Annuaire de l'Université de Sofia "St. Kliment Ohridski", Faculté de Physique, 97, 2004

A MODELLING STUDY OF THE IMPACT OF ICE PARTICLES SIZES ON NON-INDUCTIVE CHARGE TRANSFER

BORYANA TSENOVA

Department of Meteorology and Geophysics

Боряна Ценова. ВЛИЯНИЕ НА РАЗМЕРИТЕ НА ЛЕДЕНИТЕ ЧАСТИЦИ ВЪРХУ ЗАРЯДА, ОТДЕЛЕН ПРИ НЕИНДУКТИВНО НАЕЛЕКТРИЗИРАНЕ

Изследвано е влиянието на размера на ледените частици върху знака на заряда, отделен при неиндуктивното наелектризиране при взаимодействие между градово зърно и ледено кристалче. В предишни лабораторни изследвания е предположено, че скоростите на нарастване от дифузия на водна пара на взаимодействащите си ледени частици влияят на заряда, отделен при краткия им сблъсък. И двете ледени частици нарастват поради дифузия на водна пара от околната среда. Градовото зърно нараства и поради дифузия на водна пара от близкото поле, създадено от замръзващите по повърхността му водни капчици. Нарастванията на ледените частици поради дифузия на водна пара са пресметнати при различни размери. Знакът, отделен при тяхното сблъскване, е пресметнат, уповавайки се на т.нар. "Хипотезата за относително нарастване" (Baker et al., 1987). Изследването показва, че размерът на леденото кристалче оказва по-силно влияние върху отделения заряд, отколкото размерът на градовото зърно.

Boryana Tsenova. A MODELLING STUDY OF THE IMPACT OF ICE PARTICLES SIZES ON NON-INDUCTIVE CHARGE TRANSFER

Numerical studies have been carried out of the impact of the ice particles' sizes to the sign of non-inductive charge transfer during graupel/ice crystal interactions in thunderstorms. Previous laboratory studies led to the idea that the diffusional growth rates of the interacting ice surfaces may influence the sign of the charge transferred during brief collisional contact. Ice crystals grow by vapour diffusion in a saturated environment. The graupel surface may grow by diffusion under low accretion rate conditions, but will sublimate when heated sufficiently by riming. Its surface is also influenced, even under net sublimation conditions, by the vapour released to it from droplets freezing on its surface. The diffusional growth rates of ice crystals and riming graupel particles are calculated for various particles sizes, then the sign of electric charge transferred during crystal/graupel collisions is determined according to the concept of the relative vapour diffusional growth rates, according to Baker et al. (1987). The study reveals that the impact of the ice crystal's size on the non-inductive charge transfer is more significant than the impact of the graupel's size.

Keywords: graupel/ice crystal growth, riming, non-inductive charge transfer

PACS numbers: 92.60.Nv, 92.60.Pw, 92.60.Jq

1. INTRODUCTION

Some laboratory studies (Reynolds et al. (1957), Takahashi (1978), and Jayaratne et al. (1983)) indicated thunderstorm electrification might be associated with charging by rebounding collisions between riming graupel and vapour grown ice crystals. They noted that the sign of the charge transferred to a riming graupel pellet depends on the cloud temperature and liquid water content (LWC) of the cloud. Later, Jayaratne and Saunders (1985) showed the importance to charge transfer of the capture by the graupel of supercooled water droplets, indicating that the important variable is the cloud effective liquid water content, EW. The results from the various laboratory studies differ in detail. In the search of explanation of these differences in results for the charge sign reversal obtained in various laboratory simulations, we will consider the influence of the ice particles sizes in this charging process. The most considered in the literature in our days hypothesis is the so called "Relative growth rate hypothesis", proposed by Baker et al. (1987), affirming that the faster growing by vapor diffusion ice particle (graupel or ice crystal) is charged positively, while the slower one—negatively. Basing on this, we will examine the impact of the sizes of grauple and ice crystal to the sign of the non-inductive charging process.

