Empirical model of the development of electrification process in convective clouds

Y P Mikhailovskii 1,*, A A Sin’kevich 1, A M Abshaev 2, J M Gekkieva 3
1 Voeikov Main Geophysical Observatory, 7 Karbysheva, Saint-Petersburg, Russia
2 Hail Suppression Research Center «Antigrad», 137-G Tarchokova, Nalchik, Russia
3 FSBI «High-Mountain Geophysical Institute», 2 Lenin avenue, Nalchik, Russia
* E-mail: yupalych@ya.ru

Abstract. Results of the development of an empirical model of Cu electrification process are presented. A first part of the paper presents the initial stage of Cu organized electrization. It is based on aircraft investigations. The second part presents Cu characteristics during transition to thundercloud. It is based on the results of 100 experiments, where radar and lightning detection system LS8000 were used. The results confirm the crucial role of ice particles in the process of electrification of the convective cloud at all stages of its development.

1. Introduction

Electrical phenomena in clouds are among the most dangerous weather phenomena. A large number of articles in our country and abroad are devoted to field studies of the processes of electrification of convective clouds [1-5].

There were attempts to construct some parts of empirical model for a certain stage of the electrification process [6-9]. These empirical models often differ significantly due the used control instruments, measured parameters, methods of control and analysis, conditions of clouds development, research regions, and other factors [3, 4, 5, 8, 10, 11, 14]. All this makes it difficult to generalize individual studies in attempt to find general features of the development of Cu electrification.

Main Geophysical Observatory, together with colleagues from the High Mountain Institute, presents the results of research of the development of Cu electrification process, carried out for many years. Attempts have been made to identify general features and conditions for the beginning of organized electrification and the beginning of lightning activity [1, 5, 11, 12]. By organized electrification, we mean a set of micro- and macro-electrification processes that result in appearance of electric field outside the cloud [1, 5, 12]. A powerful tool for studying clouds is theoretical modelling and numerical experiments [3, 13]. A necessary condition for the successful development of numerical models is their verification by field data and by empirical physical-statistical models [12, 13].

1. An empirical model of the beginning of organized electrification

1.1. Instruments and methods

The parameters of the cloud were monitored when the aircraft flew over the cloud in a flight path and reverse course with an excess of 100-500 meters above the top. When the cloud height changed, the flight altitude changed accordingly. Studies were carried out in most cases during all cloud life cycle from its origin (when the cloud top exceeds the zero isotherm) up to its dissipation in each experiment.
The electrification of the cloud was controlled by the electric field strength $E$ above the cloud. The formation and movement of large particles in the cloud and below it was controlled by the distribution of radar reflectivity $Z$ (the radar cross-section of the studied cloud along the course of the aircraft), measured either by aircraft or ground radars, or by both radars. The probability of particles crystallization was controlled by the temperature at $C_u$ top and visually [5,12]. Isolated, single-cell, long-lived clouds were selected for the study. As a result, a series of measurements of the above mentioned parameters of the studied clouds with a discreteness of 4-7 minutes was obtained. The number of cloud traverses ranged from 1 to 20, and the total number of the studied clouds exceeds 100.

1.2. Results and discussion

The analysis of the results have made it possible to identify previously unknown general features of the development of convective clouds electrification, which can be used to adjust the parameters and verify numerical models. The process of cloud electrification begins, i.e. the $E$ above the cloud increases up to 50-100 V / m or more, only when conditions for the growth of large ice particles appear in the cloud (cloud top height is above the isotherm of -8 °C (figure 1, table 1), the maximum reflectivity under the cloud base (below the condensation level) ($Z_{oc}$) exceeds 0 dBZ by aircraft radar measurements (table 1), the thickness of the supercooled part of the cloud ($dH$) exceeds 1.6 km (table 1); The electrification of the cloud is observed always if there is an intensive process of crystallization (the formation of large ice particles) at the top of the cloud (cloud top height exceeds the isotherm of -22 °C (figure 1, table 1), the reflectivity of precipitation is above 40 dBZ (table 1), the thickness of the supercooled part is more than 2.6 km (table 1), the visual observations indicate an intensive crystallization of the cloud top [12]. For each of the monitored parameters, it is possible to determine the intervals at which there is no electrification in the cloud ($E = 0$), $E$ - may or may not be present ($E = 0$ or $= 1$), it is mandatory ($E = 1$).

