

## Investigation of Cu cong Seeding Effect during Rainfall Augmentation in India

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Received April 25, 2016; in final form, September 7, 2016

**Abstract**—The results are presented of complex investigation of clouds in India which were seeded with a glaciogenic reagent from the aircraft. The seeding effect was assessed by the comparison of radar characteristics of the seeded clouds with the characteristics of clouds within the radar field of view. The maximum reflectivity increase in the seeded clouds in comparison with clouds in the natural cycle, an increase in the precipitation flux and specific mass of precipitated hail are observed. The merging of seeded clouds was observed during the study. It is shown that this process affects cloud characteristics resulting in the significant (by several times) increase in the precipitation flux. The measurements of electric discharges registered by the lightning detection network demonstrated that there were no lightning strikes in the seeded clouds, although the calculations indicated an increase in the electric activity of the clouds.

**DOI:** 10.3103/S1068373918040015

**Keywords:** Cu cong, cloud merging, cloud seeding, seeding effect, radar data, electric discharges, India

### 1. INTRODUCTION

Cloud seeding has been conducted in many countries to reduce economic loss due to severe atmospheric events. The main objective of the rainfall augmentation experiments is to satisfy the needs of agriculture (Australia, 2008–2009; Russia, 1989–1997; Ukraine, 1973–1978; Syria, 1991–2000; Iraq, 1992–1995; Italy, 1988–1994; China, 1989–1995; Cuba, 1983–1990; Uzbekistan, 1985–1991; Ukraine, 1959–1984; Taiwan, 1992; Thailand, 1995–1998; Mexico, 1997–1998; Iran, 1997–2007; India, 2004–2005; Saudi Arabia, 2007–2010; USA, 2006–2014). The second objective is to increase water levels in reservoirs (Honduras, 1993–1997; Turkey, 1992; China, 1998; USA, 1989–2000; Greece, 1992–1993; Indonesia, 1997–2011; Japan, 2006–2011) [1–3, 5, 6, 9, 10, 14, 17, 19, 21, 22, 24, 25]. The estimates of the seeding effect differ significantly and are from several percents to 100% and more for the above experiments [14]. Such significant variations in these seeding effects result from the researchers' use of different methods; besides, the results differ considerably depending on the cloud characteristics and experiment organization. The research community has accepted that the average precipitation increase is within 10–25% [3, 14, 15].

Weather Modification International (WMI, USA) seeded cumuliiform clouds to increase the amount of precipitation using the AgI-based glaciogenic reagent. The seeding was conducted in summer and autumn of 2015 in the state of Maharashtra (India). The seeding was carried out from an aircraft equipped with instrumentation for cloud physics and atmospheric parameters.

The objective of the present paper is to study the effect of seeding of the field of Cu cong clouds with the glaciogenic reagent. A statistical approach to the data analysis is used. It is based on the comparison of radar characteristics of the seeded clouds with those of similar unseeded clouds observed within the radar field of view at the same time. The lightning detection network data were also utilized for analyzing cloud characteristics. The results of the experiment on October 12, 2015 are analyzed.

## 2. EQUIPMENT

The WR-100 radar operating at the wavelength of 5.4 cm was installed in Aurangabad city to control the aircraft and to measure cloud characteristics. The antenna was mounted at the tower with the height of 10 m. The radar has the following basic technical parameters: peak pulse power is 250 kW and beam width is 1.65°. The minimum detectable signal is 10 dBZ at the distance of 100 km.

The TITAN software was used for the radar operation. This software assimilates radar data, identifies clouds, tracks them, presents their path, and predicts their movement. The detailed data on the TITAN characteristics are provided in [20].

The data on electric discharges, both intracloud (including cloud-to-cloud) and cloud-to-ground, were obtained from the measurements of the lightning location network used by the Indian Institute of Tropical Meteorology (LLN; <http://www.tropmet.res.in/~lip/annual-reports/AR-English-2013-14.pdf>). This network in the state of Maharashtra includes 20 broadband sensors operating at the frequencies from 1 Hz to 12 MHz.

The seeding aircraft was operated for the Indian Institute of Tropical Meteorology (Pune, India) and equipped with the set of microphysical instruments. Pyrotechnical formulation using silver iodide (AgI) produced by Ice Crystal Engineering (USA) were used as a seeding reagent. The upper part of the cloud below the reagent activation temperature threshold ( $-5^{\circ}\text{C}$ ) was seeded when the aircraft was penetrating the cloud. Cartridges containing 20 g of seeding agent were injected to the upper part of growing Cu cong clouds which burned for 37 s as they fell to about 1.2 km. The efficiency of ice formation reaches about  $3.0 \cdot 10^{13} \text{ g}^{-1}$  of ice nuclei at  $-10^{\circ}\text{C}$ . The reagent tests were carried out in the cloud chamber [18].