2. THEORETICAL BACKGROUNDS

All ice surfaces in a cloud grow by vapour diffusion from the far field as described by the conventional ice particle's growth theory. The growth rate of graupel mass from the far field can be calculated by:

$$\left(\frac{\mathrm{d}\, M_{\mathrm{g}}}{\mathrm{d}\, t}\right)_{\mathrm{f}} = F_{\mathrm{f}} 4\pi C D_{\mathrm{v}} \left(\rho_{\mathrm{w}}\left(T_{\mathrm{a}}\right) - \rho_{\mathrm{i}}\left(T_{\mathrm{g}}\right)\right),$$

where F_{f} is the far field enhancement factor, C is a function of the crystal geometry, D_{v} is the coefficient of the diffusion of water vapor, ρ_{w} and ρ_{i} are the densities of the saturated water vapors over liquid water and ice surface, depending on air temperature T_{a} and graupel surface temperature T_{g}. As a graupel grows by riming, the latent heat released by the freezing of accreted supercooled cloud droplets locally raises the surface temperature of the collecting particles. Taking into account the balance between the heat released due to freezing and heat transferred to the environment by thermal and vapor transfer Macklin and Payne (1967) obtained the following equation for T_{g}:

$$EWV \frac{\left[L_{\mathrm{f}} + c_{\mathrm{w}}\left(T_{\mathrm{a}} - T_{\mathrm{m}}\right) + c_{\mathrm{i}}\left(T_{\mathrm{m}} - T_{\mathrm{g}}\right)\right]}{4} =$$

$$= \chi Re^{0.5} \frac{\left[Pr^{1/3} K\left(T_{\mathrm{g}} - T_{\mathrm{a}}\right) + Sc^{1/3} D_{\mathrm{v}} L_{\mathrm{v}}\left(\rho_{\mathrm{w}}\left(T_{\mathrm{a}}\right) - \rho_{\mathrm{i}}\left(T_{\mathrm{g}}\right)\right)\right]}{2R_{\mathrm{g}}},$$

where L and c are the latent and specific heats, T_a, T_m and T_g are the temperatures of the air, of melting and of the graupel respectively. *Re* is the Renolds number, K is the thermal conductivity of air; *Pr* and *Sc* are the Prandtl and Schmidt numbers, R_g is the graupel radius, χ is the numerical factor in the heat transfer coefficient and is determined from laboratory studies by Castellano et al. [1999], $\chi = 0.6+0.83\exp(-5.17\cdot 10^{-7}\cdot d^4\cdot V)$, where d is the mean droplet volume diameter and V is the velocity.

Taking into account the heating effects associated with crystal growth, the ice crystal's growth rate from the far field is

$$\frac{\mathrm{d}\,M_\mathrm{cr}}{\mathrm{d}\,t} = \frac{4\pi R_\mathrm{cr}\left(S_\mathrm{i}-1\right)}{\dfrac{L_\mathrm{s}^2}{KR_\mathrm{v}T_\mathrm{a}^2}+\dfrac{R_\mathrm{v}T_\mathrm{a}}{E_\mathrm{icr}D_\mathrm{v}}}.$$

The graupel surface grows also by diffusion from the vapour released by droplets while they freeze on its surface at 0 °C. Following the considerations in Baker et al. (1987), the graupel growth from the local vapor field may be calculated from

$$\left(\frac{\mathrm{d}\,M_\mathrm{g}}{\mathrm{d}\,t}\right)_\mathrm{l} = F_\mathrm{l}3D_\mathrm{v}\left(\sqrt[3]{2r_\mathrm{d}}\right)\left(\rho_\mathrm{w}\left(T_\mathrm{m}\right)-\rho_\mathrm{i}\left(T_\mathrm{g}\right)\right)\left(\frac{3S_\mathrm{g}VEW}{4\sigma_\mathrm{w}r_\mathrm{d}^3}\right)\tau_\mathrm{f},$$

where F_l is the local field enhancement factor, r_d is the droplet radius, $\rho_\mathrm{w}(T_\mathrm{m})$ is the saturation vapour density at 0 °C, S_g is the graupel-projected area, σ_w is the density of water. The supply of vapour to the riming surface is limited by the droplet freezing time, τ_f, (from Pruppacher and Klett, 1997), given by

