JP Journal of Heat and Mass Transfer

http://www.pphmj.com
http://dx.doi.org/10.17654/HM023010001
Volume 23, Number 1, 2021, Pages 1-18 **ISSN: 0973-5763**

3D MODEL OF A CONVECTIVE CLOUD: THE INTERACTION OF MICROPHYSICAL AND ELECTRICAL PROCESSES

V. N. Lesev[1], V. A. Shapovalov[2], B. A. Ashabokov[2], A. V. Shapovalov[2] and P. K. Korotkov[1]

[1]Kh. M. Berbekov Kabardino-Balkarian State University
173 Chernyshevsky st., Nalchik, 360004, Russia
e-mail: pkorotkov1984@mail.ru

[2]High-Mountain Geophysical Institute
2 Lenin Ave, Russia

Abstract

The paper presents a three-dimensional numerical model of a convective cloud taking into account electrical processes. A specific feature of this model is the use of detailed microphysical equations with several dozen classes of drops and crystals (explicit microphysics). In particular, the model takes into account 61 categories of droplet sizes and 75 categories of crystal sizes. With this model, we investigated new important aspects of the electric charge mechanism and field formation in clouds, we also noted the interaction of thermodynamic, microphysical, and electrical processes. The spatial distribution and quantitative values of volume electric charges and field strength in and around the cloud at successive time points in the evolution process are determined. The model was used to quantify the influence of electrical processes on precipitation formation.

Received: February 20, 2021; Accepted: April 4, 2021

Keywords and phrases: numerical modeling, three-dimensional model, thunderstorm clouds, electric charge, spatial distribution, electric coagulation, precipitation formation rate.

1. Introduction

For decades the development of numerical cloud models has been mainly in two most common directions: with a detailed description of microphysical processes [1-7] and with parameterized microphysics [8-15].

We propose that models with parameterized microphysics will provide a lot of useful information, assuming that the parameterization of microphysical processes in clouds is carried out correctly. But taking into account the diversity and complexity of these processes, taking into account the forward and backward connections between the processes in the clouds, such a parameterization can be correct only in the vicinity of already known cloud states or at short intervals of its development. In other words, the suitability of cloud models with parameterized microphysics for studying the long-term evolution of clouds requires careful studies. The capabilities of such models are especially limited for simulating active effects on convective clouds. According to High-Mountain Geophysical Institute (VGI) specialists, models with parameterized microphysics are not very suitable for this purpose [4], since active influence is carried out using a dispersed reagent and involves the control of microphysical processes, which are taken into account in the model in a parameterized form. Note that when modeling an active impact based on such models, changes in the natural development of clouds will also be obtained, but such models are reasonably unable to answer the questions of what they will be connected with and whether they will correspond to the reaction of a real cloud to the impact.

Taking into account that any simplification of the model narrows the range of problems for the solution of which it can be used, the advantages of models with detailed consideration of microphysical processes become noticeable. They would become even more noticeable if there were effective methods and tools for performing computational work.

A model with a detailed description of microphysics, providing calculation, and three-dimensional visualization of the fields of characteristics of a convective cloud, was developed at VGI [4]. It allows one to study the formation of macro-, and micro-structural characteristics of clouds, the processes of precipitation in clouds, electrification of particles, and other processes. To describe microphysical processes, the model uses kinetic equations for the mass distribution functions of particles of various types. This covers a wide range of particle sizes - from micron sizes to millimeter droplets and centimeter hailstones.

2. Description of the Numerical Cloud Model

The hydrothermodynamic block of the model consists of the equations of motion describing wet convection in the Boussinesq approximation, which take into account advective and turbulent transport, buoyancy, friction, and pressure gradients [1].

The equations of the microphysical unit describe the processes of nucleation, condensation, coagulation of droplets with droplets, sublimation, accretion and aggregation, freezing of droplets, deposition of cloud particles in a gravity field, and their transport by air flows [4]. In addition, they describe the processes of electrization of particles in the cloud and the formation of its electrical structure, the influence of the electric field of the cloud on the formation of its microstructural characteristics, and, conversely, the influence of the microstructural structure of the cloud on the formation of its electrical structure. The system of equations of the microphysical block consists of equations describing the transformation of the mass distribution functions of droplets $f_1(\vec{r}, m, t)$, ice particles $f_2(\vec{r}, m, t)$ and fragments of freezing drops $f_3(\vec{r}, m, t)$. To describe the formation of drops and crystals in natural conditions, the sources of drops and crystals I_1 and I_2 are introduced into the equations for the mass distribution functions of these particles.

