Cloud Seeding in Karnataka – Initial Results

Kamsali Nagaraja and Balakrishnan Manikiam
Department of Physics, Bangalore University, Bengaluru – 560056
Email: kamsalinagaraj@bub.ernet.in

ABSTRACT

The southern State of Karnataka in India falls in the rain shadow region and is highly prone to the occurrence of drought conditions. Most of the monsoon rainfall occurs in July and August with few rainy days from September to December in the northeast monsoon season. Most of the agriculture being rain-fed, the impact of deficient rainfall is very high, and the State Government took up cloud seeding operations during 2017 and 2019 to enhance rainfall. The basic infrastructure for the cloud seeding operations consisted of the installation of three Doppler Weather Radars at strategic locations and calibration to monitor potential clouds for seeding over Karnataka. The hourly INSAT satellite data was used to monitor cloud top temperature, cloud motion and potential water content. Radiosonde ascents supported the observations at Gadag, Bengaluru and Solapur. The high-resolution weather model forecasts generated by India Meteorological Department and Space Applications Centre of Indian Space Research Organisation were used to identify locations of convective cloud development. Two cloud seeding aircrafts (Beach Aircraft King Air 200) of Weather Modification INC, the USA with meteorological instruments and cloud seeding equipment were operated. The daily advisory was generated to assist the seeding operations, with aircraft observations of temperature, liquid water content and updraft winds helping in target cloud identification. Both hygroscopic and glaciogenic seeding was carried out. The data from the dense rainguage network of over 6000 automatic and telemetric rainguages operated by the Karnataka State Disaster Management Centre was utilised to study the impact of cloud seeding operations. This paper deals with the initial results of the evaluation of seeding using qualitative and quantitative methods. The impact of seeding is seen to depend on the prevailing synoptic condition, and preliminary results show an increase of 11 to 28% in rainfall in seeded areas compared to the control stations with a confidence level of >95%.

Keywords: *Cloud Seeding, Doppler Weather Radar, Weather Model, Weather modification and Rainfall analysis.*

1. Introduction

India initiated a cloud seeding program by way of the ‘Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX)’ carried out since 2009 (Kulkarni et al. 2012). The prime objective of the program was to assess the potential of cloud seeding enhancement in rainfall from convective clouds using both hygroscopic and glaciogenic seeding materials. As preliminary observation, this study shows that the convective clouds over rain-shadow areas of peninsular India are amenable for cloud seeding.

The cloud seeding methods consist of hygroscopic and glaciogenic materials for the rain enhancements based on proven scientific theories and principles of cloud development and rainfall. These hygroscopic particles trigger the rainfall process and may enhance the efficiency of clouds in converting moisture into water droplets in the warm clouds. Glaciogenic seeding material provides the active ice nuclei for initiating the development of ice formation. These grow by the Bergeron process and after growing to large size, start falling due to gravity, reaching the ground as rain. This process of initiation of the rainfall from seeded clouds takes approximately 30 to 60 minutes after seeding (WMO, 1999; Silverman, 2001).

2. Data and Methods

2.1 Study Area

Due to consecutive drought situation in the State, to mitigate the water scarcity for drinking, agriculture and catchment areas of reservoirs, cloud seeding operation was taken up during the monsoon period of 2017. The cloud seeding was taken up to bring down the water scarcity in the reservoir catchment

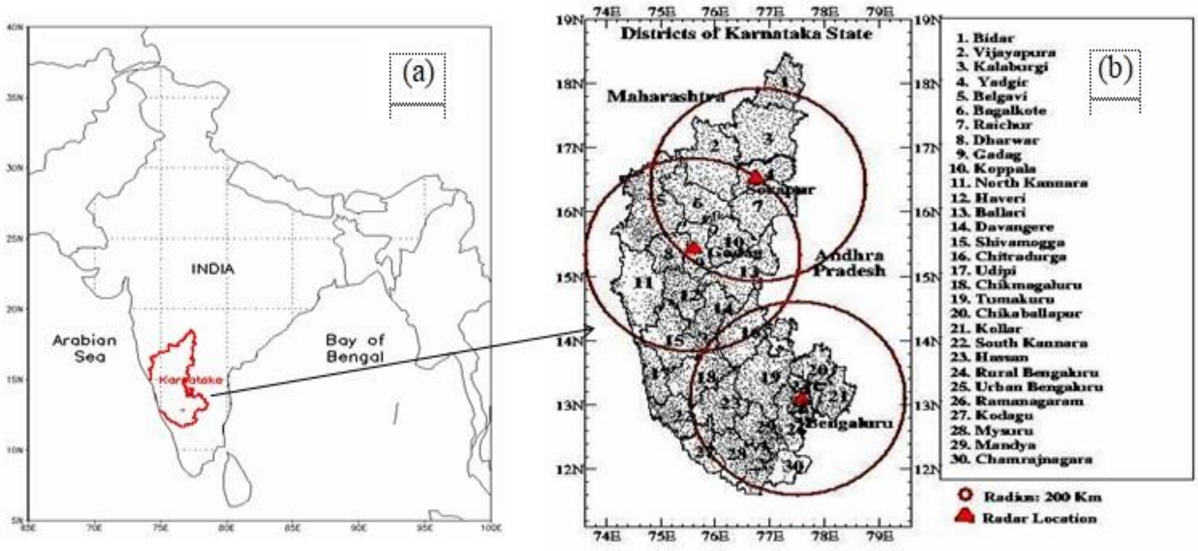


Figure 1: Karnataka State Map with locations of Doppler Weather Radars.

area and the regions of deficient precipitation. The study area is the entire State Karnataka in the southern part of peninsular India. Figure 1(a) shows the location of State and Figure 1(b) shows the boundaries of 30 districts in the State. Each district is subdivided into several Taluks and further into Hoblis. Each Hobli has a spatial scale of ~5 km and is the smallest observational unit for rainfall.

There is a strong spatial variability in rainfall from western to eastern side of the State with western parts receiving 300 cm and more while the eastern part receives only 30-40 cm (Mather et al., 1997).

Karnataka has established a dense network of Solar Powered, and GPRS enabled Telemetric Rain Gages (TRG) stations covering all the 6000 Gram Panchayats (25 sq. km each) and Telemetric Weather Stations (TWS) at all the 747 Hoblis in the State (200 sq. km each). The other key features of the entire network are, the Rainfall measuring accuracy is 0.5 mm, Data are collected at every 15 minutes with no manual intervention, all the stations work 24x7 and 365 days. The dense network of rainfall and weather monitoring stations is first of its kind in the country (KSNMDC, 2018).

2.1 Infrastructure set up for Cloud Seeding Operations

Towards getting real-time data on cloud cover and convective development, the following facilities were set up:

(i) Three C- band Doppler Weather Radars were set up and operated at Bengaluru, Gadag and Solapur (Figure 1b). These radars covered almost 90% geographical area of the State. The calibration of the radars was limited in nature and aimed at identifying and locating large convective clouds.

(ii) Radiosonde stations were operated at Bengaluru, Gadag and Solapur at 00 GMT and 12 GMT.

(iii) INSAT satellite imageries every one hour were received through the Indian Meteorological Department (IMD) network.