$$\left(2\pi r_\mathrm{d}F_\mathrm{l}\left(L_\mathrm{v}D_\mathrm{v}\left(\rho_\mathrm{a}\left(T_\mathrm{m}\right)-\rho_\mathrm{a}\right)-KT_\mathrm{a}\right)\right)\tau_\mathrm{f}-\left(T_\mathrm{g}K_\mathrm{i}r_\mathrm{d}^2\sqrt{\frac{\pi c_\mathrm{i}\sigma_\mathrm{g}}{K_\mathrm{i}}}\right)\sqrt{\tau_\mathrm{f}}-$$

$$-\frac{2\pi}{3}r_\mathrm{d}^3\sigma_\mathrm{w}\left(L_\mathrm{m}+c_\mathrm{w}T_\mathrm{a}\right)=0,$$

where K and K_i are the thermal conductivities of air and ice, c_i is the specific heat of ice, σ_g is the density of graupel.

Assuming that the graupel and ice crystals are spherical, linear growth rates, which are the controlling influence on charge transfer, are determined from

$$\frac{\mathrm{d}\,R_\mathrm{g/cr}}{\mathrm{d}\,t} = \frac{1}{4\pi R_\mathrm{g/cr}^2\sigma}\frac{\mathrm{d}\,M_\mathrm{g/cr}}{\mathrm{d}\,t},$$

where σ is the density of the vapor deposited ice.

The relative diffusional growth rate is the difference between the growth rates of the graupel from the far field together with the local vapour contribution from droplets freezing on the surface, less the growth rate of the crystals from the far field,

$$RGR = \left(\frac{\mathrm{d}\,R_\mathrm{g}}{\mathrm{d}\,t}\right)_\mathrm{f} + \left(\frac{\mathrm{d}\,R_\mathrm{g}}{\mathrm{d}\,t}\right)_\mathrm{l} - \left(\frac{\mathrm{d}\,R_\mathrm{c}}{\mathrm{d}\,t}\right).$$

If $RGR > 0$, graupel is positively charged (ice crystal—negatively); if $RGR < 0$, graupel is negatively charged (ice crystal—positively).

3. NUMERICAL RESULTS

All numerical simulations were carried out with a velocity $V = 6$ m/s and water droplets size $r_\mathrm{d} = 8$ μm. Ice particles' sizes were varied to be $R_\mathrm{g} = 1.5$, 2, 2.5 and 3 mm, and $R_\mathrm{c} = 60$, 80, 100 and 120 μm.

