DESIGN AND EVALUATION OF HYGROSCOPIC SEEDING OPERATIONS IN ANDHRA PRADESH, INDIA

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Abstract. Hygroscopic seeding operations were carried out in twelve districts of Andhra Pradesh, India from 2003 to 2008. The operations were carried out in both the southwest and northeast monsoon periods for a period from June to November. These operations were carried out with the help of two C-band radars and two pressurized aircraft. The present paper attempts to summarize the results of the operations being carried out and also evaluate these results. Statistical methods are used to estimate the percentage increase in the rainfall that could have occurred due to seeding operations. In the present context, regression equations, double ratio method, impact coefficient, target control and downwind comparisons are used to arrive at the percentage increase in rain mass over this region. A total of 2200 seeding sorties were carried out and this study presents the summary of 1600 sorties which were analyzed using various statistical software packages.

1. INTRODUCTION

Cloud seeding operations have been undertaken in 12 Rain Shadow Area Districts (RSAD) in the state of Andhra Pradesh, India for the years 2003 to 2008. The operations were carried out with the help of two radars and two pressurized aircraft for an average of 120 days every year. These operations are essentially carried out in the monsoon period, typically June to November covering both the Southwest Monsoon and Northeast Monsoon seasons. Evaluation of weather modification programs is difficult because no two clouds or even two storm systems are exactly the same, and one cannot simply compare the seeded and unseeded clouds and then observe the differences. Evaluations on a cloud or storm basis are possible using several methods like statistical–double ratio method, regression analysis, impact coefficient method, radar-based cloud comparison, target control method, and chemical analysis of seeded and unseeded rain water analysis (Changnon and Lambright, 1990; ASCE, 2004). Radar reflectivity data can be used to estimate precipitation, especially during warm-season programs when most of the precipitation is in liquid form at lower levels. Such estimates are derived from empirical relationships between radar reflectivity, Z, and rainfall rate, R, termed Z-R relationships. Once the Z-R relationships are accomplished for a particular storm, the radar can be used to estimate precipitation, providing estimates of total rainfall amount over the area covered by the radar (Super and Huggins, 1993; Woodley *et al*., 1994). Evaluation statistics comprising differences between seeded and unseeded variables are increasingly helpful (Bigg, 1997; Super and Huggins, 1993; Reisin *et al*., 1996; Kopp, and Orville, 1994; Orville and Kopp, 1990; Krauss *et al*. 1987; Stith *et al*., 1990; and Takeda and Kuba, 1982) in estimating the effectiveness of the seeding operations. Enhancement of rainfall intensity, duration, and spatial correlation can help in detecting and assessing seeding effects (Rosenfeld and Woodley, 1993; Silverman, 2001; Gabriel, 2002; Ben-Zvi and Fanar, 1997). Some experiments (e.g. South Africa and Mexico) used estimates of the quartiles to determine if cloud seeding produced significant differences (Mather *et al*., 1997; Bruintjes *et al*., 1999 Cooper *et al*., 1997). However, quartile estimates have undesirable properties when used on small samples, especially when the distribution of the samples is asymmetric or skewed. A few types of ratio statistics were devised in the course of other experiments (Silverman and Sukarnajaneset, 2000; Gabriel, 2002). Use of a standard statistical measure that is able to “cope” with small samples and skewed measurements, the Wilcoxon-Mann Whitney test, is recommended for the confirmatory phase on weather modification experiments (Gabriel, 1999).

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This paper aims to highlight some of the work undertaken in Andhra Pradesh, India. An attempt has been made to evaluate the cloud seeding operations by using various methods of analysis like linear regression equations, target control, impact coefficient and quartile analysis methods.

