HAIL CLOUD SEEDING OPTIMIZATION ON THE BASIS OF THEORETICAL RESEARCH IN SPREADING OF CRYSTALLIZING AGENTS AND THEIR INFLUENCE ON CLOUD MEDIUM

**M.T. Abshaev*, A.M. Abshaev*, Ya.A. Sadykhov*,
G.S. Burundukov, I.A. Garaba, E.A. Zasavitsky, S.D. Plyusnin, and E.I. Potapov**

**High Mountain Geophysical Institute of ROSHYDROMET, 2, Lenina ave., 360020, Nalchik, Kabardino-Balkaria, Russian Federation*
E-mail: abshaev@mail.ru
Institute of Electronic Engineering and Industrial Technologies, Academy of Sciences of Moldova, 3/3, Academiei str., MD-2028, Chisinau, Republic of Moldova
E-mail: efim@lises.asm.md
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Russian rocket technology of hail protection is based on the concept of precipitation acceleration, leading to early precipitation formation and cloud water outpouring [2-4, 10] in regions of future formation of hail of deep convective clouds. Many regulations of this technology are historically applied for active influence of hail processes in the Republic of Moldova. Seeding with a crystallizing agent is carried out in areas of new growth; it involves the following:

– Seeding of forming potentially hail-hazardous clouds *Cu cong* for hail formation prevention;
– Seeding of regions of new growth of deep convective clouds, being also *Cu cong* clouds (feed clouds), which merge with the basic hail cloud while growing, with a view of hailstorm suppression.

According to the concept, for precipitation acceleration, the concentration of imitation ice crystals in the seeded volume must be on the order of 10^7 m^{-3} and above; this leads to rapid aggregation with subsequent grain-coating formation and sleet appearance during 6-8 min. For this reason, efficiency of seeding significantly depends on concentration of crystallizing agent.

The aim of the present paper is to optimize seeding of hail clouds; to refine patterns of cloud seeding according to stage of the cloud formation; to specify required amount of aerosol particles in seeding facilities (rockets and projectiles); and to optimize discreteness of introduction of point sources (projectiles) and linear sources (rockets).

For this purpose, there was carried out a theoretical simulation of the process of crystallizing agent aerosol spreading in clouds of the *Cu cong* type [1, 9] after seeding made according to the hail suppression technology by means of antihail rockets of new generation "Alan-2", "Alazan'-6", and "As" [3] and by means of artillery projectiles "El'brus-4" as well as a theoretical simulation of interaction of crystallizing particles and cloud medium [8].

Linear seeding was simulated by launching of "Alan-2" rockets, each of them provides introduction of $N_0 = 1{\cdot}10^{16}$ of crystallizing particles on its way of 12 km [2]. Rocket introduction was carried out in the horizontal plane at a height of 4 km above sea level with discreteness in space of 1 km after the mode of hail protection practice [5]. Herein, it is assumed that rocket seeding routes are parallel to each other. Results of calculations of the crystallizing aerosol concentration fields in three moments of time (in 1, 3, and 5 min after introduction) are presented in Fig. 1.

