

"REVIEWED"

11-YEAR WARM CLOUD SEEDING EXPERIMENT IN MAHARASHTRA STATE, INDIA

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Abstract. A warm cloud modification experiment was carried out during the 11-summer monsoon (June - September) seasons (1973-74, 1976, 1979-86) using a double-area cross-over design with area randomization. An instrumented aircraft was used for the cloud physical measurements and seeding. Finely pulverized salt (sodium chloride) particles were released into the monsoon clouds (stratocumulus and cumulus) during aircraft penetrations into the clouds at a height of 200-300 m above the cloud-base. The warm cloud responses to salt seeding were found to be critically dependent on the cloud physical characteristics e.g., vertical thickness and the liquid water content. When clouds having (i) vertical thickness > 1 km, and (ii) LWC $> 0.5 \text{ g m}^{-3}$ were seeded with salt particles (modal diameter $10 \mu\text{m}$, concentration 1 per liter of cloud air) produced increase in rainfall of 24 per cent significant at 4 per cent level. The cloud physical observations made in not-seeded (control) and seeded (target) clouds have apparently provided some useful evidence to illustrate the possibility that the hygroscopic particle seeding might accelerate the collision-coalescence process.

1. INTRODUCTION

Two major randomized warm cloud seeding experiments were carried out in India. The first experiment (from hereafter called Exp-I) was carried out during the summer monsoon seasons of 1957-66 in the Delhi, Agra and Jaipur regions of northwest India. The results of the statistical analysis of Exp-I, indicated an increase in rainfall on seeded days, on the average, by about 20 per cent significant at less than 0.5 per cent level. (Biswas et al., 1967, Ramanamurty and Biswas, 1968). The Exp-I has apparently provided the statistical evidence to show that salt seeding may have modified the precipitation in spite of other limitations, e.g., ground-based generators used for seeding, lack of the physical evidence in support of the seeding hypothesis persuasive of the statistical evidence of the increases in precipitation over an area. These limitations have

been discussed by some (Mason, 1971; Warner, 1973; Cotton, 1982).

In order to verify the statistical results obtained from Exp-I and to obtain the requisite physical evidence for the warm cloud seeding hypothesis, a well designed randomized "Warm Cloud Modification Experiment" with good cloud physical measurements program was carried out in Maharashtra State during the 11-summer monsoon seasons (1973-74, 1976, 1979-86). From hereafter this second Indian cloud seeding experiment is referred to as Exp-II. A DC-3 aircraft instrumented for cloud physical measurements was used for seeding and physical measurements. The physical processes involved in the initiation and development of rain in warm clouds are condensation collision-coalescence, and break-up. The concept of warm cloud modification to increase rainfall is based on the modification of rain processes through seeding the clouds with a hygroscopic material thereby tapping the potential precipitation efficiency of the cloud systems. The physical measurements carried out in not-seeded (control) and seeded (target) clouds were used for documenting the warm cloud responses to

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seeding (physical evaluation). The results of the studies carried out as a part of Exp-II are presented in this paper.

2. EXPERIMENT

2.1 Area and Meteorological Conditions

The experimental area was located on the lee-side of the Western Ghats in the Deccan Plateau region at about an altitude of 550 m located at about 40 km east of Pune (18°32'N, 73°51'E, 559 m m.s.l.) and about 120 km from the west coast at Bombay. The experimental area is perpendicular to the westerly monsoon flow. About 80 per cent of the annual rainfall in the region is received during the summer monsoon season (June - September). Rain seems to fall primarily from clouds with tops below 3 to 4 km. Once the monsoon is established, the cumulonimbus clouds are practically absent. The freezing level in the experimental area during the summer monsoon months is at about 6 km and a large majority (more than 90 per cent) of the clouds do not extend higher than 5 km (Pramanik and Koteswaram, 1953). Hence, the dominant rain-forming process in these clouds was the collision-coalescence and break-up. There were apparently a number of occasions when the warm cumulus clouds forming in the region did not give any rain.

