The Results of Numerical Modeling of Active Influence on Hail Clouds

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Abstract — **The article discusses the state of cloud physics and active influences exerted on them. The current period of time is considered as a transition for this scientific direction: the stage of studying "elementary" processes in clouds has been completed and a new stage of formation and development of clouds, taking into account their system properties, is under active investigation by researchers. The features of existing methods used to study active impacts on convective clouds are described; some approaches to their development are proposed to discuss. The model of control over the formation of a microstructure of the convective clouds and the results of modeling the active influences on the convective clouds are introduced.**

Keywords— active influence, cloud physics, "elementary" processes, system properties, optimal control theory

I. INTRODUCTION

The development of the cloud physics and a study of active influences exerted on them have slowed down significantly in recent decades and, it should be noted, its current state is quite complex and ambiguous. It was succeeded to establish the reason for a negative phenomenon in the development of this scientific direction. It includes the fact that the present period of time is transitional: the stage of studying "elementary" processes in clouds is completed and a new stage as a transition to new knowledge is becoming relevant, which will allow to reveal the regularities on how clouds macro- and microstructural characteristics are formed, taking into account their system properties [3].

As for the existing technologies of impacts on convective clouds, they are mainly based on the concepts proposed in the

50-60s of the last century but not on the methods obtained as a result of some research addressing how microstructural characteristics of clouds are formed in the natural conditions and under active influence [1].

Therefore, the development of science-based methods for managing the processes of precipitation in clouds has become an urgent scientific problem.

The main problems of methods development dealing with the influence on convective clouds (for the purpose of control of precipitation processes) will be discussed below; some approaches to a solution regarding this problem will be proposed. The results on modeling the active influence on the powerful convective clouds giving hailstones will be presented.

II. METHODS AND MATERIALS

A. Background

The reason for some slowdowns in the development of cloud physics and the active influences exerted on them, as shown in [3], is that the present period of time is transitional for this scientific field. If we take separately the cloud physics, it can be noted that the stage of studying "elementary" processes in clouds is coming to end and now we are moving to the stage of studying the regularities according to which macro - and microstructural characteristics of clouds are formed, taking into account their system properties. To sum up the research results of the final stage of the development of cloud physics, in this direction, we can say, the significant progress has been achieved: it was possible to develop multi-

dimensional models of clouds, including models with detailed consideration of processes [4, 6, 8]. The achievements in this direction make it possible to obtain the significant and fundamental knowledge and apply the results in cloud physics.

It should also be noted that the transition of cloud physics to the next stage of its development is natural, because it is not limited to the "elementary" processes in clouds; there are many factors that affect formation processes and clouds development. Among them, there are factors a role of which in the formation and the development of clouds cannot be studied at a decent and appropriate level because there are many factors that are not fully understood and studied. Considering convective clouds as complex physical systems, [3] the factors that form the structure of clouds are defined.

These factors include the interaction of processes in clouds (emergent system properties), and the interaction of clouds with the atmosphere (a hierarchy property). The main directions of research at the next stage is its development in terms of cloud physics, the main tasks of it are introduced in [3]. It is worth mentioning that the results of studies about the influence of a wind structure in the atmosphere on the processes of clouds formation and the formation of an electric structure of clouds, which are given in [3], belong to these scientific domains. We note that the results of studies about the influence of the wind field structure in the atmosphere on the processes of cloud formation and the formation of the electrical structure of clouds, which are given in [3], are also referred to the same scientific domain.

With regard to the existing technologies of active influences on convective clouds from the point of managing precipitation processes, they still rely on the concepts proposed in the 50-60s of the 20th century, and not on the methods obtained as a result of studies relating to the formation of their microstructure in the natural conditions and under active influence. However, some practices on active influences on clouds have taken a wide scale. Therefore, in our opinion, a serious attention should be paid to the development of science-based methods towards the managing processes of precipitation formation in clouds. It is worth saying that the works [1, 7] are devoted to the analysis of practical work effectiveness relating to the suppression of hail. As an example, it can be noted that in [3] the results of the analysis of the so-called concept of precipitation acceleration [1], on which the hail suppression technology is based in Russia, are presented. The results of the analysis showed that the provisions of the concept are not introduced yet in practice.

