Interlink between lightning activity of hailstorms and their radar characteristics

M T Abshaev¹, A M Abshaev¹, J M Gekkieva², A Kh Adzhiev²
¹Hail Suppression Research Center «Antigrad», Nalchik, Russia,
²High Mountain Geophysical Institute of Russian Hydrometeorological Service, Nalchik, Russia

abshaev@mail.ru, julduz_gekkieva@mail.ru

Abstract. The time course and the relationship of radar and lightning characteristics of the powerful hail clouds of the North Caucasus are considered. The studies were conducted in 2016-2018 at the automated meteorological radar complex ASU-MRL, which provided simultaneous acquisition and processing of radar data from the MRL-5 and 4-point network of LS-8000 lightning detection sensors, visualization of thunderstorm discharges on the background of the radar reflectivity map, as well as measurement complex of radar and thunderstorm cloud characteristics, including their maximum radar reflectivity $Z_{\text{max}}$, heights, volumes and water content of clouds at different reflectivity values, frequency of intracloud lightning discharges (VHF), "cloud-to-ground" discharges with positive (LF+) and negative polarity (LF-), current and duration of discharges. An analysis of the results showed that lightning discharges begin in the developing hail clouds of the North Caucasus when their maximum radar reflectivity reaches $Z_{\text{max}} \geq 40 \text{ dBZ}$, the frequency of discharges increases with increasing reflectivity, integral water content and enhancing the process of precipitation formation. The highest thunderstorm activity is noted at $Z_{\text{max}} \approx 70-75 \text{ dBZ}$. Most low-frequency discharges of LF- and LF+ types are observed on the windward flank in the zone of intensive precipitation formation, and the majority of high-frequency VHF discharges are on their leeward side. Seeding of hail clouds with glaciogenic reagents with anti-hail rockets also leads to an increase in the frequency of discharges of all types.

1. Introduction
In many regions, the problem of ensuring life safety in the conditions of growing thunderstorm activity determines the high relevance of the development of methods for forecasting, detecting, monitoring, warning and preventing powerful hail processes accompanied by intense thunderstorm activities, heavy rains, floods and mudflows that cause serious material losses and human victims. These processes are usually a complex cluster of convective cells, in which the formation of precipitation is due to a set of interrelated thermo-hydrodynamic, microphysical and electrical processes that are difficult to adequately model theoretically. Powerful updrafts associated with thermal convection, often amplified by dynamic factors (the invasion of cold fronts and complex terrain) lead to the formation of convective clouds, condensation and freezing of huge amounts of moisture and the formation of precipitation. Phase transitions and microphysical processes of precipitation formation lead to the electrification of cloud particles and precipitation particles. Fallout of precipitation, as well as vertical flows having a complex spatial structure with alternating updraft and downdraft flows, lead
to the separation of charges of opposite signs and their accumulation at different altitudes or spaces. An increase in the electric field strength to a critical value leads to lightning discharges between different volumes of the cloud, or between the cloud and the ground.

The purpose of this work is an experimental study of the relationship of thunderstorm activity of hail clouds with their radar reflectivity and water content, the dependence of thunderstorm activity on the development stage and the study of the features of the spatial position of different types of discharges.

Research is conducted for the North Caucasus covering period 2016-2018, which is characterized by increased thunderstorm activity. In the past 30 years, there has been a tendency to increase the frequency and intensity of thunderstorms and hail in the foothill and lowland areas and a slight decrease in the mountainous areas [1]. This is apparently due to the climate change and transformation of global atmospheric circulation noted in [6] (an increase in temperature on 0.9–1.0 °C and an air humidity on 5–6%, a change in the direction of leading streams from the west and south-west to south and south-west).

