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Two-Dimensional Model of Convective cloud: Part II. Microphysics

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Abstract. **The work is a continuation of our time-dependent, two-dimensional modelling of a convective cloud and concerns some aspects of precipitation development in hailstorms.**

Six forms of water substance (water vapour, cloud water, cloud ice, rain, hail and snow) are considered.

1. Introduction

The present study is a continuation of the two-dimensional time-dependent model construction of convective clouds [18] and it deals with the microphysical processes in the cloud. Six classes of water substance are considered: water vapour, cloud droplets (cloud water), cloud crystals (cloud ice), raindrops (rain), hailstones (hail) and snow crystals (snow).

The work comprises two approaches of numerical modelling of internal cloud processes with detailed microphysics within the framework of one-dimensional stationary model [13, 14] and within the framework of one-dimensional time-dependent model [16, 17]. The compatibility of the obtained through these researches equations with "bulk water" microphysical parameterization technique is analyzed. The mathematical formulation for the accretional processes is based on the geometric sweep-out concept integrated over all sizes of the collectors: raindrops, hailstones and snow crystals.

A further development of cited works is the introduction of a new class particles - snow crystals and connected with them interactions. The melting of snow is included in the model.

2. Non-precipitating fields

The non-precipitating fields, which are water vapour, cloud water and cloud ice are treated as a single combined quantity in the conservation equations given by (15-17) [18]. Cloud droplets (cloud water) and cloud crystals (cloud ice) are with disparaging low speed of falling and they are quite lifted by the rising stream in the cloud. Obtained through our previous researches results of modelling of cloud droplets crystallization and the cloud medium transformation as a result of condensation and deposition are generalized. The compatibility of the obtained equations with parameterized schemes for autoconversion of cloud droplets [1] and for cloud crystals aggregation [6] is analyzed.

For calculation of the water vapour mixing ratio in the cloud $s = 0.622\ e/P$ a pseudosaturated vapour pressure is introduced:

$$e = \frac{e_w(S_{CW} + S_R) + e_i(S_{CI} + S_H + S_S)}{S}, \tag{1}$$

where e_w and e_i are the saturation vapour pressures with respect to liquid water and ice, respectively; S_{CW}, S_R, S_{CI}, S_H and S_S are the mixing ratios of cloud water, rain, cloud ice, hail and snow, respectively; while S is its total quantity. The values e_w and e_i are calculated by the theoretical formulae

$$e_w = e_0 \exp\left(\frac{M_v L_c}{kNT}\frac{T - T_0}{T}\right) e_i = e_0 \exp\left(\frac{M_v L_d}{kNT}\frac{T - T_0}{T}\right) \tag{2}$$

where e_0 is the saturation vapour pressure at temperature $T_0 = 273.15^{\circ}$K; M_v is the molecular weight of water vapour; L_c and L_d are the latent heat of condensation and latent heat of suplimation, respectively; k is Boltzmann constant; N is Avogadro number; T is the air temperature. The values L_c and L_d are calculated through results of our estimations by the empirical formulae

$$L_c = 597 - 0.647(T - T_0), \quad L_f = 80 - 0.647(T - T_0), \tag{3}$$

where L_f is the latent heat of fusion, and $L_d = L_c + L_f$

3. Cloud water

Supposing that in the field of integration exist sufficiently condensation nuclei upon which the saturated water vapours are deposited, the transfer of mass by the water vapour condensation on the cloud droplets P_{CWC} is calculated by the following formula

$$P_{CWC} = -\frac{M_v}{M_a P}\left(\frac{M_v L_c e_w}{kNT^2}\frac{\partial T}{\partial t} + \frac{M_a g e_w}{kNT_e} w\right), \tag{4}$$

where M_a is the molecular weight of air, P is the pressure, T_e is the temperature of the environment, w is the vertical velocity.

The autoconversion is a process of the cloud droplets transformation in rain droplets as a result of Brown's and electric coagulation and turbulent fluctuations of the water vapour supersaturation in the cloud. In the present study the mass transfer through this process P_{CWA} is calculated by the parameterized formula of [1]

$$P_{CWA} = \rho S_{CW}^2\left(\phi + \frac{\theta n_c}{D_0 \overline{\rho} S_{CW}}\right), \tag{5}$$

where $\overline{\rho}$ is the air density, the constants $\phi = 0.12$ kg cm^{-3} and $\theta = 1.59\times10^{-12}$ kg^{2}cm^{-3}, n_c is the number concentration of cloud droplets, D_0 is the dispersion of the droplet distribution.