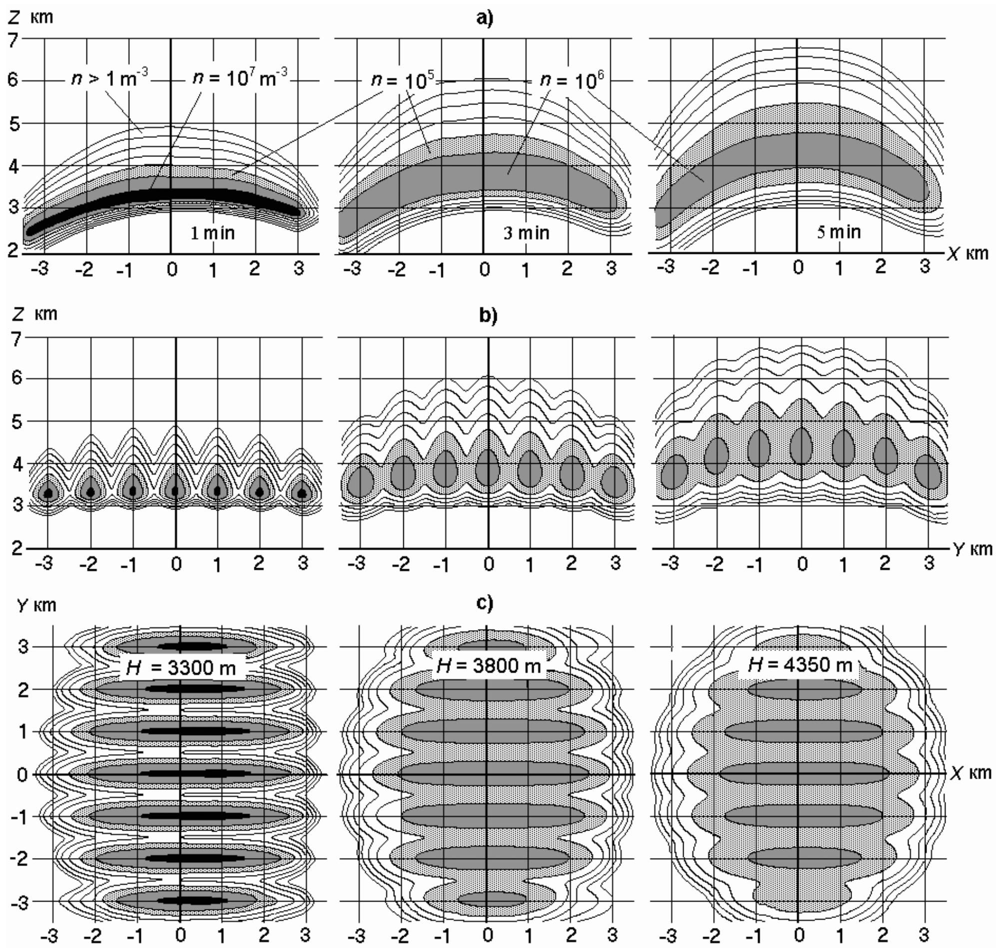

Fig. 1. Vertical ((a) and (b)) and horizontal (c) sections of the crystallizing aerosol spreading region in isograms of particle concentration n m^{-3} in 1, 3, and 5 min after seeding of *Cu cong* with anti-hail rockets "Alan-2".

It follows from Fig. 1 that the aerosol spreading volumes rapidly increase. At the turbulence factor $K \approx 80 - 100$ m^2/s, already in 1 min after seeding, one can observe merging of regions with the concentration of aerosol introduced by neighboring sources $n > 10^4$ m^{-3}. Subsequently, dimensions of the aerosol cloud rapidly increase in time, and in 3 min volumes with the aerosol concentration $n > 10^5$ m^{-3} merge. Vertical length of the aerosol spreading volume in the central part of the cloud is 1.5 km in 1 min, more than 2.5 km in 3 min, and more than 3.5 km in 5 min.

Maximum values of the aerosol concentration, being $n_0 = 10^{10} - 10^{11}$ m^{-3} in the moment of introduction, rapidly decrease: more than by a factor of 10^2 during the first minute and more than by a factor of 10^3 during 3 min. The volume of region of the aerosol concentration higher than 10^7 m^{-3}, required for realization of microphysical processes, which, according to [2, 8], provide rapid precipitation formation and hail prevention, is $1.4 \cdot 10^9$ m^3 in 1 min. In 2 min after introduction of products, the given concentration is observed only in local volumes with a size across of 0.2-0.3 km. At later stages the agent concentration is too low; a repeated seeding is required.

The present-day technology of hail prevention [2, 5] allows these repeated seedings of regions of new growth of hail clouds at time intervals of 5 min and with discreteness in space of 1 km. The time interval of 5 min is specified on the basis of minimum time of formation of

1-cm-hail after its origination [2]; the discreteness in space of 1 km is determined taking into account that regions of seeding of neighboring sources merge during 1 min. This technology contributes to reduction of hail damage by 80-90% [7]. However, in some cases attempts to completely prevent hailstorm on protected territory fail. Often, impact on superpower hail processes results only in gradual weakening of the process intensity, and hailstorm is interrupted only after multiple seeding and invasion of hail cloud on protected territory.