2. DESIGN AND METHODOLOGY

Two radars were located in areas identified according to the need for coverage over preselected districts and the main factors taken into site selection were need of the area, services available and terrain. Each location provided the best possible efficient coverage for the state. TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) developed in South Africa (Dixon and Wiener, 1993) is used to track storms on each volume scan. For each volume scan, parameters, such as storm height, volume, mass, etc., are estimated for each storm, and the time history of these constitutes a description of their life cycle. The definition of a "cell" for storm tracking purposes on the TITAN was defined as a radar echo of 20 dBZ or greater, with an echoing volume greater than 12 km^3 above the 3000 ft MSL height. Rain gauges are used to measure the ground truth rainfall recorded during the seeding operations. This measurement is taken every 24 hrs. The rainwater collected in these raingauges was analyzed for its chemical constituents.

Figure 1 shows the study area in which the operations were carried out. The area is administratively divided into districts which are sub-divided into blocks called "mandals". The ground truth for rainfall data and chemical analysis was carried out at the mandal level. The study was carried out in 12 districts viz. Ananthapur, Chittoor, Kadapa, Kurnool, Medak, Mahaboobnagar, Prakasham, Guntur, Nalgonda, Karimnagar, Nellore and Ranga Reddy. These districts are classed under RSAD as they receive an average rainfall of less then 1000mm per annum. Figure 2 shows the total number of rain gauge stations in these districts along with the normal rainfall data, which is calculated over a period of 30 years by the Indian Meteorological Department (IMD).

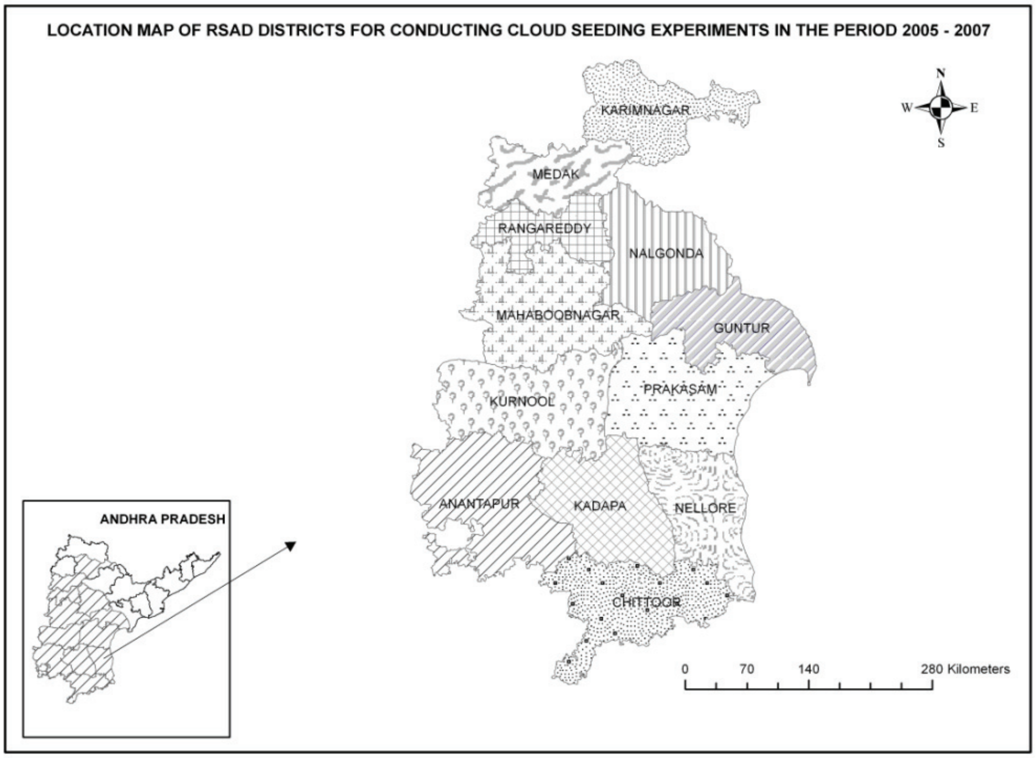

Fig. 1. The study area - 12 Rain Shadow Districts of Andhra Pradesh.

