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Result of cloud seeding experiment at Delhi as assessed by Radar

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ABSTRACT. Based on measurements made by a high power microwave radar on areal echo coverage and echo height of rain cells within 100 km around Delhi, the result of cloud seeding experiment conducted in the area during the 5 experiment years, 1961 and 1963 to 1966, has been evaluated. The trend of result has been found positive on the basis of areal echo coverage, and negative on the basis of mean echo height. The implication of the suggested trends of result is discussed.

1. Introduction

An experiment on artificial stimulation of rain using warm cloud seeding technique was undertaken at Delhi (28°35′N, 77°12′E, 714 ft a.s.l.) in 1957. The objective of the experiment was to determine whether dispersal into cloud air of salt particles of appropriate sizes from ground would help cause significant increase in precipitation in regions downwind. The experiment indicated 41·6 per cent increase in precipitation on evaluation at the end of 8 monsoon seasons (Biswas *et al.* 1967). Assessment of result reported in the study was based on comparison of the ratio T/C of rainfall over target to that over control sector, relative to the two groups of test days, one 'seeded' and the other 'not-seeded'. The rainfall amounts used in the assessment were 24-hr total rainfall, measured from raingauge network which operated within 25 km around Delhi.

As the actual seeding operation in the experiment has been limited only to 3 to 5 hours in the hot part of the day, result assessed as on the basis of 24-hr total rainfall may not be conclusive. Also as the influence of seeds released from ground-based seed generators is likely to extend beyond 25 km, the area covered by the raingauge network as limited to 25 km is not quite adequate. To meet partly this deficiency of extension in raingauge network and also to help visualise progressive developments in precipitation situation occurring soon after the seeding operation, a 3·2 cm radar has been used since the monsoon season of 1961 for systematic observation of rain incidences in the target and control sectors. Data obtained during the operation period (July to September) of 1961, and from 1963-66 are presented and discussed. The results of measurements of 1962, when the seeding experiment was conducted from aircraft have already been presented by Roy *et al.* (1964).

2. Method of observation

The equipment used is J.R.C. (Japan Radio Company) NMD-451 A radar, operating on wavelength 3·2 cm and having peak power output of 250 KW. It has a beam width of 1° in both azimuth and elevation and is equipped, in addition to the conventional Plan Position (PPI), Range Height (RHI) and Amplitude Modulated Indicators (A-scope), with a special arrangement called Range Elevation Indicator (REI) on which the depth and the range of echo are portrayed in true proportion when scanned at elevation angles between—1° and 90°. Its maximum range is 360 km on PPI, REI and A-scope, and 100 km on RHI. The maximum scanning speed of the antenna is 15 r.p.m. in the horizontal and 5 r.p.m. in the vertical. The RHI is provided with height markers at intervals of 2·5 and 5 km respectively in its 10-km and 20-km height ranges. The overall sensitivity of the radar set is such that it can just detect rain drops of diameter about 0·33 mm at a distance of 100 km, if these are present in concentration of 10 per litre.

The areas covered and the heights reached by the rain echoes in the target and control sectors within 100 km around Delhi, have been measured. For this purpose, hourly radar pictures on PPI depicting progressive developments in the areal echo coverage have been taken, at 1·5° antenna elevation, on all the test days (seeded and not-seeded) when the equipment worked satisfactorily. The total area covered by the radar echoes has been subsequently measured in arbitrary units from these pictures. The heights of the echoes have been measured partly, on the spot, from displays noticed on RHI and partly, subsequently from photographs taken

TABLE 1

Distribution of test days

Year	NW wind		SE wind		Total	
	Seeded	Not-seeded	Seeded	Not-seeded	Seeded	Not-seeded
1961	5 (11)	9 (13)	13 (21)	10 (13)	18 (32)	19 (26)
1963	9 (9)	4 (7)	16 (16)	10 (10)	25 (25)	14 (17)
1964	3 (12)	7 (13)	5 (12)	5 (14)	8 (24)	12 (27)
1965	10 (10)	10 (11)	10 (11)	9 (10)	20 (21)	19 (21)
1966	11 (14)	8 (9)	5 (6)	6 (12)	16 (20)	14 (21)
Total	38 (56)	38 (53)	49 (66)	40 (59)	87 (122)	78 (112)