(iv) High-resolution Weather Model forecasts (3x3 km) were made from NCMRWF/IMD and SAC/ ISRO.

(v) Rainfall data at 15-minutes interval were collected from 6000 plus automatic rainguages through the Karnataka State Disaster Management Centre (KSNDMC) network.

Towards cloud seeding operations, two pressurized aircrafts - N267CB and N6111V were operated by M/s Weather Modification INC, the USA for seeding clouds with hygroscopic and glaciogenic flares. Necessary clearance was obtained for operating the two aircraft over the designated areas and flight levels.

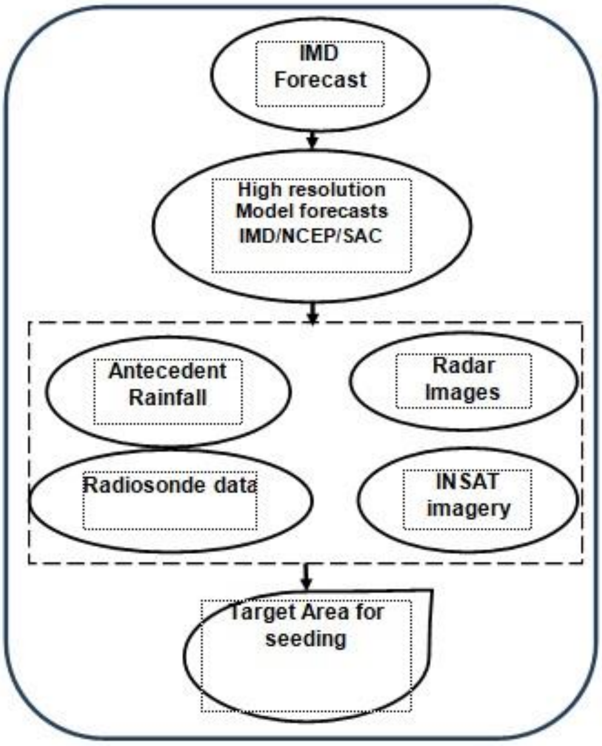


Figure 2: Methodology followed for identification of cloud seeding sites.

2.3 Methodology for identification of Seeding Areas

The methodology followed for the selection of potential seeding areas includes:

(i) Analysis of the weather situation in terms of synoptic condition, weather systems, satellite and radar imagery.

(ii) Based on the high-resolution weather model forecast, identification of potential areas wherein convective cloud development is expected over the day.

(iii) Study antecedent rainfall and prioritise the seeding areas based on rainfall deficiency, soil moisture stress and storage level in reservoirs.

(iv) Prepare a route map for seeding operations for the day and flight plan.

The aircraft sorties are carried out based on the cloud seeding advisory and seeding of specific clouds are conducted based on observations of radar onboard the aircraft and the measurements of updrafts and liquid water content in clouds by onboard meteorological instruments. Specific threshold values for radar reflectance Z and liquid water content W_c has been fixed based detailed analysis of rainfall data over the State. The schematic of the methodology followed for selection of seeding sites is shown in Figure 2.

3. Analysis of Cloud Seeding Data and Results

3.1 Monsoon Synoptic situation in 2017 and 2019

The south and interior Karnataka received below normal rainfall in the months of June, July and upto mid-August in 2017 (IMD Annual Report, 2017). Severe drought conditions prevailed in most parts of the State in the first part of the monsoon season. In 2019, the monsoon onset in Karnataka was delayed to the third week of June, and further rainfall received was deficient and scanty till mid-August (IMD Annual Report, 2019). In both years, the latter part of monsoon was very active and made up for the deficient rainfall. Thus both the years required intervention to save the crops and avoid large scale drought. The Government of Karnataka decided to carry out cloud seeding program to augment the rainfall in the State.

3.2 Cloud Seeding process and impact

At the heart of the issue are the cloud condensation nuclei (CCN), which are aerosol particles on which water vapour condenses and initial cloud droplets form and grow through the collision–coalescence process to bigger droplets and eventual precipitation (Pruppacher and Klett, 1997). The study of rainfall from the seeding operations was carried out based on the data from the dense rainguage network operated by KSNDMC. The Data consisted of 15-minute interval rainfall from over 6000 rainguage stations in the State, each rainguage station representing 5 km^2. The analysis of the rainfall data was carried out using spatial analysis and through statistical methods. Table 1 shows the details of the seeding events, the number of flares used, districts and Hoblis covered. It gives date-wise number and type of flares used, districts in which seeding was carried out.

Table 1. Data on seeding operations.

Parameter	2017	2019
Period of Operation	21 Aug. to 7 Nov.	25 July to 6 Oct.
Total hours of seeding	287	290
Total flares	1302	1307
Seeding events	781	690
Hobli covered	702	700
Taluks covered	110	109
District covered	28	28

Figure 3: (a) Aircraft conducting seeding operation (left panel) b) part of seeding operation (right panel) during 2–8, October 2017.

Figure 3 shows the aircraft from M/S Weather Modification Inc., the USA conducting the seeding operation and sites seeded during one operation between 2 to 8 October 2017.

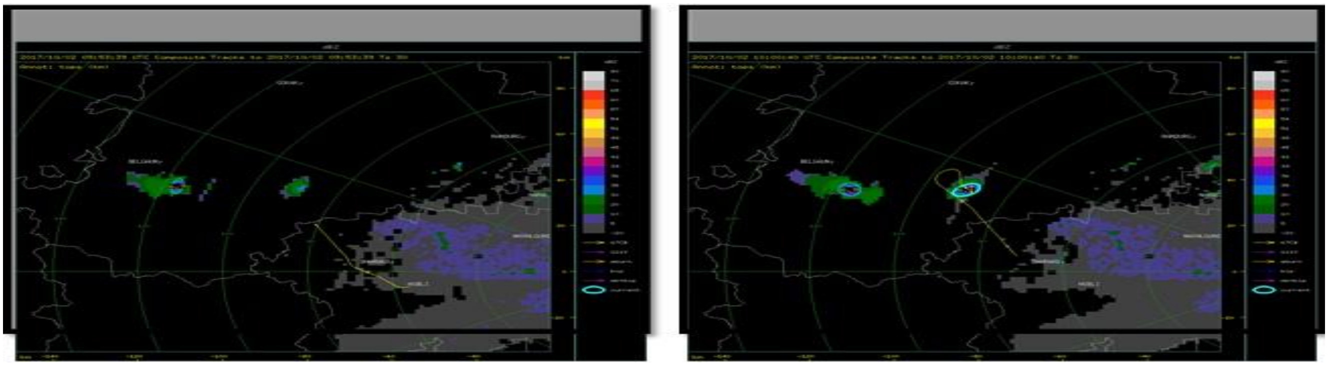
3.3 Radar data analysis of Seeded area rainfall

There are two methods used widely for evaluation of the seeding and are based on (1) Radar data and (2) Rainguage network time-series data. In the radar-based method, the cloud parameters viz., size, volume, height, life period, precipitation flux, and rain mass of the seeded cloud (target cloud) are compared with similar non-seeded clouds (control clouds) in the vicinity (WMO, 1999).