4. Cloud ice

The cloud droplets radii do not exceed 50-60 μm. They begin to freeze with a probability bigger than 50% at temperatures lower than –33°C [5, 13], while the total crystallization of cloud water occurs at temperatures of about –40°C [10, 13]. The detailed modelling of cloud crystals advent in the last study helps for the parameterization of this process through the formula

$$P_{CWF} = \left(1 - \frac{T - 233.15}{10}\right)\frac{S_{CW} - S_{CI}}{\Delta t}\delta_2 \tag{6}$$

where P_{CWF} represents the mass transfer by the cloud droplets freezing, δ_2 is unity for $233.15\ K \le T \le 243.15\ K$ and vanishes otherwise, Δt is the time step.

In conformity with the requirements of the numerical solution stability described in the first part of our study, the time increment is calculated through the following scheme

$$(\Delta_{n+1}t)_{\max} = \left(\frac{\left|u_{ij}^n\right|}{\Delta x} + \frac{\left|w_{ij}^n\right|}{\Delta z}\right)^{-1}, \tag{7}$$

where $(\Delta_{n+1}t)_{\max}$ is the maximum time step, providing computational stability for the advective terms. For saving the computer's time it is useful to adopt an inferior limit of time step decreasing $\Delta_{n+1}t > 0.6(\Delta_{n+1}t)_{\max}$. The coefficient 0.6 provides stability for non-advective terms also [12].

A great number of equations [10, 11] for calculating the cloud crystals increase through deposition is known. Our results [13], obtained applying the theory of [5] are concluded for the aims of the present study, as follows:

$$P_{CID} = 4n_{ci}\overline{D}_{CI}(s - s_{ci})\left[s_{ci}\overline{\rho}\frac{L_d}{K_a T}\left(\frac{L_d}{R_v T} - 1\right) + \frac{1}{D_v}\right]^{-1}, \tag{8}$$

where P_{CID} represents the mass transfer by the deposition, n_{ci} is the crystals number, D_{CI} is its average diameter, s is the vapour mixing ratio, s_{ci} is the saturation mixing ratio for water vapour at surface of crystals, K_a is the thermal conductivity of air, R_v is the specific gas constant for water vapour, D_v is the coefficient of diffusion of water vapour in the air.

As our estimations show for the aggregation rate of ice crystals to form snow is applicable the parameterization idea proposed by [6] to simulate the collision-coalescence for cloud droplets. For the purpose of the established model this idea is used following [8]:

$$P_{CIA} = \alpha_1(S_{CI} - S_{CI0}), \tag{9}$$

where S_{CI0} is a threshold amount for aggregation to occur, while the coefficient

$$\alpha_1 = 10^{-3}\exp[0.025(T - T_0)] \tag{10}$$

expresses the temperature dependence.

5. Precipitation particles

In the present study three types of hydrometeors are examined: rain drops, hailstones and snow crystals. Raindrops (rain), hailstones (hail) and snow crystals (snow) have appreciable terminal fall velocity. The following simplifications are adapted:

1. The spectra of the particles are described by the Marshall-Palmer distribution

$$\begin{aligned} n_R(D_R) &= n_R^0\exp(-\lambda_R D_R), \\ n_H(D_H) &= n_H^0\exp(-\lambda_H D_H), \\ n_S(D_S) &= n_S^0\exp(-\lambda_S D_S), \end{aligned} \tag{11}$$

where the indices R, H, S are related to the rain drops, hailstones and snow crystals; the parameters $n_R^0 = 8\times10^{-2}$ cm^{-4} [9], $n_H^0 = 4\times10^{-4}$ cm^{-4} [3], $n_S^0 = 3\times10^{-2}$ cm^{-4} [4], characterize the particle's number per unit diameter; λ_R, λ_H, λ_S are the slope parameters given by

$$\lambda_R = \left(\frac{\pi\rho_w n_R^0}{\overline{\rho}S_R}\right)^{1/4}, \quad \lambda_H = \left(\frac{\pi\rho_h n_H^0}{\overline{\rho}S_H}\right)^{1/4}, \quad \lambda_S = \left(\frac{\pi\rho_s n_S^0}{\overline{\rho}S_S}\right)^{1/4} \tag{12}$$

where ρ_w, ρ_h ρ_s are the density of the water, the hailstones, and the snow crystals, respectively, while D_R, D_H, D_S are its diameters.