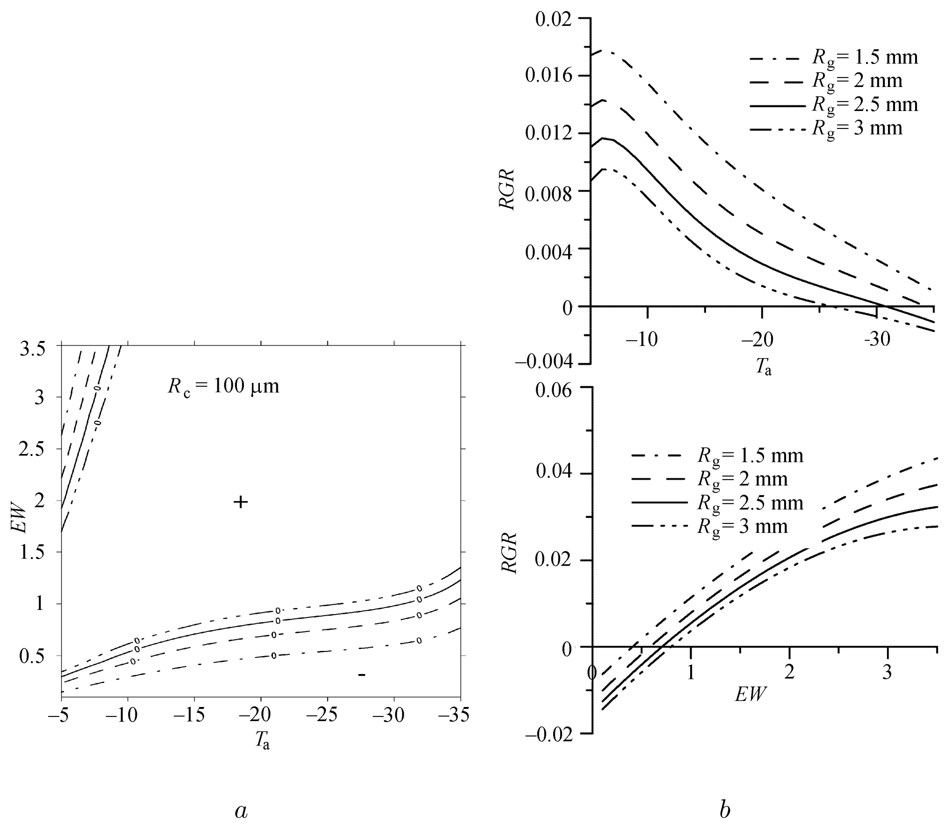

Fig. 1. The impact of the graupel size on the charge transferred, represented: a) as a function of the cloud temperature T_a and liquid water content EW; b) as a function of T_a at $EW = 1$ g/m^3 and as a function of EW at $T_\mathrm{a} = -15$ °C

Fig. 1 shows the influence of the graupel's size on the relative growth rate (RGR) as a function of the cloud temperature and effective water content (Fig. 1a), at a fixed $R_c = 100$ μm for the four different graupel's sizes. One can see that the increase of graupel's size favours negative charge at lower EW and T_a. Fig. 1b shows RGR as a function of the temperature T_a at a fixed effective water content $EW = 1$ g/m^3 and as a function of the EW at $T_a = -15$ °C. $RGR > 0$ for all considered graupel's sizes at cloud temperatures and effective water contents over -25 °C and 0.8 g/m^3. With the increase of the graupel size, the interval of cloud temperatures (at $EW = 1$ g/m^3), as the interval of effective water contents (at $T_a = -15$ °C) where the $RGR > 0$, decreases at low T_a and EW.

Table 1. The cloud temperature T_a (at a fixed $EW = 1$ g/m^3) and effective water content EW (at a fixed $T_a = -15$ °C) for the charge sign reversal

R_g, mm	T_a, °C	EW, g/m^3
1.5	—	0.4
2.0	−34	0.6
2.5	−31	0.7
3.0	−26	0.8

Table 1 shows that the reversal for the four considered graupel's sizes is moving to higher T_a and EW with the increase of the graupel.

As it was mentioned, a precise estimation of graupel surface temperature T_g is important for the correct evaluation of graupel growth rate due to deposition of water vapor. The graupel surface may grow by diffusion under low accretion rate

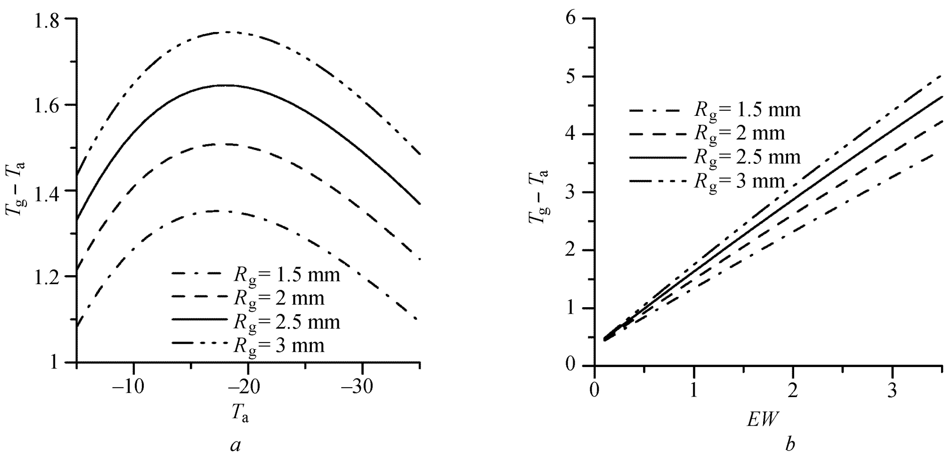

Fig. 2. The impact of the graupel size on its surface temperature T_g, represented: a) as a function of the cloud temperature T_a at $EW = 1$ g/m^3 ; b) as a function of EW at $T_a = -15$ °C