Changes in the droplet distribution function in the model occur due to the processes of condensation, coagulation of droplets, accretion of droplets and crystals, fragmentation, freezing, and formation of droplets. In the same way, changes in the crystal distribution function occur due to sublimation, accretion, and freezing of drops, and changes in the distribution function of freezing fragments of drops occur due to the formation of fragments during the spontaneous freezing of supercooled cloud drops, their accretion with crystals and the formation of crystals. To simulate the active impact, a source of artificial crystals I_{AB} is introduced into the system of equations of the hail cloud model, or more specifically, into the equation describing the transformation of the distribution function of crystals in the cloud, which depends on the parameters characterizing the coordinates, rates, start and end of the introduction of reagent particles into the cloud.

The statement of the problem of the mathematical model of a convective cloud includes the following equations of thermodynamics, microphysics and electrostatics:

$$\frac{\partial u}{\partial t} + (\vec{V} \cdot \nabla)u = -\nabla\pi' + \Delta' u + lv, \quad (1)$$

$$\frac{\partial v}{\partial t} + (\vec{V} \cdot \nabla)v = -\nabla\pi' + \Delta' v - lu, \quad (2)$$

$$\frac{\partial w}{\partial t} + (\vec{V} \cdot \nabla)w = -\nabla\pi' + \Delta' w + g\left(\frac{\theta'}{\theta_0} + 0{,}61s' - Q_S\right), \quad (3)$$

continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \sigma w, \quad (4)$$

equations of thermodynamics

$$\frac{\partial\theta}{\partial t} + (\vec{V} \cdot \nabla)\theta = \frac{L_K}{c_p}\frac{\theta}{T}\frac{\delta M_K}{\delta t} + \frac{L_C}{c_p}\frac{\theta}{T}\frac{\delta M_C}{\delta t} + \frac{L_Z}{c_p}\frac{\theta}{T}\frac{\delta M_Z}{\delta t} + \Delta'\theta, \quad (5)$$

$$\frac{\partial s}{\partial t} + (\vec{V} \cdot \nabla)s = -\frac{\delta M_K}{\delta t} - \frac{\delta M_C}{\delta t} + \Delta' s, \quad (6)$$

equations for the mass distribution functions of drops, crystals and freezing fragments:

$$\frac{\partial f_1}{\partial t} + u\frac{\partial f_1}{\partial x} + v\frac{\partial f_1}{\partial y} + (w - V_1)\frac{\partial f_1}{\partial z}$$

$$= \left(\frac{\partial f_1}{\partial t}\right)_K + \left(\frac{\partial f_1}{\partial t}\right)_{KG} + \left(\frac{\partial f_1}{\partial t}\right)_{AK} + \left(\frac{\partial f_1}{\partial t}\right)_{DR} + \left(\frac{\partial f_1}{\partial t}\right)_Z + \Delta' f_1 + I_1, \quad (7)$$

$$\frac{\partial f_2}{\partial t} + u\frac{\partial f_2}{\partial x} + v\frac{\partial f_2}{\partial y} + (w - V_2)\frac{\partial f_2}{\partial z}$$

$$= \left(\frac{\partial f_2}{\partial t}\right)_C + \left(\frac{\partial f_2}{\partial t}\right)_{AK} + \left(\frac{\partial f_2}{\partial t}\right)_Z + \Delta' f_2 + I_2 + I_{AB}, \quad (8)$$

$$\frac{\partial f_3}{\partial t} + u\frac{\partial f_3}{\partial x} + v\frac{\partial f_3}{\partial y} + (w - V_2)\frac{\partial f_3}{\partial z} = \left(\frac{\partial f_3}{\partial t}\right)_Z + \left(\frac{\partial f_3}{\partial t}\right)_{AK} + \Delta' f_3, \quad (9)$$

equations for calculating the amount of electricity

$$\rho_- = a_2\int_0^\infty m f_2 dm - \lambda_2 E - \gamma_2 \sum_i \rho_-^i,$$

$$\rho_+ = a_3\int_0^\infty m f_3 dm - \lambda_3 E - \gamma_3 \sum_i \rho_+^i. \quad (10)$$

Poisson’s equation for the potential of an electrostatic field

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = -\frac{\rho_e}{\varepsilon_0}. \quad (11)$$

The initial conditions for equations (1)-(11) are as follows:

$$u(\vec r, 0) = u_0(\vec r),\ v(\vec r, 0) = v_0(\vec r),\ w(\vec r, 0) = w_0(\vec r),$$

$$\theta(\vec r, 0) = \theta_0(\vec r),\ s(\vec r, 0) = s_0(\vec r), \quad (12)$$

$$f_1(\vec r, m, 0) = f_2(\vec r, m, 0) = f_3(\vec r, m, 0) = 0,\ \rho_-(\vec r, 0) = \rho_+(\vec r, 0) = 0. \quad (13)$$