TABLE 2

Year	Seeded days (s)		T/C(s) (A)	Not-seeded days (n.s.)		T/C(n.s.) B)	A/B	Result	By raingauge A/B	Result
	T	C		T	C					
(a) Area analysis (50 km)										
NW wind										
1961	113	57	1·98	39	40	0·97	2·0	Positive	1·8	Positive
1963	132	72	1·83	178	97	1·84	1·0	Inconclusive	2·0	,,
1964	0	0	Indeterminate	38	83	0·46	Indeterminate	,,	1·1	,,
1965	16	12	1·33	38	40	0·95	1·4	Positive	1·5	,,
1966	52	32	1·62	107	92	1·16	1·4	,,	1·1	,,
Total	66	37	1·78	67	170	0·39	4·6	,,	1·5	,,
SE wind										
1961	50	50	1·00	78	90	0·87	1·1	Positive	2·4	Positive
1963	273	275	0·99	208	249	0·84	1·2	,,	3·4	,,
1964	636	564	1·13	79	81	0·98	1·2	,,	1·6	,,
1965	262	131	2·00	246	226	1·09	1·8	,,	1·6	,,
1966	83	100	0·83	37	45	0·82	1·0	Inconclusive	1·2	,,
Total	230	190	1·21	142	152	0·93	1·3	Positive	1·8	,,
(b) Area analysis (100 km)										
NW wind										
1961	160	65	2·46	76	64	1·19	2·1	Positive		
1963	69	76	0·91	109	87	1·25	0·7	Negative		
1964	36	3	12·00	164	370	0·44	2·7	Positive		
1965	100	61	1·64	206	186	1·11	1·5	,,		
1966	145	86	1·69	320	270	1·19	1·4	,,		
Total	108	68	1·59	181	197	0·92	1·7	,,		
SE wind										
1961	48	43	1·12	35	58	0·60	1·9	Positive		
1963	210	197	1·07	162	184	0·88	1·2	,,		
1964	1701	1412	1·20	566	589	0·96	1·3	,,		
1965	868	547	1·59	509	707	0·72	2·2	,,		
1966	235	216	1·09	187	194	0·96	1·1	,,		
Total	456	353	1·29	258	322	0·80	1·6	,,		

on RHI/REI. The measured values of height have been corrected for beam width.

3. Design of the experiment

Apart from the design of the experiment and details of the seeding operation given in the earlier papers (Roy *et al.* 1961 and Biswas *et al.* 1967), some of the essential points are given here.

Hygroscopic seeds are fed into the lower air layers either by spraying from ground dilute salt solution of known concentration, using power sprayers and air compressors, or by dusting finely powdered salt mixture with the help of air compressors. Fixation of control and target sectors was based on the assumption that a substantial portion of seeds released from ground-based generators would drift in the direction of the mean wind and eventually reach cloud heights. The angular spread of the target area has been assumed to cover the entire 90° quadrant opposite to that in which the mean wind direction lay. The target and control sectors interchanged between the northwest and southeast quadrants depending upon from which of the two opposite quadrants was the mean wind at the station. The choice of the test or seedable day was based on the advice obtained daily from the local weather forecasting office, regarding wind direction, actual or expected cloud conditions and probability of rain occurrence in the region during the next 12 hours. Decision 'to seed' or 'not to seed' on the test days was taken in a randomized manner. Seeding was done on each seeded day for a period of 3 to 5 hours commencing from about one hour before noon, during the monsoon months July to September, in each year.

4. Analysis and results

The method followed for evaluation in the present study is very similar to what has been followed earlier in the case of evaluation by raingauge measurements and is based on a comparison being made of the (1) areal coverage and of (2) height attained by rain cells, as indicated by radar, in the target and control sectors, relative to the two groups of test days, 'seeded' and 'not-seeded'. Assessment was done in the first instance, windwise and later combining the winds. Radar measurements made from one hour after the start of the seeding operation and extending upto 3 hours after the cessation of seeding were taken into account for the purpose of assessment.