## 3. ATMOSPHERIC SURFACE LAYER CONDITIONS IN THE AREA OF THE CLOUD SEEDING

On October 12, 2015 the Aurangabad air temperature was  $25^{\circ}\text{C}$  at 08:00 local time (02:30 UTC). The temperature gradually rose and reached  $32^{\circ}\text{C}$  at 17:30 local time (11:30 UTC). Relative humidity was 80% at 02:30 UTC but fell considerably in the daytime (to 27%).

The aerosol concentration was high, and the visibility was only 4 km. To identify the area of dust origin, the HYSPLIT model (NOAA) was used. This model allows retrieving the trajectories of air masses which have come to the region under study. Such retrievals were made for two atmospheric levels: 1 km (950 hPa) and 6 km (500 hPa), the level close to the cloud top. It was found that air had come to the considered levels from the Arabian Sea and also provided the water vapor inflow to central India. It may be assumed that the low visibility on October 12 was associated with local aerosol sources. According to the AERONET data, the optical thickness was from 0.6 to 0.8.

The analysis of nearest radiosonde data (Mumbai, ID 43003) demonstrated that at 12:00 atmospheric conditions were characterized by the surface air temperature of  $32.0^{\circ}\text{C}$ , dew-point temperature was  $24.0^{\circ}\text{C}$  resulting in the dew-point deficit of  $8.0^{\circ}\text{C}$ . There were three shallow stable layers (temperature inversions) within the layer of active convection, at about 3.5, 4.5, and 6.0 km. The precipitable water vapor was equal to 51.9 mm.

The sounding analysis with the parcel method revealed that the cloud base should have been located at 1.5 km MSL at the air temperature of  $17.7^{\circ}\text{C}$ . Radar data (below) demonstrate that cloud base height was equal to 0.9 km. The zero isotherm was situated at the height of 5.3 km. The convective available potential energy (CAPE) was equal to 409 J/kg favoring the development of Cu cong clouds on October, 12. This value turned out to be small. The following wind shear was observed: winds were of the eastern direction in the lower atmosphere, whereas veered to the southeast starting from the height of 6.0 km. It is known that in most cases this wind shear favors the spatial separation of precipitation zone and updraft zone, intensifies convection, and leads to the formation of larger and longer-lived clouds.

## 4. CLOUD SEEDING AND ANALYSIS OF CLOUD DEVELOPMENT

Since the analyzed seeding was carried out for operational (not research) purposes, the assessment of the seeding effect required a special approach. Several cloud fields were chosen as experimental units; one was seeded and the others were used as controls. The radar data were used to estimate the effect of seeding. The TITAN software identified cloud cells as the zone where radar reflectivity exceeded 30 dBZ, the volume was more than  $10 \text{ km}^3$ , and located at the height above 2 km. From these criteria two cloud populations were formed. The first sample (seeded clouds) included the characteristics of all clouds which developed in the seeded area, and the second sample contained the clouds which simultaneously developed in all the other areas. Then the statistical comparison of cloud characteristics was provided for these two populations.

