Modeling the influence of the intensive crystallization level height on the cumulonimbus cloud parameters

A Kuznetsov¹, T Simakina²*, S Kryukova²

¹Professor, Russian State Hydrometeorological University, SPb, RU
²Associate Professor, Russian State Hydrometeorological University, SPb, RU
*E-mail: tatiana.simakina@gmail.com

Abstract. The importance of information on the ice particles amount and formation height in understanding the processes taking place in a cumulonimbus cloud is shown. In radar meteorology the intense crystallization level \( N_{IC} \) is one of the criteria for the cloud transition to the thunderstorm activity stage. Modeling of a cumulonimbus cloud parameters with the intensive crystallization level height change has been carried out. With an increase in \( N_{IC} \) there is a decrease in the hydrometeors number entering the crystallized area, an increase in the area volume with the highest water content in the cloud center, its rise, and a change in the orientation of the large drops «nursery» with a water content of more than 8 g/m³ from horizontal to vertical shape. The dependence of the hydrometeor size in the central part of the cloud jet and the lifetime on the \( N_{IC} \) level has been detected.

1. Introduction
When the growing convective cell height reaches the natural crystallization level of water droplets this leads to the transition of the cell into an active thunderstorm state and the lightning in clouds. Therefore the intense crystallization level \( H_{IC} \) is one of the criteria for the cloud transition to the thunderstorm activity stage [1-3].

The purpose of this work is to simulate the cumulonimbus cloud transformation features with a change in the intense crystallization level height. The intensive crystallization level height decrease may be due to cloud seeding using the ice-forming reagent [4-7].

The intensive crystallization level \( H_{IC} \) reflects the natural process of droplet freezing; it depends on the vertical currents speed and the droplet size distribution [8, 9].

2. Numerical modeling of thermodynamic parameters
In this work we used the cloud convection jet model [8, 9]. The water content distribution over the cloud height \( q_z \) and horizontally from the jet center \( q_i \) is approximated by the formulas:

\[
q_z = \beta \cdot \rho_{air} \cdot h_z^{\frac{1}{2}} \exp \left[ -\left( \frac{h_1 - h_0}{H_{IC} - h_0} \right)^6 \right]
\]
\[ q_r = \frac{3}{2} q_z \left( 1 - \frac{r^2}{R^2} \right)^{\frac{1}{2}}, \]  
(1)

where \( \rho_{\text{air}} \) — air density, \( h_i \) — level height, \( h_0 \) — cloud freezing level height, \( H_{IC} \) — intensive crystallization level height, \( R \) — jet radius, \( r \) — distance from the jet axis, \( \beta \) and \( \varepsilon \) — parameters individual for each cloud.

The radius of the jet at each height was calculated by the formula:

\[ R_i = R_{i-1} \sqrt{\frac{w_{i-1}}{w_i} \exp \left( C \frac{h_i}{R_{i-1}} \right) \exp \left( 10^{-4} h_i \right)}, \]  
(2)

where \( w_{i-1}, w_i \) — vertical speed in the cloud at \( i-1 \) and \( i \) levels accordingly, \( C \) — constant of entrainment (\( C = 0.22 \)) [8].

The vertical wind speed distribution in a cloud with height is calculated based on the empirical formula:

\[ w = w_0 + \alpha \cdot z^2 \cdot (z - h_i) \]  
(3)

where \( \alpha = 10^{-10} \text{ m}^2 \text{ c}^{-1} \) [8], \( z \) — cloud height (\( z = 10 \) km), \( w_0 \) — vertical speed at freezing level height (\( w_0 = 4 \) m/s).

The size and concentration of hailstones in a cumulonimbus cloud depend on the vertical and horizontal distribution of liquid water content in cloud.

An ice particle rises upward in ascending air. To calculate its size the following equation was used:

\[ r_{i,\text{ice}} = r_{i-1,\text{ice}} + \frac{dr_{i,\text{ice}}}{d\tau} \cdot \Delta \tau, \]  
(4)

where \( r_{i-1}, r_i \) — ice particle radius in a cloud in meters at \( i-1 \) and \( i \) levels respectively, \( \frac{dr_{i,\text{ice}}}{d\tau} \) — particle growth rate, \( \Delta \tau \) — time interval, s.