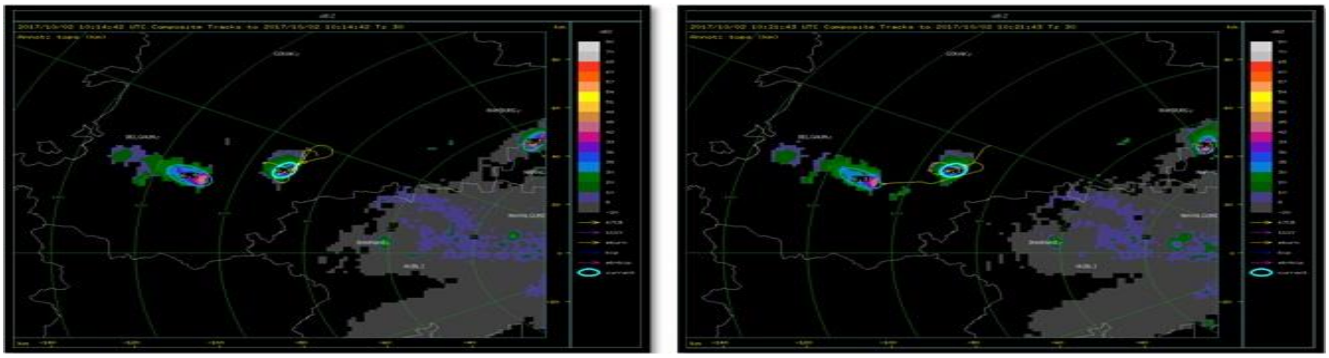
In the past, South Africa, experiments, the evaluations of seeding efficacy have been done. In the recent past, evaluation of South African seeding programs using radar data (Mather et al. 1997) triggered many cloud seeding programs in Thailand and Mexico in the research and operational modes (Bruintjes 1999 & 2013). The radar-based method is quick and comparatively easy as software like TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) provides all the required parameters on a real-time basis. However, there are limitations in deriving the rainfall using radar data as the relation of radar reflectivity (Z) to ground rainfall needs extensive calibration.

A typical sequence of TITAN radar images as RAIN 1 aircraft was dispatched for seeding in the northwest of parts of Hubli district on October 2, 2017 is shown below:

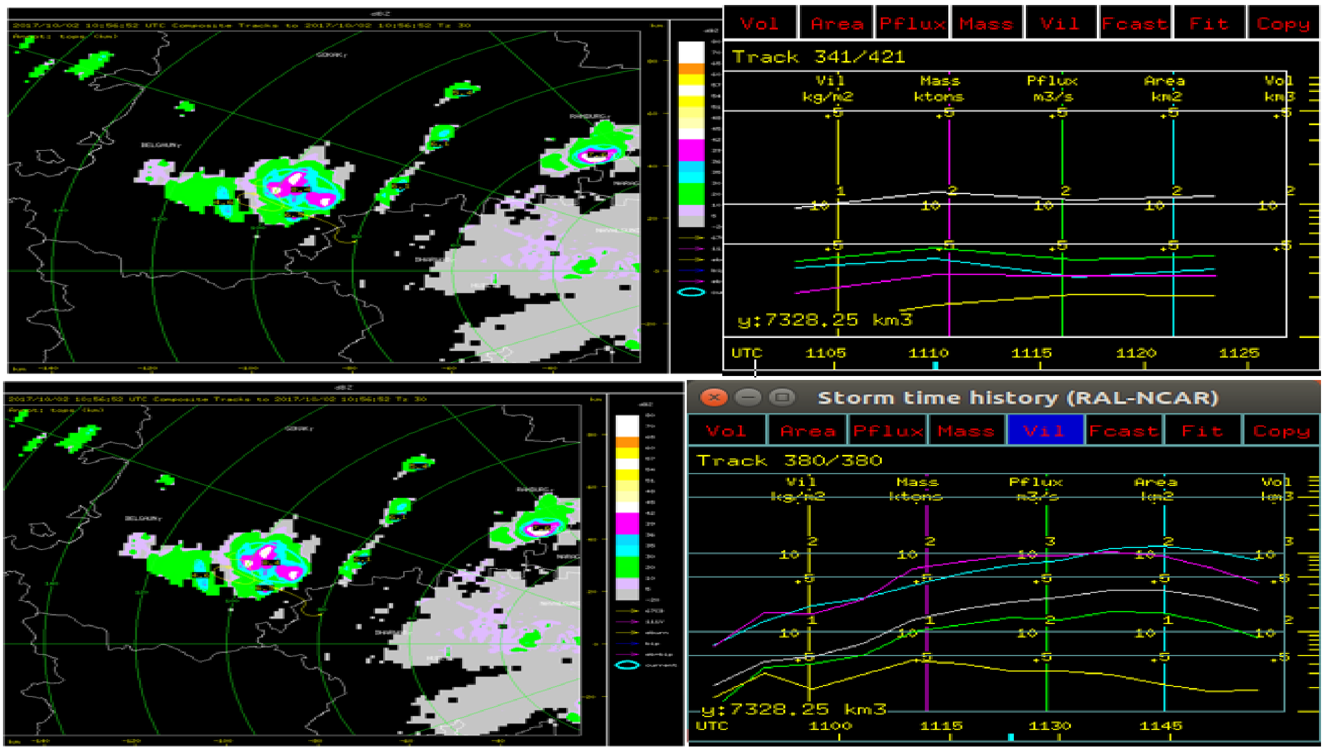
From Figure 4, the cloud development due to seeding and the spread in rainfall has over a larger area due to winds at that level may be seen. Quantitative estimation of the increased rainfall can be done using the radar reflectivity, Z relationship with rainfall as $R = Z^b$, where **b** is the constant obtained through ground calibration.



Footnote: Aircraft coded RAIN 1 departed Hubli and flew to target as directed by project meteorologist. The yellow line indicates flightpath on radar images.



Footnote: Once aircraft is on location, experienced pilots fly into specific clouds to find vertical updrafts and super-cooled liquid water. This is a favourable location for seeding which transfers the atmospheric water into precipitation.



Footnote: Pilots of RAIN 1 report positive seeding conditions and light flares to disperse the cloud seeding materials. Radar images indicate growing reflectivity and associated precipitation footprint.

Figure 4: Radar images of October 2, 2017 showing seeding, cloud evolution & rainfall spread.

