Investigation of the evolution of thunderstorm with hail in North-Western region of Russia by three-dimensional numerical simulation

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Abstract. Using numerical non-stationary three-dimensional Cu model the investigation of the evolution of thunderstorm with hail was carried out in North-Western region of Russia. Spatial and temporal variations of the main cloud and precipitation characteristics obtained, especially, cloud electrification intensity, volume charge density and electric field strength. It was shown that the main role in cloud electrification under given conditions has the polarization one. On the contrary, ice-ice collision was not so intensive because of small mass of cloud ice crystals.

1. Introduction
Thunderstorms pose a significant danger to people and economic facilities. In this regard, as well as the fact that the mechanisms of the occurrence of thunderstorms are currently not fully understood, studies of this dangerous weather phenomenon are very relevant.

One of the most effective methods of investigating convective clouds is three-dimensional numerical simulation.

The case investigated in this article is thunderstorm with hail developed in St. Petersburg and Leningrad Region on June 9, 2020. By the results of simulation special attention was paid to the study of the processes of charging cloud elements and the formation of electric fields, leading to lightning discharges. The purpose of this work is investigation of thunderstorm formation mechanisms for given particular case. Such case is not typical for this geographical region.

2. Atmospheric situation
A development of deep thunderstorm with hail and Cb were observed in Saint-Petersburg and Leningrad region (North-West region of Russia) on June 9, 2020. They developed in conditions of local low pressure troughs in combination with convective unstable stratification of the atmosphere. Temperature and humidity vertical profiles obtained from rawinsonde data at Voeikovo station, Russia (26075) for 12h are presented in the figure 1 (RAOB software was used). The sounding dew point value at the underlying surface was changed by its daily maximum (17,2 vs 15,8 °C). There is the big dew point deficit in the main cloud-forming layer. It should weaken convection. At the same time temperature profile shows large vertical gradients which are very favourable for Cu development. CAPE index reached 140 J/kg at the layer 0 – 3 km. It’s total value reached 2926 J/kg, which indicates a strong instability and possibility of thunderstorms, squalls and hail development. Lifted index reached −6,8.
3. Numerical simulation results

The numerical three-dimensional non-stationary convective cloud model was used for purposes of this research. The detailed description of this model can be found in [1]. This model contains description of the main cloud processes, including air dynamics, cloud microphysics and electric charges and electrical fields generation. Parameterized approach is used in the microphysical block. The model allows to simulate spatial and temporal changes of the main cloud and precipitation characteristics (velocity field, water and ice content, radar reflectivity, electric charge density, electrostatic field etc).

The model takes into account a large set of electrification mechanisms: ion diffusion particle charging (both induction and non-induction); charging of colliding cloud drops and rain drops (or melting hailstones); charging of colliding ice particles; addition of charges of particles during coalescence; transfer of charge of evaporating particles to atmospheric ions. An effect of corona discharges on drops freezing is also under consideration.

The initial data of the model are temperature and humidity profiles. Data presented in the figure 1 were used for the given case. Initial ion concentration is set according to good weather conditions [1].

The following results were obtained by simulation (see table 1 and figures 2–7). Cloud height reached 12.8 km (figure 2). Maximum values of updraft velocity (figure 2), liquid water content, ice content (figure 3), rain and hail intensity (figure 4) and radar reflectivity (figure 5) correspond to the parameters of hail cloud.

Temporal dynamics of radar characteristics of the cloud are of particular interest. They are: reflectivity itself and supercooled cloud volumes with reflectivity greater then certain value – 35, 40, 45, 50, 55 and 60 dBZ (figure 5). This is due to the fact that reflectivity is the measurable characteristic.

The joint analysis of the curves presented in figure 5 with those in figure 3 shows that lightning activity is preceded by the appearance of significant cloud volumes with big ice particles in the cloud.

![Figure 1. Vertical profiles of temperature and humidity obtained with the help of atmospheric sounding data.](image)
Presence of these particles is a necessary condition for intensive organized electrification. Similar patterns of changes in the presented radar parameters and lightning frequencies were observed by us in numerous experimental studies, aimed to develop of methods for predicting and diagnosing dangerous weather phenomena associated with convective clouds.

Table 1. Main characteristics of cloud and precipitation maximums, their height and time of achievement.

| Parameter                                | Maximum by coordinates and time | Time of achievement, min | Height of achievement, km |
|------------------------------------------|---------------------------------|--------------------------|---------------------------|
| Cloud top height ($H_{top}$), km         | 12.8                            | 57.8                     | –                         |
| Updraft velocity ($w$), m/s              | 28.1                            | 58.9                     | 9.8                       |
| Cloud liquid water content ($Q_c$), g/m$^3$ | 2.3                             | 50.4                     | 3.1                       |
| Rain liquid water content ($Q_r$), g/m$^3$ | 6.7                             | 47.4                     | 0.3                       |
| Cloud crystals ice content ($Q_{ic}$), g/m$^3$ | 1.3                             | 45.4                     | 7.3                       |
| Hailstones ice content ($Q_i$), g/m$^3$   | 6.9                             | 50.6                     | 3.4                       |
| Rain intensity at the earth level ($I_r$), mm/h | 182.7                           | 47.6                     | –                         |
| Hail intensity at the earth level ($I_i$), mm/h | 10.7                            | 49.3                     | –                         |
| Rain and hail intensity                  | 185.4                           | 47.6                     | –                         |
| at the earth level ($I_{Σ}$), mm/h       |                                 |                         |                           |
| Radar reflectivity ($Z$), dBZ             | 67.1                            | 50.6                     | 3.4                       |

Figure 2. Temporal dynamics of cloud top height (1) and maximum by coordinates of updraft velocity (2). The first lightning flash time is marked by (3).

