Influence of the initial thermal pulse’s temperature on the processes of cloud formation based on the results of mathematical modeling

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Abstract. The evolution of a convective cloud at different values of the initial thermal pulse at the earth's surface is considered. The research is based on a three-dimensional non-stationary cloud model developed in the HMGI. Numerical calculations are carried out for three variants of the initial overheating of 1, 2 and 3 °C. Vertical sections were obtained at the 20th, 30th, and 40th minutes of cloud development and the corresponding characteristics (water content, ice content, total water content and ice content). It is shown that an increase in overheating leads to an increase in the intensity of cloud development at the initial stage and the stage of growth. At an overheat of 3 °C, the ice content grows much faster than at lower values, due to the removal of droplets to the higher layers of the atmosphere with a below-freezing temperature, where they freeze faster.

1. Introduction
Despite the undoubted success in the study of individual physical processes occurring in clouds, there is still no comprehensive knowledge about the role of the atmosphere influence on the formation of macro- and microstructural characteristics of clouds. There are many mechanisms of atmospheric influence on cloud formation processes, and all of them are caused by the atmosphere conditions – the temperature, humidity, pressure and wind fields in the atmosphere, the structure of the electric field, the aerosol composition of the atmosphere, etc. The research of a particular mechanism’s role on the formation and development of clouds is based on the study of the influence of changes in the fields of atmospheric parameters corresponding to this mechanism. Conducting this kind of research requires the involvement of mathematical models of clouds [1-5]. In the cloud modeling the temperature fields in the surface layer of the atmosphere are used to initialize the convective flow (setting the thermal pulse).

One of the main processes that contribute to the formation of convective clouds in the atmosphere is thermal convection. And the cause of its occurrence is the overheating of the air in certain areas of the underlying surface with unstable temperature stratification in the lower layers of the atmosphere. When these conditions are created, the superheated air begins to rise up and becomes saturated at the condensation level, which contributes to the formation of cloud droplets in the presence of condensation nuclei (aerosol particles).

The aim of this work is to study the influence of the initial thermal pulse’s temperature on the processes of cloud formation.

Numerical experiments were carried out using a three-dimensional non-stationary model of a convective cloud with a detailed account of microphysics developed in the High-Mountain
The fields of meteorological parameters from the global atmospheric model were taken as the initial data [9]. The results of the studies showed that an increase in overheating causes a more intense rise of the initial «bubble» and the removal of condensed moisture to the higher layers of the atmosphere, leading to a faster formation of the ice phase.

2. Materials and methods of research
The three-dimensional non-stationary model of a convective cloud is based on solving the equations of thermodynamics, microphysics and electrostatics. For a visual representation of the calculation results, a program for three-dimensional visualization of the fields of characteristics of a convective cloud is used.

The hydrothermodynamics block contains equations of motion describing wet convection in the Boussinesque approximation and taking into account advective and turbulent transport, buoyancy forces, friction, and baric gradients [1].

The microphysical block consists of a system of equations describing the transformation of the mass distribution functions of droplets, ice particles, and fragments of freezing droplets [2]. There are 61 categories of droplets and 75 categories of crystals by mass and radius considered.

The electrical block consists of the equation for calculating the amount of electricity, the Poisson equation for the potential of the electrostatic field, and the formula for calculating the electric field strength. It is a part of the microphysics block and describes the processes of particle electrification 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 [6].

The model was initialized by setting the thermal pulse at the initial moment of time at the earth's surface with an overheating of 1-3 °C. The initial data was the output data of the global atmospheric model with geographical coordinates corresponding to the launch point of the aerological probe (point «Mineralnye Vody»).

3. Research results
Numerical experiments were carried out using a three-dimensional non-stationary model of a convective cloud, one of which is given in this paper. This is a simulation of cloud development for August 20, 2020. On this day there were observed showers, thunderstorms and hail by the Stavropol paramilitary service.

The pulse was set at the earth's surface with various options for overheating. The shape of the pulse was represented as a three-dimensional cylinder with a radius of 2.6 km and a height of 2 km. The dimensions of the calculated area were equal to 50 km horizontally and 16 km vertically. The grid spacing in the X, Y coordinates was 500 m, and in the Z coordinate was 250 m. In the figures below, there is an auxiliary grid of 2 km × 2 km.