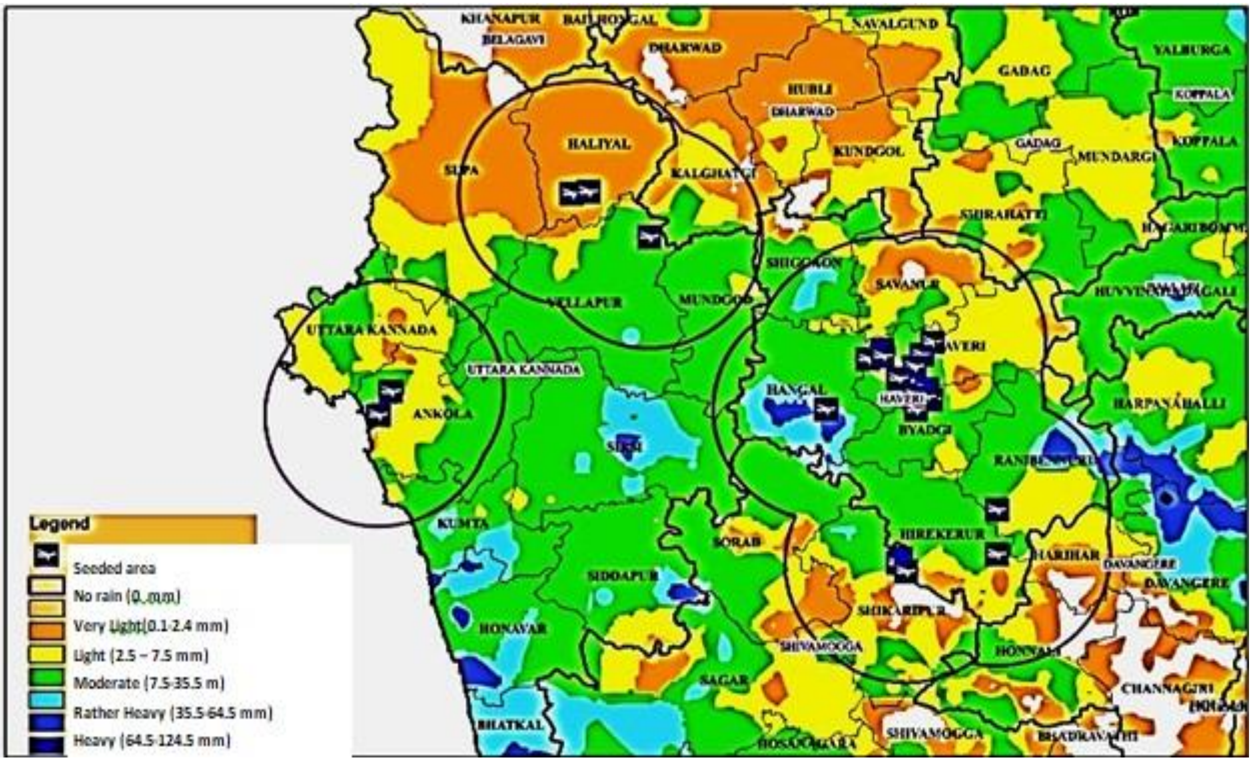


Figure 5: Spatial distribution of rainfall in seeded and non-seeded areas on 6 October 2017.

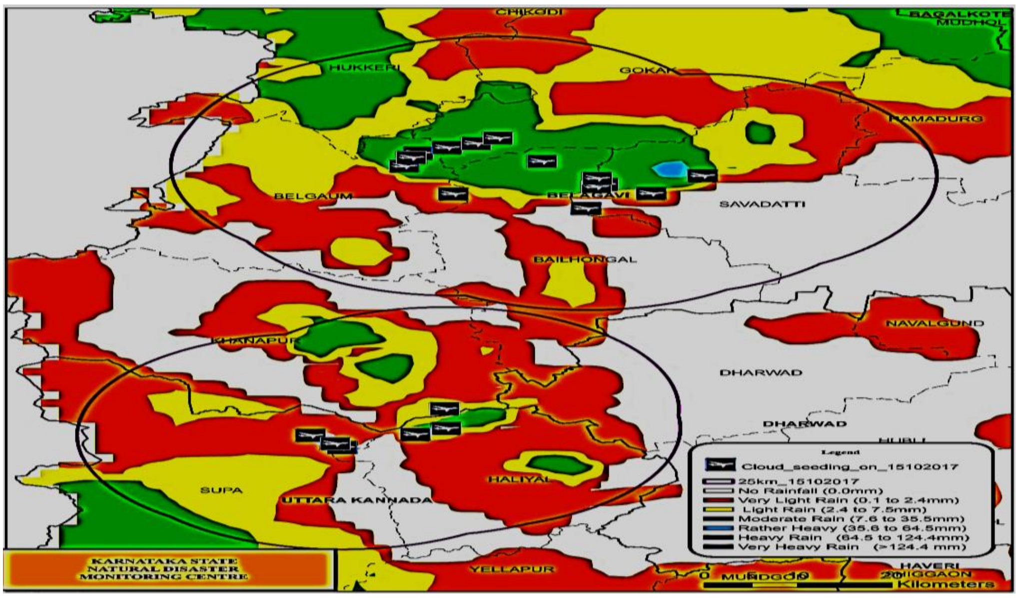


Figure 6: Spatial distribution of rainfall in seeded and non-seeded areas on 15 Oct. 2017.

3.4 Spatial rainfall data analysis

The second and more direct approach is to use the rainfall data from the network of rainguage stations over the target (seeded) and Control (non-seeded) areas. Enhancement in rainfall has been estimated using the high-resolution rainfall data from the KSNDMC rainguage network providing a resolution of 5 km^2 at 15-minute interval. Using a GIS digital database representing all the rainguage stations, the rainfall during 4-hrs from seeding time was plotted. A circle of radius of about 25 km was drawn around the seeded sites to demarcate the seeded and non-seeded areas.