2. Method and equipment of observations
The studies were carried out according to the observations of the Stavropol software-technical complex "ASU-MRL", which provided for the simultaneous acquisition and processing of 10 cm data from the radar channel MRL-5 and the 4-point network of lightning sensors [3], in which in the cities of Cherkessk, Stavropol, Zelenokumsk and Kyzburun installed (Figure 1) sensors of the company "Vaisala" LS8000.
Software-technical complex "ASU-MRL" [2] provided:

- space radar scan every 3.5 minutes;
- processing of radar data about clouds and precipitation within a radius of 250 km;
- formation and display of maps of maximum reflectivity, horizontal sections at any height, vertical sections in any azimuth, maps of size and kinetic energy of hail, intensity and precipitation, vertically integrated water content (VIL), etc. (about 30 different cards);
- measurement of more than 50 one-dimensional, two-dimensional and three-dimensional parameters of the cloud system and its individual cells;
- management of cloud seeding in order to prevent hail and artificial increase of precipitation;
- assimilation of LS-8000 lightning data and visualization of lightning discharges on the background of the maximum reflectivity map, against the background of the VIL map or any other.

Algorithms for information processing in the "ASU-MRL" are given in [1].
Each lightning detecting device has two sensors: high-frequency (VHF), which registers the intra-cloud discharges and low-frequency (LF), which registers discharges of the cloud-ground-positive (LF+) and negative (LF-) polarity. The location of each discharge is determined by the signal of at least two sensors [4]. Data synchronization is carried out on the signals of the exact time received by GPS receivers with an accuracy of 100 nanoseconds.

The LS8000 sensor network data was transmitted in the ASU-MRL in real time, which made it possible to obtain a synthesized map of radar and lightning-discharge information, which displayed all the VHF and LF discharges detected during the 3.5-minute period of the radar scan cycle. The frequency of discharges was determined by dividing the number of discharges taken during the scan cycle by the duration of the scanning.

The observations were carried out around the clock and covered the entire period of the beginning of the development of clouds before the dissipation of cloud systems.
3. Data analysis

In the period from 04/01/2016 to 09/30/2018, extensive experimental data was obtained, covering observational data for about 300 days with cloudiness, including 183 days with thunderstorms and 132 days with hail, when radar radars were obtained in real time and lightning direction data. The number of scan files with hail clouds varied from 90 to 310. Hail suppression operations were carried out at the period when these clouds were within the range of action of the rocket sites of the Krasnodar and Stavropol Antihail Services of Russian Hydrometeorological Service they.

From the extensive observational data for analysis in this work, data on the evolution of 10 powerful hail clouds were selected. As an example, consider the characteristics of one of the 6 hail clouds observed on July 1, 2018.

This cloud originated at 12\textdegree 48' of local time southwest of the radar position at a distance of 130 km and moved to the northeast with an average speed of about 60 km/h and from 13\textdegree 13' to 16\textdegree 08' passed through the territory of Krasnodar and Stavropol Territories, leaving behind a band of intensive hail and rain 180 km long. In terms of the spatial structure and structure of the radar echo, the cloud was a supercell, with an extensive radar echo overhang and a weak radar echo area (Figure 2) indicating the presence of an extensive upward jet. According to radar data, the supercell reached its maximum development at 14\textdegree 06'. According to ground-based observations, from 13\textdegree 30' to 16\textdegree 09', hail and intense rainfall accompanied by a hurricane wind fell from this cloud. The size of the hail reached 3 cm and in some places 4 cm or more. The width of the hail line varied from 4 to 9 km. Despite the high speed of movement of the cloud, a layer of hail remained on the surface of the earth, which caused serious damage to crops, gardens, cars, roofs and glass of buildings. A strong wind tore trees from the roots, destroyed the power lines and other communications. The amount of precipitation reached 30 mm, and in some places 50 mm, which led to flooding of the streets of some cities and villages.
Figure 2. Example of synthesized map of radar derived structure of the supercell hailstorm developed in Northern Caucasus on 01.07.2018 with symbols of lightning discharges: “o” intracoud VHF discharges; “+” cloud-to-ground discharges of positive polarity [LF+], “-” cloud-to-ground discharges of negative polarity [LF-], blue vector “→” denotes direction of the leading wind stream in the middle troposphere, red vector “→” denotes to the direction of cloud displacement.