According to the carried out calculations, this may be due to the fact that in superpower hail clouds, in the seeding region, so high turbulence takes place that rapid decrease of the crystallizing aerosol cannot provide acceleration of precipitation formation and hail prevention. Therefore, for interruption of hailstorm from deep hail clouds, multiple seeding is usually applied; it leads to excessive expenditure of antihail rockets. This is appreciably shown at impact on fast-developing hail processes, wherein turbulence and updrafts are maximal.

At the second stage, interaction of the introduced agent and cloud medium was studied [8] taking into account:

1. stages of burning of composition or fuel with agent, including burning of pyrotechnic composition or ice-form fuel with agent; formation of a reactive gas jet (RGJ) and dispersion of crystallizing agent; afterburning of combustion products; evaporation of cloud droplets;
2. stages of RGJ spreading and formation of a cloud of crystallizing particles (CCP): RGS spreading; CCP formation; coagulation of crystallizing particles (CP) with cloud droplets and between each other; initial concentration of CP; evaporation of cloud droplets;
3. stages of formation of imitation crystals and microphysical impact on cloud: spreading of CCP; formation of crystals; growth of crystals; variation in water content and other microphysical parameters of convective cloud.

As a result of consecutive consideration of the mentioned stages and processes, a closed equation system was obtained [8] consisting of equations of balances of water vapor and heat in the seeding volume, equations of condensation growth of cloud droplets and imitation ice crystals, and equations of variation in their concentration. Solution of the system made it possible to find values of the microphysical parameters of cloud inside the seeding volume and to study laws of their transformation in time as a result of seeding carried out by means of the antihail projectile "El'brus-4" and the rocket "Alan-2" at a height of isotherm -6°C (see Fig. 2). Analysis of this figure shows that this seeding leads to significant variation in cloud microphysics.

Temperature in the seeding region decreases as this regions rises and is partially compensated due to emission of heat of condensation and crystallization (see Fig. 2a).

Density of water vapor in the seeding volume decreases in time (Fig. 2b) due to condensation on imitation crystals.

Mean radius of cloud droplets decreases by 1-2 microns during first 2-3 min after seeding (Fig. 2c); when the concentration of ice crystals decreases to 10^6 m^{-3} (Fig. 2e) dimensions of the cloud droplets begin to restore to the initial ones. Influence of turbulence on growth of ice crystals is insignificant (Fig. 1d); in 2-3 min after seeding their radius is 30-40 μm and probability of their gravity coagulation with each other and cloud droplets is 55-65%.

Variation in time of imitation crystal concentration appreciably depends on intensity of turbulent exchange and ranges within one order of magnitude (see Fig. 2e). Herein, time of ice crystal formation on the agent particles due to formation of a critical thickness of water film on the agent particle surface averages between 5 and 10 s; rate of crystal formation and maximum concentration of ice crystals are in direct proportion to initial oversaturation of water vapor inside the seeding volume. Droplet water content of the cloud at $D_T = 50 - 300$ m^2/s

decreases by 0.3-1.0 g/m^3 in 2-3 min after seeding and then increases due to entrainment of vapor and droplets from cloud environment (CE) (Fig. 2f); ice content of the cloud or water amount in ice crystals sharply increases up to 0.1-0.8 g/m^3 in 1-2 min after seeding and then decreases due to expansion of the explosive gas cloud (EGC) (Fig. 2g).