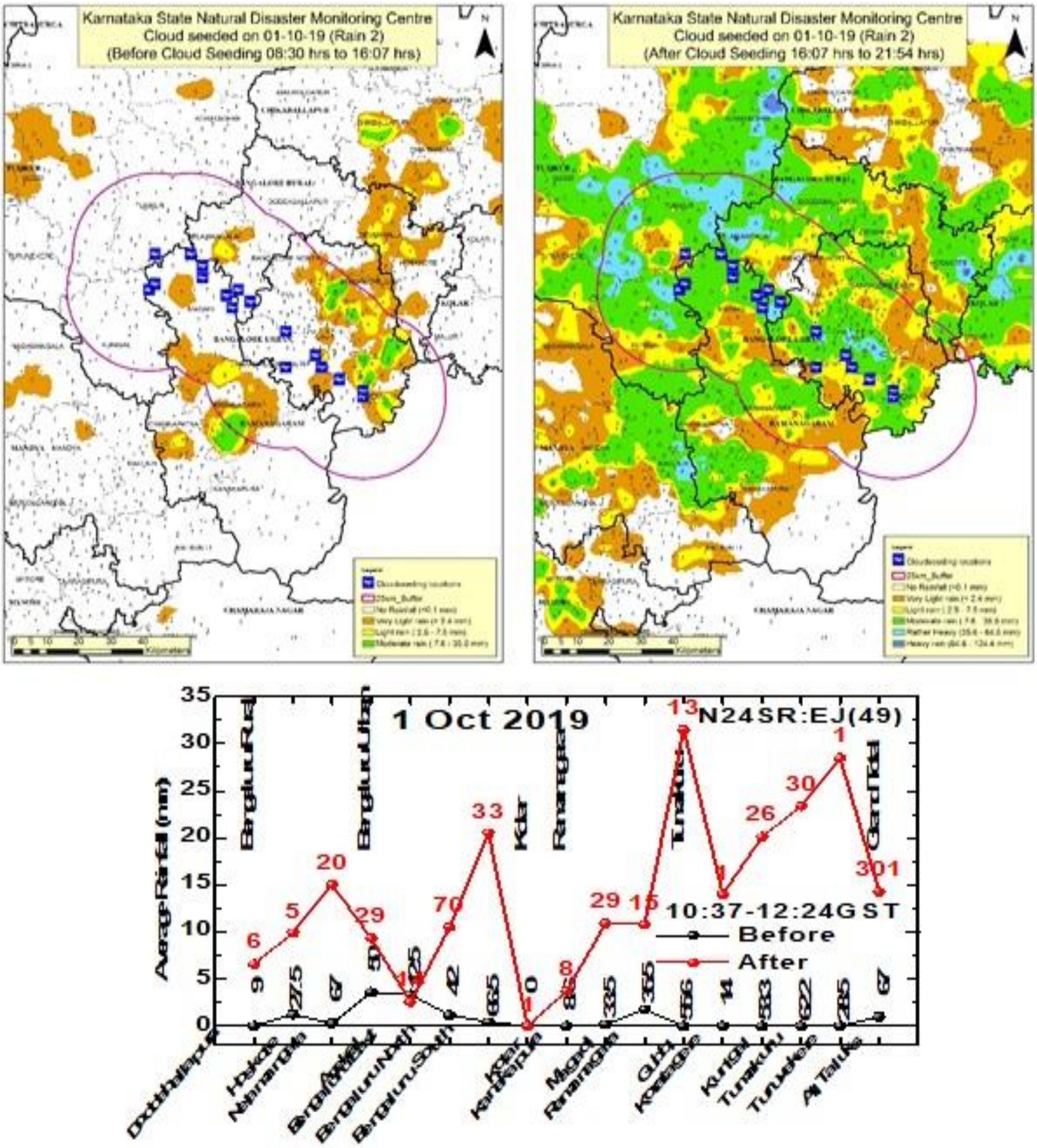


Figure 7: Spatial analysis on top and plots of rainfall before and after seeding on 1 Oct. 2019, total stations analysed is 270.

Figures 5 and 6 show the rainfall distribution in an area of the circle of radius 25 km around the seeded areas. The impact of seeding can be seen in terms of increased rainfall (green patches), whose spatial distribution is decided by the prevailing wind conditions at the cloud level. Figures 7 and 8 show spatial map of rainfall before and after seeding for two sample dates in 2019 and taluk wise rainfall plot with time. The daily-response of rainfall enhancement due to seeding is seen to depend on the large scale atmospheric conditions. If the trough or low pressure prevails over the region, the conditions are conducive for the cloud growth, which yields a better response to seeding. If the ridge of anticyclone prevails over the region, the natural cloud growth of the convective clouds is arrested, causing the inadequate response to the seeding.

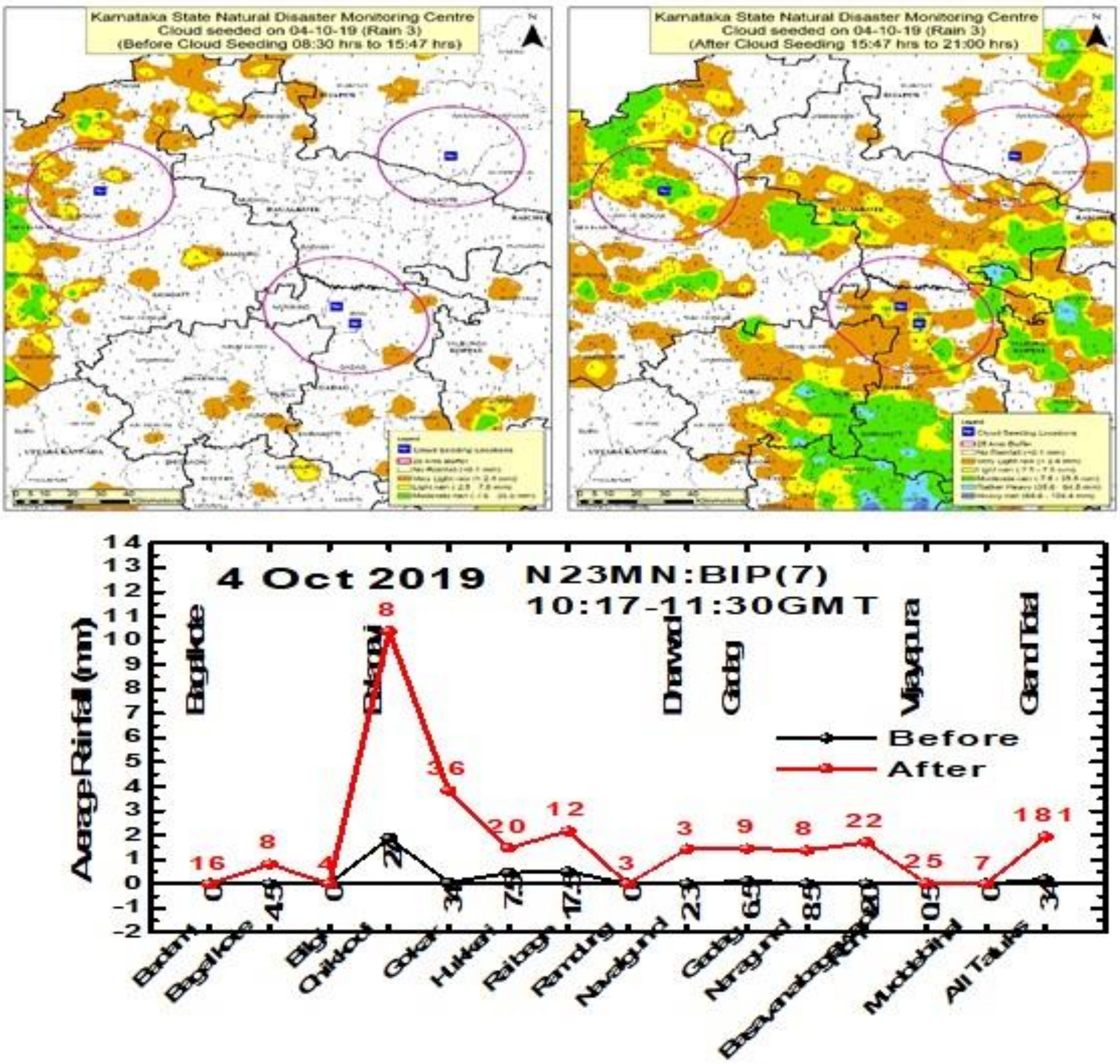


Figure 8: Spatial analysis and plots of rainfall before and after seeding on 4 Oct. 2019, total stations analysed is 235.

3.5 Quantitative assessment of seeding

Two approaches have been used for estimating the enhancement: (i) Rainfalls within 4-h after seeding was compared at station levels with the rainfalls prior to seeding. (ii) The floating control-target area rainfall analysis was used to estimate the natural rainfall that would have occurred without seeding. The station wise rainfall was analysed for the seeded areas is plotted (typical plot for 6 October 2017 is shown in Figure 9), and it shows that the rainfall increases with time for the seeded stations upto about 4 hours after seeding, and then starts declining.