2. Terminal velocity for rain droplets v_r is described by the theoretical formula of [7]

$$v_D(D)=\left(\frac{4g\rho_w}{3C_D\rho}D\right)^{1/2}, \tag{13}$$

which is deduced assuming that the drag coefficient C_D = const. This stipulation is valid for a large range of the Reynolds number - from 10^3 to 2×10^5. The author's assumption $C = 0.6$ is used in our work.

Our estimations show that using this formula one can calculate with satisfying exactness the terminal velocity of the hailstones after replacing their density respectively by the water density.

For the terminal velocity of the snow crystals the expression (13) is transformed as follows

$$v_D(D)=aD^b\left(\frac{\rho_0}{\rho}\right)^{1/2}, \tag{14}$$

where a and b are empirical parameters, ρ_0 is the surface air density.

3. The mass-weighted mean terminal velocity of the hydrometeors is expressed as

$$\bar{v}_D=\int vD\frac{S(D)}{S'}dD, \tag{15}$$

where $S(D)$ is the mixing ratio of the rain drops, of the hailstones or of the snow crystals with diameter D, S' is the total mixing ratio of the studied type of these hydrometeors.

The described simplified hypotheses help to define the accretion between cloud particles through the relation

$$P=\int ES(D)v(D)\frac{\pi D^2}{4}n(D)dD, \tag{16}$$

where E is the collection efficiency between interactive particles. The solution of the integral (16) is characterized through the examination of the respective class of hydrometeors.

Even described so by analogous structural formulae, the processes of accretion in the modelled convective cloud can be distinguished considerably by the results of the phase cloud transformation. For example, the coagulation of rain and cloud droplets is a two-component process - the mixing ratio of droplets decreases, while the mixing ratio of rain respectively increases. The accretion of rain and cloud crystals, however, is a three-component process. The new obtained crystals, depending on its density, can be hailstones or snow crystals. In the present study this new phase is separated through the criterion value of the mixing ratio of rain S_R. If $S_R < 0.1$ g/kg we will consider that the new obtained crystals stay with respective low density and form a snow. Otherwise, from the accretion of the rain and cloud crystals hailstones are formed.

6. Production term for rainwater

Resulting of the cloud droplets autoconversion, the rain drops participate in the cloud wet transformation with intensity, which depends on the phase state of the cloud. Because of the relatively large sizes of the rain drops, its role of the condensation processes decreases, but the importance of the accretion with different particles increases. The probability of its crystallisation increases also.

If we consider that the collection efficiency of rain for cloud water E_{RW} = const, after transforming the subintegral function from (16) in keeping with (11)-(13) and (15), the solution is

$$P_{RAW} = \frac{\pi}{4} \frac{\Gamma(3.5) E_{RW} n_R^0 S_{CW}}{\lambda_R^{3.5}} \left(\frac{4 g \rho_w}{3 C_D \bar{\rho}} \right)^{1/2} \qquad (17)$$

where P_{RAW} is production rate for accretion of cloud water by rain. The result of this process is an increase of the rain mixing ratio and respective decrease of the cloud water mixing ratio.

We enlarge the simplified assumptions for the rain drops as a collector of cloud water and for accretion of cloud crystals by rain. Thus, this process can be calculated by an analogous manner:

$$P_{RAI} = \frac{\pi}{4} \frac{\Gamma(3.5) E_{RI} n_R^0 S_{CI}}{\lambda_R^{3.5}} \left(\frac{4 g \rho_w}{3 C_D \bar{\rho}} \right)^{1/2} \qquad (18)$$

where P_{RAI} is the production rate for accretion of cloud ice by rain, E_{RI} = const is the collection efficiency of rain for cloud ice. This production term is separated within the hail or the snow depending on the rain mixing ratio S_R as it was defined in the general assumption concerning the precipitation particles in the model.