Border conditions:

$$\left.\begin{array}{l} u(\vec r, t) = u_0(\vec r),\ v(\vec r, t) = v_0(\vec r),\ w(\vec r, t) = w_0(\vec r), \\ \theta(\vec r, t) = \theta_0(\vec r),\ s(\vec r, t) = s_0(\vec r) \end{array}\right|_{x=0, L_x;\, y=0, L_y;\, z=L_z},$$

$$u(\vec{r}, t) = v(\vec{r}, t) = w(\vec{r}, t) = 0,\ \theta(\vec{r}, t) = \theta_0(\vec{r}),\ s(\vec{r}, t) = s_0(\vec{r})\big|_{z=0}, \quad (14)$$

$$f_1(\vec{r}, m, t) = f_2(\vec{r}, m, t) = f_3(\vec{r}, m, t) = 0\big|_{x=0, L_x;\ y=0, L_y;\ z=L_z},$$

$$\frac{\partial f_1(\vec{r}, m, t)}{\partial z} = \frac{\partial f_2(\vec{r}, m, t)}{\partial z} = \frac{\partial f_3(\vec{r}, m, t)}{\partial z} = 0\Big|_{z=0}, \quad (15)$$

$$\frac{\partial U(\vec{r}, t)}{\partial x} = 0\Big|_{x=0, L_x}, \quad \frac{\partial U(\vec{r}, t)}{\partial y} = 0\Big|_{y=0, L_y},$$

$$\frac{\partial U(\vec{r}, t)}{\partial z} = 0\Big|_{z=L_z}, \quad U(\vec{r}, t) = 0\big|_{z=0}. \quad (16)$$

The system of equations is applied to the space-time domain

$$0 \le x \le L_x, \quad 0 \le y \le L_y, \quad 0 \le z \le L_z, \quad 0 \le m < \infty, \quad t > 0. \quad (17)$$

The designations are used:

$$(\vec{V} \cdot \nabla) \equiv u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}, \quad \Delta' = \frac{\partial}{\partial x}K\frac{\partial}{\partial x} + \frac{\partial}{\partial y}K\frac{\partial}{\partial y} + \frac{\partial}{\partial z}K\frac{\partial}{\partial z},$$

$\vec{r} = \{x, y, z\}$ - vector of coordinates; $\vec{V} = \{u, v, w\}$ - velocity vector; $u(\vec{r})$, $v(\vec{r})$, $w(\vec{r})$ - velocity vector components; l - inertial parameter; $\theta(\vec{r})$ - potential temperature; $\pi(\vec{r}) = c_p\overline{\theta}(P(z)/1000)^{R/C_p}$ - dimensionless pressure; $\overline{\theta}$ - average potential temperature; R - gas constant; $s(\vec{r})$ - specific air humidity; $Q_S(\vec{r})$ - the total ratio of the mixture of liquid and solid phases in a cloud; $\sigma(z)$ - parameter that takes into account the change in air density with height; $P(z)$ and $T(\vec{r})$ - pressure and temperature, respectively; c_p - heat capacity of air at constant pressure; L_K, L_C, L_Z - respectively, the specific heat of condensation, sublimation and freezing; $\pi'(\vec{r})$, $\theta'(\vec{r})$, $s'(\vec{r})$ - deviations of dimensionless pressure, potential temperature and specific humidity from their background values in the surrounding atmosphere

$\pi_0(\vec{r}),\ \theta_0(\vec{r}),\ s_0(\vec{r});\ \frac{\delta M_K}{\delta t},\ \frac{\delta M_C}{\delta t}$ - changes in specific humidity due to vapor diffusion into droplets and crystals; $\frac{\delta M_Z}{\delta t}$ - mass of droplet water freezing per unit time per unit volume of air; $K(\vec{r})$ - turbulent diffusion coefficient. $V_1(m),\ V_2(m)$ - steady-state rates of falling of liquid and solid particles; $\left(\frac{\partial f_1}{\partial t}\right)_K,\ \left(\frac{\partial f_1}{\partial t}\right)_{KG},\ \left(\frac{\partial f_1}{\partial t}\right)_{AK},\ \left(\frac{\partial f_1}{\partial t}\right)_{DR},\ \left(\frac{\partial f_1}{\partial t}\right)_Z$ - changes in the droplet distribution function due to microphysical processes of condensation, coagulation of droplets, accretion of droplets and crystals, crushing and freezing, respectively; $\left(\frac{\partial f_2}{\partial t}\right)_C,\ \left(\frac{\partial f_2}{\partial t}\right)_{AK},\ \left(\frac{\partial f_2}{\partial t}\right)_Z$ - changes in the distribution function of crystals due to sublimation, accretion and freezing of drops; $\left(\frac{\partial f_3}{\partial t}\right)_Z,\ \left(\frac{\partial f_3}{\partial t}\right)_{AK}$ changes in the distribution function $f_3(\vec{r},\ m,\ t)$ due to the formation of fragments during spontaneous freezing of supercooled cloud drops and their accretion with crystals; I_1 and I_2 - sources of drops and crystals; I_{AB} - source of artificial crystals under active influence; $\rho_e(\vec{r},\ t)$ - total volumetric electric charge, ε_0 - dielectric constant of vacuum.