conditions and will sublimate when heated sufficiently by riming. Fig. 2 shows the impact of graupel's size on its surface temperature T_g. The temperature difference $(T_g - T_a)$ is presented as a function of the cloud temperature T_a at a fixed $EW = 1$ g/m^3 (Fig. 2*a*) and as a function of the EW at a fixed $T_a = -15$ °C (Fig. 2*b*). It is visible that the bigger graupel is hotter. An increase with 0.5 mm of its size leads to a warming with about 0.13 °C at $EW = 1$ g/m^3. For all considered sizes, $(T_g - T_a)$ as a function of T_a has a minimum at $T_a = -5$ °C. The maximum of this temperature difference moves to lower cloud temperatures with the increase of the graupel (see also the results in Table 2).

Fig. 2*b* shows that $T_g - T_a$ increases linearly with EW, and the line is steeper for the bigger graupel. With the increase of the EW, the bigger graupel is warming faster.

As it was mentioned, the negative charge ($RGR < 0$) is favoured by the increase of the graupel size, which surface temperature is higher. One can say that the hotter graupel favoures negative charge.

Table 2. The impact of the graupel's size on its surface temperature T_g

R_g, mm	Minimum of $(T_g - T_a)$, °C, at $EW = 1$ g/m^3		Maximum of $(T_g - T_a)$, °C, at $EW = 1$ g/m^3		Minimum of $(T_g - T_a)$, °C, at $T_a = -15$ °C		Maximum of $(T_g - T_a)$, °C, at $T_a = -15$ °C	
1.5	1.08	at −5 °C	1.33	at −16 °C	0.4	at 0.1 g/m^3	3.5	at 3.5 g/m^3
2.0	1.21	at −5 °C	1.48	at −17 °C	0.4	at 0.1 g/m^3	4.1	at 3.5 g/m^3
2.5	1.32	at −5 °C	1.62	at −18 °C	0.4	at 0.1 g/m^3	4.7	at 3.5 g/m^3
3.0	1.42	at −5 °C	1.77	at −19 °C	0.4	at 0.1 g/m^3	5.2	at 3.5 g/m^3

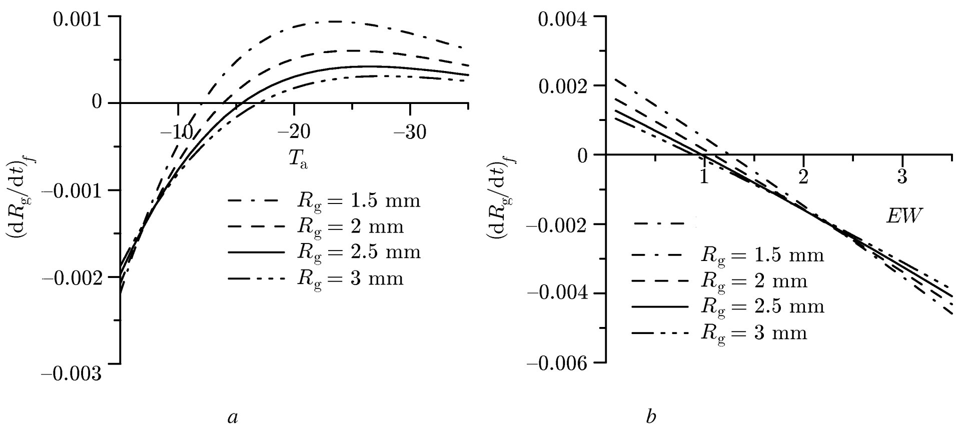

Fig. 3. The impact of the graupel's size on its growth rate from the far field, presented *a*) as a function of T_a at $EW = 1$ g/m^3; *b*) as a function of EW at $T_a = -15$ °C