2.2 Design

A cross-over design having two sectors with a buffer in-between was adopted. The three sectors were designated as North (N), South (S), and Buffer (B) sectors (Figure 1). The area of each sector was 1600 km². In the cross-over design, paired target areas were set-up and one area was seeded at random (area randomization); in each test event, the unseeded area serving as the control for that event. The data are obtained in the form of two series. One of the two areas was kept as target in a series and the other acted as control and vice-versa for the other series. The effect of seeding was obtained from the root double ratio (RDR), expressed as

$$RDR = \left(\frac{N_S}{N_{NS}} \times \frac{S_S}{S_{NS}} \right)^{1/2} \dots\dots\dots(1)$$

where N and S denote the average rainfall in the North and South sectors and the subscripts S and NS denote the seeded and not-seeded days respectively. When the North area (N) is allocated for seeding (target) correspondingly the South area (S) is

allocated for not-seeding (control). Before the commencement of the experiment in each year a series of random numbers (Fisher and Yates, 1953) was taken and used for allocation of the seeding of the North and the South sectors. Each series used for the experiment in any year was subjected to randomization tests for avoiding any possible bias due to the repetition of the series. In an experiment of sufficient duration the root double ratio provides an estimate of the factor by which the mean rainfall has been increased by seeding. The expected value would be close to 1.0 if the seeding has no effect.

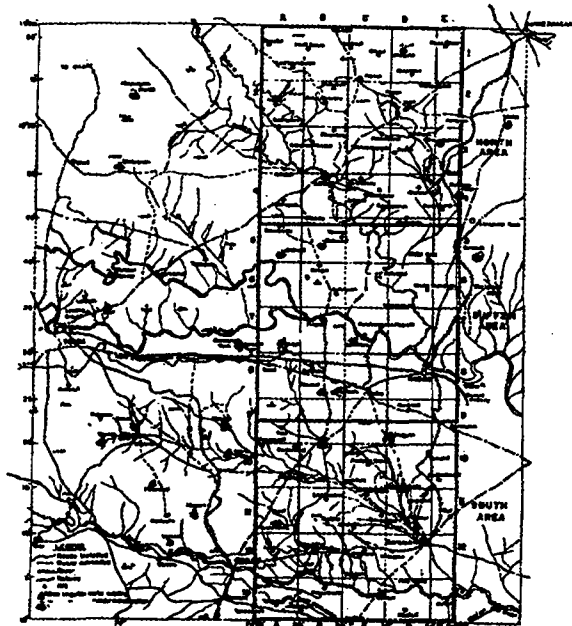


Fig. 1. Experimental area.

2.3 Rain Gauge Network

In the Experimental area 90 standard type meteorological rain gauges were installed and their distributions in the three sectors of the Experimental area were as follows : North sector (36), South sector (34) and Buffer (20). The above rain gauge network was installed and maintained by the India Meteorological Department (IMD). The 24-hour daily rainfall data recorded by these rain gauges were obtained by the IMD. After scrutiny checks for the reliability of the rainfall data by the IMD, the data were supplied to the Institute for the statistical analysis and evaluation of the results of the Experiment. The 24-hour rainfall measured from 0830 AM of the given day (seeded) to 0830 AM of the next day was used in the analysis. Various investigators envisage the possible after effects of seeding and therefore, the inclusion of the night

following a day with seeding does not seem objectionable (Neyman, 1980).

2.4 Seedable Days

The classification of the seedable days has been based on the following criteria : (i) forecast amount of low clouds (ii) forecast winds, (iii) special radiosonde observations carried out at Pune a few hours before the commencement of actual seeding, (iv) current weather conditions particularly with respect to cloud formation and development as inferred from the synoptic charts, (v) meteorological debriefing reports obtained from the aircraft reconnaissance flights in the region, (vi) special current weather observations recorded at two stations (Ahmednagar in the North sector and Baramati in the South sector) in the experimental area, 4-6 hrs. before the commencement of the actual seeding. A day was considered seedable when the forecast amount of low clouds was 3 Okta or more, westerly wind with speed not exceeding 20 knots up to a height of 3 km m.s.l., relative humidity was more than 75 per cent in the lower atmosphere (up to 700 hP) and the synoptic conditions were favorable for the formation of low-clouds in one or more of the cases at (iv), (v) and (vi).

3. SEEDING METHODOLOGY

3.1 Seeding Aircraft and Instruments

The aircraft used for seeding was a Dakota (DC-3) which was fitted with the seeding equipment (Figure 2) and several instruments for obtaining the cloud physical observations.



