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Numerical study dependence of cloud microphysics on ice crystal shapes and intensity of ice nucleation

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1. INTRODUCTION

Cloud and precipitation formation processes are subjects of experimental and theoretical studies in the UHRI in the past half-century. In the presented research the particular attention was devoted to ice crystals development in real thermodynamic conditions that can affect on cloud microphysics and precipitation. Particularly, study is concentrated on shapes of ice crystals approximated by spheres or plates and on intensity of ice nucleation processes.

2. A SHORT DESCRIPTION OF THE METHOD

So-called Combined Model of the Cloudy Troposphere (CMCT), which is a composition of the 3D mesoscale diagnostic LAM and 1D microphysical bin CRM, was used for the research. Only the essential details for a full understanding of the presented results and the principles of models' construction will be described. Reader is referred to Pirnach et al. (1994), Pirnach (1998) and Krakovskaia et al. (1998, 2000) for a detailed presentation of the methodology, sets of equations and numerics.

Thermodynamical state (vertical profiles of temperature, pressure, specific humidity of the air and three projections of wind speed) of the troposphere is obtained from the

3-D mesoscale stationary model. The simulated domain was 1200x800x6.75 km with variable horizontal spacings from 100 km near the edges of the domain to 12.5 km near the central point, vertical spacing was 50 m. The inputs for 3-D model were data of 26 sound ascendings of six stations in Ukraine.

In the 1D microphysical model the spectrum of liquid cloud drops is divided into two parts: cloud droplets (radii < 20 μm) and drops (radii > 20 μm). The spectrum of cloud droplets is the result of condensation, turbulent diffusion and dynamical motion. Additionally, the spectrum of drops is determined by the collection of droplets. The size distribution function of the ice particles is assumed to result from sublimation, riming, glaciation (heterogeneous freezing), turbulent diffusion and motion. Coefficients for droplet gravitational collection by drops and ice crystals are variable and depend on cloud particles (CP) radii. The kinetic equation of CP size distribution functions f_i (hereinafter, i= 1 is for water or droplets, i= 2 is for ice CP and$i$= 3 is for drops) is used in the following form:

$$\frac{df_i}{dt} + \frac{\partial}{\partial r_i}\left(R_i f_i\right) - v_i \frac{\partial f_i}{\partial Z} = I_{\alpha i} \pm I_{fi} - I_{ci} + \Delta f_i \quad , \tag{1}$$

$$I_{\alpha 2} = A_S \exp\left(B_S T_S\right) \frac{dT}{dt} \delta\left(r - r_{20}\right) \Theta\left(-\frac{dT}{dt}\right) \Theta\left(\Delta_2\right) \Theta\left(T_S\right), \tag{2}$$

$$v_i = 10^6 \rho_i \left(\frac{0.787}{r_i^2} + \sqrt{\frac{\rho_i}{r_i} 503}\right)^{-1}, \quad T_S = 273.15^\circ K - T, \tag{3}$$

where R_i are rates of CP's growths due to condensation (sublimation); v_i is the fall speed of CP; r_i and ρ_i are radii and densities of CP; $I_{\alpha i}$ describe generation of cloud condensation nuclei (CCN) and ice nuclei (IN); I_{fi} describe freezing of droplets;I_{ci} describe the coagulation processes; Δf_i describe turbulent transfer;T is the temperature of the air; A_S and B_S are the empirical constants (Bujkov et al., 1975); Θ(x) = 1 for $x > 0$ and $\Theta(x)$ = 0 for $x < 0$. Every of three CP populations in the model consisted of 41 bins.

Some assumptions were accepted in the simulations: 1) for $T < -40\,^o$C all droplets are frozen (presume by homogeneous freezing) and nucleation on CCN is absent; 2) for $T < -30\,^o$C all drops are frozen (presume by homogeneous or heterogeneous freezing), coagulation processes are stopped and intensity of ice nucleation is the same as for T = -30 ^{o}C (or T_S is constant and equal to 30 ^oK).

