Bulgarian Geophysical Journal, 2006, Vol. 32
Geophysical Institute, Bulgarian Academy of Sciences

THE IMPACT OF ICE CRYSTAL NUCLEATION MECHANISM ON CLOUD MICROPHYSICS AND DYNAMICS – NUMERICAL STUDY

S. *Petrova* [1], *R. Mitzeva*[2]

[1]Sofia University, Faculty of Physics, Department of Meteorology and Geophysics, 5 James Boucher Blvd., 1164 Sofia, Bulgaria, e-mail: asavita@phys.uni-sofia.bg
[2]Sofia University, Faculty of Physics, Department of Meteorology and Geophysics, 5 James Boucher Blvd., 1164 Sofia, Bulgaria, e-mail: rumypm@phys.uni-sofia.bg

Abstract. Numerical simulations are carried out to investigate the effect of ice crystals formation mechanism on the dynamics and microphysics of mixed-phase convective clouds. Three different in power convective clouds are simulated by 1-D numerical model with bulk-water microphysical parameterization. Two types of parameterizations of ice crystals formation are used: primary nucleation given by Fletcher approximation and Hallet-Mossop mechanism (secondary nucleation) parameterized by constant enhancement factor in specific temperature band. The results reveal that precipitation starts earlier and at lower levels in the three simulated clouds when secondary nucleation is taken into account in comparison with the case when only primary (Fletcher) nucleation is used. However, the simulations indicate that the impact of ice nucleation (primary and secondary) depends on the power of the simulated cloud: there is an increase in the precipitation of most powerful cloud and decrease in the other two clouds when the secondary nucleation is included.

Key words: ice crystals formation mechanism, numerical cloud models

1. Introducrion

It is known that ice crystals usually form as a result of activation of ice nuclei (Prupacher and Klett, 1997, Rogers and Yau, 1989). The number of activated ice nuclei is usually described as a function of supercooling given by Fletcher,1962. This process is known as primary ice nucleation. However the field measurements show that the ice crystal concentration varies from cloud to cloud and that the concentrations of ice particles in natural clouds are sometimes much greater than the concentrations of ice nuclei; often 10^4 times more numerous (Hobbs, 1969). Hence, primary nucleation of ice, as described in Fletcher (1962) cannot be the only ice production process in operation in clouds to account for the large number of ice particles present at relatively high temperatures. A powerful mechanism or perhaps mechanisms must be responsible for such large and rapid multiplication of ice crystals, observed in clouds (Hobs, 1969)

The Hallet-Mossop process is generally accepted as a contribution factor to ice multiplication (Prupacher and Klett, 1997). In its simplest form, Hallet-Mossop process is an ice-particle production process which occurs in clouds under very specific conditions when graupel pellets are growing by accretion of supercooled water droplets which freeze onto their surface by impact. This process can drastically change the mass of ice crystals, because the ice particles created by Hallet-Mossop mechanism can be produced in significant quantities at temperatures where primary nucleation is inefficient. It is expected that the change of ice crystal concentration can affect the cloud microphysics and dynamics, which in turns may affect precipitation on the ground.

The aim of the present study is to evaluate the impact of ice crystals nucleation mechanisms on microphysical and dynamical properties of convective clouds. One-dimensional cloud model with parameterization of microphysical processes is used for the study.

Similar studies have been carried out in the past - for example Katherine et al., (2001), Baker et al.,(1995), Blyth and Lathanm (1995). However, in Katherine et al., (2001), the formation of graupel is parameterized very roughly by artificial injection at particular temperature and the calculations in Baker et al, (1994) are with constant updraft velocity. That is why the above mentioned studies are not appropriate for the investigation of the impact of ice crystals concentration on cloud dynamics and they were directed to the investigation of the impact of ice crystal formation on the electrification of the cloud.

Brief description of the model (Mitzeva et al., 2003) used for numerical simulations of clouds is given in section 2. The used parameterizations of ice crystals formation are presented in section 3. Numerical simulations and results are discussed in section 4.

2. Model description

Convective clouds are assumed to be composed of active and non-active cloud masses (Andreev et al, 1979). The active mass is modeled by successive ascending spherical thermals, while the non-active cloud region is formed by thermals that have previously risen and stopped at the level of zero velocity.. This multi-thermal concept simulates the time dependence of the microphysical and thermodynamic characteristics of cumulus development and has been used in model studies by Mason and Jonas, (1974), Blyth and Latham, (1997) and others. One can speculate that the ascending thermals represent the updraft region of convective clouds, while non-active masses represent the environment surrounding the updrafts.