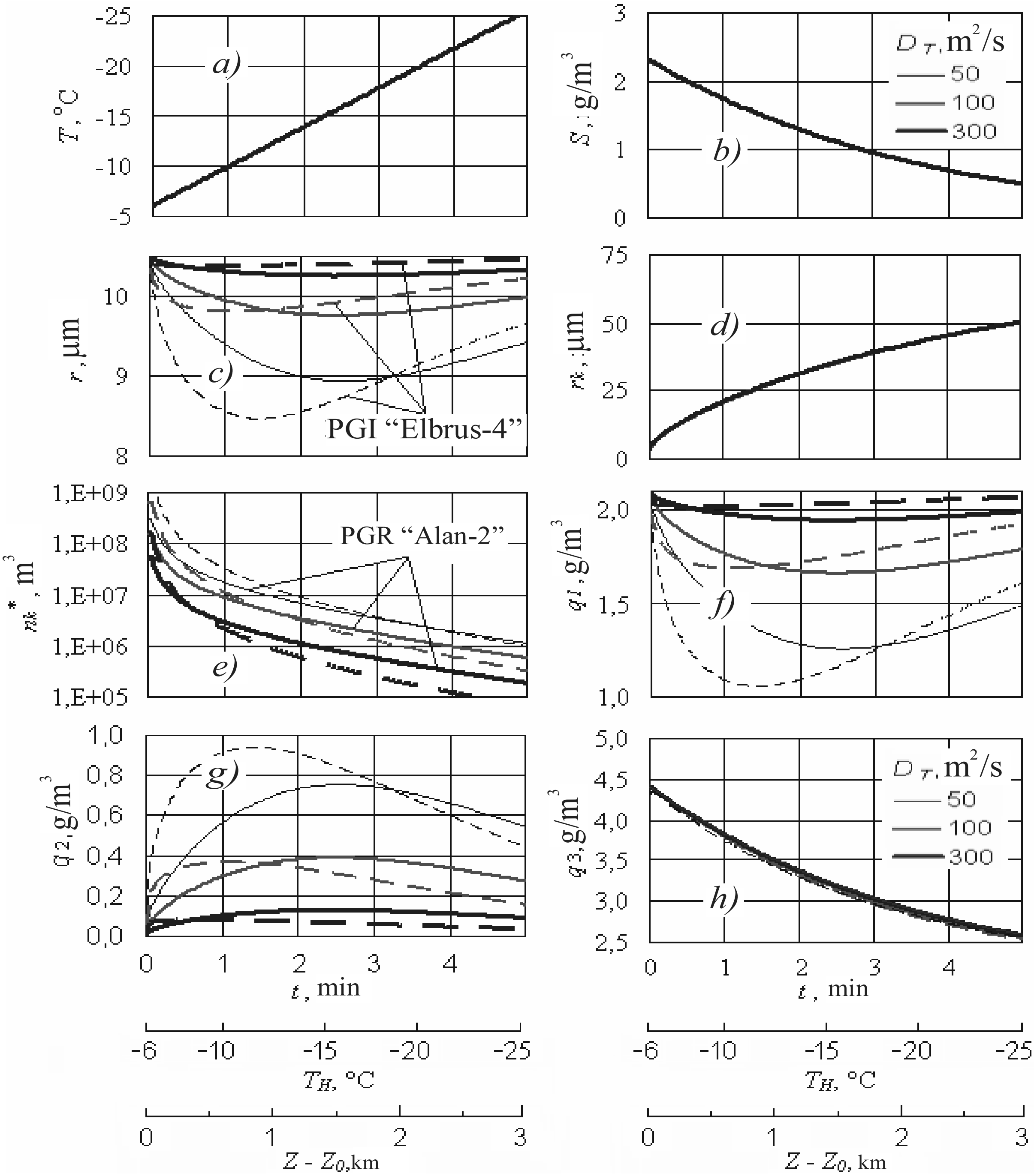

Fig. 2. Time variation of cloud parameters inside the spreading agent cloud at different values of the turbulence diffusivity coefficient D_T (m^2/s) for PGI "El'brus-4" and PGR "Alan-2": (a) temperature θ (°C); (b) vapor density S (g/m^3); (c) radius of cloud droplets r (μm); (d) radius of moist or ice crystals r_k (μm); (e) ice crystal concentration n_k^* (m^{-3}); (f) droplet water content of cloud q_1 (g/m^3); (g) ice content of cloud q_2 (g/m^3); (h) sum of water content, ice content, and density of water vapor of cloud q_3 (g/m^3).

The lower the temperature at the seeding level, the higher the initial oversaturation of water vapor with respect to water and ice, and its absorption occurs more intensively. Formation of ice crystals on the crystallizing agent particles accelerates, since a thinner film of water on their surface is sufficient for freezing. However, in 4-6 min after seeding, influence on the cloud microphysics exerted by the initial temperature at the seeding level, which in calculations varies from -3 to -9°C, gradually weakens.