3.6 Frequency distribution of the increase in rainfall

Further, the taluk level mean value of rainfall is computed from 45 years of standard rainfall data from India Meteorological Department (IMD, 1984). Mean rainfalls at taluk levels within 4-hours after seeding in the area of 25 km radius of the seeding places were compared with the rainfalls prior to seeding at the same stations. Mean daily rainfall at the location has been taken as a proxy for rainfall that might have occurred naturally within 4-hours after seeding. These values have been verified by statistical methods and found to be reasonably good. The values of rainfall above this natural rainfall have been considered as the increase in rainfall due to cloud seeding. Figures 10 and 11 shows the frequency distribution of the increases in

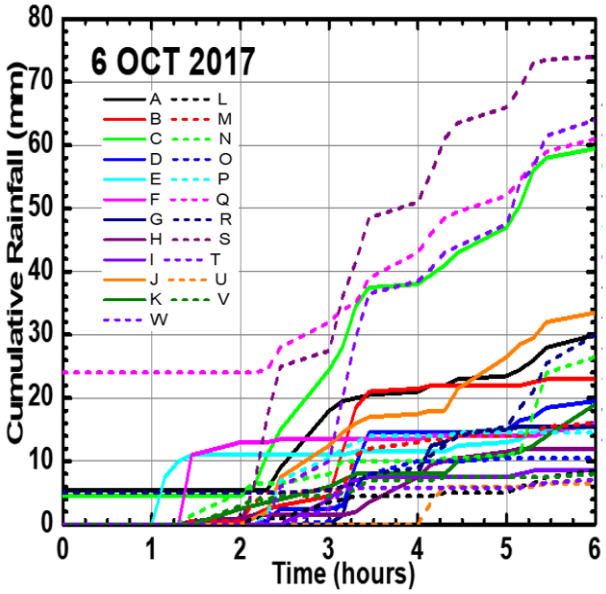


Figure 9: Plot of Accumulated Rainfall within 6 hours after seeding on 6 Oct 2017 RG Stations: A-Hanagal, B-Rattihalli, C-Akki-Alur, D-Kabbur (GP), E-Kurabgondm (GP), F-Belgalpet (GP), G-Asundi (GP), H-Sunakalbidiri (GP), I-Billahalli (GP), J-Havanagi (GP), K-Hirehullal (GP), L-Balambeed (GP), M-Hirehalli (GP), N-Kummur (GP), O-Koda (GP), P-Hullatti (GP), Q-Heerur (GP), R-Mantagi (GP), S-Kusanur (GP), T-Kallapur (GP), U-Kadaramandalagi, V-Suttakoti (GP), W-Benakanakonda (GP)…. GP…Gram Panchayat.

rainfall within 4-hours after seeding compared to rainfall from 08:30 in the morning till the time of seeding. The maximum frequency occurs at 0-2 mm interval. The clouds after seeding moves in downwind direction after shedding rainfall at the station and it is in the process of further development by the seeding. The distribution is positively skewed, which is consistent with many of the cloud parameters such as area and height observed over the rain-shadow region (Morwal et al. 2016, 2018). The maximum increase of the order of 55 mm has been observed but with very low frequency. Figure 10 gives the frequency distribution of the accumulated 4-hour rainfall after seeding. Total of 618 cases has been considered for analysis in which accumulated increase is >0 mm. The mean increase in rainfall considering all the stations is 5.5 mm/area at taluk basis as well as at station level.

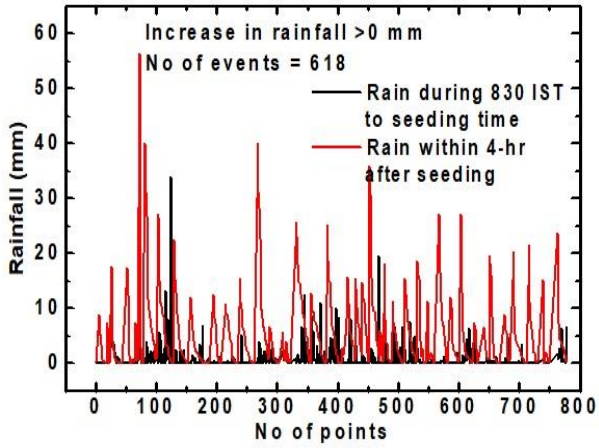


Figure 10: Taluk Averaged Rainfalls from 0830 IST to seeding time (black line) and in 4-hours from seeding time (red line).

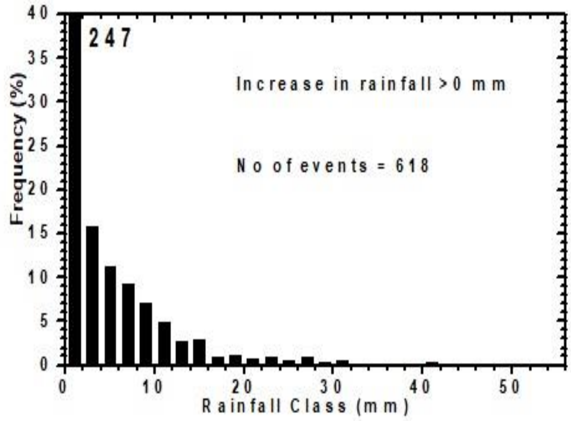


Figure 11: Frequency Distribution of rainfall within 4-hour after seeding at Taluk level.

3.7 Floating control-target & Statistical Analysis

The target and control areas are decided based on the rainfalls at stations within 4-hours of seeding. Areas which showed increase within 4-hours of seeding are considered as target (seeded) areas. The stations in the surrounding areas that showed no increases in rainfalls within 4-hours of seeding or rainfall within the expected normal are the stations not influenced by the seeding and considered as control stations. Care is taken to select control area stations which are not contaminated by drifting of seeded clouds by taking into account the wind

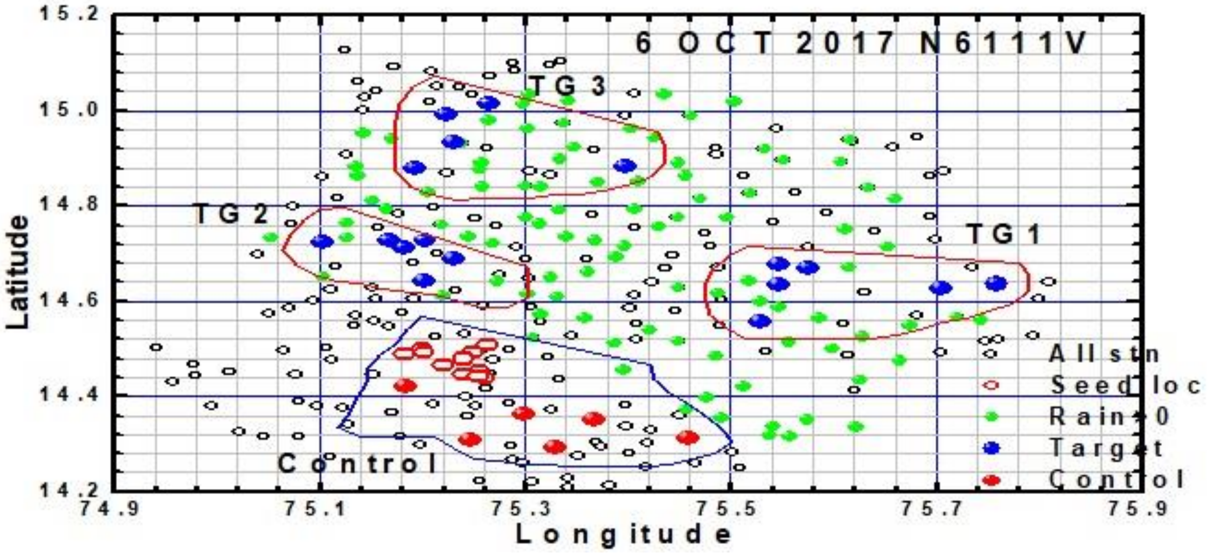


Figure 12: Control-target area analysis on 6 October 2017.