![Figure 1](image_url)

**Figure 1.** Probability of the beginning of organized electrification ($P$) in dependence on the temperature at the cloud top ($T_{top}$) (red circles), $N$ is the number of considered cases (black squares).

Table 1 shows the range of these zones for the «thickness» of the supercooled part $dH$ (km), the maximum reflectivity in the cloud $Zc_1$ (dBZ), the maximum reflectivity below the condensation level (precipitation) $Zr$ (dBZ), the cloud diameter $D$ (km), the cloud top height $H_{top}$ (km), the temperature...
at cloud top $T_{\text{top}}$ °C. The vertical component $E$ above the cloud is positive at the initial stage of development, i.e. it has the same direction as the «good weather» electrical field strength. This is typical for a cloud dipole with an upper negative charge. $E$ usually changes its sign to the reverse, i.e., the equivalent cloud dipole is inverted [12] at mature and dissipation stages.

### Table 1. Threshold values of controlled parameters.

| Cloud Parameters | $E=0$ dBZ | $E=0+1$ dBZ | $E=1$ dBZ |
|------------------|-----------|-------------|-----------|
| $dH$ km          | $<1.6$    | $>1.6$ $<2.6$ | $>2.6$    |
| $Z_{\text{cl}}$ dBZ | $<10$     | $>10$ $<40$ | $>40$     |
| $Z_{\text{r}}$ dBZ | $<0$      | $>0$ $<40$  | $>40$     |
| $D$ km           | $<3$      | $>3$ $<6$   | $>6$      |
| $dH$ km          | $<2.0$    | $>2.0$ $<3.2$ | $>3.2$    |
| $H_{\text{top}}$ km | $<3.2$   | $>3.2$ $<4.6$ | $>4.6$    |
| $T_{\text{top}}$ °C | $>-8$    | $<-8$ $>-22$ | $<-22$   |

2. **Empirical model of the beginning of lightning activity.**

2.1. **Instruments and method**

Studies were carried out using the automated radar system AMRK «ASU-MRL» and the LS-8000 lightning detection network [6, 11, 15]. The LS8000 lightning detection network detects radio emission from electrical discharges in two frequency bands—VHF (Very High Frequency range, 110-118 MHz) and LF (Low Frequency range, 30-350 kHz) [6, 11, 15]. Radar observations were carried out at a wavelength $\lambda = 10$ cm during all period of clouds existence within a radius of 250 km by conducting a panoramic sounding of atmosphere at 16 angles of antenna inclination with a period of about 220 seconds.

Results of observations of the evolution of clouds that originated and transformed into thundercloud stage during the observation period were selected as the initial data. The selection criterion from a variety of multiple cloud processes was the ability to track all cycle of cloud development from the origin to the dissipation stage, using lightning activity as criteria. The data sample included 100 such clouds observed in the North Caucasus from 2010 to 2018. To determine the radar criteria for the transition of the cloud to thundercloud stage, 2 scans were analyzed for each of the 100 cases: «before the first discharge» and «at the time of the first discharges». All types of discharges (VHF, LF+, and LF -) were considered. It was accepted that the cloud transformed into thundercloud state if a discharge of any type was recorded in the cloud.

2.2. **Results and discussion**

The analysis of the types of the first lightning shows that the largest part is a combination of negative (LF-) and intra-cloud (VHF) lightning (37%). At the same time, the LF-lightning is 29%, and VHF - 27% of the total number of discharges. The smallest part (1%) is the combination of positive (LF+) and VHF lightning.
Figure 2. Distribution of the «first» lightning type.