Fig. 3 shows the impact of the graupel's size on its growth rate from the far field. The graupel surface grows by diffusion under low accretion rate conditions. The increase of graupel size favours negative growth rate (decreasing graupel) from the far field. When heated sufficiently by riming, the graupel surface will sublimate. At lower cloud temperatures and effective water contents, $(\mathrm{d}\,R_{\mathrm{g}}/\mathrm{d}\,t)_f > 0$ for all sizes. The smaller graupel is growing faster. With the increase of the size, the maximum of $(\mathrm{d}\,R_{\mathrm{g}}/\mathrm{d}\,t)_f$ is moving to lower temperatures (Fig. 3*a*). The bigger graupel sublimates at lower cloud temperatures when $EW = 1$ g/m^3 and lower effective water contents when $T_{\mathrm{a}} = -15$ °C (Fig. 3*b*). When -7 °C $< T_{\mathrm{a}} < -12$ °C (Fig. 3*a*) or 1.3 g/m^3 $< EW <$ 2.2 g/m^3 (Fig. 3*b*), the bigger graupel sublimates faster. At higher cloud temperatures and effective water contents—vice versa.

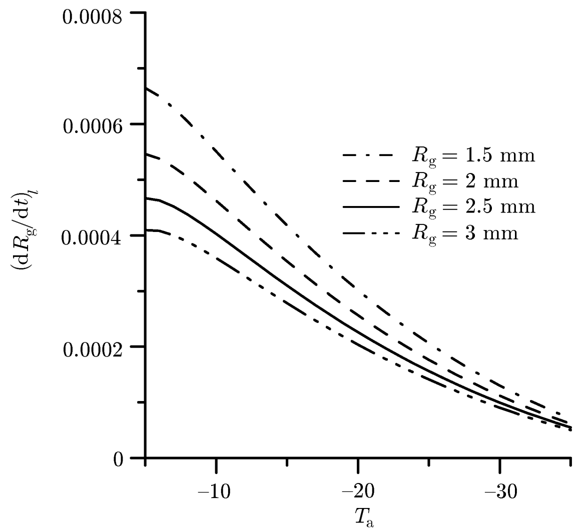

Fig. 4. The impact of the graupel's size on its growth rate from the local field, as a function of T_{a} at $EW = 1$ g/m^3

The graupel surface is also influenced, even under net sublimation conditions, by the vapour released to it from droplets freezing on its surface. Fig. 4 shows the impact of the graupel's size on its growth rate from the so-called local vapour field. An influence of the graupel size on $(\mathrm{d}\,R_{\mathrm{g}}/\mathrm{d}\,t)_l$ is more visible at higher cloud temperatures. One can see that the smaller graupel grows faster.

Fig. 5 shows the impact of ice crystal's size on the *RGR*, as a function of the cloud temperature and effective water content, at a fixed $R_{\mathrm{g}} = 2.5$ mm for the four different crystal's sizes (Fig. 5*a*). One can see that the increase of