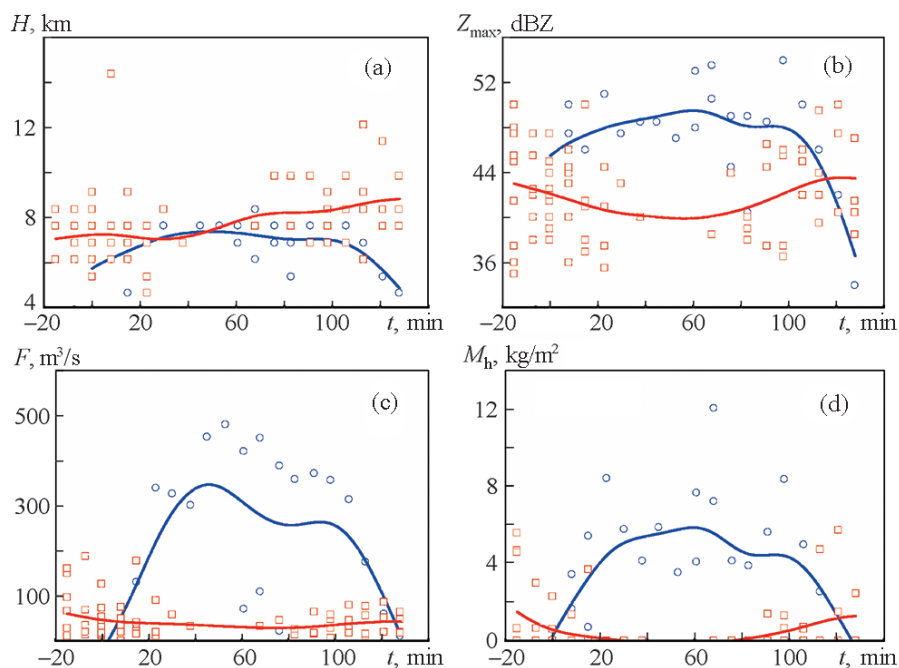


**Fig. 1.** The radar measurements of the seeded (red) and natural (blue) clouds: (a) cloud top height; (b) maximum reflectivity; (c) precipitation flux; (d) specific mass of precipitated hail.

The observations of clouds started at 09:41 UTC, when the aircraft arrived in the area to seed. The flight altitude was 6.7 km ( $-8^{\circ}\text{C}$ ). The seeded clouds were present as a cloud bank 20 km long stretched to the southeast and located at about 50 km from Aurangabad. A Cu cong cloud situated in the southern part of this bank was seeded first at 09:54 (hereinafter, UTC time is given). In total, eight Cu cong clouds were seeded which consecutively developed in the cloud bank under study. The last seeding was carried out at 11:11. In total, 12 pyrotechnic cartridges were used. Their number was defined by the extent of developing clouds and by the methodology of microphysical seeding used by WMI. The cloud which was seeded at 09:54 was identified by TITAN as a separate cloud at 10:04. The seeding led to the formation of clouds whose characteristics were measured by the radar until dissipation. The last cloud in the seeding zone disappeared from the radar screen at 12:04; the longest lifetime of a seeded cloud was 51 minutes. According to the aircraft observation data, the crystallization of cloud tops was observed after seeding. According to radar data, precipitation was observed under the clouds.

As noted above, the seeding effect was assessed by the comparison of radar characteristics of seeded clouds with the unseeded clouds which developed elsewhere, at the same time, within the radar field of view (within a range of 150 km). Radar echoes within the sector of  $180^{\circ}$ – $225^{\circ}$  were removed from consideration, because radar data in this direction were distorted due to permanent echoes (ground clutter).

Let us consider the time period of 09:41–12:04. The zero point is 10:04, i.e., the time of appearance of the first cloud detected by TITAN. Over the analyzed period TITAN provided 71 measurements of cloud characteristics for the natural clouds and 25 measurements for the seeded clouds (Fig. 1).

The cloud top height for the analyzed cells (defined as a minimum reflectivity of 30 dBZ) which developed after the seeding, did not exceed 8.4 km (Fig. 1a). The unseeded cells had greater vertical extent: the mean value of cloud top height exceeded that of the seeded cells by 900 m. The median value for the unseeded clouds was by 700 m greater than that of the seeded cells. It may also be noted that the most intensive cloud development in the group of clouds without seeding was observed during the initial and final observation periods. The intensity of convection development was considerably reduced during the period between the 20th and 80th minutes. These resulted in unseeded clouds having cloud tops that exceeded those of seeded clouds.

The maximum radar reflectivity for the investigated clouds varied from 34 to 54 dBZ (Fig. 1b). The seeded clouds were characterized by much higher reflectivity: the median values for two groups of clouds were equal to 48.5 and 42 dBZ, respectively, the maximum value of reflectivity for the group with seeding was 54 dBZ and that for the group without seeding was 50 dBZ.

The precipitation flux and the specific mass of precipitated hail calculated by TITAN for the group with seeding also essentially exceed those for the group without seeding (Figs. 1c and 1d). For example, the mean value of the precipitation flux is  $213 \text{ m}^3/\text{s}$  for the seeded clouds and  $43 \text{ m}^3/\text{s}$  for unseeded clouds; the specific mass of precipitated hail is  $3.9$  and  $0.6 \text{ kg/m}^2$ , respectively. The seeding increased the mean value of the precipitation flux by several times. For the seeded cells the maximum precipitation flux value exceeded the respective value for unseeded clouds ( $488$  and  $181 \text{ m}^3/\text{s}$ ), the ratio is similar for precipitated hail ( $12.0$  and  $5.7 \text{ kg/m}^2$ ).