Thus, the study of the regularities on macro-and microstructural characteristics formation of convective clouds with the account of the mentioned factors and the development of effective and scientifically based methods of active influence on them have become extremely urgent issues in cloud physics.

B. To Issue on Method Development about Active Influence in Convective Clouds

As already noted, the existing technologies of active influence on clouds to manage sedimentation processes are based on the concepts proposed in the second half of the 20th century. Obviously, such technologies can not be sufficiently effective. As an example, it can be noted that in [3] the results of the analysis of the so-called concept of precipitation acceleration [1], on which the hail suppression technology is based in Russia, are presented. As the results of the analysis have shown, the provisions of the concept are not practically introduced.

Let us focus on the difficulties that arise when developing methods on managing processes relating to precipitation formation in clouds:

- finding a local area in a cloud where conditions are favorable to achieve the impact target;
- finding a concentration of reagent particles that should be provided in this area each time.

It is obvious that the solution of these problems on the basis of some assumptions and assumptions about precipitation processes in clouds, as it is proposed in the existing concepts, is not possible. Their solution should be based on modeling the clouds formation and its development in the natural conditions and under the active influence.

To solve this problem, an approach that currently is used, is based on the modeling of various options aimed at introducing reagent particles into a cloud and at choosing the most effective one in terms of achieving the target impact. These parameters differ in values relating to the reagent particle sources that are introduced into a cloud model. Depending on the way they are applied to a cloud, they can be dots, lines, or have more complex shape. But it is important to note that by sorting out the different variants of adding a reagent to a cloud, the solution the problems to be mentioned is possible only with approximation. To a greater extent, it can be applies to the second task. A source of some difficulties also can be a need to use a small size of spatial mesh in calculations, because at larger sizes the cloud area in which there are the particles of a reagent may not be "seen". These difficulties can be felt when a size of the area is small (clouds of arid and semi-arid regions).

In work [3] an interesting (to the authors' opinion) view was expressed regarding methods development dealing with controlling precipitation in clouds. One approach considers this problem within the framework of optimal control theory [9], the other approach deals with the methods of bifurcation theory [2].

III. RESULTS

A. Modeling Active Influence on Convective Clouds

The need to solve the problems that arise when developing the methods enabling to control the precipitation processes in clouds is shown below in the example of hail clouds. As already stated, the second half of the 20th century is a period of the rapid developments in physics of hail clouds and active influences on them. At present, the extensive material has been accumulated in terms of macro - and microstructural characteristics formation in these clouds in the natural conditions and under the active influence.

Let us focus on the results of modeling the active influence on the hailstorm processes, which indicate a complex dependence of the impact effect upon a position and a shape of a diffusing area and the concentration of the artificial crystals, introduced into this area. The number of large hailstones formed in the cloud during its evolution was used to estimate the change in the hail hazard degree of the cloud. The calculations were carried out on the basis of a two-dimensional model of microphysical processes in the hail cloud with a given thermo-hydrodynamics [4]. The results of the calculations have showed that the cloud diffusing effect to a significant extent depends on a position of the diffusing area in the cloud (Fig.1). When area is located in the region of weak upstream flows at -10°C (point A in Figure 1), the cloud diffuse is leading to a decrease in a number of large hailstones formed in the cloud during its evolution (by about 30% compared to their number without cloud seeding). In the case where the source of the artificial crystals was located at point B, there was a decrease in this value by about 60 %. More effective there was a case when the source was at point D on the isotherm at -10°C in the zone of more intense upward flows. Adding a source of the artificial crystals to this point has led to a decrease in the hail hazard degree of the cloud by almost 90 %.