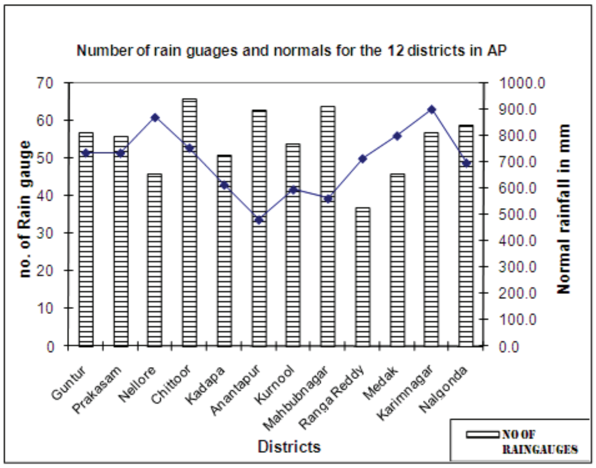

Fig. 2: Rainfall and Rain gauge details in the study area.

The operations were essentially carried out using hygroscopic flares with a typical chemical composition of 65% oxidizing agent (Potassium per chlorate), 18% organic binder, 2% magnesium, 15% calcium chloride that acts as the cloud condensation nuclei. The average particle size after burning was 5 to 10 micros. Once a cloud is seeded it takes 4 seconds for flare to ignite, the time aircraft moves 0.3 km (aircraft speed 250 km/hour). It takes 4 minutes for the hygroscopic flare to burn, during which the aircraft travels a flight path of 16.7 km. For cloud to respond to seeding material, it takes 8 to 13 min with a flight path of 33.3 to 54.2 km (mean value 43.7 km). Sometimes cloud response to seeding material takes more time. Assuming the aircraft is moving in a straight path, aircraft might have traveled 60.7 km from the ignition time. The buffer zone (zone of influence) is the area surrounding the operational area over which suitable clouds are seeded before they moved. The width of the buffer zone depends on the maximum speed at which the storm clouds are expected to move. The area is calculated as reaction time (h) * speed with which cloud moves (km/h) = km. Based on this it was found that the average reaction time varied from 30 to 40 mins and the wind speed during the season was on average 30 to 40 km/hr. A 40-km zone of influence from the point of seeding was drawn using ARC GIS software and the rainfall in this zone was estimated from the rainfall recorded in the rain gauge located at each mandal. The VIL values are normalized by the corresponding values of cloud depth and the derived liquid. The formula used to calculate LWC (g/cubic meter) is = (VIL kg/m^2) / (cloud depth km). The precipitation mass is calculated as: Precipitation mass (ton) = Precipitation flux (cum per sec) * cloud lifetimes (sec).

Records of the variable to be tested are acquired for an historical (not seeded) period of many years duration (10 years). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites are selected in an area meteorologically similar to the target, but one that would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period as that of the proposed or previous seeding. The target and control sets of data for the unseeded seasons are used to develop a linear regression equation that estimates the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period to estimate what the target area precipitation would have been without seeding, based on that observed in the control areas. This allows a comparison between the predicted target area natural precipitation and that actually occurred during the seeded period to determine if there are any differences potentially caused by cloud seeding activities.

The historical data are analyzed mathematically to develop a regression equation, which predicts the amount of target area precipitation, based on observed precipitation in the control area in district wise. The values of the average control area precipitation (*x* observed), the observed target area precipitation (*y* observed), the calculated target area precipitation (*y* calculated), the ratio of *y* observed to y calculated, and the difference between *y* observed and calculated values. This equation is then modified and months predicts the amount of target area precipitation used during the seeded period to estimate what the target area precipitation should have been based on that observed in the control area. This is the target area actual expected precipitation. Seeded cells were compared with similar, non-seeded cells that could have been seeded. Storms were called seeded if they were seeded at any time during their lifetime. Areas under similar meteorological conditions were grouped into regions. For this study two regions were identified – Rayalaseema Region and Telangana Region.

3. RESULTS AND DISCUSSION

The linear regression equations were developed based on the 30 years of historical data set available. This equation was used to estimate the target area average precipitation. A comparison was then made between the actual target area precipitation and after seeded estimation during the same time and region. Figure 3 shows that calculated estimated rainfall and that observed during the season. Sufficient data sets were not available for all the 12 districts hence only 9 districts were estimated using this method. The result indicated the average total expected estimated precipitation was 66 mm but the actual seeded observed rainfall was 118 mm, which is a 44% increase of the expected value.