An increase in initial concentration of crystallizing particles introduced into cloud from $6.6 \cdot 10^{10}$ m^{-3} to $3.0 \cdot 10^{11}$ m^{-3} leads to more intense evaporation of cloud droplets and to a decrease in droplet water content. During 2-3 min after seeding the radius of droplets decreases by 0.2 and 4.5 μm; then it begins to restore due to entrainment of additional vapor from cloud medium and weakening of influence of crystals at the decrease in their concentration to 10^6 m^{-3}. At higher concentrations of ice crystals their condensation growth weakens only by 2-10% during 5 min after seeding due to competition with each other for cloud moisture; it is obvious that “reseeding” does not play a significant role in growth of imitation ice crystals. Appreciable decrease in droplet water content of cloud is observed at the crystal concentration on the order of 10^{11}-$3 \cdot 10^{11}$ m^{-3} (by a factor of 1.5-10). In the case of higher water content and, respectively, higher concentration of cloud droplets, greater quantity of the crystallizing agent particles must be introduced.

The ice crystal dimension decreases as the initial concentration of the crystallizing aerosol increases. Thus, in 1 min after seeding the mean radius of the crystals is 22.0 μm at $n_{k0} = 10^9$ m^{-3} and 20.0 μm at $n_{k0} = 10^{11}$ m^{-3}. In 3 min, these radii are 38.5 μm and 36.5 μm, respectively; that is, influence of concentration of introduced crystallizing particles on crystal dimension is not great. However, according to [1], high initial concentrations ensure transformation of the microstructure in more significant cloud volumes.

Droplet water content of cloud, or quantity of water in cloud droplets, begins to decrease appreciably at initial concentrations of crystallizing particles $n_{k0} = 5 \cdot 10^{10}$ m^{-3} and above; a complete depletion of water content exclusively due to vapor distillation on crystals occurs in 2-3 min after seeding at $n_{k0} = 3.7 \cdot 10^{11}$ m^{-3}.

Conclusions

1. Seeding of *Cu Cong* by antihail rockets and projectiles generates concentrations of crystallizing particles required for realization of the concept of hail suppression only in local volumes and in short periods of time. Influence of seeding on evolution of the microphysical parameters is shown weaker at higher turbulent diffusion and the effects of seeding disappear faster. In the case of superpower hailstorms with intense turbulent diffusion and high velocities of updraft, rapid decrease of the concentration may weaken the seeding effect.

2. Seeding with initial concentration of crystallizing particles along the rocket path of 10^{11} m^{-3} and above ensures significant transformation of all microphysical parameters of cloud medium during 3-4 min after seeding. This stimulates formation and rapid condensation growth of ice crystals up to dimensions of 50-80 μm with subsequent active coagulation growth and increase in ice content due to decrease of water content.

3. The increase in initial concentration of crystallizing particles from 10^{10} to 10^{11} m^{-3} leads to an increase in the seeding effect; further increase in the concentration up to $3 \cdot 10^{11}$-$3.7 \cdot 10^{11}$ m^{-3} results in appreciable increase in the seeding effect. Thus, taking into account characteristic values of water content and intensity of turbulent diffusion observed in clouds seeded for hail prevention, initial concentration of crystallizing particles $n_0 \geq 10^{11}$ m^{-3} is the key concentration for increasing effect of active impacts.

For more successful prevention of hail in the case of rapidly forming superpower hailstorms, *it is recommended to carry out more massive seeding* by one of the following methods:

A) To increase the initial concentration of active crystallizing particles created in the seeding zone by a factor of 5-10 due to an increase in crystallizing efficiency of pyrotechnic compositions applied in antihail rockets and due to an increase in the agent amount in antihail rockets.

B) To decrease discreteness of seeding in time and space: interval between repeated seedings to 3 min and distance between the rocket trajectories to 0.5 km.

This can require an increase in quantity of rockets and antihail projectiles in each separate seeding; however, it may provide a better effect and, as a result, reduce total expenditures for protection from hail due to reduction in repeatance of seeding and achievement of faster effect.

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