The aircraft penetrated the clouds during seeding. The measurements of microphysical parameters including liquid water content were obtained. The maximum value of water content in the penetrated cloud varied from  $0.2$  to  $1.9 \text{ g/m}^3$ . It may be noted that the greatest water contents were recorded in the first half of the experiment, and the maximum values decreased after 10:40. Perhaps, this was caused by the convection intensity reduction.

Thus, the above data on the maximum value of reflectivity, the precipitation flux, and hail depth reveal that in the seeded clouds the precipitation generation process intensified. The following is also noteworthy. The choice of clouds for seeding was limited by their range from the radar (the aircraft home airfield) and by their proximity to Aurangabad. The flight was held in the afternoon. It was feared that the aircraft would arrive late to more distant desired seeding region, and convection intensity would start decreasing before seeding cloud occur. These “best” targets for seeding were the clouds located at the distance of  $100\text{--}150 \text{ km}$  too far for the aircraft to fly before peak heating would end and clouds would begin to weaken. Certainly, there is a risk that such positive results of the seeding is associated with the selection of “the best” clouds; however, the authors suppose that this probability is low in the analyzed case.

## 5. THE CLOUD MERGING EFFECTS ON CLOUD CHARACTERISTICS

The early studies by the authors demonstrated that the cloud merging might exert considerable influence on the precipitation formation [7, 8, 23]. This phenomenon was also observed in the considered experiment.

The process of cloud merging is illustrated in Fig. 2. The figure presents the projection of the maximum values of reflectivity to the underlying surface for four times and the vertical radar section in the northeast–southwest direction.

At 10:11 the “parent” cloud had the zone of high reflectivity at the height of about  $4.5 \text{ km}$ . The feeder cloud was at the development stage, its reflectivity was small and equal to  $36 \text{ dBZ}$  (Figs. 2a and 2c).

At 10:19, TITAN merged these two clouds into one; as follows from the analysis of the vertical section, the actual merging of clouds began (Figs. 2b and 2d). The precipitation zone formation in the lower part of the “parent” cloud and the increase in feeder cloud reflectivity at the height of  $4\text{--}6 \text{ km}$  were observed. The aircraft penetrated the top of this merged cloud at 10:17. Droplets of  $25 \text{ }\mu\text{m}$  were detected. The presence of such large droplets close to the cloud top also indicates the precipitation generation due to the coagulation mechanism.

At 10:26 one cloud including both merged clouds was formed (Figs. 2e and 2g); the merging completed at 10:34. The considerable increase in the precipitation zone extent was observed in the lower part of the cloud (Figs. 2f and 2h).

Let us consider how the cloud characteristics varied as a result of its merging with the feeder cloud. This case differs from those studied before in the fact that both clouds (“parent” and feeder) were seeded before the merging [8, 23]. At 10:13 the cloud situated in the northernmost part of the bank (the “parent” cloud) was seeded. Then at 10:17 the cloud was seeded which was located approximately in the center on the western side of the bank in its middle part at  $4 \text{ km}$  to the south of the “parent” cloud.

The characteristics of the “parent” cloud for different times are given in Table 1. As the cloud was developing from 09:49 till the moment of merging at 10:19, the maximum reflectivity of the cloud  $Z_{\text{max}}$  increased from  $23$  to  $49.5 \text{ dBZ}$ ; after that it decreased. Precipitation appeared in the cloud at 10:11, but its rate  $I$  was very low, hence, the precipitation flux  $F$  was also small ( $25 \text{ m}^3/\text{s}$ ). The cloud merging led to the considerable precipitation increase: according to radar data, the precipitation rate reached the maximum and was equal to  $68 \text{ mm/hour}$ . The precipitation flux increased significantly, by  $6.8$  times. This occurred both due to the precipitation rate increase and due to the increase in the area occupied by precipitation that is observed from the radar cross section. The maximum value of the precipitation flux was reached in 7 minutes and was  $230 \text{ m}^3/\text{s}$ . This value changed little for the next radar scan, although the precipitation rate dropped to  $19.5 \text{ mm/hour}$ .