Figure 3 shows the time course of the cloud parameters: maximum radar reflectivity \( Z_{\text{max}} \), heights of isolines of reflectivity \( Z = 25, 35, 45 \ldots \ 65 \) dBZ (\( H_{Zi} \)), the volume of the radar echo \( V_{Zi} \), and the integral water content of the cloud \( M_{Zi} \) inside the isolines \( Z = 15, 25, 35 \ldots \ 65 \) dBZ, observed on 07/07/2018. Figure 4 shows the time course of hail size \( d_{\text{max}} \), radio echo area \( S_{\text{radar echo}} \), precipitation areas in the form of rain \( S_{\text{rain}} \) and hail \( S_{\text{hail}} \), current values of LF discharges and the frequency of lightning discharges of all types (VHF, LF_{total}, LF_{+}, LF_{-}).

It follows from Figures 3 and 4 that thunderstorm activity in this cloud began at 12:54, when reflectivity reached the value \( Z_{\text{max}} = 50 \) dBZ and intensified as the process of precipitation formation increased. It is noteworthy that at first there were only cloud-ground discharges of LF_{+} and LF_{-} types, and the VHF discharges began only at 13:33 before the formation of hail in the cloud. Peak discharge current values ranged from 10 to 80 A.

From 12:38 to 13:28 the frequency of electrical discharges increased with increasing of \( Z_{\text{max}} \), heights \( H_{Zi} \), volumes \( V_{Zi} \) and total water content \( M_{Zi} \). During the quasi-stationary state of the cloud from 12:38 to 14:34, when the values of \( H_{Zi}, V_{Zi} \) and \( M_{Zi} \) changed little, the frequencies of lightning discharges of LF_{+} and LF_{-} types were approximately the same and ranged from 10 to 20 discharges per minute. The frequency of VHF discharges was less, but gradually increased.

In the period from 14:34 to 15:41, the frontal part of the radar echo canopy was seeded with the help of Alazan-6 antithail rockets, each of which contains 630 grams of pyrotechnic composition with 8% AgI content and can create \( 6.6 \cdot 10^{15} \) crystallizing nuclei at -10 °C. In the course of 67 minutes, 200 rockets were introduced into the region of weak updrafts, which could create about \( 10^{18} \) of ice-nucleating particles.
Figure 3. Time course of radar-derived characteristics $Z_{\text{max}}$, $H_{Zi}$, $V_{Zi}$, and $M_{Zi}$ of the supercell hailstorm, observed in northern Caucasus in 01.07.2018.

During the period of seeding and subsequently a gradual spreading of the cloud, an increase in the area of the radar echo and the area of rain, as well as a gradual increase in the frequency of electrical discharges of all types are noted. The frequency of the intra-cloud discharges of the VHF type increases especially noticeably, reaching to $15^{58}$ up to 350 discharges/min. At the same time, an almost constant flickering glow of the cloud was visually noted by local observers.
Figure 4. Time course of hail size ($d_{\text{max}}$, cm), squares of radar echo ($S_{\text{radar echo}}$), precipitation ($S_{\text{rain}}$) and hailfall ($S_{\text{hail}}$), values of LF discharges current and frequency of lightning discharges of all types (VHF, LF$_{\text{total}}$, LF+, LF-) produced by supercell hailstorm on Northern Caucasus in 01.07.2018.

Of particular note is that the LF+ and LF- discharges are mainly concentrated on the upwind flank of the cloud in the area of increased reflectivity and water content, where hail is formed and growing.
and the VHF discharges are mainly concentrated on the leeward side in the area of weaker precipitation and the anvil (Figure 5).