For the boundaries of the spatial area, the notation is $0,\ L_x,\ 0,\ L_y,\ 0,\ L_z$.

To describe coagulation processes in a cloud, an integro-differential equation is used in the form:

$$\left(\frac{\partial f}{\partial t}\right)_{KG} = -f_1(\vec{r},\ m,\ t)\int_0^{\infty}\beta_1(m,\ m')\cdot\ f_1(\vec{r},\ m',\ t)dm'$$

$$+\int_0^{m/2} f_1(\vec{r},\ m-m',\ t)\beta_1(m,\ m-m')\,f_1(\vec{r},\ m',\ t)dm', \qquad (18)$$

where $\beta_1(m,\ m') = \pi(r(m)+r(m'))^2\cdot|V_1(m)-V_1(m')|\cdot e_1(m,\ m');\ r(m)$ and

$r(m')$ - colliding particle radii; $V_1(m)$ and $V_1(m')$ - their falling rates; $e_1(m, m')$ - capture ratio for drops.

The calculation of the interaction between drops and crystals is carried out on the basis of the following relations:

$$\left(\frac{\partial f_1}{\partial t}\right)_{AK} = -f_1(\vec{r}, m, t)\int_0^{\infty} \beta_2(m, m') \cdot f_2(\vec{r}, m', t)\,dm', \tag{19}$$

$$\left(\frac{\partial f_2}{\partial t}\right)_{AK} = -f_2(\vec{r}, m, t)\int_0^{\infty} \beta_2(m, m') \cdot f_1(\vec{r}, m', t)\,dm'$$

$$+\int_0^{m} \beta_2(m, m-m')\, f_2(\vec{r}, m-m', t)\, f_1(\vec{r}, m', t)\,dm', \tag{20}$$

where

$$\beta_2(m, m') = \pi(r(m) + r(m'))^2 \cdot |V_1(m) - V_2(m')| \cdot e_2(m, m'),$$

$e_2(m, m')$ - capture coefficient for drops and crystals. The condition is accepted that the collision of crystals with drops leads to the freezing of the latter.

Let us stop on the scheme to account for electrical processes in the model. It should be noted that mathematical modeling of cloud parameters taking into account electrical processes is developing in our country [4, 15] and abroad [16-18]. Models of various dimensions and various degrees of detail for accounting for microphysical and electrical processes have been developed. In the VGI model, the following physical process of charge separation at the stage of precipitation formation is adopted - charging of supercooled droplets when they freeze (charge sign “minus”), the resulting freezing fragments (microejections) are positively charged. At the same time, to calculate the electric charge and field of the cloud, the experimental dependences of the emissions of microparticles on the size of the freezing droplet and the values of the charge separation coefficients associated with freezing of water droplets and the interaction of crystals with supercooled droplets obtained at the Vysokogorny Geophysical Institute were approximated.

While carrying out calculations at each time step the volume charges in the cloud, the potential of the electrostatic field created by these charges, as well as the horizontal and vertical components of the electric field strength of the cloud E_x, E_y, E_z are calculated.

The value of the total (positive and negative) space charges $\rho_e(\vec{r})$ is used to determine the potential $U(\vec{r})$ of the electrostatic field they create. For this, at each time step, the Poisson equation for the potential is solved with the corresponding boundary conditions.

The electric field strength at any point in the cloud, caused by charges, is defined as the potential gradient. The values of the electric field strength are taken into account when calculating the coefficients of electric coagulation of cloud particles. For this purpose, we used the approximation formulas constructed from the existing theoretical and experimental data for this parameter.

The system of equations of the model, describing the processes of thermohydrodynamics and microphysics, was supplemented with initial and boundary conditions. The calculations were carried out by the method of splitting according to physical processes and component wise splitting. To compare the calculation results with the observational data (with the data of meteorological radars), among other parameters, the radar reflectivity of the cloud is calculated at wavelengths of 3,2 and 10cm.

