cloud top attained 24 200 ft, with occasional lightning.
12/11/74	S	222/212	235	-18	11 600	Trace	Trace	Nil	Nil	Nil	28	3	Good liquid water content near top, but high cloud base.
19/11/74	S	215	225	-15,5	14 000	Very heavy			Very heavy		290	262	Randomised, but merged with a thunder storm. Total rain from both was nearly 4 000 kilocumes.
2/12/74	N	–	185	-7	9 500	Trace	Nil	Nil	Nil	Nil	20	10	Surrounded by layer cloud.
5/12/74	S	210	225	-14	14 500	Heavy	Heavy	Heavy	?	?	?	?	Gave heavier rain than other similar clouds nearby.

TABLE IV (Contd.)

Supplementary Experiments, 1974/75

Date	Seeded or not	Seeding flight level	When selected: Cloud top FL	Temp of top °C	Cloud Depth ft	RAIN ($10^3 \cdot m^3$) from x mins. after seeding: x=10	x=20	x=30	x=40	x=50	Mins. after seeding rain ceased	Rain Duration (mins.)	Other notes
6/12/74	S	193/180	198	-7	11 800	Nil	Nil	Nil	Nil	Nil	–	Nil	Base broken.
11/12/74	S	186	194	-8	?	Nil	Nil	Nil	Nil	Nil	–	Nil	Top collapsed 4 minutes after selection, but revived 5 minutes later. Poor base.
18/12/74	S	207	215	-12	13 500	Nil	Nil	Nil	Nil	Nil	–	Nil	Good liquid water content. Identification difficult : surrounded by layer cloud. Base very broken.
[illegible]/ 1/75	S	190	200	-9	11 500	Nil	Nil	Nil	Nil	Nil	–	Nil	Good liquid water content near top : poorish base.
14/ 1/75	S	188	194	-8	11 800	>82,0	>56,6	>18,9	?	?	>39	>26	Followed a randomised non-seeded occasion with similar cloud-top which gave a very small quantity of rain.
30/ 1/75	N	–	217	-12,5	12 200	Mod	Light	Nil	Nil	Nil	24	>18	High water content.
25/ 2/75	S	200	205	-9,5	12 600	?Mod	?Mod	?Mod	?	?	>38	?	Top collapsed 4 minutes after seeding, but revived 3 minutes later. Cloud was absorbed by an adjacent storm-line.
5/ 3/75	S	186	190	-6	10 300	90,4	18,3	10,8	0,8	Nil	45	>35	Followed a randomised non-seeded occasion with similar cloud-top which gave a very small quantity of rain.
11/ 3/75	S	182	185	-8,5	10 500	Nil	Nil	Nil	Nil	Nil	–	Nil	
11/ 3/75	S	181	193	-10	11 500	Mod	Mod	Mod	Mod	Mod	>65	>44	Top attained 19 700 ft 13 minutes after seeding Rain remained light in the first 50 minutes after seeding.
20/ 3/75	S	188	191	-7,5	11 700	>583	>508	>405	>237	>109	>50	>35	Situated on the Umvukwes range, and eventually linked up with other showers also over this range.
24/ 3/75	S	211/202	220	-12,5	12 500	Heavy	Heavy	Mod	Light	Trace	52	>34	

therefore interesting to note that on both these days the seeded cloud gave more rain than the untreated one. However, as explained in the 1973-74 report (McNaughton, 1975) it is unlikely that any increase in rain can be produced at cloud base earlier than 20 to 30 minutes after seeding. Even from the two seeded members of the pairs described above, the rainfall yield in the later stages of the cloud life can only be described as modest, and of little or no benefit to agriculture.

Apart from another two occasions when the cloud selected belonged to a line of clouds, most of which were already raining, five non-randomized seeding experiments with cloud-tops warmer than -10°C are listed in Table IV as having failed to rain. It therefore seems that it is a waste trying to seed the majority of clouds whose tops are warmer than -10°C, although the two experimental "pairs" discussed above indicate that on rare occasions it might be possible to induce light rain from them.

(2) The Experiments with Colder Clouds

Table V compares the depths and top temperatures of seeded and untreated clouds in both the 1973-74 and 1974-75 seasons. In each year the randomization happened to select deeper clouds for the non-seeded category. In 1973-74 they were only 400 feet deeper than the seeded clouds, on average, but in 1974-75 the non-seeded clouds had a 1,500 foot advantage. The implication of this is that in both seasons the deduced rainfall yield will be a conservative estimate.