Using the nonparametric Wilcoxon test, the significance of the difference in the samples of 26 radar parameters on the pre-thundercloud and thundercloud scans were analyzed. The lowest p-values, which characterize the degree of difference in the samples, were obtained for the mass and volume of the cloud and the part of the cloud above the 0 oC isotherm with a reflectivity greater than 15-35 dBZ, dM and dV, respectively. Mean and median, where the change in the distribution is significant, increase for most parameters during the transition of the cloud to thundercloud stage. The increase in these characteristics indicates that thundercloud activity begins when a cloud has large sizes, large number and sizes of solid hydrometeors. This confirms the hypothesis, developed in the MGO, about the decisive role of large ice particles in the electrification of convective clouds [1, 5, 6, 9, 12]. The Y criterion, which is currently actively used in Russia as a thundercloud hazard criterion, is less sensitive to the transition of the cloud to thundercloud stage than some other parameters, related to the volume and integral water content of the supercooled part (dM and dV) [6, 9]. This follows from a comparative analysis of the p-value of these characteristics.

Similar conclusions were obtained earlier in the analysis of complex studies of the development of single thunderstorms with hail. A comparative correlation analysis of Y and dV_{35} with the frequency of lightning discharges was carried out [1, 5, 6, 9, 12]. The correlation of the discharge frequency with Z_{max} was less than that with Y and dV_{35}. Similar data were obtained in [6, 9].

The correlation between the frequency of lightning discharges and precipitation intensity (SRI) was investigated in [6, 9]. The correlation coefficient was lower than that of the above-mentioned values. Similar results were obtained in this study – the difference in SRI values at two scans under consideration was less significant than that for the Y criterion, this follows from p values.

The following trend is observed – the differences between the samples of the two scans under consideration become less significant with an increase in the reflectivity threshold for the characteristics of height (Hzi, dHzi), volume (Vzi, dVzi) and integral water content (Mzi, dMzi).

This can be explained by the fact that large values of reflectivity in the selected clouds are observed not so often. Figure 3 shows the distributions of some parameters for three radar scans in the form of Box and Whisker plots. Radar data at scans 0 min and at -4 min is presented. Additional scan (-8 min) was analyzed also in order to retrieve dynamics of the analyzed characteristics. The -8 min scan was available only for 61 clouds, so the chart is based on the parameters measured for these cases.

Figure 3 confirms the conclusions made earlier. There is an increase in 25%, 75% quintiles, and in median during the transition of clouds to thundercloud stage for all the above discussed parameters. This indicates that the selected clouds, at the time of the first lightning discharges, were the developing clouds in most cases. It is worth to mention that the following characteristics: dV_{35}, dM_{35}, SRI, VIL and VIH have a marked left-sided asymmetry. Despite the fact that the samples of the presented parameters for -4 and 0 min are statistically distinguishable (p-value < 0.05), they have a rather
noticeable intersection (figure 3). The distributions for −8 and 0 min have fewer intersections. The most noticeable differences in the samples for −8 and 0 min are observed for the parameter \( dH_{35} \). \( dH_{35} \) does not exceed 3.7 km 8 min before the discharges for 75% of cases, while at the time of the beginning of thundercloud activity, 75% of the cases exceeds 3.7 km. The distributions of the parameters, shown in figure 3, indicate that it is not easy to reliably separate clouds with and without lightning, using specific radar parameter, presented in this study. For the same parameter one can observe both absence and presence of lightning.

**Figure 3.** Diagram «Box with Whiskers», to compare radar characteristics \( dV_{35}, dM_{35} \), \( Y \) criterion, \( Z_{\text{max}}, \text{VIL, } H_{\text{top}}, \text{SRI, } \text{VIH, } H_{Z_{\text{max}}} \) for three radar scans. «Box» determines the position of the quantiles 25 and 75%, the line inside the box is the median, «whiskers» denotes the minimum and maximum value in the sample. Parameters \( dV_{35}, dM_{35}, \text{SRI, VIL и VIH} \) are presented at logarithmic scale. Zero indicates 8 min prior first discharges, 1 - 4 min prior first discharge, 2 – the moment of discharge (x-axes).