The thermals are driven by the buoyancy force reduced by entrainment and the weight of the hydrometeors present. They entrain air from a cloud-free environment or from a non-active cloud region depending on their position at a particular moment. The entrainment is parameterized as in Mason and Jonas (1974), with the entrainment rate α inversely proportional to the radius of the ascending thermals: $\alpha = 0.6 / R(z)$, where $R(z) = R_0 + 0.2z$ is the thermal radius at height z above cloud base and R_0 is the thermal radius at cloud base.

Parameterization of the merging of thermals during their ascent is included in the model. As the thermals ascend, their temperature changes due to cooling by expansion of the air, entrainment of environmental air and the release of latent heat. The model uses bulk microphysical parameterizations with five classes of water substance - water vapor, cloud water S_c, rain S_p, cloud ice S_{cf}, and precipitating ice (graupel) S_{pf}. The cloud droplets and ice crystals are assumed to be monodisperse and to have negligible fall velocities and so move upward with the air in the ascending thermals. A Marshall-Palmer (1949) type size distribution is assumed for raindrops and graupel.

In the model cloud droplets are formed by condensation. Rain drops form by autoconversion of the cloud droplets (Kessler, 1969) and grow by collision and coalescence with cloud drops. At temperatures below 0^oC, ice crystals originate by heterogeneous freezing at the expense of cloud droplets and grow by deposition of water vapor. Homogeneous freezing occurs below -40^oC. Precipitating ice (graupel) forms by freezing of rain drops (Bigg, 1953), contact nucleation of ice crystals and rain drops (Cotton, 1972) and conversion of ice crystals (Hsie et al., 1980). Ice crystals grow by deposition of water vapor; graupel grows by coalescence with cloud and rain drops. Precipitation fallout is calculated in the same manner as in Cotton, (1972), and comprises the portion of the rain drops and graupel having terminal velocities greater than the updraft speed. Evaporation of rain drops and melting of graupel during their descent (Farley and Orville, 1986) as well as recycling of precipitating particles are included in the model. The model takes into account the changes of the mass of drops and crystals due to the entrainment of environmental air and by the incorporation of the mass of rain drops and graupel falling out from the upper ascending successive thermals.

The differential equations, describing the dynamical and microphysical processes in the ascending thermals are integrated numerically by the Runge-Kutta method. The calculations are carried out for thermals ascending from cloud base to the height of zero velocity. The numerical integration of the equations, describing the changes with time of the characteristics of the non-active cloud region, begins after one of the ascending thermals stops. The calculated temperature, vapor mixing ratio, cloud liquid and ice mixing ratio of the diffusing thermals, are used in the estimation of the environmental conditions of the successive ascending thermals. The mass of raindrops and graupel falling out from ascending thermals are calculated at each integration step. The terminal fall speed depends on the mass-median diameter, which changes because of melting and evaporation.

3. Parameterizations of ice crystal formation

3.1 Primary nucleation

The most popular and simplest parameterization of primary nucleation of ice crystals used in several numerical models (see for example Rogers and Yau, 1989 and Young, 1993) is based on the assumption that the concentration of ice crystals is equal to the number of activated ice nuclei N_i as a function of supercooling given by Fletcher

(1962). It is assumed that ice crystals are formed at the expense of cloud droplets and their concentration N_i increase exponentially as the temperature falls:

$$N_i(T) = A\exp[\beta \Delta T] \tag{1}$$

where N_i is the number of ice crystals per m^{-3} and ΔT = T-273.15 is the suppercooling, T is temperature in K, and A and β are parameters, with vales $0.01m^{-3}$ and $0.6(K)^{-1}$ respectively. In our study we assume as in Katherine et al., (2001) that at temperatures lower than -25°C the number of ice crystals is constant based on some field measurements (e.g., Hobbs, 1969)

3.2. Secondary nucleation - Hallet-Mossop process

The parameterization is based on the laboratory experiments of Hallett and Mossop (1974), in which it was discovered that within a restricted temperature band (-3 °C to -8 °C) the freezing of supercooled water droplets accreted onto the surfaces of growing graupel or hail particles may be accompanied by the ejection of splinters. Hallet and Mossop (1974) and Mossop (1976) demonstrate that the process depends on several factors, such as the drop size distribution, the liquid water content, the velocity of the drops impacting on a riming ice particle, the air temperature, and the surface temperature of ice particles. Later, study by Heymsfield and Mossop (1984) established that the temperature of riming ice particle surface, rather than the air temperature is more important for the splinter formation mechanism. Some other experiments reveal that the multiplication of ice crystals is observed at colder temperatures when the relatively large drops freeze on graupel surface.

This mechanism of secondary particle production, sometimes called rime-splintering, may account for high concentrations of ice crystals that are sometimes observed in maritime cumulus clouds with temperatures no colder than -10°C (Rogers and Yau, 1989).