It is interesting to note that in the case where the source of the crystals is located at point C above the isotherm at -10°C, there is an increase in a number of large hailstones compared to their number without exposure, i.e. the impact leads to the stimulation of hailstones. Existing technologies do not take into account the possibility of increasing the degree of a cloud safety as a result of an active impact.
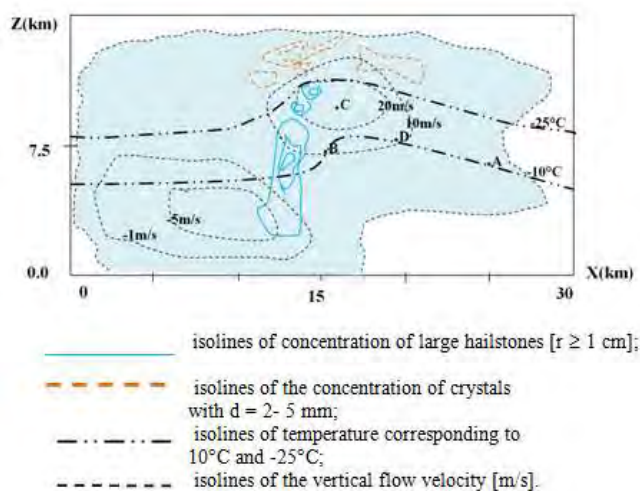

Fig. 1. Cloud structure for t = 18 min

Let us consider some options for modeling the active influence on a cloud, which differed in 1) the volume of the seeding area, 2) a form of the seeding area, 3) the concentration of artificial crystals in this area. Table 1 shows the results of calculations in the case when the same amount of artificial crystals (3×10^{13}) was provided in each "elementary" volume (500m x 250m) of the seeding area during the exposure time. The "elementary" volume, the conditions that

are more favorable for the active influence, is showed in Table I (point D in Fig. 1).

As seen in Table I the volume increase in the diffusing area in comparison with the first option has little impact on the cloud diffusing effect. This indicates that in order to prevent the formation of large hailstones, it is sufficient to diffuse the local cloud region in which the conditions are favorable to achieve the target impact. It follows that the development of methods to control the precipitation processes in the convective clouds requires the solution of the first problem to be mentioned above that implies finding this area in the cloud. For the cloud diffuse in this area, a point-like source of the artificial crystals should be used.

TABLE I. CLOUD DIFFUSING EFFECT DEPENDING ON VOLUME AND GEOMETRY OF REAGENT APPLICATION AREA

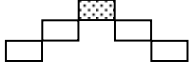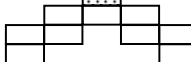| Number of variant	Form source's	Intensity source's ($m^{-3}s^{-1}$)	The degree hail hazard of cloud (%)	The cloud diffusing effect (%)
1		10^6	14.8	85.2
2		10^6	8.2	91.8
3		10^6	4.5	95.5
4		10^6	8.3	91.7
5		10^6	8.1	91.9
6		10^6	10.1	89.9

A comparison of Variants 1, 2 and 3 shows that the expansion of the horizontal diffusing area leads to a certain decrease in the hail hazard degree of the cloud. Variant 6 shows that the expansion of the diffusing area corresponding to Variant 1 by adding an "elementary" volume located on the isotherm -10°C also reduces the degree of hail hazard of the cloud. At the same time, its expansion due to the layers of the cloud, located below the isotherm, and though it leads to some decrease in the degree of hail hazard of the cloud, but it is noticeably less than in the case of Variant 3, for example.

It is interesting to compare Variants 4 and 5 in which the diffusing areas are increased by 5 and 10 times, respectively, compared to Variant 1. The diffusing areas in both variants are expanded due to the cloud layers located below the isotherm-10°C. It can be noted that the values of the degree of hail hazard of the cloud, corresponding to these variants, differ only by 0.2%, although, the volume of diffuse, respectively, and a number of the artificial crystals introduced in option 5 is 2 times more.

Some calculations were also carried out, which differ from those presented in Table I in terms of the intensity of the artificial crystal sources in the "elementary" volumes of the diffusing area that was less than n times (n – a number of

"elementary" volumes). Accordingly, each" elementary" volume of the diffusing area is made n times less than the artificial crystals, compared with the cases given in Table I. The values of the sources intensity, the degree of the hail hazard of the cloud and the efficiency of the active influence corresponding to the different variants of the artificial crystals in the cloud are given in Table II.