Measurements have been made on a relatively small number of days as compared to the total number of test days during the period, on account of frequent equipment breakdowns and other operational difficulties. However, when the total number of 'seeded' and 'not-seeded' days for which measurements are available during the 5 seeding years are considered separately, these are about the same, namely, 87 and 78 respectively. The year-wise break-up of figures for the two category of winds considered is given in Table 1. The figures in brackets denote the total of test days which fell into each category according to the numbers in the random series.

(*a*) *Measurement on areal echo coverage* — The mean areal echo coverage in the target and control sectors for the seeded and not-seeded days are shown in Table 2(a) separately for the two classes of the winds, for 50-km range. The values for the 100-km range are given in Table 2(b). The ratio T/C or the areal echo coverage over target to that over the control sector relative to the two groups of seedable days is given in column 8. The corresponding ratio values of T/C obtained as on the basis of 24-hr total rainfall are given (column 10 in Table 2a) for comparison.

If a higher ratio value of T/C for seeded days compared to that for the not-seeded is considered as suggestive of positive result, trials made in 3 out of the 5 seasons showed positive trend, the remaining having indicated inconclusive trend, as far as wind from the NW sector is concerned. Positive trend of result was indicated in 4 out of the 5 seasons when wind was from SE quadrant. On the 100-km range, positive trend was indicated in 4 seasons and negative trend in one season on days with NW wind. The trend was positive in all the 5 seasons when wind was from the SE quadrant. Combining the winds the result was found to be positive in all the 5 seasons in 50 and 100-km ranges (Table 3 a and b).

Double ratio test — The effect of seeding was evaluated by the double ratio test. If seeded days alone are taken into account, it is equivalent to considering that the experiment has been conducted in two adjacent areas, the area to be seeded being determined by the wind direction because the target and control sectors have been interchanging on these days according to the wind. Designating the sectors as E and W the ratios of areal echo coverage over the eastern to that over the western sector on the east seeded (Ee/We) and on the west seeded (Ew/Ww) occasions for each season and for all the 5 seasons combined are given in Table 4.

The value of the double ratio (Ee/We)/(Ew/Ww), *i.e.*, the ratio of areal coverage in the east area to that in the west area during east-seeded period divided by the similar ratio during west-seeded period, is given in columns 4 and 10 for 50-km and 100-km range respectively. Considering that the expected value of this double ratio is unity if seeding has no effect and that a positive seeding

TABLE 3

Area analysis — Combind wind

Year	Seeded days (s) T	Seeded days (s) C	T/C(s) (A)	Not-seeded days (n.s.) T	Not-seeded days (n.s.) C	T/C (n.s.) (B)	A/B	Result	By raingauge A/B	Result
					(a) 50 km area					
1961	68	52	1·31	60	66	0·91	1·4	Positive	1·9	Positive
1963	222	202	1·10	199	205	0·97	1·1	,,	3·0	,,
1964	398	353	1·13	55	82	0·67	1·7	,,	1·2	,,
1965	139	71	1·96	136	128	1·06	1·8	,,	1·8	,,
1966	62	54	1·15	77	72	1·07	1·1	,,	1·4	,,
Total	158	127	1·24	106	110	0·96	1·3	,,	1·6	,,
					(b) 100 km area					
1961	79	49	1·61	54	61	0·89	1·8	Positive		
1963	159	153	1·04	147	156	0·94	1·1	,,		
1964	1077	882	1·22	315	461	0·68	1·8	,,		
1965	484	304	1·59	349	433	0·81	2·0	,,		
1966	174	127	1·37	262	237	1·11	1·2	,,		
Total	304	228	1·33	221	262	0·84	1·6	,,		