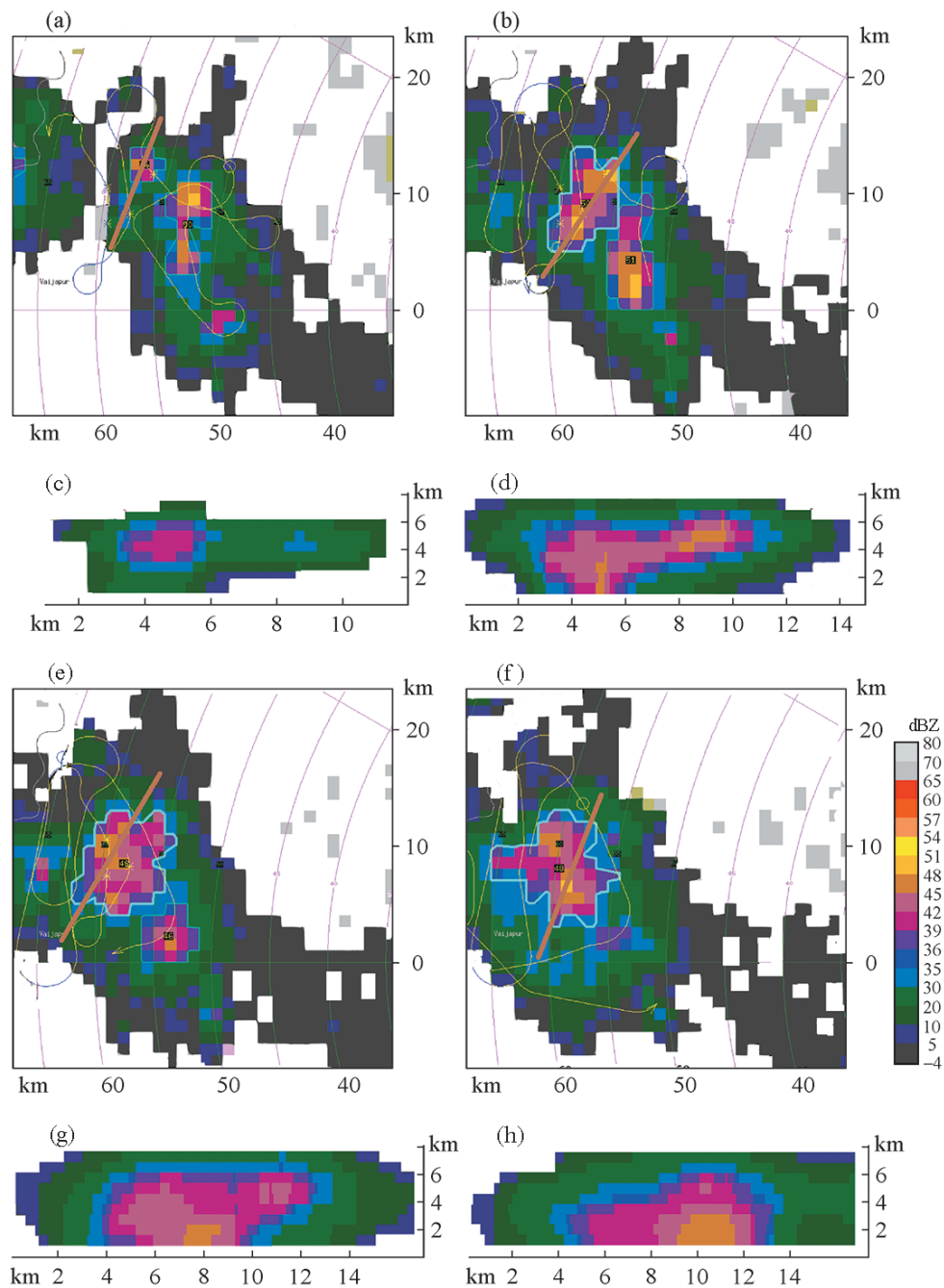


**Fig. 2.** (a, b, e, f) The projection of the maximum values of reflectivity to the underlying surface and (c, d, g, h) the vertical radar section in the northeast–southwest direction for the following moments of time: (a, c) 10:11; (b, d) 10:19; (e, g) 10:26; (f, h) 10:34. The brown line is the direction of the cross section; the solid yellow line is the aircraft flight route; the asterisks are the seeded areas.

The specific mass of precipitated hail  $M_h$  increased by 10 times after the cloud merging at 10:19. This might also be caused by the increase in the number and size of crystals due to the seeding. Its gradual decrease started at the next radar scan.