Based on the above observations, the Hallet-Mossop process in our study is presented in a way similar to Katherine (1997) by introducing multiplication factor $N_{HM} > 1$ in the eq.1 within the temperature band (-3°C to -11°C). In contrast to Baker at el (1995), who assumed that when the ice crystals are formed as a result of Hallet-Mossop mechanism the values of N_i are constant at lower temperature , we assume that N_i is calculated by eq.1 at $T<-11^o$ C. Thus, when Hallet-Mossop type nucleation operates together with primary nucleation the values of ice crystals concentration N_i in our model is parameterized by

$$N_i(T) = A\exp[\beta \mathit{\Delta} T] N_{HM} \tag{2}$$

where N_{HM} is a fixed multiplication factor. In our calculations we used N_{HM} = 100 and N_{HM} =1000 in temperature band (-3°C to -11°C), and N_{HM} = 1 at temperature outside this temperature interval.

The temperature dependence of ice crystals nucleating as a result of both ice formation mechanisms is presented on Fig.1.

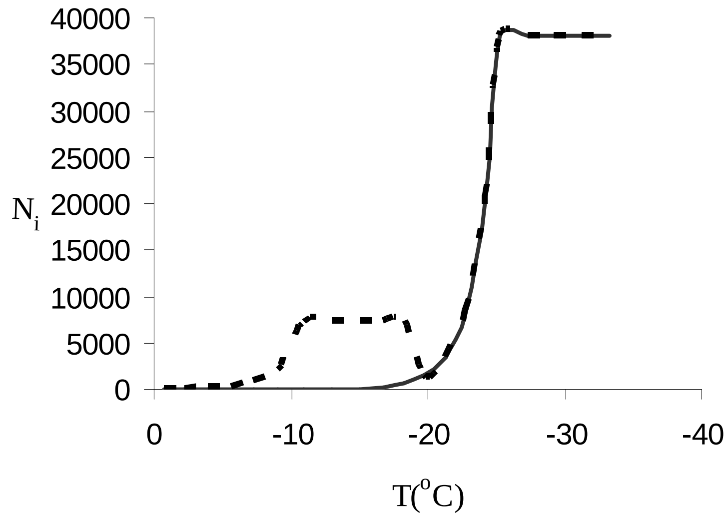

Fig. 1. The number of ice crystals Ni as a function of in-cloud temperatures using only primary (bold line) and primary together with Hallet-Mossop (dashed line) nucleation mechanism.

Numerical simulation and results

Three cloud cases observed at Gelemenovo, Bulgaria (5 July 1975, 8 June 1976 and 7 May 1979) are simulated using sounding of temperature and humidity observed on these days. Liquid precipitation from these clouds was detected on the ground. These cloud cases are chosen to be simulated because the measurements showed that they differ in radar cloud top height or by the rainfall on the ground. Thus, it is expected that the impact of crystal formation mechanism will be different for different clouds.

The values of the parameters necessary for the numerical simulations by the model (Table 1) are taken in the range of real values in such a way that the cloud top height of the model cloud to be close to the observed cloud top height.

Table 1. The values of the parameters used in the numerical simulations. Thermal radius and updraught velocity at cloud base - R_o and W, time interval between the ascending thermals - dt, number of ascending thermal - N, turbulent diffusion coefficient in the non-active cloud mass – K. Cloud base above the ground – Ho.

	5 July 1975	8 June 1976	7 May 1979
H_o (km)	1.2	2	2
R_o (km)	1	2	1
W (m/s)	2	1	1
dt (min)	5	3	3
N	4	5	5
K (m^2/s)	30	200	30

The simulations are carried out using two types of ice crystal formations: only primary nucleation (Fletcher parameterization) and secondary nucleation (Hallet–Mossop parameterization) together with the primary.

Figures 2,3 and 4 show the mass of ice crystals S_{cf}, mass of precipitating drops S_p, mass of graupel S_{pf} , updraft velocity W, mass of falling out of the thermal precipitating drops S_r and graupel S_{rf}, respectively for 5 July 1975, 7 May 1979cloud and 8 June 1976 cloud. The impact of the secondary nucleation is well pronounced in the all threee simulated cases. Taking into account the secondary nucleation (Hallet- Mossop) we find that the mass of ice crystals S_{cf} increases and the ice crystal formation begins at lower levels in the early stage of cloud development. The coalescence of more numerous ice crystals (at secondary nucleation) with rain drops S_p leads to a decrease of the mass of rain drops and an increase of the mass of graupel S_{pf}. As a results of the release of additional latent heat of freezing in the process of formation of more solid particles (S_{cf} and S_{pf}) due to Hallet-Mossop mechanizm there is a change of cloud dynamics. Fig.6 and Fig.7 show that when the secondary nucleation is included in the model there is a positive dynamical effect for the simulated 8 June 1976 cloud case – an increase of the cloud top height (Z_{top}) and of the maximum updraft velocity (W_{max}). For the other two simulated cloud cases (5 July 1975 and 7 May 1979) the maximum updraught velocity and the cloud top height do not differ significantly for the two parameterizations. One can explain this result by the smaller quantity of latent heat of freezing released in these clouds due to the smaller mass of ice crystals and graupel.