TABLE 4

Area analysis — Double ratio test

Year	Range 50-km Ec/We (P)	Range 50-km Ew/Ww (Q)	Range 50-km P/Q	Range 50-km Result	By raingauge P/Q	By raingauge Result	Range 100-km Ec/We (P)	Range 100-km Ew/Ww (Q)	Range 100-km P/Q	Range 100-km Result
1961	1·98	1·00	2·0	Positive	2·81	Positive	2·44	0·90	2·7	Positive
1963	1·83	1·01	1·8	,,	4·99	,,	0·91	0·94	1·0	Inconclusive
1964	Indeterminate	0·89	Indeterminate	Inconclusive	3·59	,,	12·00	0·83	14·5	Positive
1965	1·33	0·50	2·7	Positive	1·47	,,	1·63	0·63	2·6	,,
1966	1·62	1·20	1·4	,,	0·86	Negative	1·69	0·92	1·8	,,
Total	1·78	0·83	2·1	,,	2·65	Positive	1·75	0·79	2·2	,,

effect would increase with both the numerator factors without affecting the denominator, it is seen from the table that trials made in 4 seasons indicated positive trend of result and in 1 season inconclusive trend. The corresponding values of the double ratio as obtained by analysis of 24-hr rainfall amounts are given in column 6 for comparison.

(*b*) *Height analysis* — As the data collected on heights attained by rain echoes have been more sparse than on real echo coverage, the height evaluation has been done only for 100-km range. The mean heights in km attained by the echo in the target and control sectors, on seeded and not-seeded days, is given in Table 5 for the two classes of winds separately and also combined.

TABLE 5

Height analysis

Year	Seeded days (s) T	Seeded days (s) C	T/C(s) (A)	Not-seeded days (n.s.) T	Not-seeded days (n.s.) C	T/C (n.s.) (B)	A/B	Result
				NW wind				
1961	6·6	8·0	0·83	7·1	5·6	1·27	0·7	Negative
1963	6·5	6·5	1·00	6·3	6·2	1·02	1·0	Inconclusive
1965	5·9	5·8	1·02	6·2	5·3	1·17	0·9	Negative
1966	5·5	6·1	0·90	6·4	6·2	1·03	0·9	,,
Combined	6·2	6·5	0·95	6·6	5·7	1·16	0·8	,,
				SE wind				
1961	6·6	6·2	1·06	6·6	6·1	1·08	1·0	Inconclusive
1963	5·8	6·4	0·91	8·3	7·6	1·09	0·8	Negative
1964	9·8	12·1	0·81	8·5	7·8	1·09	0·7	,,
1965	8·0	7·8	1·03	8·5	7·1	1·20	0·9	Inconclusive
1966	4·8	5·1	0·94	5·6	6·2	0·90	1·0	,,
Combined	6·6	6·9	0·96	7·6	7·0	1·09	0·9	Negative
				Combined wind				
1961	6·5	6·0	1·08	6·9	6·6	1·05	1·0	Inconclusive
1963	6·0	6·4	0·94	7·6	7·2	1·06	0·9	Negative
1965	7·3	7·2	1·01	7·6	6·2	1·23	0·8	,,
1966	5·3	5·8	0·91	5·8	6·2	0·94	1·0	Inconclusive
Combined	6·5	6·5	1·00	7·3	6·6	1·11	0·9	Negative

TABLE 6

Volume analysis (100 km)—Combined wind

Year	Seeded days (s) T	Seeded days (s) C	T/C(s) (A)	Not-seeded days (n.s.) T	Not-seeded days (n.s.) C	T/C (n.s.) (B)	A/B	Result
1961	513·5	294·0	1·75	372·6	402·6	0·93	1·9	Positive
1963	954·0	979·2	0·97	1117·2	1123·2	0·99	1·0	Inconclusive
1965	353·3	2188·8	1·61	2652·4	2684·6	0·99	1·6	Positive
1966	922·2	736·6	1·25	1519·6	1469·4	1·03	1·2	,,
Total	1960·8	1482·0	1·32	1613·3	1729·2	0·93	1·4	,,

The results of analysis showed negative trend in 3 seasons and inconclusive trend in 1 season for days with wind from NW sector. The result for the monsoon season of 1964 could not be evaluated in this manner because of lack of height measurements on seeded days. As far as wind from the SE sector is concerned the analysis showed negative trend in 2 seasons and inconclusive trend in 3 seasons. Combining both the winds and omitting 1964, the trend of result is negative in 2 seasons and inconclusive in 2. Considering all the 4 seasons together the trend of result is nagative.