The variations in the cloud mass  $M$  derived from the data of the TITAN software for the secondary processing of radar data indicate the cloud merging. After the merging at 10:19, the mass of the united cloud increased by about 8 times (from 10 to 84 kt). At the next radar scan (10:26), the mass increased to 142 kt.

The height of the maximum reflectivity zone  $H_{Zmax}$  was equal to 4–6 km and decreased to 2 km by 10:34 that was evidently caused by falling precipitation.

**Table 1.** The characteristics of the “parent” cloud for different time periods

| Time         | $F$ , m <sup>3</sup> /s | $I$ , mm/hour | $H_{cb}$ , km | $H_{ct}$ , km | $Z_{max}$ , dBZ | $H_{Zmax}$ , km | $M_h$ , kg/m <sup>2</sup> | $M$ , kt  |
|--------------|-------------------------|---------------|---------------|---------------|-----------------|-----------------|---------------------------|-----------|
| 09:49        | —                       | —             | 4             | 6             | 23              | 5               | —                         | —         |
| 09:56        | —                       | —             | 1             | 6             | 33              | 4               | —                         | —         |
| 10:04        | —                       | —             | 1             | 8             | 41              | 4               | —                         | —         |
| 10:11        | 25                      | 0             | 1.6           | 8             | 46              | 4.3             | 0.7                       | 10        |
| <b>10:19</b> | <b>170</b>              | <b>68</b>     | <b>0.9</b>    | <b>8</b>      | <b>49.5</b>     | <b>5</b>        | <b>7</b>                  | <b>84</b> |
| 10:26        | 230                     | 24            | 0.9           | 8.4           | 47.7            | 5.7             | 5.7                       | 142       |
| 10:34        | 228                     | 19            | 0.9           | 8             | 48.5            | 2               | 4.1                       | 140       |

Note:  $H_{cb}$  is the cloud base height;  $H_{ct}$  is the cloud top height. The moment of cloud merging is bolded.

## 6. ELECTRIC ACTIVITY OF CLOUDS

The seeding of clouds led to the considerable variations in their microphysical characteristics associated with the formation of the crystal fraction. The change in the crystal concentration could affect electrification processes and the generation of electric discharges [11, 12]. In view of this, let us consider the measurement data on the characteristics of electric discharges registered in the analyzed region using the lightning location network.

The measurement data revealed that no lightning strikes were registered in the seeded clouds. Lightning strikes were also absent in the clouds situated at the distance to 150 km from the radar during the observation period. Only one cloud was an exception, within it intracloud lightning strikes were registered from the 113th to the 121st minute (Table 2). In total, 16 lightning strikes were registered at the height from 11267 to 19469 m (the mean height is 16700 m). The current of these lightning strikes determined by the lightning detection system varied from 2.1 to 14.1 kA, with the mean value of 4.5 kA. During the next radar scan (122nd–130th minutes), 22 more intracloud lightning strikes and three cloud-to-ground lightning strikes were registered. As well as for the North Caucasus clouds [13], intracloud lightning strikes were generated at first, and cloud-to-ground lightning strikes were observed in 5 minutes.

The radar data demonstrated that the thundercloud top exceeded the top of seeded clouds by 2–3 km, and the maximum reflectivity of this cloud was smaller. However, the zone of the maximum reflectivity in the thundercloud was situated at the height of 7 km, i.e., by 1–2 km higher than for the seeded clouds.

The seeding effects on the lightning generation have been investigated poorly so far; therefore, the authors thoroughly compared the characteristics of seeded clouds with the characteristics of the only thundercloud in the analyzed region.

To assess the electric conditions of clouds, the indirect criteria based on radar data are utilized [4, 12, 16]. In aviation meteorology, the complex thunderstorm criterion is used:  $Y = H \lg Z_3$ , where  $H$  is the maximum height of echo (cloud top height);  $\lg Z_3$  is reflectivity at the height of 2–2.5 km above the zero isotherm (for this case, at the height of 7.25 km). The level of thunderstorm risk is defined by the relationship between the value of  $Y$  and parameter  $Y_{cr} = H_{-22\text{ C}}(\lg Z_3)_{\min}$ , where  $H_{-22\text{ C}}$  is the height of the  $-22\text{ C}$  isotherm,  $(\lg Z_3)_{\min}$  is the minimum value of  $\lg Z_3$  for thunderstorms [4]. It was empirically found that the thunderstorm probability is >90% if  $Y > Y_{cr} + 14$ , it is 70–90% if  $Y > Y_{cr} + 6$ , and equals <70% if  $Y > Y_{cr}$ . For all clouds studied in this experiment,  $H_{-22\text{ C}} = 8.9\text{ km}$ ,  $(\lg Z_3)_{\min} = 1.5$ ; hence,  $Y_{cr} = 13.4$ .