For modelling the rain drops freezing, the compatibility of the developed scheme [13, 15] based on the homogeneous theory with the parameterized scheme obtained in [19] after laboratory examinations [2] is analyzed. The comparative analysis shows that the parameterized scheme is suitable also for our model. This scheme can be expressed as

$$P_{RF} = 20\pi^2 B_1 n_R^0 \lambda_R^{-7} \left(\frac{\rho_w}{\bar{\rho}} \right) \left\{ \exp\left[A_1 (T_0 - T) \right] - 1 \right\}, \qquad (19)$$

where P_{RF} is production rate for freezing of rain, A_1 and B_1 are constants in Bigg's freezing.

7. Production term for hail

In the present study the hailstones have to be considered as spherical particles with relatively high density between 0.8 and 0.9 g cm^{-3}. By definition hailstones have above 5 mm of diameter, but for the present the graupel which are with smaller sizes are added to the group of these particles. For calculating the terminal velocity of the hailstones according to our evaluations, the formula (13) is applicable after replacing the water density by ice density.

The hailstones appear in the modelled cloud as a result of some processes: freezing of raindrops, accretion of cloud ice and snow crystals by rain, autoconversion of snow. When the cloud wet transforms, the hail does not exerts an important influence on the water vapour redistribution in the cloud, but the process of accretion by hailstones is intensified. The result is an increase of the mixing ratio of the hail and a decrease of the mixing ratio of the respective substance joining in the process. At determined conditions, this process can lead to third component appearance. This depends on the regime of the hailstones growth. Under the so-called "dry" regime the particles freeze instantly on the hailstone surface. When the regime is "wet" the hailstones grow under the water layer. This water layer can be decomposed and relatively big droplets are formed, causing the mixing ratio of rain increase in the cloud. Our study refers to the first regime.

Assuming that the collection efficiency of hailstones for cloud water E_{HW} and for cloud ice E_{HI} are constants, after the transformation of the subintegral function from (16) according to (11)-(13) and (15), the production rates for accretion of cloud water and cloud ice by hail are:

$$P_{HAW} = \frac{\pi}{4}\frac{\Gamma(3.5)E_{HW}n_H^0 S_{CW}}{\lambda_H^{3.5}}\left(\frac{4g\rho_h}{3C_D\bar{\rho}}\right)^{1/2}, \qquad (20)$$

$$P_{HAI} = \frac{\pi}{4}\frac{\Gamma(3.5)E_{HI}n_H^0 S_{CI}}{\lambda_H^{3.5}}\left(\frac{4g\rho_h}{3C_D\bar{\rho}}\right)^{1/2}, \qquad (21)$$

where P_{HAW} is the production rate for accretion of cloud water by hailstones, P_{HAI} is the production rate for accretion of cloud ice by hail.

The accretion of cloud water and cloud ice by hailstones is considered as a two-component process. The result is an increase of the mixing ratio of hail and a decrease of the mixing ratios of the cloud water and cloud ice, respectively.

For the accretion of rain by hail we have to write (16) as

$$P_{HAR} = \int E_{HR}\frac{\pi(D_H + D_R)^2}{4}|v_H - v_R|\frac{\pi D_R^3}{6}n_H(D_H)dD_H n_R(D_R)dD_R, \qquad (22)$$

where P_{HAR} is the production rate for accretion of raindrops by hailstones, $E_{HR} = const$ is the collection efficiency of hail for rain. The absolute value in (22) complicates the solution. This difficulty is surmounted assuming that the module can be moved before the integral. This means that the hailstones and raindrops fall with a terminal velocity equal to the respective mass-weighted velocity. The obtained formula is

$$P_{HAR} = \pi^2 E_{HR} n_H^0 n_R^0 |\bar{v}_H - \bar{v}_R| \left(\frac{5}{\lambda_H \lambda_R^6} + \frac{2}{\lambda_H^2 \lambda_R^5} + \frac{0.5}{\lambda_H^3 \lambda_R^4} \right), \tag{23}$$

where $\bar{v}_H$ and $\bar{v}_R$ are the mass-weighted mean terminal velocities of the hailstones and raindrops, respectively. According to R.D. Farley's evaluations (personal communication) of hail accreting rain using discrete size intervals for rain, the substitution of the coefficients-numerators in the last two terms (2 and 0.5) respectively by 1.33 and 0.22 is more suitable for the "bulk water" form.