TABLE II. EFFECT OF THE ACTION DEPENDING ON THE GEOMETRY OF THE REAGENT APPLICATION AREA (THE CONCENTRATION OF ARTIFICIAL CRYSTALS IN ALL VARIANTS IS THE SAME).

The number of variant	Form *source's*	Intensity source's $(m^{-3}s^{-1})$	The degree hail hazard of cloud (%)	Effect (%)
1		10^6	14.8	85.2
2		$1/3*10^6$	11.3	88.7
3		$1/5*10^6$	8.5	91.5
4		$1/5*10^6$	14.2	85.9
5		$1/10*10^6$	16.3	83.7
6		$1/2*10^6$	12.4	87.6

The Table II shows that the nature of changes in the degree of hail hazard of the cloud was not so big from the qualitative point, when the artificial crystals were added to it in smaller quantities. But in general, as seen from Tables I and II, the decrease in the intensity of the sources has led to a decrease in the effect of exposure. At the same time, its reduction is more significant in the case of Variants 4 and 5, which correspond to a greater number of "elementary" volumes, located below the isotherm -10°C. In general, the results of the calculations indicate the importance to determine the diffuse area in which conditions are favorable to prevent the formation of dangerous sized hailstones, and the concentration of the reagent particles to be provided for in this area.

Let us focus on the results of modeling the active influence on the hail cloud based on a three-dimensional model with a detailed account of the processes of thermo-hydrodynamics and microphysics [5]. Figure 2 shows the vertical sections of the cloud at the same time (40 min), corresponding to its development in the natural conditions and under the active influence. Figure 2.a corresponds to a naturally developing cloud, Figure 2.b - to the crystallizing reagent diffused at the 30th minute of the development.

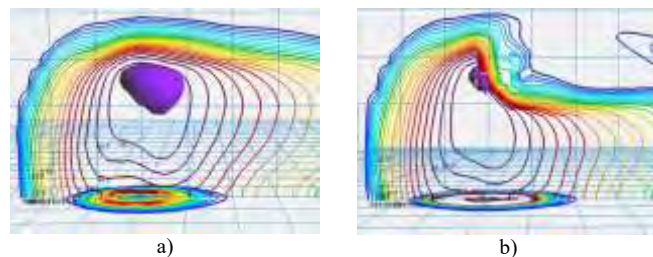a)   b)

Fig. 2. Describing isolines in natural development of the cloud (a). A zone of localization of large ice particles inside the cloud. Describing isolines of the clouds by diffusing with crystallization reagent (b).

Figure 2 shows the isolines of radar reflectance (dBZ) and the large ice particle localization zone. It should be noted that the active influence resulted in considerable changing the radar structure of the cloud in the area where the artificial crystals were added. It can also be seen that the influence has led to the almost complete disappearance of the zone where the large ice particles were localized.

The calculation results show that in order to prevent the incidents with hail, it is very important to determine the local area in the cloud in which the conditions are favorable to prevent the formation of dangerous dimension hailstones, as well as the concentration of the reagent particles that should be provided for in this area.

C. Model to Manage Hail Clouds Microstructure Formation and its Calculation Results

In early works we find some positions towards the approaches geared at the solution regarding the development of some methods covering the sedimentation control in the clouds. One approach considers this problem within the framework of optimal control theory [9], the other approach deals with the methods of bifurcation theory [2].

The calculation results show that the effect on the convective clouds can significantly depend on the area position in the cloud that must be diffused to achieve the goal, for example, to prevent the formation of hailstones of dangerous dimensions. Let us dwell further on the results of studies depicting the dependence relating to some changes in the degree of danger of the cloud upon the amount of the reagent added into the cloud at different time during diffusion. For the research, the first of the noted approaches was used, i.e. the active influence on the hail clouds was considered within the framework of optimal control theory.