Fig. 2 : Instrumented aircraft (DC-3) used for seeding and cloud physical measurements.

The seeding equipment consisted of a funnel fitted inside the aircraft. The funnel was coupled through a venturi, to a dispensing duct assembly fitted to the fuselage of the aircraft (Figure 3). The funnel ends in an adjustable slit which was operated by a calibrated mechanical gate valve arrangement fitted inside the aircraft. The funnel accommodated 150 Kg of the seeding material at a time.

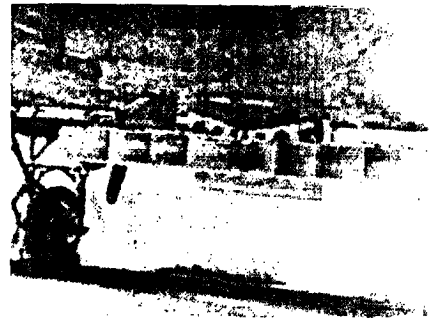


Fig. 3 : Seeding equipment (rear view) fitted to the fuselage of the aircraft.

The seeding equipment operated due to the pressure developed inside the venturi during the aircraft flight. Also, at the base of the funnel, just above the slit, an agitator operated at 300 r.p.m.; was fitted for facilitating free flow of the salt seeding material. The rate of dispersal of the salt mixture was adjusted to any value between 0 and 30 kg per minute or 0 to 30 kg per 3 km of the aircraft flight path. The cruising speed of the aircraft was about 180 kmph. A photograph of the plume of the seeding material released from the aircraft into the clear air is shown in Figure 4.

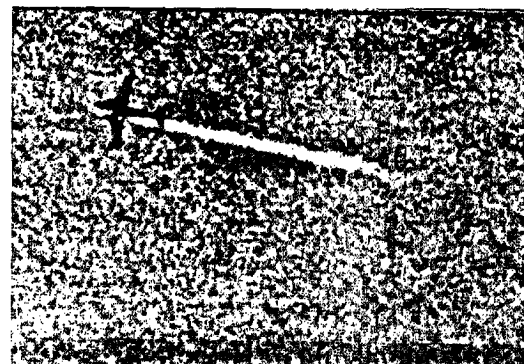


Fig. 4 : Plume of the seeding material released from the aircraft into the clear air.

The details of the instruments fitted to the aircraft for making cloud physical measurements in

seeded (target) and not-seeded (control) clouds are furnished in Table 1.

S.No.	Parameter	Type and make of instrument	Principle of operation	Range
1.	Aitken nuclei	Optical, Gardener Associates, USA	Light scattering by cloud droplets formed on nuclei in a highly super-saturated chamber	$10^3 - 10^6 \text{ ml}^{-1}$
2.	Cloud Condensation nuclei	Optical, Indigenously developed	Estimation of concentration of cloud droplets formed in a cloud chamber	$10 - 10^3 \text{ ml}^{-1}$
3.	Giant condensation nuclei	Cascade Impactor, Casella, UK	Impaction of nuclei on glass slides	$10 - 10^3 \text{ ml}^{-1}$
4.	Cloud droplet size distribution	Impactor Indigenously developed	Impaction and replication of cloud droplets on Magnesium oxide/soot coated glass slides	$10 - 10^3 \text{ ml}^{-1}$
5.	Cloud liquid water content	Hot-wire meter, Johnson Williams, USA	Resistance variation caused by cooling due to impaction of droplets	$0-6 \text{ gm m}^{-3}$
6.	Vertical air velocity	Variometer, Ball Engineering, USA	Ultrasensitive pressure Altimeter	$\pm 20 \text{ ms}^{-1}$
7.	Temperature	Platinum Resistor, Rosemount, USA	Measurement of micro-variations in the resistance of the platinum wire	$-60 \text{ to } +40^\circ\text{C}$
8.	Dew point temperature	Optical, E. G & G, Cambridge, USA	Light scattering by dew formed on thermoelectrically cooled mirror	$-50 \text{ to } +50^\circ\text{C}$
9.	Pressure altitude	Pressure altimeter Indigenously Developed	Ultrasensitive pressure altimeter	$10^3 \text{ to } 10^2 \text{ mb}$
10.	Vertical component of atmospheric electric field	Cylindrical field mill Indigenously developed	Measurement of static charges	$10 - 10^3 \text{ vm}^{-1}$
11.	Cloud / rain drop charge	Double sheath induction ring indigenously developed	Measurement of variations in the capacitance of the induction ring	$10^{-14} \text{ to } 10^{-12} \text{ coulombs}$
12.	Electrical conductivity	Gerdian tube indigenously developed	Measurement of static charge on Insulated conductor	$10^{-14} \text{ to } 10^{-12} \text{ ohm}^{-1} \text{ m}^{-1}$