8. Production term for snow

In the present study the term "snow crystals" is equivalent for a great number of particles. Here they are not differentiated by form, while in the formulae its "mean" diameter takes part. Its density can vary in wide limits between 0.1 and 0.8 g cm^{-3} [10].

The snow crystals appear in the modelled cloud as a result of cloud crystals aggregation and accretion of cloud crystals by rain. The last process forms snow when the mixing ratio of rain S_R < 0.1 g/kg.

At the water vapour deposition of ice particles, the principal difficulty is modelling of the ventilation effect because of the complicated geometry of the particles. The analysis of this problem studying [11] proves that this problem is surmountable through analogy with the diffusion flow to water droplets application and by the average ventilation coefficient introduction. In that case the calculation of the water vapour supersaturation in the cloud medium is determinant. According to our results form the studying of this characteristic [13] for the aims of the present model the formula of [8] is suitable

$$P_{SDP} = \frac{2\pi(\varepsilon - 1)}{\bar{\rho}(A_2 + B_2)} n_S^0 \left[0.78\lambda_S^{-2} + 0.31 S_c^{1/3} \Gamma\left(\frac{b+5}{2}\right) a^{1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{1/4} \nu^{-1/2} \lambda_S^{-(b+5)/2} \right] \tag{24}$$

where P_{SDP} represents depositional growth of sublimation of snow, ε is supersaturation of water vapour, S_c is Schmidt number, ν is kinematic viscosity of air, while

$$A_2 = \frac{L_d^2}{K_a R_v T^2}, \quad B_2 = \frac{1}{\bar{\rho} s_{ci} D_v}. \tag{25}$$

When water vapour supersaturation is absent, i.e., ε < 1, by formula (23) the sublimation (a negative contribution) can be calculated.

In the present study the established evaluations show that the parameterization scheme for snow crystals aggregation can follow the form used to express the aggregation of cloud ice. By analogy with (9) one can write

$$P_{SAU} = \alpha_2 (S_S - S_{S0}), \tag{26}$$

where P_{SAU} is the production rate for aggregation of snow to form hail, S_{S0} is a mass threshold for snow. The rate coefficient

$$\alpha_2 = 10^{-3}\exp[0.09(T - T_0)], \tag{27}$$

here is an indicator of the snow crystals transformation in graupel or hailstones [8].

The accretion of cloud droplets and crystals by snow is considered for the present time as a two-component process. Resulting of that is the mixing ratio of snow increase and the mixing ratios of cloud water and cloud ice respectively decrease. According to our general assumptions for the accretional processes simulation, after (11), (12), (14)-(16) and respective transformations we obtain

$$P_{SAW} = \frac{\pi}{4}\frac{\Gamma(3.5)E_{SW}an_S^0S_{CW}}{\lambda_S^{3+b}}\left(\frac{\rho_0}{\rho}\right)^{1/2} \tag{28}$$

$$P_{SAI} = \frac{\pi}{4}\frac{\Gamma(3.5)E_{SI}an_S^0S_{CI}}{\lambda_S^{3+b}}\left(\frac{\rho_0}{\rho}\right)^{1/2} \tag{29}$$

where P_{SAW} P_{SAI} are production rates for accretion of cloud water by snow and for accretion of cloud ice by snow, respectively, while the collection efficiency of snow crystals for cloud water E_{SW} and for cloud ice E_{SI} are constants. The development of this scheme will concern the temperature dependence of collection efficiency which may lead to the appearance of third substance - graupel or hail.

The accretion of rain drops by snow crystals in the present work is modelled after the physical assumption that all snow crystals fall with terminal velocity equal to its mass-weighted mean terminal velocity. Concerning the rain drops this simplification is enlarged by the conclusion of (22). Hence for the production rate for accretion of rain by snow one obtains:

$$P_{SAR} = \pi^2 E_{SR} n_S^0 n_R^0 |\bar{v}_S - \bar{v}_R| \left(\frac{5}{\lambda S \lambda_R^6} + \frac{1.33}{\lambda_S^2\lambda_R^5} + \frac{0.22}{\lambda_S^3\lambda_R^4}\right) \tag{30}$$

where $\bar{v}_S$ is mass-weighted mean terminal velocity of the snow.