Considering the impact of ice nucleation process on the precipitation, one should take into account that the model simulations are carried out from the cloud base height to the height of zero updraft velocity, i.e. the model does not give information about precipitation at the ground. That is why, in our study the impact of ice crystals concentration on the precipitation is evaluated indirectly and is based on the analyses of the amounts of liquid and solid fallout from the ascending thermals. We assume that there will be a positive correlation between these amounts and those reaching the ground. Of course, part (probably all) of the solid fallout may melt during descent to the ground.

In Fig.5 one can see that when the secondary nucleation is taken into account there is a decrease in the total precipitation fallout in two of the simulated cloud cases (5 July 1975 and 7 May1979), while there is an increase in the total fallout in the simulated 8 June 1976 cloud case This can be explained by the fact that in the 8 June 1976 cloud the solid fallout S_{rf} due to Hallet-Mossop mechanism increases (Fig.4.) because graupel S_{pf} stays longer and falls out from higher levels (Fig.4.) due to the significant increase of updraft velocity W in the 3-th thermal (Fig.4)

Another effect of the secondary nucleation is that solid fallout starts earlier and at lower levels in all simulated clouds, because formation of ice crystals S_{cf} and graupel S_{pf} begins at lower levels in the early stage of cloud development (Fig.2, Fig.3, Fig.4).

Conclution

The main results from our study are:

1. The impact of ice nucleation (primary and secondary) depends on the power of the simulated cloud: when the secondary nucleation is included there is an increase of the precipitation in the most powerful cloud (8 June 1976) and a decrease in the other two cloud cases (5 July 1975 and 7 May1979).

2. In the three simulated cloud cases the precipitation starts earlier and at lower levels when secondary nucleation is included, in comparison with the precipitation when only the primary (Fletcher) nucleation is taken into account.

3. In all simulated cloud cases the maximum updraught velocity and the cloud top height do not differ significantly at the two different parameterizations. Only for the simulated 8 June 1976 cloud case there is a significant increase of the updraft velocity and of the cloud top height in the early stage of cloud development when Hallet-Mossop parametrisation is included.

Acknowledgements. This work was supported by the Science Foundation of Sofia University (grant 64/2006).