Analysis of the product values of the mean echo area and mean echo height, which may be roughly representative of the mean echo volume (Table 6), indicated positive trend in 3 seasons and inconclusive trend in 1 season.

5. Discussion

Evaluation by radar, based on measurements made on areal echo coverage, indicated positive trend of result in all the 5 seasons considered. The result, on the basis of raingauge data, is also positive in all these 5 seasons (*vide* figures under column 10 in Table 2a). The order of magnitude of the ratio T/C over target to that over control sector relative to the two groups of seedable days, is the same when considered either on the basis of radar data or raingauge data (*vide* figures in columns 8 and 10 of Tables 2a and 3a). If it is hypothesized that the amount of water rained out is roughly proportional to the area of the precipitating cloud, the positive trend and result indicated by the radar analysis lends support to the findings based on the 24-hr rainfall amounts, suggesting that the seeding operation has caused definite enhancement of rainfall in the area. Also, the radar analysis suggests that the positive seeding effect indicated by the raingauge network within 25 km extends well beyond.

Findings on the basis of mean height analysis have pointed out inconclusive or negative trend of result. It is not clear whether in an experiment of the present type, where it is intended to correct only possible deficiencies in the concentration of giant hygroscopic aerosols in the cloud air, an increase in the average height of the precipitating cloud is what is to be sought as indicative of positive result. Howell (1960) points out greatly accelerated growth and activity having been reported accompanying the onset of rain following efforts at stimulation of convective clouds. According to Howell and also as noticed by Ramana Murty and Biswas (1961) the feature seems to be a frequent accompaniment of shower development whether stimulated or not. Explanation for such phenomenon has been sought in the increase of cloud buoyancy as a result of removal of a mass of water from the body of the cloud.

No doubt, in experiments in which cloud modification is carried out by introducing ice-forming nuclei in large numbers into cloud air, the latent heat released as a result of freezing of a portion of super-cooled droplets may sometimes bring about an enhancement of the height of the cloud (Simpson *et al.* 1967). Favourable conditions for influencing cloud dynamics in this manner by triggering release of latent heat of fusion, through introduction of artificial ice nuclei exist by virtue of the small amount of liquid-water super cooled present in the cloud. Conditions are not very similar in the case of warm-cloud seeding. Considering that the vapour supersaturation in natural clouds is rarely greater than about 1 per cent — this is on account of the abundance of natural condensation nuclei present in the atmosphere—prospects to influence cloud dynamics through release of latent heat of condensation of supersaturated vapour by addition of condensation nuclei are not bright. The seeds released in the case of warm cloud seeding would be comparatively few in number and also, in the case of ground-based seed generators, the giant size hygroscopic aerosols released from surface air layers would be formed into droplets (these to become raindrops later) much before these would have actually entered into the cloud. It is considered, therefore, that the negative trend of result indicated by the method of echo height analysis does not contradict the positive trend of result shown by analysis based either on areal echo coverage or on 24-hr rainfall amounts. However, the meaning of the observed decrease in height of rain cells in the target on seeded days is not clear.

6. Conclusion

Assessment by radar alone or by raingauge network alone is not conclusive. Wherever possible, the assessment should be carried out by both the methods because one is complementary to the other. Judged by the limited data as available by radar in the present experiment, it is seen that cloud seeding by salt particles produces positive effects in and around the Delhi region. However, as the assessment made is only qualitative in nature it does not help confirm that the natural rain over the area, as a result of seeding, has increased by the specified amount indicated by analysis based on 24-hr rainfall amounts. For this purpose, the radar used should be equipped with a rain measuring device.

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