S.No.	Parameter	Type and make of instrument	Principle of operation	Range
13.	Corona discharge current	Static discharger indigenously developed	Measurement of corona Current	-1 to + 1 μ A
14.	Cloud water	Impactor indigenously developed	Impaction of rain drops	---
15.	Rain water	Impactor indigenously Developed	Impaction of raindrops	---
16.	Cloud photography	Time lapse camera	Photography	---
17.	Data recording	Data logger consist-ing of electronic equipment and multi-channel recorder	--	---

The cloud physical parameters were recorded using a data logger consisting of electronic equipment and a multichannel recorder. Additionally visual observations and cloud photography were also carried out to document the important cloud conditions during the experiment.

3.2 Seeding Material and Methodology

The seeding material consisted of finely pulverized mixture of sodium chloride (salt) and soapstone (hydrated silicates and carbonates of magnesium) in the ratio 10:1. The median particle mass is approximately 10^{-9} g corresponding to a dry particle diameter of 10 μ m. Analysis of the salt particle size distribution indicated that about 75 per cent of the particles had diameters less than 10 μ m. The salt seeding material was released into the clouds during the aircraft penetrations at a height of 200 - 300 m above the cloud-base. The level of aircraft flights was maintained constant during the seeding operations. The rate of seeding as stated above varied between 0 and 30 kg per 3 km aircraft flight path depending on the density of clouds in target area and their vertical thickness. Higher rates of seeding were used to seed clouds with greater vertical thickness. Two types of seeding techniques were adopted depending on the type of distribution of clouds present in the experimental area on any day of the experiment. The details of the two types of seeding techniques follow.

On any seedable day, when the experimental area was covered with a large number of stratocumulus and cumulus clouds having vertical thickness of 1 km or more and cloud liquid water content of 0.5 g m^{-3} or more as recorded by the JW hot wire instrument, all the clouds present in the

target area were seeded. On these days of the experiment, about 1000 kg of the seeding material was released into the clouds at a slow rate (10 kg per 3 km flight path) so as to treat as many clouds as possible. As most of the clouds in the target area were seeded, it was designated as the 'Area Seeding Technique'. The estimated concentrations of the salt particles artificially released into the clouds during their seeding on the area seeding days could be 1-10 per liter of cloud air. These estimates were based on (i) computations of the dispersion of the salt particles in the plume (Figure 4) released from the aircraft in clear air at the cloud-base level (about 2 km m.s.l.) and direct measurement of the concentrations of the giant size condensation nuclei (GCN) with time along the path of the aircraft.

The flight path followed on area seeding days was in the form of a loop covering the 40 km width of the target area in about 12 longitudinal tracks e.g., 6 tracks during the forward direction and 6 tracks during the return direction of the aircraft flight covered in the target area (Figure 5).

On any seedable day when the experimental area was covered with a few isolated cumulus clouds, a pair of clouds of nearly same physical characteristics (vertical thickness of 1 km or more and liquid water content of 0.5 g m^{-3} or more) were selected for the experiment. Out of the two clouds of the pair, one of the clouds was selected by random choice (target cloud) and repeatedly seeded. The neighboring cloud was designated as the control cloud. Identical cloud physical measurements were carried out in both the target and control clouds by making the same number of repeated aircraft penetrations at a height of about 200 - 300 m above the cloud-base. The number of traverses made in such