Note that research to improve this model in the VGI is ongoing. In recent years, these were carried out in the direction of improving the accounting of electrical processes in the model and in the direction of improving the formation of input data (initial conditions for the system of model equations), which is still a rather “weak” point of cloud models. A new method was developed for the formation of input data (initial values) of numerical models of convective clouds, based on the use of the output information of the global forecasting system for atmospheric parameters GFS [19]. The possibilities of its use for modeling the formation and development of hail clouds are investigated. In addition, the model is used to study the formation of macro- and micro-structural characteristics of convective clouds in natural conditions and under active exposure. Note that research to improve this model in the VGI is ongoing. In recent years, these were carried out in the direction of improving the accounting of electrical processes in the model and in the direction of improving the formation of input data (initial conditions for the system of model equations), which is still a rather “weak” point of cloud models. A new method was developed for the formation of input data (initial values) of numerical models of convective clouds, based on the use of the output information of the global forecasting system for atmospheric parameters GFS [19]. The possibilities of its use for modeling the formation and development of hail clouds are investigated. In addition, the model is used to study the formation of macro- and micro-structural characteristics of convective clouds in natural conditions and under active exposure.

3. Several Calculation Results

Numerical experiments were carried out to study the role of the interaction of processes in clouds in the formation of their macro- and micro-structural characteristics. The cloud was modeled in a $50 \times 50 \times 16\,\text{km}$ domain. Based on the simulation results in this work, the spatial distribution of microstructural parameters of convective clouds (water content and ice content), is positive, negative and total space charges in the cloud, electrostatic field strength, radar reflectivity at wavelengths of 3,2 and 10cm, and other parameters in different moments in time.

Figures 1 and 2 show the isosurfaces of water content and ice in the vertical section of a thunderstorm cloud at the 30th and 40th minutes of development. The figures were obtained using the program of three-dimensional visualization of parameters [20]. Figures 3 and 4 show the isosurfaces of the upward flow of 15m/s and the space charge of $8 \cdot 10^{-10}\,\mathrm{Kl/m^3}$ and the isolines of the radar reflectivity at the 30th and 40th minutes, respectively. Figure 5 shows the isolines of the vertical component of the electric field strength at the 30th minute.

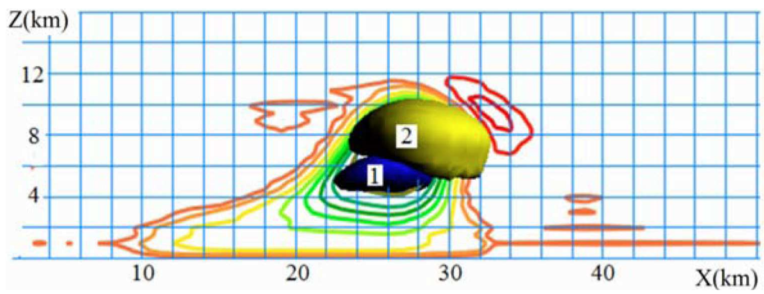

Figure 1. Isosurfaces of water content $3{,}00\,\mathrm{g/m^3}$ (1) and ice content $3{,}00\,\mathrm{g/m^3}$ (2) against the background of isolines of the vertical component of the velocity in the vertical plane at 30 minutes.

The maximum cloud parameters at the 30th minute of development were: water content: $4{,}20\,\mathrm{g/m^3}$, $H = 6{,}0$km; ice content: $6{,}57\mathrm{g/m^3}$, $H =$ 8,5km; summary of ice and water content: $6{,}68\mathrm{g/m^3}$, $H = 8{,}5$km; vertical speed w: 21,0 (–3,73) m/s, $H = 7{,}0$ (9,5) km; turbulent diffusion coefficient: $558\mathrm{m^2/s}$, $H = 9{,}5$km; reflectivity (3,2cm): 53,7dBZ, $H = 9{,}0$km; space charge: $8{,}8 \cdot 10^{-10}(-7{,}0 \cdot 10^{-10})\,\mathrm{Kl/km^3}$, $H = 10{,}5$ (4,0) km; potential value: $2{,}8 \cdot 10^{8}(-1{,}2 \cdot 10^{8})\,B$, $H = 10{,}0$ (4,0) km; field voltage: 379 (–975) V/cm, $H = 2{,}0$ (7,0) km.

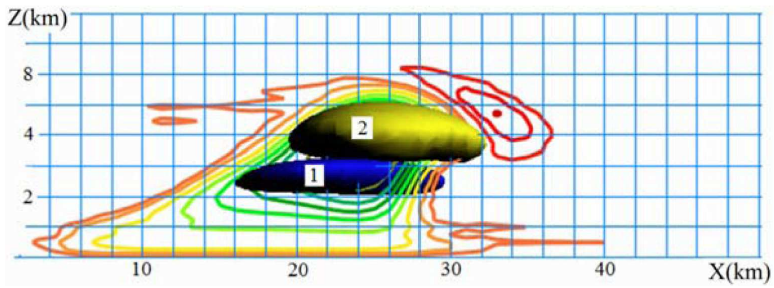

Figure 2. Isosurfaces of water content $3{,}00\text{g}/\text{m}^3$ (1) and ice content $3{,}00\text{g}/\text{m}^3$ (2) against the background of isolines of the vertical component of the velocity in the vertical plane at 40 minutes.