We have to note that the optimal management problems under implementation has difficulties, which are the barriers in using full cloud models. In this regard, this problem (the problem of optimal control towards the evolution of the microstructure of city clouds) is considered here for a cloud model, in which the microphysical processes in the clouds are described against the background of a given thermo-hydrodynamics [3]:

$$\frac{\partial f_1}{\partial t}+V_x\frac{\partial f_1}{\partial x}+(V_z-V_1)\frac{\partial f_1}{\partial z}=\left(\frac{\partial f_1}{\partial t}\right)_{cd}+\left(\frac{\partial f_1}{\partial t}\right)_{cg}+\left(\frac{\partial f_1}{\partial t}\right)_{ac}+$$

$$+\left(\frac{\partial f_1}{\partial t}\right)_{cr}+\left(\frac{\partial f_1}{\partial t}\right)_{fr}+\Delta' f_1+I_1 \qquad (1)$$

$$\frac{\partial f_2}{\partial t}+V_x\frac{\partial f_2}{\partial x}+(V_z-V_2)\frac{\partial f_2}{\partial z}=\left(\frac{\partial f_2}{\partial t}\right)_{cd}+\left(\frac{\partial f_2}{\partial t}\right)_{Acg}+\left(\frac{\partial f_2}{\partial t}\right)_{cr}+\left(\frac{\partial f_2}{\partial t}\right)_{fr}+$$

$$\Delta' f_2 + I_2 + u$$

$$0\le x\le L_x, 0\le z\le L_z, 0\le m<\infty, t>0,$$

where $f_1(x, z, m, t)$ and $f_2(x, z, m, t)$ – a distribution function for the mass of droplets and ice particles in the cloud at time t at point *(x, z)*; $\left(\frac{\partial f_1}{\partial t}\right)_{cd}$, $\left(\frac{\partial f_1}{\partial t}\right)_{cg}$, $\left(\frac{\partial f_1}{\partial t}\right)_{ac}$, $\left(\frac{\partial f_1}{\partial t}\right)_{cr}$, $\left(\frac{\partial f_1}{\partial t}\right)_{fr}$ - change of the distribution function of droplets due to the microphysical processes of condensation*(cd)*, coagulation*(cg)* of drops, accretion*(ac)* of droplets and crystals, crushing*(cr)* and freezing *(fr)* respectively; $\left(\frac{\partial f_2}{\partial t}\right)_{S}$, $\left(\frac{\partial f_2}{\partial t}\right)_{ac}$, $\left(\frac{\partial f_2}{\partial t}\right)_{ag}$, $\left(\frac{\partial f_2}{\partial t}\right)_{fr}$ - change of function of distribution of crystals due to sublimation *(s)*, accretion*(ac)*, aggregation*(ag)*, and freezing*(fr)* the droplets, respectively.

The other terms in the right parts of the equations describe the change in the function $f_1(x, z, m, t)$ due to the formation of droplets and crystals in the natural conditions *(I_1 (x, z, m ,t), I_2(x ,z, m ,t))* and the formation of the artificial crystals of the active influence *(u(x, z, m, t))*, as well as some changes in these functions due to the turbulent transport. The inclusion of an artificial crystal source controls the evolution of the cloud microstructure.

The conditions are fulfilled at the boundaries of the spatial region

$$f_1(x,z,m,t) = f_2(x,z,m,t) = 0$$

$$at \quad x=0, x=L_x, z=L_z \qquad (2)$$

$$\partial f_1(x,z,m,t)/\partial z = \partial f_2(x,z,m)/\partial z = 0$$

$$at \quad z=0$$

The distribution functions by mass of droplets and ice particles at the initial time are known as

$$f_1(x,z,m,0) = f_1^0(x,z,m)$$

$$f_2(x,z,m,0) = f_2^0(x,z,m) \qquad (3)$$

Thus, the control in the task is the function $u(x, z, m, t)$, describing the source of the artificial crystals. Based on the fact that in real situations only some parts of the cloud should be exposed at any given time, we write $u(x, z, m, t)$ as a point source:

$$u(x, z, m, t) = u_0(m, t)\cdot\delta(x-x_0(t))\cdot\delta(z-z_0(t)), \qquad (4)$$

where $x_0(t)$ and $z_0(t)$ are the coordinates of the diffusing region along the axes *OX* and *OZ*; $u_0(m, t)$ are the intensity of the source of the artificial ice crystals, the distribution of which is given, δ is the Delta function. For $u_0(m, t)$, $x_0(t)$ and $z_0(t)$ there are some obvious limitations:

$$u_0(m, t)\ge 0,$$
$$x_0(t)\in [0,L_x],$$
$$z_0(t)\in [h_1,h_2],$$

where h_1 and h_2 are the lower and upper boundaries of the region in which the ice that generates the activity of the reagent is acted out (at $z < h_1$ crystals are not formed due to high temperature, and at $z > h_2$ there is a large number of crystals formed naturally).