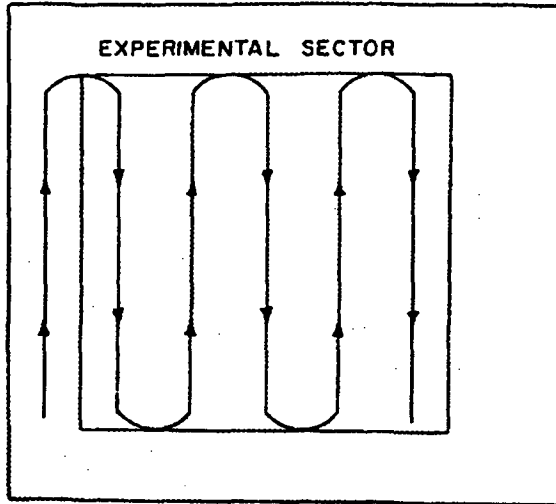


Fig. 5 : Aircraft flight path followed on area seeding days.

pairs of clouds varied from 5 to 10. The target cloud was seeded with massive doses of salt. The maximum amount of seeding material used for seeding these individual target clouds varied from 700 to 1000 kg.

In some of the cold cloud seeding experiments, the concentration of AgI in the precipitation was used to study the seeding effects (Hess, 1974). Similarly, it was desirable to evaluate the variations noticed in the Cl and Na ion concentrations in the cloud and the rain water samples collected from the not-seeded (control) and the seeded (target) clouds. Hence, cloud and rain water samples were collected during the experiment

using a specially designed equipment installed on the top of the aircraft. The equipment was fabricated using a high quality stainless steel sheet and the details were reported elsewhere (Khemani et al., 1982). Cloud and raindrops were collected by the impaction technique on a specially designed honeycomb arrangement in the gadget. The gadget was cleaned thoroughly by flushing it with double distilled water repeatedly before the aircraft flight every day and the cloud and rain water samples were collected separately in clean polyethylene bottles. The water samples were stored in the refrigerator till they were analyzed in the laboratory for the Cl and Na ion concentrations using the standard analytical methods (Khemani et al., 1987). The cloud water samples were collected from the initial penetrations into the clouds when no precipitation was observed. The rain water samples were collected from the precipitating clouds by flying the aircraft below the cloud base i.e., penetrating through the rain shaft. The cloud and rain water sampling equipment was installed on the top of the aircraft above the cockpit and the seeding gadget was fitted to the belly of the aircraft towards its tail portion. Hence, there is no possibility of the dry salt particles, entering the cloud water sampling gadget while collecting samples from the target clouds.

4. RESULTS AND DISCUSSION

4.1 Statistical Evaluation of Rainfall

The rainfall data relating to area cloud seeding technique have been analyzed and the results of the 11-year experiment are shown in Table 2.

Table 2. Average rainfall (mm) in the target and control sectors during different years and results of the rainfall analysis.

Sr. No.	Year	Number of days of experiment		North seeded		South seeded		RDR	
		Year-wise	Cumulative	Target T1	Control C1	Target T2	Control C2	Year-wise	Cumulative
1.	1973	16	16	40.18	18.97	54.35	91.86	1.12	1.12
2.	1974	12	28	43.11	22.31	19.37	19.26	1.39	1.16
3.	1976	24	52	41.73	27.35	19.66	13.37	1.50	1.17
4.	1979	10	62	46.82	30.01	71.47	68.78	1.27	1.22
5.	1980	16	78	27.88	19.84	17.37	8.02	1.74	1.24
6.	1981	20	98	42.64	22.63	21.29	30.89	1.14	1.23
7.	1982	14	112	6.45	2.14	0.60	0.24	2.74	1.24
8.	1983	10	122	5.72	4.37	3.27	1.22	1.87	1.24
9.	1984	10	132	10.20	6.20	32.70	17.55	1.75	1.28
10.	1985	10	142	15.76	26.23	11.41	4.36	1.25	1.24
11.	1986	18	160	10.13	2.47	1.70	5.93	1.08	1.24

The cumulative root double ratio (RDR) was computed using the following equation.

$$RDR = \left(\frac{\sum N_S}{\sum N_{NS}} \times \frac{\sum S_S}{\sum S_{NS}} \right)^{1/2} \dots\dots\dots(2)$$

The results relating to the 160 days of the area seeding experiment indicate a 24 per cent increase in rainfall significant at a 4 per cent level. The statistical significance of the root double ratio values was evaluated using the Man-Whitney test (Siegel, 1956). In 5-years of Exp-II the root double ratio was 1.24 and thereafter remained stable during the remaining 6-years of the experiment. The results of the numerical simulation of the cloud seeding experiment carried out using the historic rainfall data of 32 rain gauge stations located in the region of Exp-II (Mary Selvam et al., 1979) also suggested that a 20 per cent increase in rainfall due to seeding could be detected during a 5-year Experiment with an 83 per cent probability of detection. The results of the rainfall analysis of Exp-II and the results of the numerical simulation of the cloud seeding experiment are in agreement i.e., an increase in rainfall of 24 per cent could be detected in a 5- year experiment.