It is important to remember that in 1973-74 the clouds were primarily selected with tops reaching beyond the -10°C level. In 1974-75, on the other hand, the main objective was to choose clouds with tops in the

TABLE V

AVERAGE TOP TEMPERATURES AND CLOUD DEPTHS OF COLD CLOUDS, WHEN SELECTED

Season	Number and Treatment	Depth, Ft.	Top Temperature °C
1974-75	9 seeded	11,200	-13,2
	3 non-seeded	12,700	-13,5
1973-74	20 seeded	13,100	-13,3
	16 non-seeded	13,500	-13,7
Both Seasons: 73-74 and 74-75	29 seeded	12,500	-13.3
	19 non-seeded	13,400	-13,7

-5^{o}C to -10^{o}C range. By the time the aircraft had reached them some of these had actually grown slightly beyond the -10^{o}C level, and they were therefore disqualified from inclusion in the main experiment, but were only just good enough for the continuation of the 1973-74 investigation of colder clouds. Five out of the nine 1974-75 seeded "cold" clouds were warmer than -12^{o}C, but only three of the twenty 1973-74 ones were (see Appendix I). From Table V it will be noticed that, on the average, the 1974-75 seeded clouds were nearly 2,000 feet shallower than in 1973-74. The three non-seeded 1974-75 cold clouds were 800 feet shallower than in the previous season.

The rainfall yields are compared in Table VI. In 1973-74, when the majority of clouds reached far beyond -10^{o}C to the -13^{o}C level, the seeded clouds averaged about 150 kilocumes of rain more than the untreated ones. In 1974-75, when many of the clouds were included in the cold category only because of a small overshoot, the rain from seeded clouds was only about 40 kilocumes more than that from the non-seeded ones. This is not surprising in view of the significantly smaller development in the 1974-75 clouds. However it is worth noting that, as in 1973-74, the ratio of seeded to non-seeded rain yield still shows a marked increase as the time of start of rain calculation is made later.

When both seasons' results are combined into the period 1973-74-75 then the increase of rain from the seeded clouds is about 120 kilocumes.

THE LIKELIHOOD OF THE RESULTS BEING PURE CHANCE

Table VI also gives the results of Mann-Whitney significance tests on the "cold" cloud rankings in order of their rainfalls, combining both seasons together. With the 40-minute and 50-minute starting times the possibility that the good results are due to chance is less than ten percent.

It can be seen from the original list of clouds in Table I that, as in the previous season and indeed in overseas experiments, there were many occasions of nil rainfall from seeded clouds. In other words seeding does not always succeed in producing extra rainfall, although the times when it does work more than compensate for the failures. In any event, it would appear that the occurrences of nil rainfall after seeding do have a marked adverse effect on the overall rankings, which are given in Appendix II.

However, it is worth noting that, with the 30-minute starting time and later, the first six positions in the ranking are all occupied by by seeded clouds. Permutation theory shows that the possibility of this being pure chance is less than four percent; the calculation is given in Appendix II. This is a twenty-five to one indication that the seeding treatment influenced the six heaviest rainfall occasions.

TABLE VI

INDICATED INCREASES IN RAINFALL, 1973-75

COLD CLOUDS	Rain Measurement From x Minutes After "Seeding"				
	x = 10	x = 20	x = 30	x = 40	x = 50
1974-75 only:					
Average rain, seeded clouds (kilocumes)	96	85	61	33	18,4
Average rain, non-seeded clouds (kilocumes)	57	44	15,7	2,1	0,1
Rainfall difference, seeded minus non-seeded clouds (kilocumes)	39	41	45	31	18
1973-74 only:					
Average rain, seeded clouds (kilocumes)	259	213	180	149	91
Average rain, non-seeded clouds (kilocumes)	90	59	15,8	1,6	nil
Rainfall difference, seeded minus non-seeded clouds (kilocumes)	169	154	164	147	91
Both Seasons - 1973-74 and 1974-75:					
Average rain, seeded clouds (kilocumes)	208	173	143	113	68
Average rain, non-seeded clouds (kilocumes)	85	56	15,8	1,6	trace
Rainfall ratio, seeded/non-seeded clouds	2,4	3,1	9,1	70,6	v.large
Rainfall difference, seeded minus non-seeded clouds (kilocumes)	123	117	127	111	68
Significance level	0,42	0,28	0,15	0,07	0,09

CONCLUSION

When the tops of cumulus clouds fail to reach the -10°C level, seeding by the silver iodide pyrotechnic method is not successful. For cloud-seeding to be economically viable, cloud tops should reach beyond this level. If they reach even higher, say to the -13°C level, then the yield from seeding is very much better.