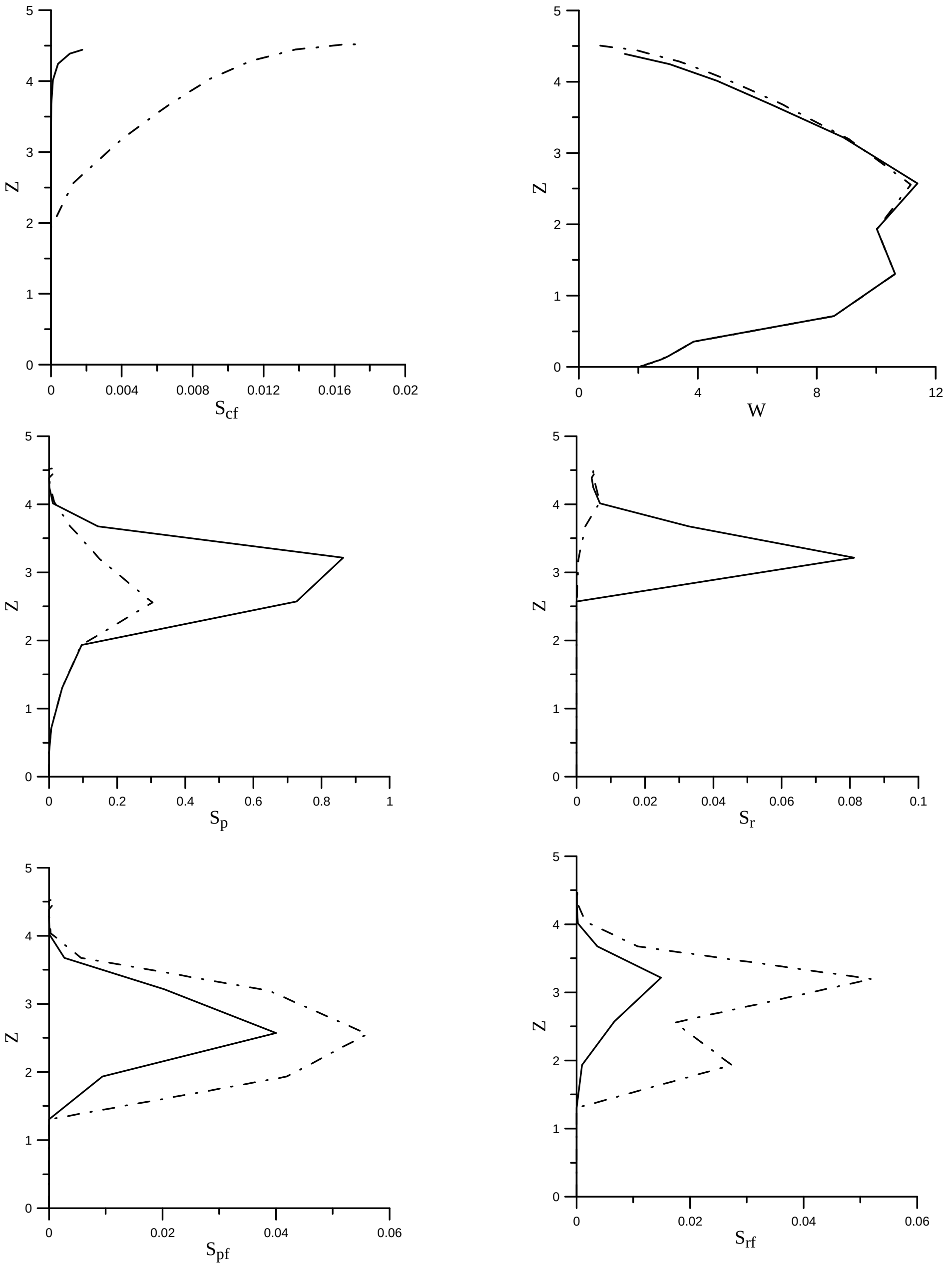

Fig. 2. Ice crystals content S_{cf} (g/m^3) precipitating drops content S_p (g/m^3), graupel content S_{pf} (g/m^3), updraft velocity W (m/s), rain fallout S_r (g/m^3) and graupel fallout S_{rf} (g/m^3) during the ascent of 3th thermal as a function of height Z (km) in the simulated 5 July 1975 cloud at primary nucleation (bold line) and at secondary (Hallet-Mossop parameterization – dash line)