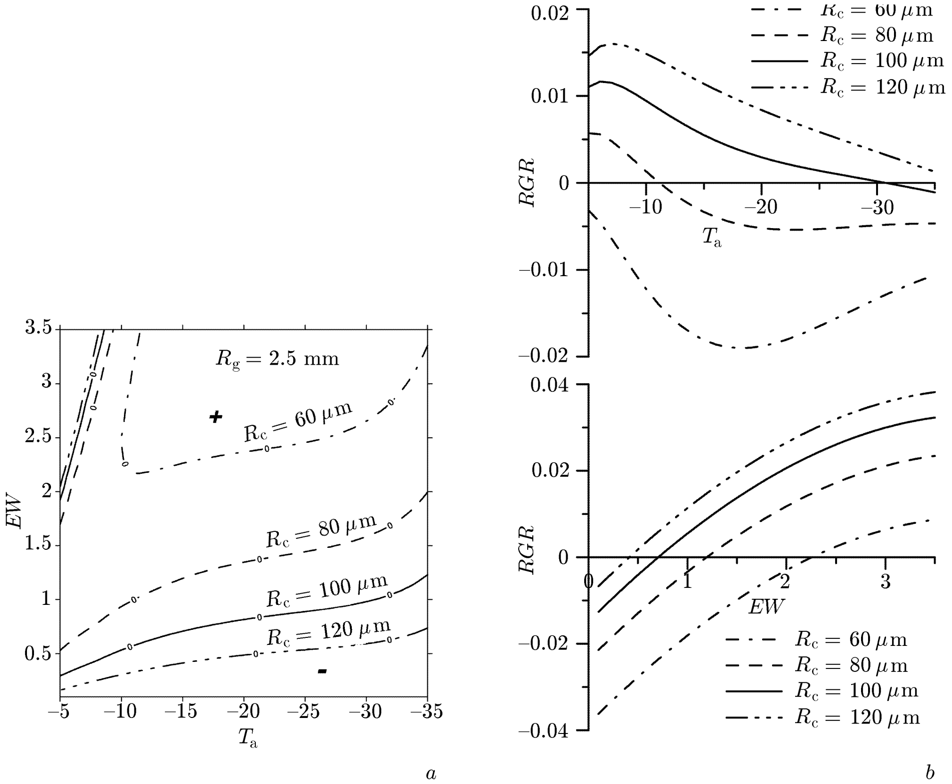

Fig. 5. The impact of the crystal's size on the charge transferred, represented: a) as a function of the cloud temperature $T_{\rm a}$ and liquid water content EW; b) as a function of $T_{\rm a}$ at $EW = 1$ g/m^3 and as a function of EW at $T_{\rm a} = -15$ °C

the ice crystal's size favours positive charge, which can be seen on Fig. 5b. With the increase of the crystal's size the interval of cloud temperatures where $RGR > 0$ at $EW = 1$ g/m^3 grows. The ice crystal with $R_{\rm c} = 120$ μm leads to $RGR > 0$ in the entire temperature interval, while for $R_{\rm c} = 60$ μm, $RGR < 0$. An increase of the size of the ice crystal with 20μm may decrease the reversal temperature with more than 15 °C (at $EW = 1$ g/m^3) and the reversal EW (at $T_{\rm a} = -15$ °C) with more than 0.5 g/m^3.

Fig. 6 shows the impact of the crystal's size on its growth rate. The smaller ice particle grows faster. The maximum of $\mathrm{d}\,R_{\rm c}/\mathrm{d}\,t$ moves to lower temperatures with the increase of the crystal. It is 0.059 μm/s at -13 °C for $R_{\rm c} = 60$ μm, 0.044 μm/s at -13.5 °C for $R_{\rm c} = 80$ μm, 0.034 at -14 °C for $R_{\rm c} = 100$ μm, and 0.028 μm/s at -15 °C for $R_{\rm c} = 120$ μm.

Fig. 7 shows the impact of the ice particles' sizes on the RGR. Their sizes were varied, in the way to have a crystal 2.5 times smaller than the graupel. One can see

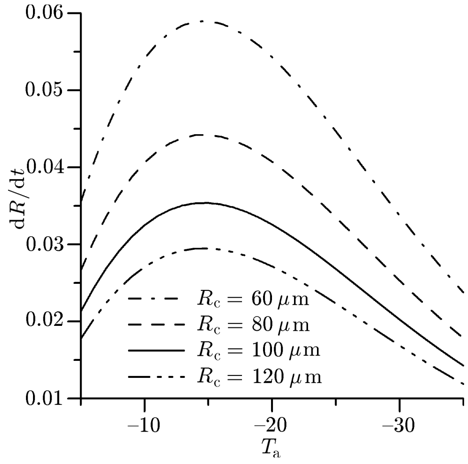

Fig. 6. The impact of the crystal's size on its growth rate as a function of T_a at $EW = 1$ g/m^3

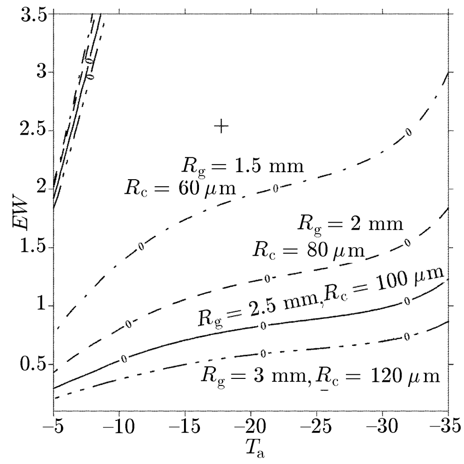

Fig. 7. The impact of the ice particles' sizes on RGR, as a function of the cloud temperature T_a and liquid water content EW

that in this case, as a function of the cloud temperature and the effective water content, the area with positive RGR grows with the increase of both ice particles. This is in contradiction with the considered before impact of the graupel's size on the charge. It is also confirming the obtained influence of the ice crystal's size. This leads us to conclude, basing on the relative growth rate hypothesis, that the impact of the size of the ice crystal on the charge transferred during the rebounding collisions between graupel and ice crystal is more significant than the impact of the graupel size.