In the temperature region $T < T_0$, if $S_R > 0.1$ g/kg or $S_S > 0.1$ g/kg, the process is assumed to be three-component and hailstones occur in the modelled cloud. If the mass threshold criteria are not met, i.e., if S_R and S_S are less than 0.1 g/kg, the process is a two-component.

The snow crystals begin to melt at temperature $T > T_0$. Three general processes are simulated: air and snow crystal heat exchange; heat exchange with the captured by the crystal cloud droplets; heat exchange with captured rain drops.

At the first process studying the heat transportation over the water layer on the crystal is neglected. Thus, if we consider dhat the temperature of its surface remains equal to the temperature of ice melting T_0, for the heat flux Φ_1 between the snow crystal with diameter D_S and the air we can write

$$\Phi_1 = 2\pi D_S K_a C_v (T - T_0), \tag{31}$$

where C_v is the ventilation coefficient fo heat, which is a function of Reynolds number R_e [10]:

$$C_v = 1.6 + 0.3\mathrm{Re}^{1/2}. \tag{32}$$

The heat flux Φ_2 at the second process, accretion of cloud droplets by snow crystals, we introduce as

$$\Phi_2 = c_w (T - T_0) \bar{\rho} \bar{v}_S \frac{\pi D_S^2}{4} E_{SMW} S_{CW}, \tag{33}$$

where c_w is the specific heat of water, E_{SMW} is the collection efficiency of melting snow crystal for cloud droplets.

For the third heat flux Φ_3, result from accretion of rain drops by snow crystals, basing on the general assumptions for the accretional processes, we can write

$$\Phi_3 = c_w (T - T_0) \int E_{SMW} \frac{\pi}{4} (D_S + D_R)^2 \left| \bar{v}_S - \bar{v}_R \right| \frac{\pi}{6} D_R^3 \rho n_R^0 dD_R, \tag{34}$$

where E_{SMR} is the collection efficiency of melting snow crystal for rain drops.

The total heat flux to the melting snow crystal is

$$\Phi_1 + \Phi_2 + \Phi_3 = L_f \frac{dm_s}{d_t}, \tag{35}$$

where m_s is the mass of the melting snow crystal of diameter D_S. Then the production term of snow melting

$$P_{SM} = \int \frac{1}{\bar{\rho}} \frac{dm_s}{dt} n_S dD_S. \tag{36}$$

Integrating for all sizes of snow crystals and assuming that collection efficiency $E_{SMW} = const$ and $E_{SMR} = const$, accounting to (28), (30) and (34), for the mass transportation due to snow melting, we get

$$P_{SM} = -\frac{2\pi}{\rho L_f} K_a (T - T_0) n_S^0 \left[\frac{1.6}{\lambda_S^2} + \frac{0.3\Gamma\left(\frac{b+5}{2}\right) a^{1/2}}{\lambda_S^{-\left(\frac{b+5}{2}\right)} \nu^{1/2}} \left(\frac{\rho}{\bar{\rho}} \right)^{1/4} \right] - \frac{c_m}{L_f} (T - T_0)(P_{SAW} + P_{SAR}) \tag{37}$$

Some of the principal equations represented in this work are tested by a one-dimensional time-dependent model of convective cloud [16, 17]. The implemented analysis shows that these equations with satisfying exactness describe the inside cloud characteristics. A verification is forthcoming concerning the new constructed two-dimensional time-dependent model possibilities of real situations simulating with cloud convection development.

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Двумерен нестационарен модел на конвективни облаци Част II: Микрофизика

С. Стоянов, М. Тодоров, Хр. Христов

Р е з ю м е

В работата е представена втората част на конструирания двумерен нестационарен модел на конвективни облаци – облачната микрофизика. Изследването обединява два по-рано разработени подхода към численото моделиране на вътрешнооблачни процеси: с детайлизирана микрофизика, изпълнена в рамките на няколко стационарни задачи (едномерна, двумерна и тримерна) и с параметризирана микрофизика, изпълнена в рамките на едномерен нестационарен модел на облачна конвекция.

Моделирани са процесите на отлагане на водни пари върху облачните капчици и кристалчета, сублимацията на ледените частици, коагулацията между дефинираните шест класа водни субстанции, топенето на снежните кристали.