The maximum cloud parameters at the 40th minute of development were: water content: $3{,}93\text{g}/\text{m}^3$, $H = 5{,}5\text{km}$; ice content: $5{,}86\text{g}/\text{m}^3$, $H = 8{,}5\text{km}$; summary of ice and water content: $6{,}25\text{g}/\text{m}^3$, $H = 7{,}5\text{km}$; vertical speed w: 18,7 (–4,2) m/s, $H = 6{,}5$ (7,0) km; turbulent diffusion coefficient: $559\,\text{m}^2/\text{s}$, $H = 11{,}0\,\text{km}$; reflectivity (3,2sm): 54,8dBZ, $H = 0{,}5\,\text{km}$; space charge: $1{,}1 \cdot 10^{-9}(-5,\ 7 \cdot 10^{-10})\,\text{Kl}/\text{km}^3$, $H = 9{,}0$ (3,5) km; potential value: $1{,}1 \cdot 10^9(-3{,}1 \cdot 10^7)B$, $H = 9{,}5$ (1,5) km; field voltage: 813 (–2155) V/sm, $H = 11{,}5$ (6,0) km.

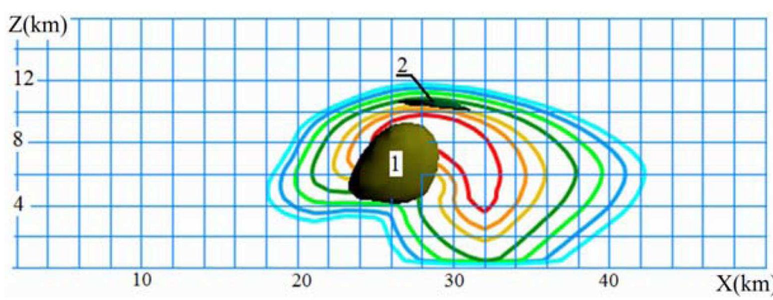

Figure 3. Isosurfaces of the vertical component of the velocity 15,0m/s (1) and the volumetric electric charge $8{,}0 \cdot 10^{-10}\text{Kl}/\text{km}^3$ (2) against the background of isolines of the radar reflectivity in the vertical space at 30 minutes.

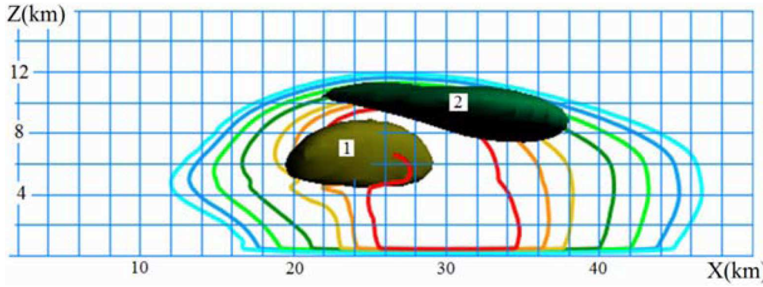

Figure 4. Isosurfaces of the vertical component of the velocity 15,0 m/s (1) and the volumetric electric charge $8{,}0 \cdot 10^{-10} \mathrm{Kl/km}^3$ (2) against the background of the isolines of the radar reflectivity in the vertical space at 40 minutes.

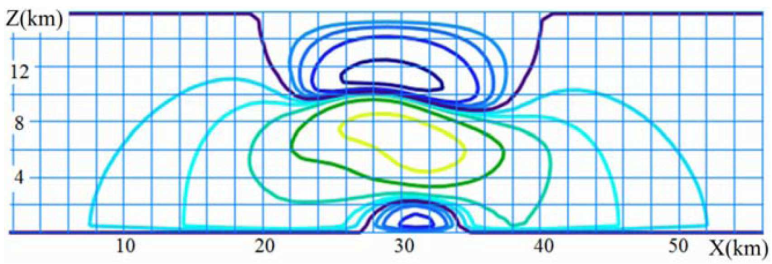

Figure 5. Isolines of the vertical component of the field strength in the vertical space at 30 minutes.