From the results of studying clouds in the North Caucasus and the data of the LS8000 lightning detection system (Vaisala) used in that region, regression equations were derived that relate the flash rate of “cloud-to-ground” (CG) and “intracloud” (IC) lightning strikes with the criterion  $Y$  [13]:

$$F_Y^{CG}(Y) = 0.9 - 0.0003Y - 0.0046Y^2; \quad (1)$$

$$F_Y^{IC}(Y) = 22.6 - 1.7Y - 0.055Y^2. \quad (2)$$

It was also shown that the volume of the supercooled part of the cloud with the reflectivity above 35 dBZ ( $dV_{35}$ , km<sup>3</sup>) correlates well with the lightning flash rate; the corresponding regression equations are provided below:

$$F_Y^{CG}(Y) = 0.21 - 0.023(dV_{35}) - 1.4 \cdot 10^{-5}(dV_{35})^2; \quad (3)$$

**Table 2.** The variations in radar parameters and calculated lightning flash rates

| Cloud | $t$ ,<br>minute | $Z_{\max}$ ,<br>dBZ | $H_{Z\max}$ ,<br>km | $Z_3$ ,<br>dBZ | $H$ , km | $dV_{35}$ ,<br>km <sup>3</sup> | $Y$  | $F_Y^{\text{CG}}$    | $F_{35}^{\text{CG}}$ | $F_Y^{\text{IC}}$ | $F_{35}^{\text{IC}}$ |
|-------|-----------------|---------------------|---------------------|----------------|----------|--------------------------------|------|----------------------|----------------------|-------------------|----------------------|
|       |                 |                     |                     |                |          |                                |      | minute <sup>-1</sup> |                      |                   |                      |
| 63S   | 23              | 49.5                | 5                   | 30             | 8        | 41                             | 23.6 | 1                    | 1                    | 48                | 34                   |
|       | 30              | 47.5                | 6                   | 34             | 9        | 53                             | 30.1 | 3                    | 1                    | 78                | 48                   |
|       | 38              | 44                  | 5                   | 26             | 9        | 35                             | 23.4 | 1                    | 1                    | 47                | 29                   |
|       | 45              | 45                  | 5                   | 26             | 9        | 23                             | 23.4 | 1                    | 1                    | 47                | 23                   |
| 70S   | 45              | 47.5                | 5                   | 35             | 10       | 42                             | 34.5 | 4                    | 1                    | 102               | 35                   |
|       | 53              | 44                  | 5                   | 31             | 10       | 51                             | 31   | 3                    | 2                    | 83                | 77                   |
|       | 61              | 41.5                | 5                   | 30             | 12       | 35                             | 35.4 | 4                    | 1                    | 107               | 29                   |
|       | 68              | 53.5                | 5                   | 36             | 11       | 58                             | 39.6 | 5                    | 2                    | 131               | 55                   |
| 79S   | 76              | 46.5                | 6                   | 30             | 11       | 39                             | 33   | 3                    | 1                    | 93                | 33                   |
|       | 76              | 49                  | 5                   | 28             | 10.5     | 22                             | 29.1 | 2                    | 1                    | 73                | 22                   |
|       | 83              | 44                  | 5                   | 26             | 10.5     | 15                             | 27.3 | 2                    | 1                    | 65                | 21                   |
|       | 83              | 46.5                | 5                   | 23             | 12       | 20                             | 27.6 | 2                    | 1                    | 66                | 22                   |
| 81S   | 91              | 47                  | 5                   | 33             | 12       | 42                             | 39   | 5                    | 1                    | 127               | 35                   |
|       | 98              | 54                  | 5                   | 32             | 11       | 59                             | 34.6 | 4                    | 2                    | 102               | 57                   |
|       | 106             | 48.5                | 5                   | 35             | 11       | 44                             | 38.5 | 5                    | 1                    | 124               | 37                   |
|       | 113             | 45                  | 5                   | 27             | 10.5     | 18                             | 27.8 | 2                    | 1                    | 67                | 21                   |
| 88TH  | 106             | 42                  | 7                   | 42             | 10.5     | 23                             | 44.1 | 7                    | 1                    | 159               | 23                   |
|       | 113             | 50                  | 7                   | 50             | 14       | 62                             | 69.3 | 18                   | 2                    | 366               | 61                   |
|       | 121             | 50                  | 7                   | 50             | 14       | 62                             | 70   | 19                   | 2                    | 366               | 61                   |

$$F_Y^{\text{IC}}(Y) = 22.7 - 0.36(dV_{35}) - 0.0016(dV_{35})^2. \quad (4)$$

The flash rates of lightning strikes and discharges in the clouds were calculated using the above equations (Table 2). Four seeded clouds (63S, 70S, 79S, and 81S) and the natural thundercloud (88TH) are considered.