At the same time, just at this stage of research, it is possible to determine the probability that of a specific parameter obtained by the AMRK «ASU-MRL» to belong to the «thundercloud» or «pre-thundercloud» sample. One can estimate the «thundercloud danger» of the cloud at this stage of development, using these probabilities.

Further development of the empirical model is planned in the direction of search and studies of new factors, or simultaneous consideration of a set of factors, using modern methods of multiparameter
statistics, which provide possibility to get more reliable criteria for distinguishing of a cloud transition into a thundercloud stage.

3. Conclusion
Some general features of the processes of electrification of convective clouds were established. They were based on the analysis of the results of field studies of a significant number of convective clouds (about 100 clouds for each part of the model). These features are described in the relevant sections. They confirm the important role of large ice particles in the electrification of convective clouds at various stages of their development.

Acknowledgments
The work was carried out with the financial support of the BRICS grant (18-55-80020)

References
[1] Imyanitov N M, Chubarina E V and Shvarts Ya M 1971 Electricity of Clouds (Leningrad: Hydrometeorological publishing house) p 96
[2] MacGorman D R and Rust W D 1998 The Electrical Nature of Storms (New York: Oxford University Press) p 534
[3] Qie X S, Zhang Y, Yuan T, Zhang Q, Zhang T, Zhu B, Lu W, Ma M, Yang J, Zhou Y and Feng G 2015 A review of atmospheric electricity research in China Adv. Atmos. Sci. 32(2) 169–91
[4] Liu C et al. 2012 Relationships between lightning flash rates and radar reflectivity vertical structures in thunderstorms over the tropics and subtropics J. Geophys. Res. 117 D06104
[5] Mikhailovsky Yu P, Kashleva L V and Stepanenko V D 1992 Aircraft investigation of the convective clouds electrification Proc. of the 9th Conf. of the Atm. Electricity St.Petersburg Russia p 193
[6] Mikhailovskii Yu P et al. 2017 Russian Meteorology and Hydrology 42(6) 377–87
[7] Futyan J M and Del Genio A D 2007 Relationships between lightning and properties of convective cloud clusters Geophys. Res. Lett. 34 p 5
[8] Pessi A T and Businger S 2009 J. Appl. Meteorol. Climatol. 48(4) 833–48
[9] Sin’kevich A A, Mikhailovskii Y P, Matrosov S Y, Popov V B, Snegurov V S, Snegurov F V, Dovgalyuk Yu A and Veremei N E 2019 Russian Meteorology and Hydrology 44(6) 394–403
[10] Sin’kevich A A, Mikhailovskiy Y P, Toropova M L, Popov V B, Starykh D S, Dovgalyuk Yu A and Veremei N E 2020 Lightning Frequency on its Characteristics Atmospheric and Oceanic Optics 33(6) 645–49
[11] Abshaev M T, Abshaev A M, Mikhailovsky Yu P, Sin’kevich A A, Popov V B and Adziev A Kh 2020 Investigation of the processes of electrification and hail formation in a supercell cloud by remote radiophysical means Proceedings of Voeikov Main Geophysical Observatory 596 96–130
[12] Mikhailovsky Yu P 2016 On verification of numerical models of convective clouds based on the results of aircraft studies of electrification Proceedings of Voeikov Main Geophysical Observatory 580 125–38
[13] Sin’kevich A A at al. 2017 Investigations of the development of thunderstorm with hail. Part 3. Numerical simulation of cloud evolution Russian Meteorology and Hydrology 42(8) 494–502
[14] Pawar S D, Murugavel P and Gopalakrishnan V 2010 Anomalous electric field changes and high flash rate beneath a thunderstorm in northeast India Journal of Earth System Science 119(5) 617–25
[15] Adzhiev A Kh, Stasenko V N and Tapaskhanov V O 2013 System of lightning direction finding in the North Caucasus Meteorology and Hydrology 1 5–11