4. The Discussion of the Results

The main directions of research using this model and some of their results can be formulated as follows:

- a numerical study of the formation of fields of various characteristics of convective clouds, in particular, the coefficient of turbulent diffusion and radar reflectivity was carried out. It was found that at the stage of cloud development, the coefficient of turbulent diffusion has the highest values in the upper part of the cloud from 100 to $400 \mathrm{m}^2/\mathrm{s}$. At the stage of maximum cloud development (in the pre-city and hail stage), the radar reflectivity increases to 55-65dBZ, the turbulent diffusion coefficient reaches $1500 m^2/s$ and more. The water content of the cloud is rather heterogeneous. The concentration of liquid cloudy water in the frontal part of the cloud varies from 0,1 to $6 gm^{-3}$;

- a study was carried out on the formation of fields of microstructural, radar and electrical parameters in the course of the evolution of a thunderstorm. In this direction, studies were carried out on the influence of the electrical parameters of powerful convective clouds on the formation of their microstructural characteristics. The quantitative values of positive and negative volumetric electric charges in clouds at different points in time (at the stage of growth and maximum development) have been determined. The values of the potential and the electric field strength in and around the cloud are calculated. It was found that there is a positive feedback between the increase in the mass of ice particles and the volumetric electric charge. Equations are constructed that approximate the course of the main characteristics of a powerful convective cloud at two time intervals in the growth stage;

- the study of the formation and development of convective clouds was started taking into account their systemic properties. Methods and methods have been developed and numerical experiments have been carried out to study the role of the interaction of processes in clouds in the formation of their macro- and micro-structural characteristics;

- in particular, studies were conducted on the role of the interaction of processes in clouds on the formation of their microstructural characteristics. It was found that the deformation of these characteristics in the cloud, which is a consequence of the interaction of processes in the clouds, has a significant effect on the formation of microstructural characteristics of clouds and on the processes of precipitation in clouds;

- in addition, a study has begun on the influence of the interaction of powerful convective clouds with the atmosphere on the formation of their macro- and micro-structural characteristics. It was found that the shape and size of the zone of formation and growth of precipitation particles have been significantly affected by the structure of the fields of the thermodynamic characteristics of the atmosphere.

In conclusion, let us briefly dwell on one approach to the formation of input data for convective cloud models, which is used in VGI. Note that the possibility of obtaining the required “cloud” as a result of calculations depends on the successful formation of these data. The solution to this problem becomes especially relevant for complete and multidimensional numerical cloud models. The problems of forming the input data of cloud models are known and are caused by the impossibility of obtaining detailed information on the parameters of the atmosphere that characterize its state in the region in which the processes of cloud formation and development take place. But, as is known, the features of the development of each cloud are largely determined by the state of the atmosphere in this region, and the possibility of obtaining the corresponding cloud depends on the completeness of the information used about this state. The formation of the initial conditions for the system of equations included in the cloud model is carried out on the basis of atmospheric sounding data, and the number of sounding points is limited. Therefore, it may turn out that for completely different clouds, the initial conditions will differ little from each other.

5. Conclusions

With the use of mathematical modeling, new important aspects of the electric charge formation mechanism and thunderstorm clouds field have been studied for the first time, taking into account the interaction of thermodynamic, microphysical and electrical processes. The spatial distribution and quantitative values of volumetric electric charges and field strength in the cloud and around it at successive moments of time in the process of evolution are determined. The values of positive and negative volumetric electric charges reach values of $\pm 10^{-9}\,\mathrm{Kl/m^3}$ field strengths up to ±2000V/cm and more, which is consistent with the measurement results. It was found that the mechanisms of spontaneous crystallization of large supercooled droplets and the growth of hailstones due to accretion are one of the key physical processes of electrification at the stage of growth and maximum development of thunderstorm clouds.

For the first time, a three-dimensional numerical model of a convective cloud has been implemented, in which the coagulation coefficient of particles of various sizes changes depending on the strength of the electrostatic field of the cloud. Using the model, a quantitative assessment of the influence of electrical processes on the formation of precipitation was carried out. For the conditions of the North Caucasus region, it was determined that due to the mutual influence of microphysical and electrical processes on each other, the time of precipitation formation in powerful thunderclouds is reduced by $20\text{-}30\%$.

The study confirmed the concept of the existence of a positive feedback between the growth of precipitation particles in a cloud and an increase in the strength of the electrostatic field, which consists in their mutual influence on each other. Analysis of the results of numerical experiments made it possible to establish that the electric field accelerates the growth of particles in the cloud, on the other hand, a larger amount of electric charge is generated, which increases the field itself. The general picture of mutual influence is manifested in the acceleration of the passage of the cloud through stages of development, except for the initial one, when the influence of electric forces is still small.

Based on the simulation results, it was found that at the stage of maximum development of the convective cloud due to electrical coagulation, the most intense growth of liquid and solid precipitation occurs. In particular, the formation of hail particles occurs in 6-8 minutes.