ACKNOWLEDGEMENTS

Mr. Fraser of the Department of Civil Aviation must be praised for the capable way in which he piloted the aircraft. He contributed much to the success of the experiments.

Thanks also go to the Rhodesia United Air Carriers for the competent and efficient manner in which they maintained the aircraft during the 1974-75 season.

During the first half of November a second aircraft was available for the experiments, crewed by Mr. J. Ward of the Meteorological Department and S/Ldr. Barnett of the R.U.A.C., and useful information accrued from their participation in the work.

Reference was often made to work done and articles published by Dr. St.-Amand of the United States Naval Weapons Center.

APPENDIX I

For seeded clouds in the "cold" category, top temperatures when selected were as follows:

1974-75

-9; -10,5; -11; -11; -11,5; -14;
-16,5; -17,5; -18.

Number of clouds: 9
Average: 13,22

1973-74

-10; -10,5; -10,5; -12; -12; -13;
-13; -13; -13; -13,5; -14; -14;
-14; -14; -14; -14,5; -14,5; -15,5;
-16; -16.

Number of clouds: 20
Average: 13,35

APPENDIX II

During the two seasons 1973-74 and 1974-75, excluding the warmer clouds there were 48 randomized experiments, 29 of which were seeded and 19 untreated. The rankings of rainfalls measured from the different starting times are given below; tied ranks are denoted by brackets. One seeded cloud still raining had to be abandoned before 50 minutes had elapsed, and in this category there are therefore only 28 seeded clouds.

10 minutes

$$\mathrm{SSSNSSSNSSSSNNNNNSNNSSSSNSNSNSNNSNSS} \begin{Bmatrix} \mathrm{SSS} \\ \mathrm{N} \end{Bmatrix} \begin{Bmatrix} \mathrm{SSSSS} \\ \mathrm{NNN} \end{Bmatrix}$$

20 minutes

$$\mathrm{SSSNSSSNSSNSNSNSNNSSNSSNSNNSSSNSN} \begin{Bmatrix} \mathrm{S} \\ \mathrm{N} \end{Bmatrix} \begin{Bmatrix} \mathrm{SS} \\ \mathrm{N} \end{Bmatrix} \begin{Bmatrix} \mathrm{SSSSSS} \\ \mathrm{NNNN} \end{Bmatrix}$$

30 minutes

$$\mathrm{SSSSSSNNNSNSSSSSSSNNSSN} \quad (\mathrm{NN}) \begin{Bmatrix} \mathrm{SS} \\ \mathrm{N} \end{Bmatrix} \mathrm{S} \begin{Bmatrix} \mathrm{SSSSSSSSSSS} \\ \mathrm{NNNNNNNNN} \end{Bmatrix}$$

40 minutes

$$\mathrm{SSSSSSNNNSS} \begin{Bmatrix} \mathrm{S} \\ \mathrm{N} \end{Bmatrix} \mathrm{SSS} \begin{Bmatrix} \mathrm{SSSSSSSSSSSSSSSSS} \\ \mathrm{NNNNNNNNNNNNNNN} \end{Bmatrix}$$

50 minutes

$$\mathrm{SSSSSN} \begin{Bmatrix} \mathrm{SSSSSSSSSSSSSSSSSSSSSSS} \\ \mathrm{NNNNNNNNNNNNNNNNNN} \end{Bmatrix}$$

The chance of drawing six S's (without replacement) from a collection of 29 S's and 19 N's is given by the hypergeometric probability law, and is:

$$\frac{29!}{23!\ \ 6!} \Big/ \frac{48!}{42!\ \ 6!} = 0{,}0387 = \frac{1}{25{,}8}$$

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