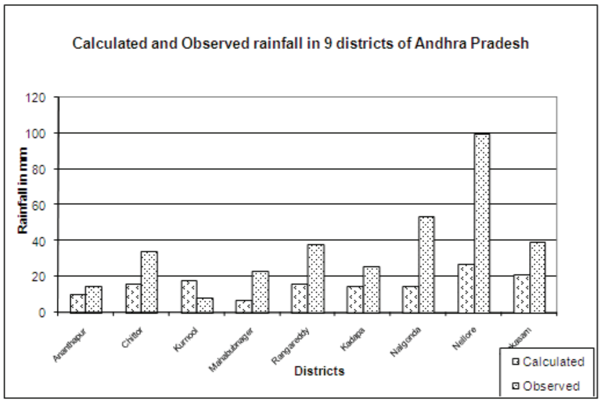

Fig. 3: Calculated and observed rainfall in 9 districts of Andhra Pradesh.

Generally, the closer the target and control areas are in terms of elevation and topography, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable in the seeded years. An equation indicating perfect correlation would have an r value of 1.0. In the present study the correlation values varied from a minimum of 0.67 for Anantapur district to a maximum of 0.88 for Nalgonda district.

To further substantiate the results obtained by the regression equation, various other evaluation techniques were also used. One of these was to study the effects of seeding rain gauges by categorizing into target, control, and downwind regions for selected seeding districts. The downwind regions were determined by the mean storm flow on days seeded from years 2004 to 2008. For each district, a wind flow was determined where the majority of days seeded originated. The control regions were selected by determining areas not affected by seeding and upwind to the target and downwind regions. Precipitation amounts were calculated for each region. All the gauges in the regions for that wind regime were averaged to get the mean daily rainfall for that region. At the end of the month and season means for the region were calculated. A percentage difference was calculated between the target regions and their corresponding control regions. Climatological rainfall amount for the region was calculated. A ratio between the target and the control regions and between the downwind and control regions was also calculated. A percent difference was calculated between the target regions and their corresponding control regions and downwind regions. Figure 4 shows the percentage difference between the control region, target region and the downwind region. The Region 1 (Rayalaseema Region) target mean rainfall was 18% greater than the control mean total rainfall amount. However, for Region 2 (Telangana Region) the target region rainfall was only 8% more than the control region but the downwind region received 6% less than the control region.

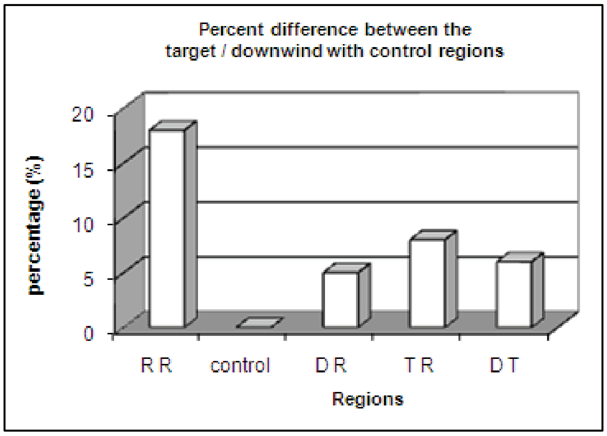

Fig. 4: Percentage difference between the target, downwind and control regions.
RR – Rayalaseema Target Region; DR – Downwind Rayalaseema Region, TR – Telangana Target Region, DT – downwind Telangana Region.

