On the influence of glaciogenic seeding on the radar characteristics of hail clouds

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Abstract. 40 hail and hail-hazardous clouds of various strengths were considered, which were seeded with the help of a glaciogenic agents in order to prevent and interrupt hail. An unseeded control cloud was matched for each seeded cloud. For this, the parameter $dV_{35}$ was used – the volume of the radio echo of the cloud with a reflectivity of more than 35 dBZ above the level of zero isotherm. A cloud was considered to be a control cloud if at the time of the beginning of seeding and 10 minutes before that $dV_{35}$ differs by no more than 15% from the same value of the seeded cloud. To assess the possible impact of seeding, the radar characteristics of pairs of seeded and control clouds were analyzed. It was found that in the seeded clouds the average, maximum and minimum values of the maximum reflectivity, the height of the upper boundary, the vertically integrated water content, the intensity of precipitation and $dV_{35}$ are higher, and the height of the maximum reflectivity is slightly lower than the similar values of the control clouds.

1. Introduction

Experimental and production work on weather modification (WM) and impact on cloud processes in order to enhance precipitation and reduce damage from hail have been carried out since the middle of the last century [1, 3, 14, 7]. The main method of influencing clouds is considered to be the introduction of an aerosol of a glaciogenic [1, 7, 15] or hygroscopic [16, 17] action. It is assumed that such an aerosol leads to microphysical [7] changes in the cloud volumes subjected to seeding, which ultimately can affect the thermodynamic processes and the precipitation regime in the cloud [18].

But, despite such a long period of development and improvement of WM technologies, there are still many unresolved and insufficiently studied issues. One of them is to determine the magnitude of the effect, which manifests itself, for example, in an increase in the amount and duration of precipitation, suppression of hail precipitation, etc. Due to the high natural variability of clouds and the relatively small change in their characteristics as a result of WM, it is often extremely difficult to assess the effect of the impact.
With the development of computer technology, numerical models of clouds [8, 19] began to be used more and more often, on which it is possible to approximately estimate the difference between clouds development in natural mode and during WM.

Another widely used method for determining the WM effect is the use of statistical methods with the processing of large enough data samples [2]. The methods of historical series [1, 20], control samples [21] and randomization [22] are used. For this, radar, satellite, aircraft and ground measurements of clouds and precipitation are used.

The goal of this work is to compare the radar characteristics of seeded and unseeded convective clouds of various strengths that developed in areas where rocket technology was used to protect against hail.

2. Methodology and data

2.1 Hail suppression technology

The data included in the current analysis are based on the results of anti-hail work carried out in the Stavropol District of Russia using Russian rocket technology [1], based on the concept of precipitation acceleration [1]. This concept assumes seeding of areas of new growth of powerful hail clouds or seeding objects (SO), which are usually on the right upwind flank, or also called feeder clouds, as well as the first radio echo of newly formed convective clouds. In both cases, convective clouds corresponding to the Cumulus and Cumulus Congestus types are seeded [5].

Seeding is carried out by launching of anti-hail rockets with an ice-forming agents based on silver iodide [1] into the supercooled part of the feeder clouds in the $-6 \div 3 \, ^\circ C$ layer. The reagent is sublimated in a pyrotechnic way and is sprayed into the cloudy medium in the form of a submicron aerosol, the effective crystallizing effect of which begins at a temperature of $-6 \, ^\circ C$ and increases with decreasing temperature [9].

Subsequently, artificial ice crystals actively grow due to the Bergeron-Findeisen mechanism [23], actively absorbing water vapor from evaporating cloud droplets, participate in the formation of snowflakes, which are numbered, capturing cloud droplets, ice grains, and under favorable conditions for precipitation particles.

Stimulation of precipitation earlier than it could fall during the natural development of the cloud worsens the conditions for the nucleation and growth of hailstones and thus can lead to a positive WM effect.

2.2. Radar measurements

An integral element of any WM technologies is the conduct of radar measurements of clouds in the centimeter wavelength range, based on the processing of radio echo reflected by hydrometeors of various types (water drops, crystals, croup, hailstones, water-cut hailstones) [1, 4].

In this analysis, we used the data of the dual-wavelength radar MRL-5 [4], installed at the airport of Stavropol, and equipped with an automated system ASU-MRL [3]. The radar operates in the mode of sequential circular scanning of space at 18 elevation angles from 0º to 82º relative to the earth's surface with a thickening of the angular grid near the ground and in the middle layer of the troposphere. This scanning mode allows receiving volumetric scan files every 3.5 minutes, and then the software calculates and displays more than 50 cloud parameters on the operator's screen. For this, a single-wavelength method was used in the 10-cm wavelength range according to the method described in [1].

2.3. Selection of data for analysis

To determine the effect of glaciogenic seeding on the development of powerful convective clouds, 40 cases were selected. Of these, at the time of the seeding start, there were 9 SO of II category, 29 SO of III category and 2 SO of IV category. According to the classification [1], Category I SO is a potentially hail-hazardous cloud, the first radio echo (or maximum radio echo) of which originates in a layer from 0 to 5 km above the 0ºC isotherm, with a tendency to develop; SO of the II category - a hail-hazardous cloud with a tendency of development; Category III SO - hail cloud, from which,
according to radar data, hail falls; Category IV SO is a super-powerful hail cloud from which a large intense hail falls.