Since the largest cloud particles become hail nuclei their growth occurs mainly due to coagulation. The coagulation growth rate was calculated by the formula:

\[ \left( \frac{dr_{i,\text{ice}}}{d\tau} \right)_{\text{coag}} = \frac{\mathcal{E}_{\text{ice}} \cdot q_z}{4 \cdot \rho_{\text{ice}}} \cdot V_{\text{ice}}, \]  
(5)

where \( \mathcal{E}_{\text{ice}} \) — capture coefficient, \( \rho_{\text{ice}} \) — ice density, \( V_{\text{ice}} \) — hail fall rate:

\[ V_{\text{a}} = 200 \sqrt{r_{\text{a}}}. \]

For calculating the capture coefficient the following relations were used:

\[ \mathcal{E}_{\text{ice}} = \begin{cases} 1 & \text{at } w > V_{\text{ice}} \\ \left( \frac{z - h_0}{h - h_0} \right)^{\frac{1}{2}} & \text{at } w < V_{\text{ice}} \end{cases}. \]  
(6)

The simulation of the water content evolution was carried out with the following initial data: the \( H_{IC} \) height was set in the range 5500-8000 m, \( h_0 = 2000 \) m, \( R = 4000 \) m, \( \beta = 0.0001 \), \( \varepsilon = 2 \), the cloud base height is 0.5 km, the cloud top height is 10 km.
As a result of the calculations two-dimensional arrays of water content distribution over the cloud cross-section were obtained - figure 1.

**Figure 1.** Distribution of water content greater than 0.008 kg/m³ over cloud cross-section.

A “nursery” of large droplets was identified [10] with water content greater than 0.008 kg/m³. Isolines are drawn through 0.005 kg/m³.

An increase in the intensive crystallization level from 5.5 km to 8 km contributes to the rise of the region with the highest water content in the center of the cloud by more than 1 km, the shape of the «nursery» becomes more round, and its volume will increase by 33%.

An increase in the $H_{IC}$ level leads to an increase in the cloud water content, a significant increase in the coagulation rate of droplets and consequently to the hydrometeors growth. The radius growth with increasing $N_{IC}$ level is shown in figure 2.

**Figure 2.** Hydrometeor radius growth in the cloud jet center from the $H_{IC}$ level.

With an increase in $N_{IC}$ from 5.5 to 8 km the hydrometeor size in the cloud central part increased by more than 40%.

The time dependence required for a particle to rise from a certain level to its maximum value and descend to the freezing level on the height $N_{IC}$ is shown in figure 3. This dependence was able to be approximated by a logarithmic formula (shown in figure 3). When the $N_{IC}$ level is lowered the chances of the particle melting increase as the particle lifetime increases.
3. Conclusion
The rise of the $N_{IC}$ level leads to an increase in the volume of the area with the highest water content in the cloud center, its rise, and the approach of the shape of the «nursery» to the ball shape. An increase in $N_{IC}$ also leads to an increase in the hydrometeor radius in the cloud jet center and a decrease in its lifetime.

References
[1] Ashabokov B A et al 2013 Physics of hail clouds and their modification: state and development tendency (Nalchik: Print House) p 216
[2] Ashabokov B A, Fedchenko L M, Shapovalov A V and Shapovalov V A 2017 Physics of clouds and their modification (Nalchik: Pechatnyy dvor) p 239
[3] Koloskov B P, Korneev V P and Shchukin G G 2012 Methods and equipment of cloud, rain and fog modification (SPb: RSHU) p 342
[4] Malik S, Bano H, Rather R A and Ahmad S 2018 Cloud Seeding: its prospects and concerns in the modern world J. Pure App. Biosci. 6(5) 791-6
[5] Korneev V P, Shchukin G G, Kim N S, Koloskov B P, Nesmeyanov P A, Sergeev B N, Petrunin A M, Bychkov A A and Chastukhin A V 2019 Artificial regulation of precipitation and fog dispersal (Moscow: Zelenaya kniga) p 300
[6] Danelyan B, Kovalev N and Korneev D 2017 Clouds modification for the purpose of regulating of precipitation in Russia. Operational projects and scientific research The 10th Workshop Cloud Physics and Aerosol (Korea) p 245
[7] Garstang M, Bruintjes R and Serafin R 2005 Weather Modification Finding Common Ground. Bull. Amer. Meteor. Soc. 86 647–5
[8] Bekryaev VI Workshop on the course 1991 Physical foundations of weather modification (L.: Hydrometizdat) p 144
[9] Bekryaev V I 2007 Some questions of the clouds physics and their modification (SPb: RSHU) p 337
[10] Imyanitov I M, Chubarina E V and Schwartz Ya M 1971 Electricity of the clouds (L.: Hydrometekoizdat) p 93