The initial vertical profiles of thermodynamic characteristics as inputs for 1D model were got from the diagnostic 3D model and move through the 3D domain. It means, that the vertical column, where cloud microphysics is calculated, moves along horizontal axes opposite to the front displacement at every time step (*dt* = 120 s) in 1-D model with variable speeds calculated as Z-averages of horizontal wind projections for the every point of the horizontal grid. One track through the cloud frontal system well-studied previously (Pirnach, 1998, Krakovskaia et al. 1994, 2004, Krakovskaia, 1995) was chosen for the numerical study. There were found updrafts exceeded 40 cm/s in the first two hours of cloud development caused significant ice (Δ_2) and water (Δ_1) supersaturations, maximums of ice (IC) and liquid water contents (LWC), and following maximums of precipitation. Maximum Δ_2 in the upper part of clouds indicates on seeder-zone where ice crystals are generated and grew intensively.

3. RESULTS AND DISCUSSION

As it was noted, numerical study microphysics of the real winter frontal cloud system was performed in two directions. The first part of the numerical experiments was devoted to investigation of cloud microphysics and precipitation formation processes in dependence of ice crystals' shape when it was approximated by spheres or plates. Note, that the rate of fall of spherical ice crystals v_2 was calculated from the modified equation of Krystanov – Schmidt as function of radii and densities of ice crystals (Eq.3). Plate ice crystals fell with the constant v_2= 30 cm/s in the simulations. Maximum of IC = 0.16 g/kg was found in the simulation with plate ice crystals. IC was just 0.05 g/kg in the run with spherical ice crystals. Opposite for ice precipitation rate (I) at the ground: maximum I= 0.17 mm/h was found in the run with spherical ice crystals from 2 to 4 hours of cloud's development, and in the run with plate ice crystals maximum of Iachieved just 0.05 mm/h and more late at t = 6.2 h. In summary, plate crystals stayed longer in the cloud due to less fall speed and had opportunity to grow in favorable conditions to achieve maximum of IC, but for the same reason (low fall speed) plate crystals stayed longer under the cloud in warm undersaturated air where they melted, evaporated and finally not reached the ground.

In the second part of the numerical study the empirical constant A_S from Eq.2 responsible for activation of ice nuclei in a cloud was varied. Usually, coefficient A_S is equal to 10^{-5}(g·s)$^{-1}$ (Bujkov et al., 1975, Pirnach et al., 1994, Krakovskaia et al., 1998). In the simulation with spherical ice crystals maximum sum of precipitation for 10 h of numerical run (S = 86 mm) was found at A_S = 1(g·s)$^{-1}$ and the value is much higher than in the unmodified run when S = 4.9 mm. Further rising of the coefficient resulted in higher concentrations but less average radii of ice crystals, IC and less precipitation totals, that demonstrated so-called effect of "overseeding" of clouds. Note, while maximum of IC increased from 0.05 to 5.0 g/kg, at the same time maximum of LWC decreased from 0.85 g/kg to 0.05 g/kg. It means that microphysical properties and phase state of the cloud in particular changed remarkably.

4. CONCLUSION

The conducted series of the numerical experiments on the study ice phase in the real mixed clouds demonstrate that:

- chosen numerical models and approach are suitable for the research and allow to obtain specific features of studied clouds, particularly, simulations confirm that studied cloud system was suitable for precipitation increasing as was suggested in field experiments;
- preferably to have both shapes in the CRM for approximation of ice crystals (spheres and plates) in order to have more natural mixed clouds since approximation by just one shape has some disadvantages;
- intensity of ice nucleation has a limit obviously defined by moisture reserve in a cloud after which effect of "overseeding" by IN is achieved;
- in a whole, increasing of activated IN can notably modify a cloud microphysics and precipitation formation processes;
- in what extend a cloud microphysics and precipitation formation processes will be affected, greatly depends on thermodynamics and the specific features of studied clouds.

5. REFERENCES

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