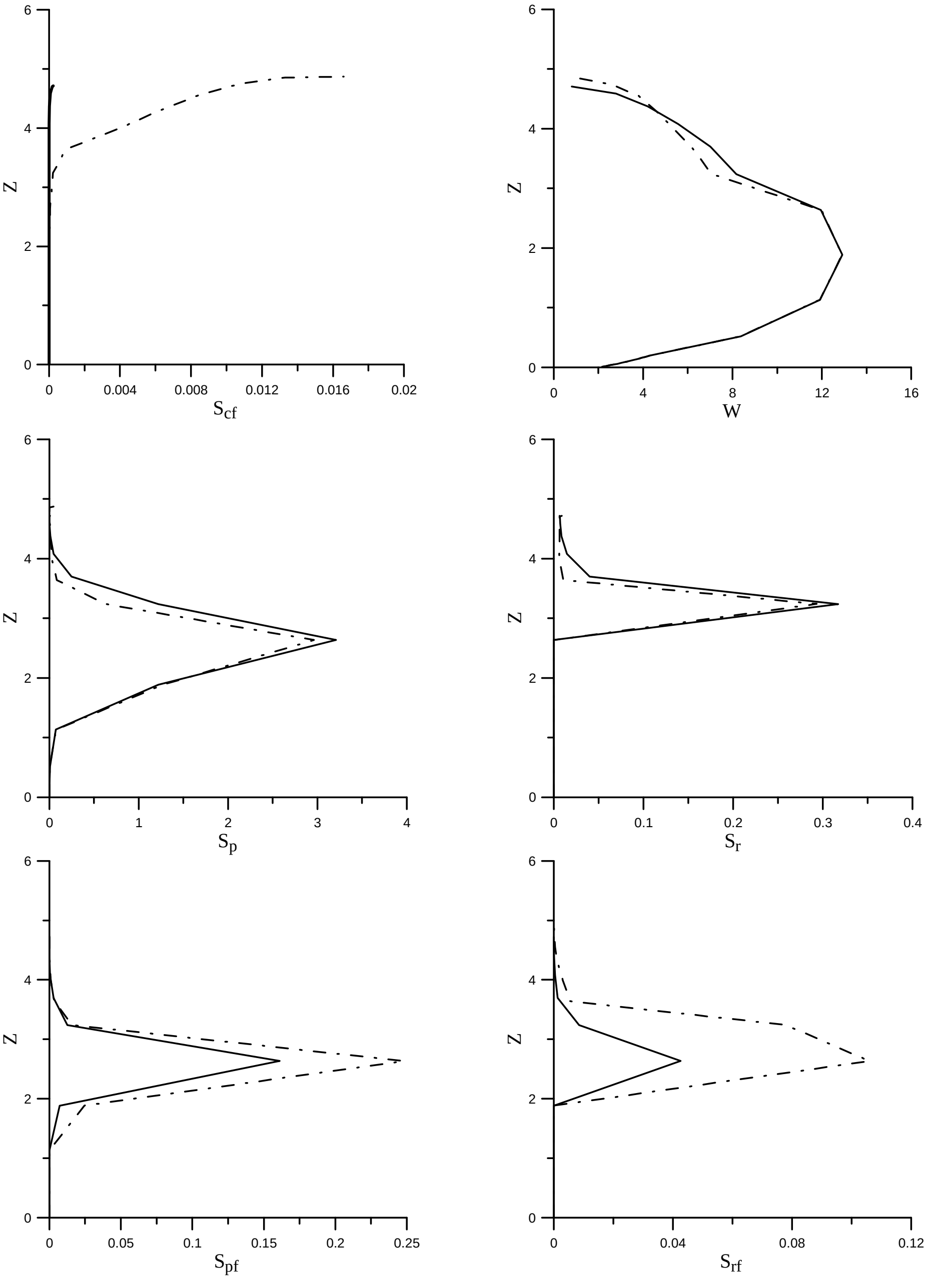

Fig. 3. Ice crystals content S_{cf} (g/m^3), precipitating drops content S_p (g/m^3), graupel content S_{pf} (g/m^3), updraft velocity W (m/s), rain fallout S_r (g/m^3) and graupel fallout S_{rf} (g/m^3) during the ascent of 5th thermal as a function of height Z (km) in the simulated 5 May 1979 cloud at primary nucleation (bold line) and secondary (Hallet-Mossop parameterization - dash line)