The initial overheating varied from 1 to 3 °C. The results of the calculations are presented as a function of the distribution of droplets and crystals by size (mass), according to which the isolines of water content, ice content and total water content and ice content, their time course due to the transformation of droplets and solid particles are calculated and constructed. Figure 1 shows the isosurfaces of water content of 3 g/m³ and ice content of 3 g/m³ against the background of the isolines of the vertical component of the velocity w in the vertical plane at the 20th, 30th and 40th minutes of the cloud development. Table 1 shows the numerical values of the maximum cloud characteristics, and the heights at which they are reached indicated in italics.

For the first variant (figure 1 a, b, c) the distributions of water content and ice content (isolines in vertical cross-section) with respect to the upstream flow with w (isosurface in the center) at the 20th, 30th and 40th minutes of cloud development are shown. From the pictures it can be seen that at the 20th minute of development only a drop fraction was formed in the cloud. The vertical section of the cloud at the 30th minute of development indicates the presence of a significant amount of ice particles in the cloud, at the 40th minute there are a large number of drops and ice particles in the cloud, water content and ice content become comparable (approximately 5 and 4 grams).
Figure 1. Isosurfaces of water content equal to 3 g/m$^3$ and ice content equal to 3 g/m$^3$ in the vertical plane against the background of the isolines of the vertical component of the velocity $w$ at: a), d), g) 20th minute; b), e), h) – 30th minute; c), f, i) – 40th minute; c), b), c) – first variant; d), e), f) – second variant; g), h), i) – third variant.
The formation of ice content lags behind the formation of water content in time, since the ice fraction is formed due to the freezing of mainly large drops. After the formation of ice particles, both drops and crystals can be present in a unit volume at the same time, the sum of these fractions reaches 7 g/m$^3$ in the developing cloud (table 1).

The second (figure 1 d, e, f) and third (figure 1 g, h, i) variants of cloud development are slightly different from the first. So, at the 20th minute of cloud development in the second variant, there is already a certain volume of ice equal to 3 g/m$^3$ (figure 1 d), and in the third variant, this volume is already very significant (figure 1 g).

Table 1. Maximum values of water content, ice content, and the sum of water content and ice content at different stages of cloud development.

| Cloud characteristics | Variants of calculation |
|-----------------------|-------------------------|
|                       | 1          | 2          | 3          |
| Vodn(g/m$^3$)         | 4.97       | 4.75       | 5.25       | 4.69       | 4.42       | 4.97       | 5.13       | 5.14       |
| H (km)                | 4.40       | 5.50       | 6.00       | 5.00       | 5.00       | 5.00       | 4.50       | 4.50       | 4.50       |
| Ledn(g/m$^3$)         | 0.1        | 3.90       | 5.51       | 4.91       | 4.47       | 4.27       | 4.09       | 4.28       | 4.29       |
| H (km)                | 6.5        | 7.00       | 7.50       | 6.50       | 7.00       | 7.00       | 6.00       | 6.00       | 6.00       |
| Vold(g/m3)            | 4.41       | 5.82       | 6.83       | 7.07       | 6.63       | 6.41       | 6.89       | 6.87       | 6.84       |
| H (km)                | 5.50       | 6.50       | 7.50       | 6.00       | 6.00       | 6.00       | 6.00       | 6.00       | 6.00       |

At the cloud growth stage (the 30th minute), the characteristics in the second and third variants are closer to each other, in contrast to the water content and ice content of the first variant. At the stage of the maximum development of the cloud (the 40th minute), the difference in the maximum characteristics of the cloud in all variants is small. At the 30th and 40th minutes of cloud development, the heights at which the maximum values of ice content, water content, total water content and ice content are reached are the same.

Thus, the results of numerical experiments showed that an increase in overheating from 1 to 3 °C leads to an increase in the intensity of cloud development at the initial stage and the stage of growth. By the 40th minute of development, the cloud parameters in variants 1 and 2 tend to the cloud parameters of variant 3. The more intense the pulse, the stronger the deformation of the initial stage of cloud development.

4. Conclusion
An increase in overheating from 1 to 3 °C leads to an increase in the intensity of cloud development at the initial stage and the stage of growth. At the stage of maximum development (the 40th minute), the cloud parameters in all three variants become comparable.

The physical meaning of this fact can be explained by the removal of drops to the higher layers of the atmosphere with a below-freezing temperature, where the drops freeze faster. Additional overheating causes a more intense rise of the initial «bubble» and the removal of condensed moisture to the higher layers of the atmosphere. A faster growth of the upper boundary of the cloud and a faster formation of the ice phase are observed.

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