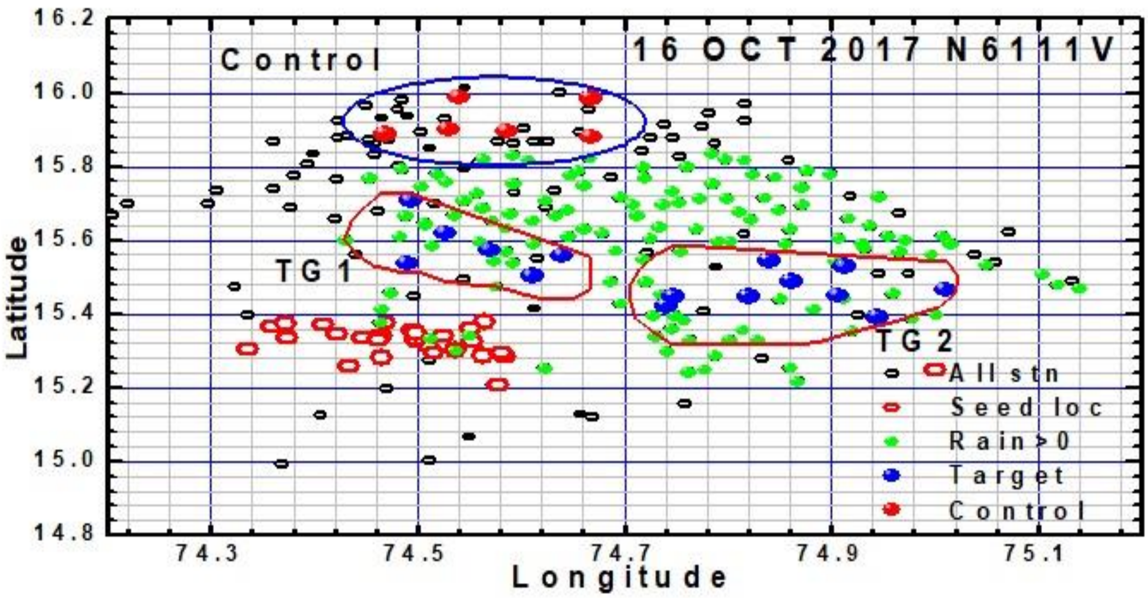


Figure 13: Control-target area rainfall on 16 October 2017.

direction in the lower levels. Mostly the upwind side of the target area is taken as control areas. The mean increase in rainfall at the seeding locations is due to seeding as well as due to natural rainfall that would have occurred within that time.

So the increase in rainfall due to seeding is estimated as the difference between the actual and the natural mean rainfall that would have occurred in the absence of seeding. This is then compared with rainfall in the control area.

3.7.1 Rainfall plots of seeded and non-seeded areas

Plots were made for seeded (target) and non-seeded (control) areas with the observations of rainfall from the dense network of SRG stations of KSNDMC. Typical sample plots for a few days in 2017 and 2019 are shown in Figures 12 to 15. Red contours denote the target-area (TG1, TG2 and TG3) and blue contours denote the control-area. Green dots are stations within 25 km radius of seeded locations.

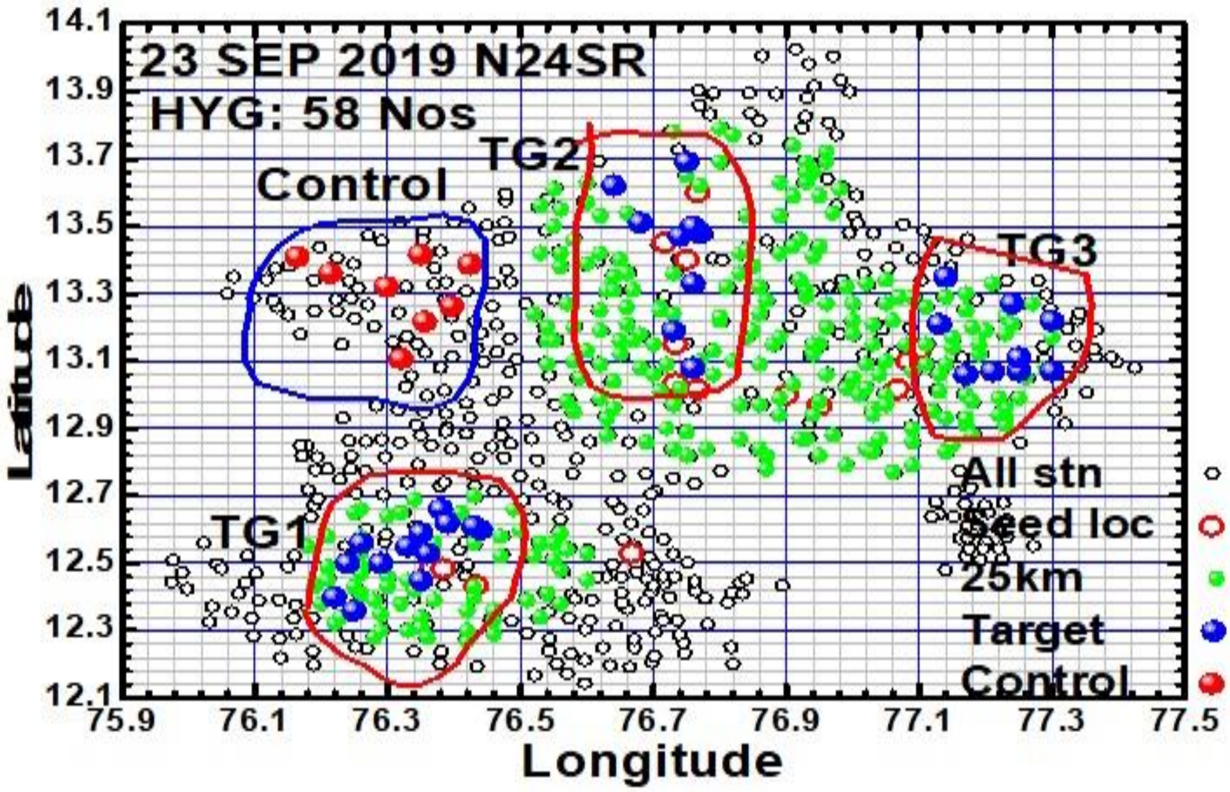


Figure 14: Control-target area rainfall on 23 September 2019.