Since the distribution functions $f_1(x, z, m, t)$ and $f_2(x, z, m, t)$ of the cloud particles and monitoring $u(x, z, m, t)$ have a distributed character, we have an optimal managing problem with distributed parameters [9].

The solution of the problem (1) - (3) with a given control function (4) implies the evolution of the cloud particle system for a particular type of control. At $u(x, z, m, t)=0$ we have a natural course of the process. The trajectory of the cloud evolution will depend on monitoring (4), and its quality is determined by the target impact degree. The number of large hailstones that had been formed in the cloud during the evolution time *[0, T]* was used as a functionality to estimate the degree of the target impact:

$$F[f_2,u] = \int_0^{L_x}\int_0^{L_z}\int_{m_k}^{\infty}\int_0^T f_2(x,z,m,t)dx\,dz\,dm\,dt \qquad (5)$$

where m_k is the mass of the hailstone reaching the Earth's surface and capable to cause damages.

Then, the problem of optimal cloud microstructure monitoring is stated as follows: for a controlled system (1) - (3) an acceptable form of the control function (4) is to be found that delivers the minimum to the functionality (5):

$$F[f_2,u]\to \min \qquad (2)$$

Figure 3 shows some calculation results towards the problem (1) - (6).

Figure 3 shows the optimal monitoring obtained for the particular hail cloud. You can see that the function $u(x, z, m, t)$ (the intensity of the source of the artificial ice crystals) changes over time in a complex way. It decreases rapidly from its value at the initial time and after a short period of time becomes almost zero. Then, it increases rapidly and when reached some value does not change over time.

The coordinates of the point at which the artificial crystals are added also change in a complex way over time. We have to note that the transition of the source of the artificial crystals (a function $u(x, z, m, t)$) into a stationary regime (after a

certain period of time when the action has begun) is associated with the model features (thermo-hydrodynamics).
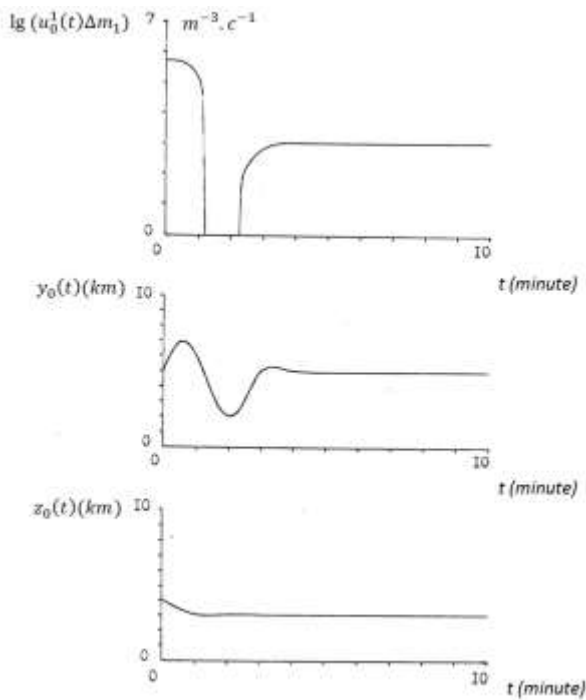

Fig. 3. View of optimal functions $u_0^1(t)$, $y_0(t)$ and $z_0(t)$.

IV. CONCLUSION

The above figures show that the position in the cloud of the diffusing zone, obtained in calculations, differs from the position of the zones that have been diffused within the currently in-use technologies. These differences are also significant in the case of the technology used in the Russian Federation to influence the hail clouds [1].

The authors declare that there is no conflict of interest.

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