The warm cloud responses to salt seeding were found to be critically dependent on the physical characteristics of the clouds particularly with respect of the vertical thickness (greater than 1 km or more) and the cloud liquid water content (greater than 0.5 g m^{-3} or more). When the experimental area was covered with such clouds and all of them were seeded their response to seeding was found to be positive. Shallow clouds (vertical thickness $< 1 \text{ km}$ and $\text{LWC} < 0.5 \text{ g m}^{-3}$) when seeded showed a tendency for dissipation. A photograph depicting the cloud distribution in the experimental area on a typical area seeding day is shown in Figure 6. One of the clouds shown by an arrow in Figure 6 developed rain in 20 minutes following seeding and the photograph of the raining cloud is shown in Figure 7. The fallstreak of the raining cloud is seen clearly in the photograph.

The results presented in Table 2 suggest that the value of the root double ratio during the year of the lowest rainfall, namely, 1982, was very high. The monsoon rainfall in the Indian region during 1982 was deficient and it was classified as a drought, the rainfall variability would be very large particularly in the semi-arid region where the experimental area is located. The anomalous value of the root double ratio

observed during 1982 was due to the large variability in rainfall associated with drought. Also, a critical



Fig. 6 : Cloud distribution in the experimental area on a typical area seeding day. One of the seeded clouds which developed rain following seeding is shown by the arrow.

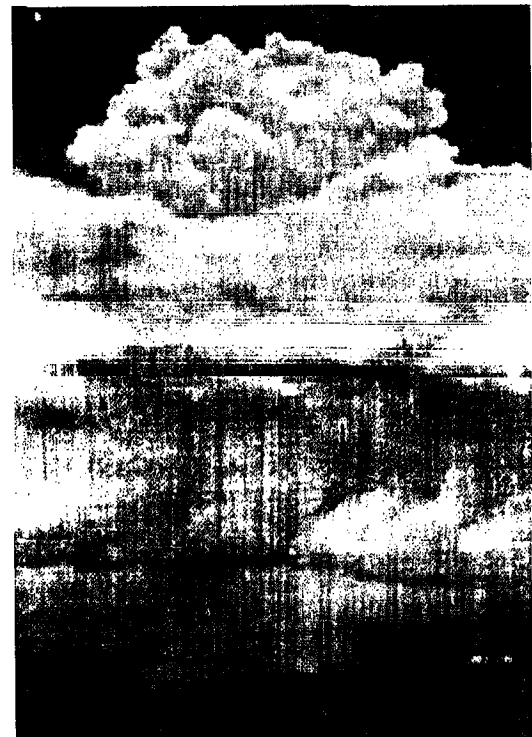


Fig. 7 : Seeded cloud which developed rain following seeding in 20 minutes. Fallstreak of the raining cloud is clearly seen in the photograph.

examination of the monsoon rainfall in the Indian region during 1982 was deficient and it was classified as a drought year by the India Meteorological Department. When their average values of the rainfall in the target and control sectors showed greater consistency on the North seeded days as compared to those on South seeded days. This could be due to the variability in the rainfall of the North and South sectors. However, this would not affect the cumulative root double ratio as explained in the following.

The cross-over design used for the experiment minimizes the noise of the natural variability because the fluctuations of the rainfall in the seeded area, to some extent, get neutralized by the parallel fluctuations in the highly correlated control areas. Historic rainfall data were available for 6 raingauge stations located three each in the North and South sectors of the experimental area prior to the commencement of Exp-II. The correlation coefficient of the 24-summer monsoon rainfall (1946-62 and 1964-70) between the North and South sectors was found to be 0.7, significant at 0.1 per cent. Also, a pairwise randomization scheme was adopted with the cross-over design for preventing possible chain of seeding events over the same area, to mitigate the persistence effect and thus prove its sensitivity and efficiency (Moran, 1959). This design is considered to be the most efficient and requires a high correlation between the rainfall of the target and control areas. The provision of the buffer area of the same size as the target and control areas would help to avoid possible effects due to contamination. The highly correlated rainfall in the North and South sectors and the double cross-over design with pairwise randomization scheme used for the experiment could be the factors responsible for the stable root double ratio, observed in 5 years of the experiment.