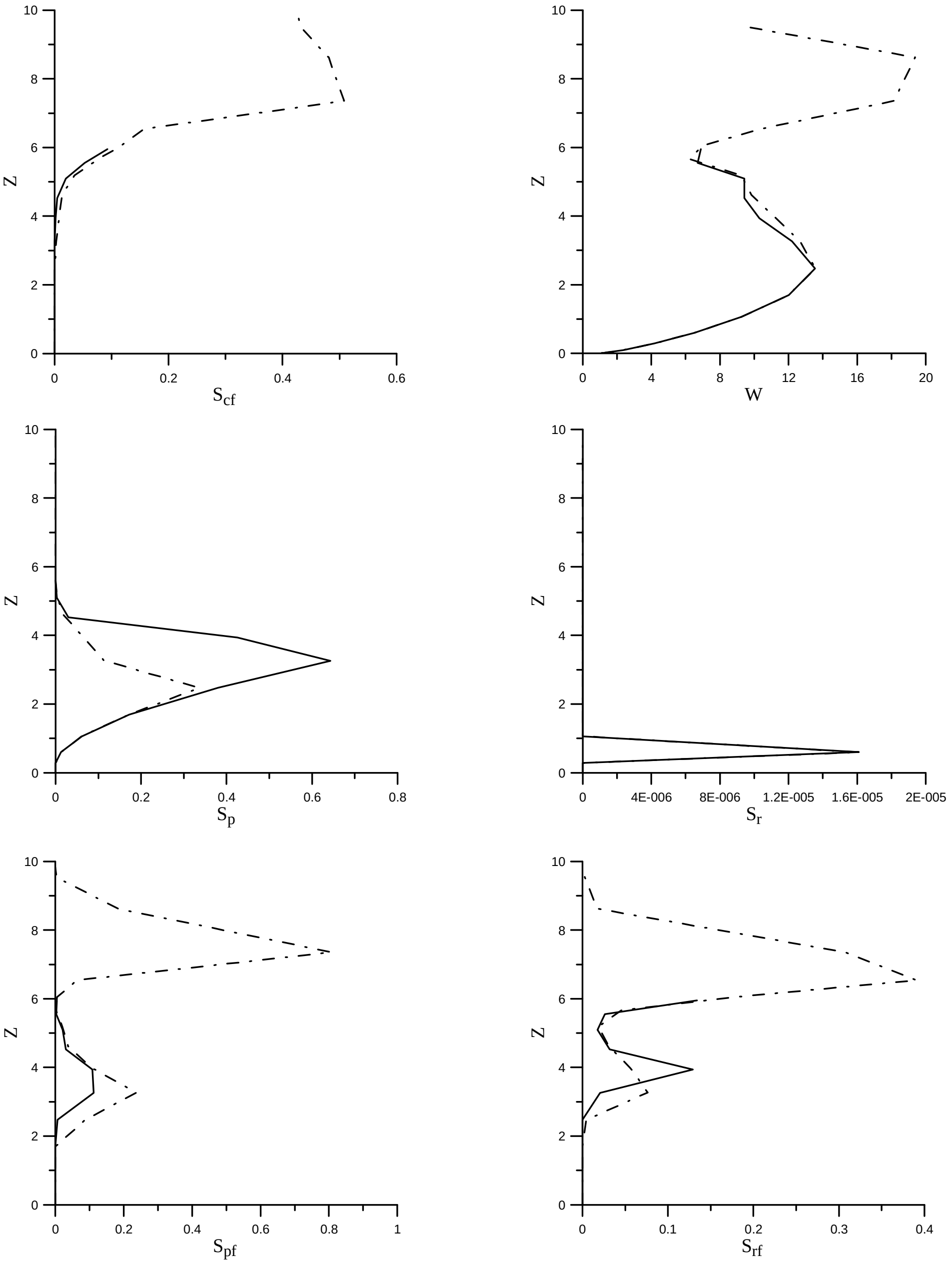

Fig. 4. Ice crystals content S_{cf} (g/m^3) precipitating drops content S_p (g/m^3), graupel content S_{pf}(g/m^3), updraft velocity W (m/s), rain fallout S_r (g/m^3) and, graupel fallout S_{rf} (g/m^3) during the ascent of 3th thermal as a function of height Z (km) in the simulated 8 June 1976 cloud at primary nucleation (bold line) and at secondary (Hallet-Mossop parameterization - dash line)

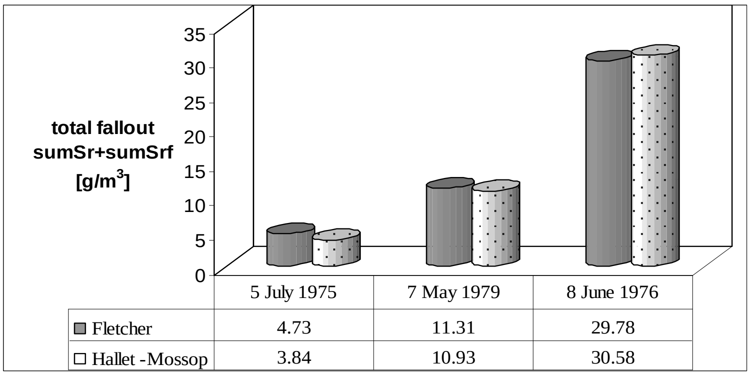

Fig. 5. Total fallout ($sumS_r$+$sumS_{rf}$) (g/m^3), at primary (Fletcher) nucleation and at secondary (Hallet-Mossop) nucleation in the three simulated clouds

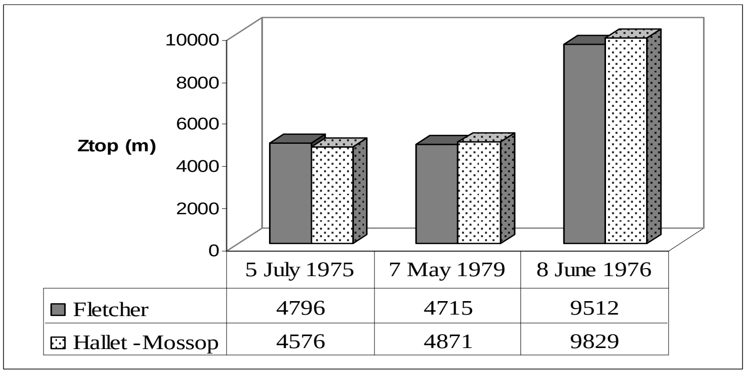

Fig. 6. Cloud top height Z_{top} (m) at primary (Fletcher) nucleation and at secondary (Hallet -Mossop) nucleation in the three simulated clouds

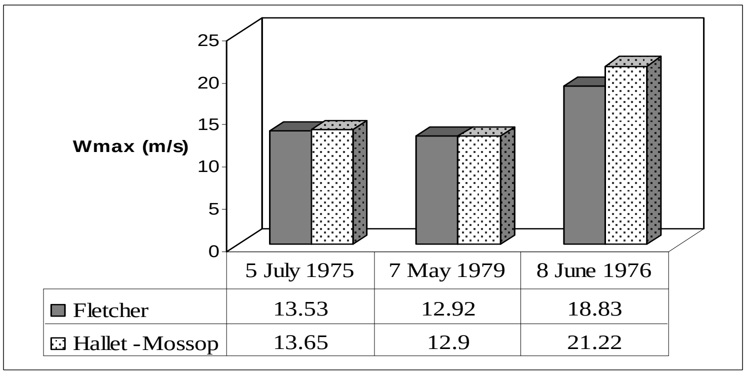

Fig. 7. Maximum updraft velocity W_{max} (m/s) at primary (Fletcher) nucleation and at secondary (Hallet -Mossop) nucleation in the three simulated clouds