References

[1] E. L. Kogan, I. P. Mazin, B. N. Sergeev and V. I. Khvorostyanov, Numerical Modeling of Clouds, Moscow, 1984, p. 186 (in Russian).

[2] V. I. Khvorostyanov and J. A. Curry, Thermodynamics, Kinetics, and Microphysics of Clouds, Cambridge University Press, 2014, p. 777.

[3] A. P. Khain and B. H. Lynn, Simulation of a supercell storm in clean and dirty atmosphere using weather research and forecast model with spectral bin microphysics, J. Geophys. Res. 114 (2009), 2963-2982.

[4] B. A. Ashabokov, L. M. Fedchenko, A. V. Shapovalov and V. A. Shapovalov, Physics of Clouds and Active Influences on Them, Nalchik: Publishing House Printing House, 2017, p. 240 (in Russian).

[5] V. A. Shapovalov, A. V. Shapovalov, B. P. Koloskov, R. Kh. Kalov and V. N. Stasenko, Numerical study of the dynamic, thermodynamic and microstructural parameters of convective clouds, Natural Science 10(2) (2018), 63-69. doi: 10.4236/ns.2018.102006.

[6] X. L. Liu and S. J. Niu, Numerical simulation of macro- and micro-structures of intense convective clouds with a spectral bin microphysics model, Adv. Atmos. Sci. 27(5) (2010), 1078-1088. http://dx.doi.org/10.1029/JC080i003p00439.

[7] B. Lynn, A. P. Khain, J. Dudhia, D. Rosenfeld, A. Pokrovsky and A. Seifert, Spectral (bin) microphysics coupled with a mesoscale model (MM5), Part 1-2, Mon. Wea. Rev. 133 (2005), 44-71.

[8] J. Straka, Cloud and Precipitation Microphysics: Principles and Parameterizations, Cambridge University Press, Cambridge, 2009, p. 408.

[9] W. R. Cotton et al., RAMS 2001: Current status and future directions, Meteor. Atmos. Phys. 82 (2003), 5-29.

[10] D. R. MacGorman, J. M. Straka and C. L. Ziegler, A lightning parameterization for numerical cloud models, American Meteorological Society 3 (2001), 459.

[11] E. R. Mansell, C. L. Ziegler and E. C. Bruning, Simulated electrification of a small thunderstorm with two-moment bulk microphysics, J. Atmos. Sci. 67 (2010), 171-194.

[12] M. P. Meyers, R. L. Walko, J. Y. Harrington and W. R. Cotton, New RAMS cloud microphysics parameterization, Part II: The two-moment scheme, Atmos. Research 45(1) (1997), 3-29.

[13] N. E. Veremey, Yu. A. Dovgalyuk, M. A. Zatevakhin, A. A. Ignatiev, V. N. Morozov and R. S. Pastushkov, Description of the basic numerical non-stationary three-dimensional model of a convective cloud, TRUDY GGO im. A.I. Voeikov. 282 (2016), 45-91.

[14] Yu. A. Dovgalyuk et al., The concept of developing a numerical non-stationary three-dimensional model of the evolution of a sediment-forming convective cloud in natural conditions and under active influences, Proceedings of the GGO 282 (2016), 7-44.

[15] N. E. Veremey, Yu. A. Dovgalyuk and V. N. Morozov, On the parametrization of microphysical electrification processes in a three-phase model of a convective cloud, Meteorology and Hydrology 10 (2007), 42-54.

[16] O. Altaratz, T. Reisen and Z. Levin, Simulation of electrification of winter thunderstorm using the three-dimensional Regional Atmospheric Modeling System (RAMS) model: single cloud simulation, J. Geophys. Res. 110 (2005), D20205, Doi: 10.1029/2004.JD005616.

[17] C. Barthe, G. Molinie and J. P. Pinty, Description and first results of an explicit electrical scheme in a 3D cloud resolving model, Atmospheric Research 76(1-4) (2005), 95-113.

[18] F. Rawlins, A numerical study of thunderstorm electrification using a three dimensional model incorporating the ice phase, Quart. J. Royal Met. Society 108 (1982), 779-801.

[19] B. A. Ashabokov, A. Kh. Kagermazov, A. V. Shapovalov and V. A. Shapovalov, About one approach to the formation of initial conditions for modeling convective clouds, TRUDY GGO im. A.I. Voeikov 582 (2016), 159-173.

[20] A. V. Shapovalov and V. A. Shapovalov, Three-dimensional visualization of geophysical information for solving applied problems, Nauka. Innovatsii. Tekhnol. 1 (2014), 65-73 (in Russian).