The area seeding clearly was intended to increase the rainfall in the target area. The isolated single cloud experiments were intended to compare the physical changes in seeded and not-seeded clouds. Hence, the single cloud experiments were not evaluated for rainfall changes.

4.2 Aircraft Cloud Physical Observations

The variations noticed in the cloud physical parameters recorded in the target and control clouds

were used for the physical evaluation of the warm Cloud responses to salt seeding. The results of the analysis of the cloud physical observations are presented in the following.

The concentrations of GCN with diameter greater than $10 \mu\text{m}$ were measured using the Casella cascade impactor. The details of the sampling, analysis of the size distributions and retrieval of the dry particle size of the GCN were reported elsewhere (Ramana Murty et al., 1962). The GCN observations made in the 46 pairs of control and target clouds suggested that their concentrations were found to be 2.8 (standard deviation 1.2) and 5.0 (standard deviation 2.3) per liter, respectively. Aircraft measurements made in clear air at the cloud-base levels (2 km m.s.l.) in the region suggested that the background concentration of GCN was about 2.0 l^{-1} . These observations indicate that the concentration of GCN in the target clouds was higher by about 2 particles per liter. The GCN could be of great importance in the initial development of precipitation-size-drops (Woodcock, 1952; Johnson, 1982; Caylor and Illingworth, 1987).

The cloud droplet spectra obtained from 50 pairs of the control and target clouds were analyzed and the time variations noticed in the control and target clouds are shown in Figures 8 and 9 respectively. The cloud droplet spectra obtained in

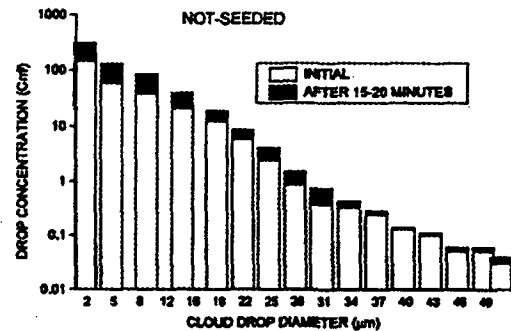


Fig. 8 : Average cloud drop size distributions measured about 200 m above the cloud base in not-seeded clouds. The distributions obtained during the initial penetrations were compared with those obtained during the subsequent penetrations (after 15-20 minutes).

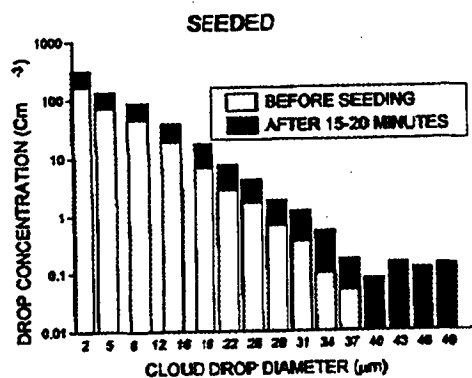


Fig. 9 : Same as Fig. 8 for seeded (target) clouds.

the first aircraft penetration were compared to those obtained after 15-20 minutes following seeding and the drop spectra in control and target clouds showed statistically significant differences. The cloud drop concentration in all the size groups showed an increase with time. In control clouds, large drops (with diameters greater than 40 μm) were present in the initial sampling whereas they were absent in target clouds. The above differences in the concentration of large drops in control and target clouds could probably be due to the differences in the lifecycles of the control and target clouds at the time of the initial penetrations. However, the increase noticed in the concentration of the large drops in target clouds is significantly marked as compared to that observed in control clouds. The average Median Volume Diameter (MVD) in control clouds increased from 9.8 to 10.0 μm and in target clouds it increased from 8.7 to 11.7 μm .