Impact coefficient

The assessment presented here is based on the findings and report by Sen O, S. Incecik and E. Omay, (1993). Double Ratio method was used to assess impact of the cloud seeding on the local rainfall. Impact Coefficient is defined by the equation IC = (S / NS) / (H/K); where, I.C = Impact coefficient (decrease or increase of rainfall); S = Total rainfall in the target area during seeding period; NS = Total rainfall in the control area during seeding period; H = 10 years of total rainfall in the targeted area; K = 10 years of total rainfall in the control area. Table 1 shows the percentage change that is observed for two districts, Anantapur and Nalgonda, where the operations were carried out extensively during the years 2004-2008. When IC exceeds 1.0, increase in rainfall may be attributed to cloud seeding activities in these areas. If I.C. equals 1, there is no change in rainfall as a result of the cloud seeding applied.

Separation of clouds data

In an attempt to further find methods of estimation of the impact of seeding in the state of Andhra Pradesh, India data sets from the radar were evaluated and the results are presented below (Table 2).

The data of all eleven parameters of the seeded clouds available from the TITAN was segregated depending on its time of residence in the atmosphere after they have been seeded. Earlier studies have indicated that four classifications can be made based on the residence time viz. clouds whose life is less than 20 minutes after they have been seeded; clouds whose life is in between 20 to 40 minutes after they have been seeded; clouds whose life is in between 40 to 60 minutes after they have been seeded; clouds whose life is greater than 60 minutes after they have been seeded. In this study the first type whose lifetime is less than 20 min is not considered.

Clouds were divided into three basic types based on the areas Type A (small seeded clouds), Type B (seeded clouds) and Type C (large seeded clouds). In the operations carried out in the study area approximately 2200 seeding sorties were carried out, randomly 1600 (72%) samples cases have been selected and analyzed.

Quartile analysis

The database of 1600 storm couples was developed. A quartile analysis of these groups was done and the results of the upper quartile (75% of data below the line and 25% above the line) are presented in Fig. 5a and 5b. The results

Table 1. Calculation of Impact Coefficient for two districts in Andhra Pradesh

Target / Control	**S / NS**	**H / K**	**(S / NS) / (H/K)**	**% Change**
Anantapur / Kadapa	0.90	0.75	1.22	22
Anantapur / Kurnool	1.18	0.81	1.47	47
Anantapur / Chittoor	0.73	0.54	1.34	34
Nalgonda / Ranga Reddy	1.04	0.85	1.22	22
Nalgonda / Medak	1.88	0.83	2.27	127
Nalgonda / Mahaboobnagar	1.39	1.07	1.30	30

Table 2. Number of cases examined in each type of cloud

S.No	Type of cloud	Life time of clouds (min)	Couples analyzed
1	A type	20 to 40	433
2	B Type	40 to 60	960
3	C Type	more than 60	207
	Total		**1600**

showed that the mean rain mass for the seeded storms was significantly larger than for the control. The maximum variation was for Group B type of clouds. The means of the total radar estimated rain mass between 40 to 60 mins after the seeding decision were 212 kilo tons for the seeded storms and 98 kilotons for the non seeded storms. The estimated seeding effect was 335%.