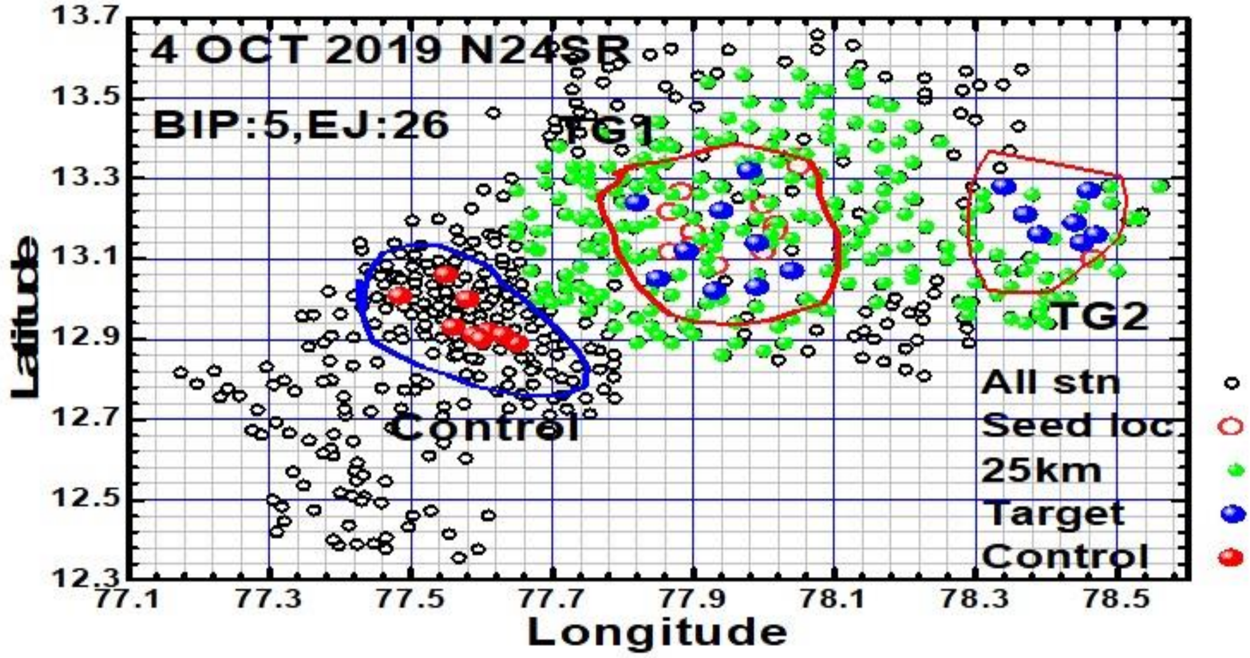


Figure 15: Control-target area rainfall on 4 October 2019.

Table 2 and 3 below gives the details of seeding rainfall analysis for selected days in 2017 and 2019. Three control stations were taken in the upwind side of the seeded area, and correlation has been carried out using a regression model.

Table 2. Correlation analysis of rainfall after seeding for selected days in 2017.

Control	No. of stations	Correlation	Significance Level	Equation	Target Rain within 4 hrs of Seed (mm)	Rain Control (mm)	Rain Natural (mm)	Rain Seeding (mm)
(Control & Target area rainfall analysis for 6 October 2017) [Control: (Shivamogga: Soraba, Shikaripur), Target 1: (Haveri: Ranebennur), 2: (Haveri: Hangar), Target 3: (Haveri: Shiggaon)]								
Target 1	37	0.32	95%	Y=3.43+0.32X	20.5	1.5	3.9	16.6
Target 2	30	0.41	95%	Y=3.45+0.29X	35.7	1.5	3.9	31.8
Target 3	34	0.45	99%	Y=2.73+0.32X	16.5	1.5	3.2	13.3
Mean increase in rainfall at the target due to seeding (%)								20.6
Control & Target area rainfall analysis for 11 October 2017 [Control (Dharwad-Hubli), Target 1 (Gadag-Gadag), Target 2 (Gadag-Ranebennur), Target 3 (Gadag-Naragund, Dharwad-Navalgund)]								
Target 1	32	0.71	99%	Y=1.82+0.63X	29.3	0.0	1.8	27.5
Target 2	43	0.57	99%	Y=2.28+0.64X	31.0	0.0	2.3	28.7
Mean increase in rainfall at the target due to seeding								**28.1**
Control & Target area rainfall analysis for 16 October 2017 [Control (Belagavi: Belagavi), Target 1(Belagavi: Khanapur), Target 2(Dharwad: Dharwad)]								
Target 1	42	0.46	99%	Y=2.77+0.48X	10.9	0.0	2.8	8.3
Target 2	44	0.43	99%	Y=2.66+0.23X	17.5	0.0	2.7	14.8
Target 3	30	0.48	99%	Y=4.0+0.50X	13.6	0.0	4.0	9.6
Mean increase in rainfall at the target due to seeding (%)								10.9

Table 3: Correlation analysis of rainfall after seeding for selected days in 2019.

Target	No. of stations	Correlation	Significance level	Equation	Target rainfall within the 4-h seed (mm)	Control rainfall (mm)	Natural rainfall (mm)	Rainfall due to seeding (mm)
Control & Target area rainfall analysis for 23 Sept 2019								
Target 1	36	0.55	99%	Y=0.538*X+2.629	38.28	30.89	19.25	19.03
Target 2	36	0.62	99%	Y=0.398*X+1.539	42.02	30.89	13.83	28.19
Target 3	33	0.48	99%	Y=0.647*X+1.945	50.22	30.89	21.93	28.29
Mean increase in rainfall at the target due to seeding on 23 Sept 2019								25.17
Target 1	36	0.51	99%	Y=0.567*X+3.739	46.55	0	12.26	34.29
Target 2	36	0.36	99%	Y=0.435*X+3.751	44.06	0	10.29	23.48
Mean increase in rainfall at the target due to seeding on 1 Oct 2019								28.89
Target 1	36	0.63	99%	Y=0.333*X-0.324	16.06	0.36	0	16.06
Target 2	36	0.80	99%	Y=0.164*X+0.647	8.17	0.36	0.71	7.46
Mean increase in rainfall at the target due to seeding on 4 Oct 2019								11.76
Target 1	36	0.90	99%	Y=0.637*X+0.922	17.57	4.64	3.88	13.69
Target 2	32	0.69	99%	Y=0.456*X+1.388	28.42	4.64	3.50	24.92
Target 3	36	0.94	99%	Y=0.728*X+0.736	16.20	4.64	4.11	12.09
Mean increase in rainfall at the target due to seeding on 5 Oct 2019								16.90

* The results show that an increase in rainfall ranging from 11 to 28 % is observed in seeded areas compared to the control stations with a confidence level of >95%.

4. Summary and Conclusions

The initial results of the study are as follows:

(i) An operational procedure has been successfully developed to identify areas for seeding using various inputs such as Satellite and Radar data, High-Resolution Weather Model Forecasts and Antecedent Rainfall.

(ii) There is a mean enhancement in rainfall due to seeding, and depending on favourable conditions, the increase is in the range of 11 to 28 % above the mean expected climatological rain.

(iii) The spatial data analysis of rainfall after seeding showed a spread of rainfall due to atmospheric wind flow over large area benefiting more areas.

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