4. CONCLUSION

This modelling study of the influence of ice particles has shown that the characteristic charge sign reversal, from a negative to positive rimer on increasing the rime accretion, as noted in many laboratory studies of ice crystal/graupel collisions may be accounted for in terms of the relative diffusional growth rates of the interacting ice surfaces. The results demonstrate that graupel size as well the size of the ice crystal influences significantly their growth rates. The increase of graupel size, due to the warmer surface, favours negative growth rate (sublimation) from the far field. The smaller graupel is growing faster by the diffusion of vapour from the far and the local field. The increase of the crystal's size moderates its growth rate. The smaller ice crystal grows faster than the bigger one. The increase of the graupel size favours negative charge, while the increase of the ice crystal size favours positive charge. The increase of both ice particles favours positive charge. The impact of the ice crystal size on the charge transferred during the rebounding collisions between graupel and crystal is more significant. It leads us to conclude the necessity to indicate them in the implementation of the laboratory experiments. Based on this one can conclude that at the laboratory experiments related with the non-inductive charge transfer, where the ice particles sizes play a significant role, one cannot compare the different experiments if they were carried out with different sizes of the crystals.

REFERENCES

1. Avila, E. E., G. G. Aguirre Varela, G. M. Caranti. *J. Geophys. Res*, **101**, 1996., 29609.
2. Baker, B., M. B. Baker, E. J. Jayaratne, J. Latham, C. P. R. Saunders. *Q. J. R .Met. Soc.*, **113**, 1987, 1193.
3. Baker, M. B., J. G. Dash, *J. Geophys. Res.*, **99**, 10, 1994, 621.
4. Brooks, M., C. P. R. Saunders, R. P. Mitzeva and S. L. Peck. *J. Atmos. Res*, **43**, 1997, 277.
5. Castellano, N. E., E. E. Avila, C. P. R. Saunders. *J. Geophys.Res.*, **104**, 1999, 27399.
6. Dash, J. G., B. L. Mason, J. S. Wettlaufer. *J. Geophys. Res.*, **106**, 2001, 20, 395.
7. Jayaratne, E. R., C. P. R. Saunders. *J. Geophys. Res.*, **90**, 1985, 13063.
8. Macklin, W. C., G. S. Payne. *Q. J. Roy. Met. Soc.*, **93**, 1967, 195.
9. Mason, B. L., J. G. Dash. *J. Geophys. Res.,* **105**, 2000, 10,185.
10. Pereyra, R. G., E. E. Avila, N. E. Castellano, C. P. R. Saunders. *J. Geophys. Res.*, **105**, 2000, 20,803.
11. Pruppacher, H. R., J. D. Klett. *Microphysics of Clouds and Precipitation*, 1997.
12. Reynolds, S., M. Brook, M.F.Gourley. *J. Met.*, **14**, 1957,426.
13. Saunders, C. P. R., W. D. Keith and R. P. Mitzeva. *J. Geophys. Res.*, **96**, 1991, 11, 007.
14. Saunders, C. P. R., S. L. Peck. *J. Geophys. Res.*, **103**, 1998, 13, 949.
15. Saunders, C. P. R., E. E. Avila, S. L. Peck, N. E. Castellano, G. Aguirre Varela. *Atmos. Res.*, **51**, 1999, 99.
16. Takahashi, T. *J. Atmos. Sci.*, **35**, 1978, 1536.
17. Takahashi, T. *J. of Atmos. Sci.*, **59**, 2002, 1018.
18. Williams, E., R. Zhang and J. Rydock. *J. Atmos. Sci.*, **48**, 1991, 2195.

Received April 2004

Boryana Tsenova
St. Kliment Ohridski University of Sofia
Faculty of Physics
Department of Meteorology and Geophysics
5, James Bourchier Blvd.
BG-1164 Sofia, Bulgaria
E-mail: tboriana@abv.bg