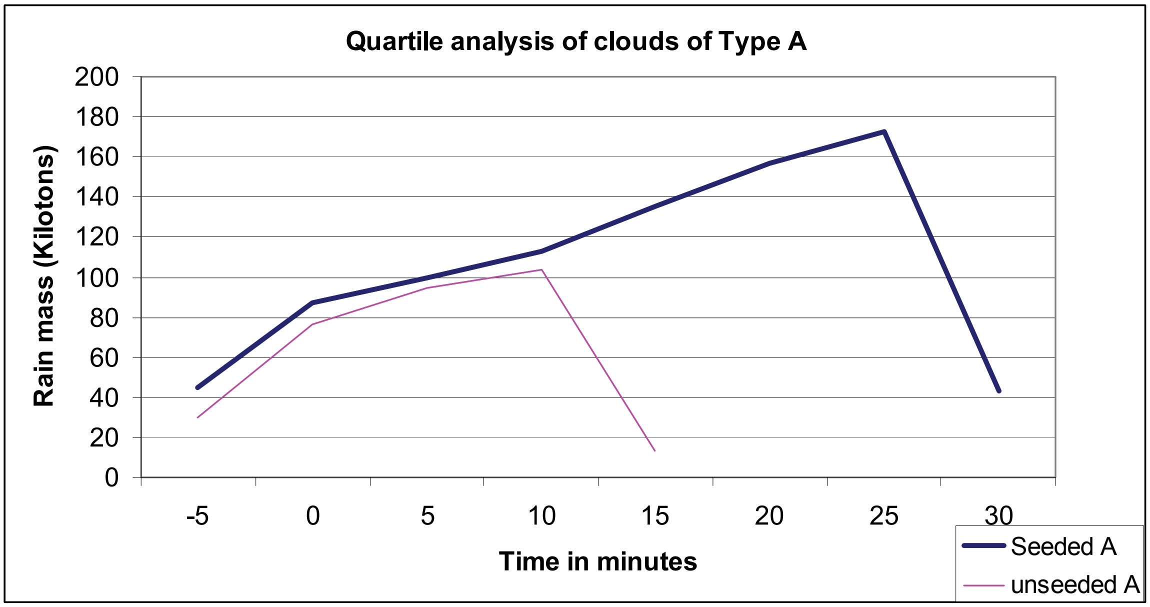

Fig. 5a: Quartile analysis for the selected groups of seeded and unseeded clouds.

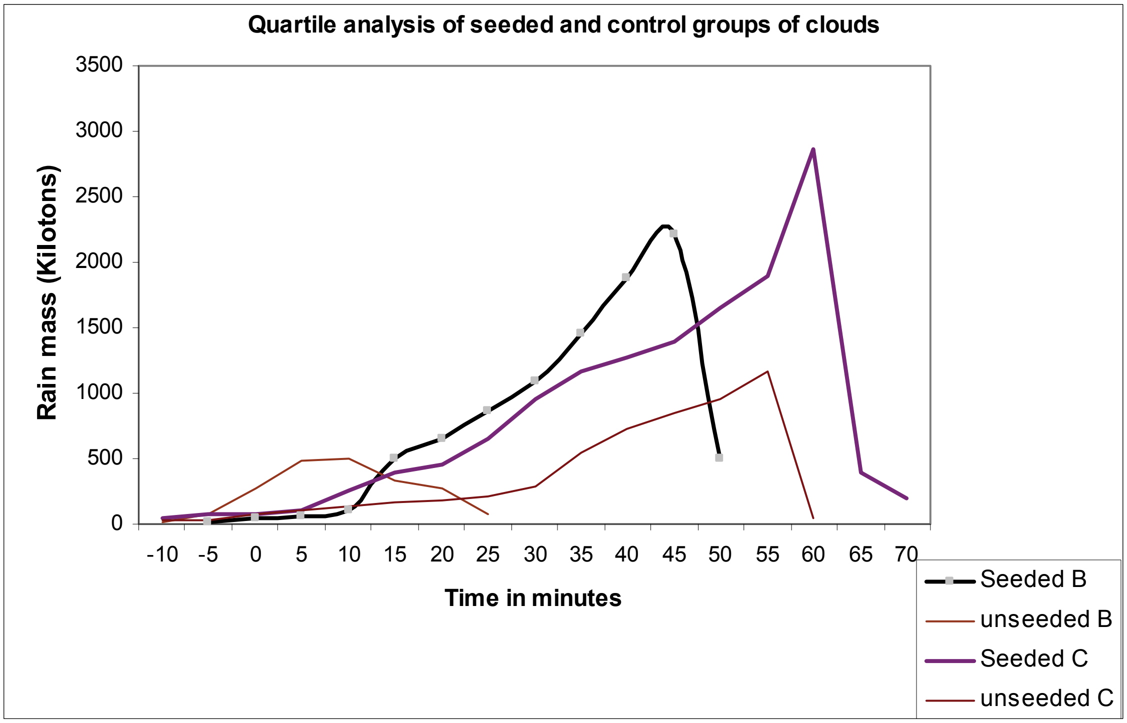

Fig. 5b: Quartile analysis for the selected groups of seeded and unseeded clouds.