Referense

Andreev V., D.Syrakov and R.Mitzeva, 1979: Modelling of convective cloud formation as successive ascending thermals (in Russian). *Bulg.Geophys*.J.,V,1,3-9.

Baker, M.B., Christian, H.R. & Latham, J. 1995. A computational study of the relationships linking lightning frequency and other thundercloud parameters. *Quart J Roy Met Soc.*, 121, 1525-1548.

Blyth, A. M., Latham, J., 1997. A multi-thermal model of cumulus glaciation via the Hallett-Mossop process. Quart. J. Roy. Met. Soc., 123, 1185-1198

Bigg, E. K., 1953.The supercooling of water. Proc. R. Soc., London, Ser. B, 66, 688-694.

Cotton W., 1972. Numerical simulation of precipitation development in super-cooled cumuli - Part II. Mon. Wea. Rev., 100, 764 – 784.

Farley, R. D. and H. D. Orville, 1986.Numerical modelling of hailstones and hailstone growth, I, Preliminary model verification and sensitivity tests. J. Clim. Appl. Meteorol., 25, 2014-2036.

Fletcher, N. H., 1962. The Physics of Rainclouds, Camb., pp 386 Univ. Press.

Hallet, J. and Mossop, S.C.,1974. Production of secondaryice crystals during the riming process, *Nature*,249, pp. 26-28.

Hobbs, P.V. 1969 Ice multiplication in clouds, *J. Atmos. Sci.*, 26, pp. 315-318

Heymsfield, A. J., and Mossop, S.C., 1984:*Quart. J. Roy. Meteor. Soc.*pp 110-765

Katherin M.L., 1997. Numerical modelling of thundercloud electrification and lightning. *PhD-thesis*, pp72 Uni of Manchester Institute. January 1997

Katherine M., Gardian A., Saunders C, Latham J. and Cristian H., 2001. Modelling and observations of thundercloud electrification and lightning, *Atmospheric Research*, v. 58, p.89-115

Kessler, E., 1969. On the distribution and continuity of water substance in atmospheric circulations, Meteorol. Monogr., Boston, 10, No 32,

Mason, B. J., Jonas, P. R., 1974. The evolution of droplet spectra and large droplets by condensation in cumulus clouds. *Quart. J. Roy. Met. Soc.*, 100, 23-38.

Mossop, S.C.1985. The origin and concentration of ice crystals in clouds. *Bull. Amer. Met .Soc* , 66, pp.264-273

Mitzeva R., N. Samarjiev and C.Saunders, 2003: Charge density in the updraughts of thunderstorms: a numerical study in the frame of a Lagrangian model, *Atmospheric Research*, v. 69, p.51-71

Palmer H.P., 1949.Natural ice-particle nuclei, quart.J. Royal Meteor. Soc., 75, pp.15

Pruppacher , H.R. and Klett, J.D. 1978. *Microphysics of Clouds and Precipitation.*, pp. 355-360, D.Reidel Publishing Company.

Rogers R. R. and M.K. Yau, 1989, A Short Course in Cloud Physics, pp. 155-159, Pergamon Press,

Young, K. C., 1993, Microphysical Processes in Clouds, pp. 97-99 Published by Oxford University Press.

Влияние на механизма на образуване на ледените кристалчета върху микрофизиката и динамиката на облака – числено изследване

С. Петрова и Р. Мицева

Резюме. Изследвано е влиянието на механизма на образуване на ледените кристалчета върху динамиката и микрофизиката на смесени конвективни облаци. Възпроизведени са три различни по мощност облака като е използван едномерен модел с параметризирана микрофизика. В модела са включени две параметризации за образуване на ледените кристалчета: първично ледообразуване и процес на размножаване на ледените кристалчета в резултат на механизма на Hallet-Mossop (вторично ледообразуване). Резултатите показват, че и в трите възпроизведени облачни случая валежът започва по-рано и от по-ниски нива, когато участва и механизмът на Hallet-Mossop. Според числените експерименти влиянието на механизма на образуване на ледените кристалчета зависи от мощността на облаците: наблюдава се увеличаване на валежа в най-мощния случай, и намаляване в другите два, в резултат на вторичното ледообразуване.