From figure 4 it also follows that in 10 minutes after the start of seeding, in addition to increasing the frequency of discharges, a decrease in hail size, volume ($V_{65}$) and integral water content of the hail core is noted. The contours of $Z = 75$ dBZ, the volume of $V_{75}$ and $M_{75}$ disappear as well as decrease of LF+ and LF- discharges currents. The discharge currents, which reached 5060 A before seeding also decrease to 10 A. After the seeding has stopped, there is a manifold increase in the frequency of discharges of all types, and an increase in discharge currents, especially of LF+ discharges, reaching 70 - 80 A.

**Figure 5.** The maximum reflectivity map with lightning discharge bearings in the quasistationary state of the supercell (15:00, 15:15, 15:30, 15:30) and at the start of dissipation 16:00. It can be clearly seen that the LF+ and LF- discharges are observed in the area of increased reflectivity, and the VHF discharges on the leeward flank. The blue vector indicates the direction of the average wind in the atmospheric layer from 700 to 500 mbar.

In the considered example of the evolution of a single hail cloud, it can be seen that its thunderstorm activity increases as it develops, intensifies the process of precipitation formation and increases radar reflectivity (Figure 6).

**Figure 6.** Dependence of VHF, LF+ и LF- lightning frequency from maximum radar reflectivity $Z_{\text{max}}$.

A summary of this data across many hailstorms confirms this conclusion. Figure 7 portrays the common for 10 hail clouds dependence of the frequency of the VHF and LF discharges from the maximum radar reflectivity, the height of the radar reflectivity $H_{45}$ and the integrated vertical water
content (VIL). It is shown that all types of lightning discharges begin at $Z_{\text{max}} > 40 \text{ dBZ}$ and increase with increasing values of $Z_{\text{max}}$, $H_{45}$ and VIL.

4. Discussion of results and conclusions

An analysis of the field data showed that electrical discharges in the developing hail clouds of the North Caucasus begin after a radar reflectivity of about 40 dBZ is achieved. As the cloud further develops and the process of precipitation formation is intensified, the frequency of intracloud VHF discharges and the cloud-ground discharges of positive LF + and negative LF - polarities increase. This is explained by the fact that the growth processes of raindrops, their splashing, crystal formation and splintering, nucleation and growth of hail, lead to the electrification of cloud particles [5], spatial separation by updrafts of small and large particles having opposite charges up to breakdown values.

Frequency of all types of discharges increases with increase of radar reflectivity $Z_{\text{max}}$, upper boundary of cloud ($H_z$) and cloud volumes ($V_z$) covering areas with reflectivity $Z_i = 45, 55, 65, 75 \text{ dBZ}$, and also with increase of vertically integrated liquid (VIL) and total water content ($M_z$) of clouds. The maximum lightning activity of hailstorms is observed at the stage of their development, when $Z_{\text{max}} \geq 70 \text{ dBZ}$. It can be assumed that the more intense the process of precipitation, the greater the frequency of lightning discharges.

The cloud-ground discharging frequency of LF + is usually less than 15 per minute, but in powerful hail clouds it can be 25 - 30 per minute. The frequency of discharges LF - is about 2 times higher than the frequency of discharges LF+. The frequency of intra-cloud VHF discharges is even higher. Their number is usually less than 50 pcs/min, but in the most powerful hail clouds it can reach value 350 pcs/min.

In developing hail clouds, the location of the first discharges of all types is noted in the area of increased reflectivity and water content of clouds. In mature hail clouds, LF + and LF- discharges continue to also be observed in the area of increased reflectivity on the windward flank of the cloud, and the location of most VHF discharges shifts to the leeward flank. Especially well this tendency is noticeable in the days with a large speed of the leading stream and rapid cloud displacement, as in 01/07/2018 (Figure 5). It can be assumed that this is due to ascend of light crystals and small particles in the upper part of the cloud, where they fall into a strong horizontal flow and are carried to the lee flank, where high microphysical and dynamic heterogeneities and increased turbulence are noted.
Seeding of hail clouds with glaciogenic reagents leads to an increase in the frequency of lightning discharges of all types (especially intraclouds), which is apparently due to the intensification of the process of crystallization of cloud droplets and the formation of crystals.

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