For each seeded cloud, an unseeded control cloud of similar characteristics was found in the adjacent upwind or lateral territory far from the anti-hail protection zone in order to exclude the possible ingress of the agent during its horizontal transfer due to the wind. For this, the radar parameter $dV_{35}$ was used - the volume of the radio echo of the cloud with a reflectivity of more than 35 dBZ above the level of the zero isotherm. It was considered that a cloud is a control cloud if at time moment $t_0$ (beginning of seeding) and $t_0 - 10$ min, the value of the parameter $dV_{35}$ differed by no more than 15% from the same value of the seeding cloud.

The radar characteristics of pairs of seeded and control clouds were analyzed. In this case, the entire period of cloud seeding was covered, with the exception of the first 3.5 minutes after the start of seeding, associated with some delay in the beginning of the agent action.

3. Results

To compare the median, quartiles, minimum and maximum values, as well as the asymmetry of the distributions of the radar characteristics of the seeded and reference clouds, diagrams of the “Box and Whiskers diagram” type were constructed (see figure 1).

![Box-Whiskers diagram](image)

**Figure 1.** «Box-Whiskers» diagram for the distribution of the series of radar characteristics of unseeded (left) and seeded (right) clouds:

(a) - maximum reflectivity $Z_{\text{max}}$, dBZ; (b) - altitudes of the cloud upper boundary $H_{\text{TOP}}$, km; (c) - vertically integrated water content $V_{\text{IL}}$, kg/m$^2$; (d) - the volume of the cloud with reflectivity more than 35 dBZ in km$^3$; (e) - precipitation intensity $S_{\text{RI}}$, mm/h; (f) - heights of the maximum reflectance level $H_{Z_{\text{max}}}$, km.
Thus, for the maximum reflectivity (figure 1a) of seeded clouds, there is a pronounced increase in the median value by 5.7, the maximum by 3, and the minimum by 4 dBZ, while the distribution becomes narrower than for unseeded clouds. Both samples are distributed symmetrically.

The median of the distribution of the upper boundary of seeded clouds (figure 1b) increases by 2.1 km, and the upper quintile by 2.2 km relative to unseeded clouds.

The largest increase is observed in the vertically integrated water content VIL (figure 1c). The median of the distribution of this characteristic for seeded clouds is 45.1 kg/m², while for unseeded clouds it is only 16.0 kg/m², that is, the difference is 2.8 times. Both samples have a moderate asymmetry, stretched into the region of large values of the parameter.

The average value of the parameter dV_{35} (figure 1d) for seeded clouds increases by 3-4%, while the median increases by 36%. It should be noted that for unseeded clouds there was a pronounced asymmetry with stretch towards high values, while for seeded clouds the shape of the distribution was almost symmetric.

For seeded clouds, a sharp increase in precipitation intensity is observed (figure 1e), at which the median increases from 56 to 155 mm/h, that is, more than 2.7 times. Both samples are distributed almost symmetrically.

A decrease by 0.5 km shows only the parameter of the height of the maximum reflectivity level H_{Zmax} (figure 1f) of the seeded clouds. The lower quartile decreases from 3.5 to 3 km, and the upper one from 6 to 5.5 km. The spread of the values of this parameter for unseeded clouds is much wider than for seeded clouds.

4. Discussions
An increase in the maximum reflectivity and the height of the upper boundary of the clouds may indicate the stimulation of the development of seeded clouds, due to the so-called dynamic effect, in which the latent heat of condensation on the glaciogenic aerosol leads to an increase in convection and updrafts in the cloud. This effect was discovered back in the 60s of the last century, for example, in [24] and served to formulate the concept of dynamic seeding utilized in precipitation enhancement works. Indeed, our analysis showed a significant increase in the vertically integrated water content and the intensity of precipitation of seeded clouds.

The dV_{35} parameter can be associated with the ice grains and graupels, which serves as the embryo of large hailstones. Its slight increase in the seeded clouds indicates an increase in the concentration of such embryos, which, according to the concept of favorable competition by G.K. Sulakvelidze [12] may lead to increased competition for supercooled cloud moisture and a decrease in the size of growing hailstones.

A decrease in the height of the maximum cloud reflectivity by 0.5 km indicates a decrease in the hail hazard of hail clouds and is consistent with the concept of trajectory lowering by Browning and Foote [25], according to which hailstones growing at lower altitudes have smaller sizes and lower kinetic energy upon falling.

Thus, it can be argued that the seeding of hail and hail-hazardous clouds, carried out according to the concept of precipitation acceleration by M.T. Abshaev [1, 6], led to significant changes in the considered radar characteristics of hail and hail-dangerous clouds.

5. Conclusions
40 pairs of seeded and control clouds were considered. According to the hail clouds classification accepted in precipitation acceleration concept the first group of clouds by the beginning of seeding included 9 SO of category II, 29 SO of category III, and 2 SO of category IV. It was found that the maximum reflectivity, the height of cloud top, the intensity of precipitation, and the vertically integrated water content of the seeded clouds significantly exceed the analogous parameters for unseeded clouds. The exception is the maximum reflectivity height, which decreases with seeding.

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