Table 3 shows the results from the classic TITAN evaluation for the seeded clouds for which proper control clouds were obtained.

Table 3. Seeded samples versus control samples (couples, averages)

Variable	Seeded sample (S)			Control sample (C)			Simple ratio (S/C)			Increase (%)		
Cloud type	A	B	C	A	B	C	A	B	C	A	B	C
Life time [min]	35	46	126	30	28	64	1.16	1.64	1.97	16	64	97
Area [km^2]	51.26	161.04	159.27	31.75	67.46	120.93	1.61	2.39	1.32	61	139	32
Volume[km^2]	228.46	872.70	741.62	103.12	319.53	484.86	2.21	2.73	1.53	121	173	53
Cloud Top [km]	7.86	10.11	8.5	5.54	8.06	7.8	1.41	1.25	1.08	41	25	8
VIL [kg/m^2]	5.01	25.64	8.65	2.78	6.16	10.52	1.80	4.16	0.8	80	316	20
Thickness(T) [kms]	6.16	9.41	7.11	4.01	6.66	6.54	1.53	1.41	1.09	53	41	9
LWC=VIL/T [g/m^3]	0.8	2.72	1.2	0.78	0.9	1.6	1.02	3.0	0.75	02	200	25
Prec. Flux [m^2/sec]	82.26	801.79	378.72	57.93	221.9	303.33	1.41	3.61	1.25	41	261	25
Prec. Mass [Ktons]	172.7	2210	2863.1	104.2	507.38	1164.78	1.66	4.35	2.46	66	335	146
Cloud Mass[Ktons]	76.4	546.87	319.86	56.75	123.93	234.4	1.34	4.41	1.36	34	341	36
Efficiency (E)	2.26	4.04	8.95	1.83	4.0	4.96	1.23	1.01	1.80	23	10	80
Rain = P mass/area [mm]	3.36	13.7	17.97	3.28	7.52	9.63	1.02	1.82	1.87	02	82	87
Rain rate = [s/200]**0.625[mm/hr]	15.22	65.2	26.76	12.84	21.71	27.58	1.18	3.0	0.97	18	200	03

In Type B an increase in 335% of the precipitation mass together with an increase of percentage in cloud mass illustrates that the seeded clouds grew at the expense of the environmental moisture and used only a fraction of the moisture for their own maintenance. Notable increase in lifetime, volume, precipitation flux was observed. The increase of percentage in precipitation mass for a control value of kton in various case means would indicate that the Δ can be calculated as Δ_i (Kilotons) = no. of cases * % increase in precipitation mass * precipitation mass of control value. The details of the Δ for each case is given in Table 4. The total Δ_i for the period from 2004 to 2008 is **2011566** Kilotons.

4. CONCLUSIONS

Hygroscopic cloud seeding operations carried out in Andhra Pradesh India for the last 5 years are studied on a case to case base using various statistical methods. The measurements included radar based analysis and ground truth measurement of rainfall. The districts chosen for the study are predominantly rain shadow areas, i.e. areas which receive less than 1000 mm of season rainfall. Regression equations developed for the districts in this study indicate that on an average 44% increase has occurred in the study area. The correlations between the control and target areas vary from a minimum of 0.67% at Anantapur to a maximum of 0.88% for Nalgonda district.

Table 4. Increase in the Δ values for the various clouds during the period 2004-2008.

S. No	Type of cloud	Control Prec. Mass	% increase	Δ **(Kilo tons)**
1	Type A	104	65	29270
2	Type B	507	335	1630512
3	Type C	1164	146	351784
	Total			**2011566**

The analysis using the target-control and downwind methods shows that in the Rayalaseema target region 18% more rainfall than the control and downwind regions could be achieved. Similarly in the Telangana region 8% increase was calculated. The calculations of impact coefficient for Anantapur and Nalgonda districts show a considerable percent change. 1600 couples were analyzed for the comparison between seeded and non seeded clouds. Three classes were studied. Type A showed a 65% increase, Type B a 335% increase and Type C 146% increase in precipitation mass that results in an increase of Δ by 2011566 kilotons.

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