The increase observed in cloud drop concentration with time may be due to the following reasons. The droplet concentration is determined, primarily, by the cloud nucleus concentration in the subcloud air and the mixing processes. Also, there is a strong tendency for high liquid water content to be associated with higher-than-average droplet concentration in any particular horizontal traverse (Warner, 1979). Simultaneous observations of cloud liquid water content (LWC) made using the JW hot wire instrument in 60 pairs of control and target clouds during Exp-II suggested that the values of the LWC were found to be respectively 0.6 g m^{-3} and 1.0 g m^{-3} . The increase in the cloud drop concentration noticed in the present study could be attributed to the higher values of the LWC ($> 0.5 \text{ g m}^{-3}$) observed in the clouds. Also, the simultaneous measurements of the vertical air velocity and temperature in control and target clouds during the experiment suggested an

association between the LWC, vertical velocity and the temperature in any particular horizontal traverse. The above observations are in agreement with those reported by other investigators (Warner, 1955; Squires, 1958; Telford and Warner, 1962).

Recent observations of the cloud drop spectra made in the continental clouds using a Forward Scattering Spectrometer Probe (FSSP) suggested that the spectra in cloud base following hygroscopic seeding showed substantial decrease in the total concentration and a corresponding increase in the sizes of the largest drops (Cooper et al., 1997). The above observations were carried out using a high speed aircraft (Learjet) which introduces some uncertainty into measurements of sizes from the FSSP (Cooper et al., 1997). The above result is different from that observed in the present study which may be attributed to the differences in the physical characteristics of the clouds (maritime versus continental) and sampling techniques used for the observations. In the present study the data were retrieved from the sooted glass sampling slides exposed to drops in clouds with an impactor which has low collection efficiency particularly for the smaller size drops. The details of the impactor, sampling and data retrieval were reported elsewhere (Clague, 1965, Paul et al., 1985). However, the results of the theoretical computations relating to the maritime cloud cases (Cooper et al., 1997) suggested an increase in the total cloud droplet concentration following seeding which are in agreement with the present study i.e., the observed increase in the concentration of cloud drops in the target clouds following seeding.

The results of the chemical composition of cloud and rain water samples collected from the not-seeded (control) and seeded (target) clouds are presented in Table 3. The Cl and Na ion concentrations are significantly higher in the target clouds suggesting that the giant size salt particles released into the target clouds may have entered the lifecycle of the warm rain process.

The higher concentrations of GCN, large size cloud drops (diameter $> 40 \mu\text{m}$), increases in the Median Volume Diameter (MVD), LWC, vertical velocity observed in target clouds may perhaps provide the physical evidence to support the possibility that hygroscopic particle seeding might accelerate the collision-coalescence process. The GCN can play an important role in precipitation initiation in warm clouds when injected in developing clouds, these particles will produce a tail of large drops on the upper end of the droplet distribution. In

Table 3. Chemical composition of cloud and rain water samples collected from not-seeded and seeded clouds			
Clouds sampled	No. of samples	Ionic concentration (mg l ⁻¹)	
		Cl	Na
Cloud water			
Not-seeded (control)	42	6.3 (3.4)*	3.5 (3.2)
Seeded (target)	42	23.5 (6.0)	14.3 (3.2)
Rain water			
Not-seeded (control)	53	3.2 (0.7)	1.9 (0.2)
Seeded (target)	42	10.2 (1.2)	4.5 (0.6)

Figures in brackets indicate the standard deviation.

a favourable environment, this tail of large drops is capable of rapid growth to precipitation sizes (Johnson, 1982). Also, the GCN concentration seems associated with the appearance of the raindrops without invoking complex mixing processes with the clouds (Caylor and Illingworth, 1987).

5. CONCLUSIONS

The results of the 11-year Indian warm cloud modification experiment have suggested that warm cloud responses to seeding are critically dependent on the cloud vertical thickness and measured liquid water content (LWC). Clouds with vertical thickness greater than 1 km, LWC greater than 0.5 g m⁻³ when seeded with salt particles (modal size 10 µm; concentration 1 per liter of cloud air) produced increase in rainfall of 24 per cent significant at a 4 per cent level. The cloud physical observations made in not-seeded (control) and seeded (target) clouds have apparently provided some useful evidence to illustrate the possibility that the hygroscopic particle seeding might accelerate the collision-coalescence process.

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