The intensive formation of precipitation (hail especially) caused intense electrification of the cloud and separation of charges. The first lightning discharge occurred at $t=2589$ s (this moment is marked by vertical line on figures 2–6). Temporal dynamics of vertical component of electrostatic field strength ($E_z$) and intensity of two the most significant mechanisms of volume charge ($\tau$) changing are presented on figure 6. These mechanisms are:

- charge separation during collisions and rebounds of cloud drops and rain drops and melting hailstones in the external electric field (polarization mechanism);
- electrification during collisions and rebounds of hailstones and cloud ice crystals.
Figure shows that intensity of ice-ice mechanism changed smoothly and reached maximum $2.3 \times 10^{-10}$ Cl/(m$^3$·s). This process is not inductive and does not depend on electric field. But it strongly depends on the presence of ice particles in the cloud. Moreover, this process requires the joint presence of ice particles of different size (hailstones and cloud crystals) in the same part of the cloud. Really, the curve (3) on the figure 6 is in good compliance with $Q_i$ and $Q_{ic}$, dynamics (figure 3). However, the high temperature in the lowest part of the cloud and in the sub-cloud layer contribute ice melting. So, the role of ice-ice mechanism is comparatively small in the investigated case.

![Figure 3](image-url)  
**Figure 3.** Temporal dynamics of maxima by coordinates of cloud liquid water content (1), rain liquid water content (2), hailstones ice content (3) and cloud ice crystals content (4). The first lightning flash time is marked by (5).

![Figure 4](image-url)  
**Figure 4.** Temporal dynamics of maxima by horizontal coordinates of rain (1), hail (2) and total precipitation intensity (3) at the earth level. The first lightning flash time is marked by (4).
Figure 5. Temporal dynamics of maximum by coordinates of total radar reflectivity (1), and temporal dynamics of the volume of supercooled part of the cloud with reflectivity value greater then 35 (2), 40 (3), 45 (4), 50 (5), 55 (6) and 60 (7) dBZ.

The first lightning flash time is marked by (8).

On the contrary, the intensity of the polarization mechanism strongly depends on $E_z$ and is associated with it by positive feedback. The curve (2) at the figure 6 shows that it’s peaks are close to those of $E_z$ (curve 1). These peaks correspond to the lightning discharges. The value of intensity of this mechanism reached maximum $1.8 \cdot 10^{-9} \text{C/(m}^3 \cdot \text{s})$. Our earlier results [2 – 4] also show the significant role of polarization mechanism in convective cloud electrification. Moreover, investigation performed in [5] confirmed the observed formation of the thunderstorm with inverted charge structure in other geographical region (India). This process has been explained with the help of polarization mechanism, using the model of smaller dimension (the model is described in [3]).

A review of various methods of cloud electrification simulation was presented in [6, 7]. Investigations, which have been carried out by specialists of USA, Russia, Israel, Japan, Argentina and other countries, are briefly described in this review. Most of the authors agree that the main mechanism of charging is charge separation during particles collision. The greatest role in the electrification of the cloud is attributed to ice – ice interaction. Our results are in controversy with this concept.

However, in our investigation presented in [8] (another thunderstorm with hail in North-Western region of Russia) ice – ice collision electrification has been shown to play much more significant role in thunderstorm electrical structure formation.

The above points out, that the role of a particular electrification mechanism strongly depends both on physical and geographical features of the region and meteorological situation.
Figure 6. Temporal dynamics of maxima by coordinates of vertical component of electrostatic field vector (1), and particle electrification intensity: polarization mechanism (2) and ice-ice interaction (3). The first lightning flash time is marked by (4).

Temporal dynamics of lightning discharge frequency is presented on figure 7. This frequency in maximum reaches 1 per min. This dynamics shows good match with that of hailstones ice content (figure 3). This can be explained by the fact that polarization mechanism occurs the most effectively when cloud drops interact with melting hailstones. The same mechanism with participation of cloud and rain drops is more weak.

Figure 7. Temporal dynamics of lightning discharges frequency (for the period of 360 seconds).

4. Conclusion
The case of development of deep thunderstorm with hail in North-Western region of Russia was investigated with use of three-dimensional convective cloud model.
By a result of simulation were obtained spatial and temporal variations of the main cloud and precipitation characteristics (updraft velocity, cloud and drop liquid water content, cloud and hail ice content, radar reflectivity, electric charge density, electrostatic field). Precipitation intensity, lightning discharges frequency and volumes of supercooled part of cloud with the given radar reflectivity were calculated also. It was confirmed that at a the given atmospheric situation deep convective clouds should form.

Special attention was paid to formation of charge structure of the cloud. Calculations showed that the most intensive cloud particles electrification mechanism is the polarization one for the given case. It should be kept in mind, that the role of a particular electrification mechanism strongly depends both on physical and geographical features of the region and meteorological situation.

The research is carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University [9].

The results of the work were obtained using computational resources Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (http://www.spbstu.ru).

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