The data in Table 2 demonstrate that according to the thunderstorm criterion  $Y$ , all clouds are thunderclouds with the probability of 90%. The cloud-to-ground lightning flash rate ( $F_Y^{\text{CG}}$ ) computed from the thunderstorm criterion  $Y$  is up to 5 minutes<sup>-1</sup> for the seeded clouds and up to 19 minutes<sup>-1</sup> for the natural thundercloud; in the case of calculation based on the criterion  $dV_{35}$ , it varies from 1 to 2 minutes<sup>-1</sup> for all analyzed clouds.

The rate of intracloud discharges ( $F_Y^{\text{IC}}$ ) calculated from the thunderstorm criterion  $Y$  is up to 131 minutes<sup>-1</sup> for the seeded clouds and to 366 minute<sup>-1</sup> for the natural thundercloud. The lightning rate based on the criterion  $dV_{35}$  varies from 21 to 77 minute<sup>-1</sup> for all seeded clouds and from 23 to 61 minute<sup>-1</sup> for the thundercloud.

The sizes of the supercooled parts of the cloud with the reflectivity of >35 dBZ were compared. The comparison demonstrates that in the thundercloud the significant size of this zone persisted much longer than in the seeded clouds. The value of  $dV_{35} = 62 \text{ km}^3$  was registered in the thundercloud for more than 16 minutes. For non-thunderclouds, the similar values of  $dV_{35}$  were registered (at the 68th and 98th minutes), but the considerable decrease in this parameter was already recorded at the next radar scans.

Thus, if one assesses the risk of thunderstorm formation for the clouds based on parameters  $Y$  and  $dV_{35}$ , it is noteworthy that the investigated seeded clouds were quite close to the thunderstorm stage. Perhaps, the transition to this stage did not occur, because the volume of the supercooled part of these clouds was insufficient for the significant electrification of clouds generating lightning discharges [12]. It is also important that the level of maximum reflectivity in them was characterized by higher temperature than the respective level in the thundercloud.

It should be noted that the considered thunderstorm criteria considerably overestimate the lightning flash rate as compared with the observed one for the investigated clouds developing in India. In particular,

the calculated values of criteria  $Y$  and  $dV_{35}$  indicate the formation of lightning strikes in the seeded clouds; however, this was not corroborated by the lightning detection system data. It is obvious that the radar-based thunderstorm criteria are to be specified using the new capabilities provided by modern lightning detection systems.

## 7. CONCLUSIONS

The characteristics of clouds seeded with the glaciogenic reagent from the aircraft were investigated in detail. The seeding was carried out in India.

The seeding effect was assessed by the comparison of radar characteristics of the seeded clouds with those of the clouds observed within the radar field of view at the same time. The presented radar data indicate the positive result of the seeding on the analyzed day: the considerable increase was registered in the values of the maximum reflectivity of clouds after the seeding as compared with natural clouds. In the seeded clouds the precipitation flux and specific mass of precipitated hail (ice particles) demonstrated more than twofold increase as compared with the unseeded clouds. It should be taken into account that the nonrandomized scheme of the experiment was applied, and the number of experimental units was not very large.

It was found that the merging of seeded clouds leads to the significant (by several times) increase in the precipitation flux.

According to the measurement data on the characteristics of electric discharges obtained using the lightning detection network, no lightning strikes were registered in the clouds in the analyzed area after the seeding. The analysis revealed that the thunderstorm criterion  $Y$  used in Russia essentially overestimates the lightning flash rate as compared with the observed one for the investigated clouds developing in India. The use of the new criteria  $dV_{35}$  for the estimation of lightning flash rate leads to more realistic results.

## ACKNOWLEDGMENTS

The research was supported by the Russian Foundation for Basic Research (grants 16-05-00197\_a, 17-05-00965, BRIKS\_t 18-55-80020, 15-55-45026 IND\_a).

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