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The effect of charge separation in upper cloud layers on thunderstorm electrification – numerical simulations

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ABSTRACT: Numerical simulations are performed to test the effect of the charge separation that may occur at low cloud temperatures and liquid water contents on thunderstorm electrification. For this purpose, the proposed parameterization in Mitzeva et al. [2006] for charging at low cloud water content and the results of Avila et al. [2011] for charging at cloud temperatures below -37 ºC are used. Charge distribution and lightning activity obtained with the above mentioned parameterizations for three simulated idealized cloud cases are compared and contrasted with relevant cases for zero charge transfer in cloud regions with low temperature and liquid water content. The numerical simulations are performed with the 3D non-hydrostatic cloud model MésoNH.

INTRODUCTION

The charge separation that occurs in the upper regions of convective clouds reaching temperatures below -40ºC is not fully investigated. Aircraft in situ measurements at such temperatures in such clouds reported the presence solely of ice particles (Rosenfeld and Woodley, 2000). As is widely believed, based on laboratory experiments (Reynolds et al. 1957; Takahashi 1978; Saunders et al. 1991; ...), thunderstorm electrification is mainly due to charge transfer during collisions between ice particles in cloud regions containing supercooled water droplets. Some laboratory experiments (Jayaratne et al. 1983) showed that in the absence of cloud droplets, the separated charge during rebounding collisions between ice crystals and graupel is up to two orders of magnitude smaller than in the presence of cloud water. Based on this, in numerical models usually it is assumed that there is no charge separation at cloud conditions with very low liquid water content and at cloud temperatures below -40 ºC. Mitzeva et al. [2006], proposed parameterizations for the charge transfer in the non-riming regions based on theoretical assumptions. The first assumption relied on the “Sublimation/Deposition” hypothesis for the charge separation, according to which if there is sublimation/deposition of vapor from/to the graupel surface, graupel charges negatively/positively, respectively. The second assumption was based on the “Relative Growth Rate” hypothesis (Baker et al. 1987), according to which the ice particle surface growing faster by vapor

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diffusion charges positively. Results showed that charge transfer in non-riming cloud regions, even with two orders lower magnitude compared with charge separated in riming cloud regions, may influence the total cloud charge density, especially in the upper part of thunderstorm updraughts. Avila et al. [2011] performed new sets of laboratory experiments to determine the charge separation at laboratory cloud conditions similar to those occurring in glaciated cloud regions. The authors reported predominantly negative graupel charging in the temperature range -37 ºC to -47 ºC, with estimated charge transfer per collision magnitude between 0.01 and 0.1 fC.

Based on these results, the aim of the present study is to test the effect of the electrification in higher cloud regions on cloud charge structure and lightning activity. For this purpose, three idealized cloud cases were simulated with the 3D non-hydrostatic model MésoNH. For each cloud case, simulations were performed in the non-riming cloud regions using the parameterization proposed in Mitzeva et al. [2006] that is based on the “Relative Growth Rate” hypothesis; and using the Avila et al. [2011] charge values in the cloud temperature range between -37 ºC and -47 ºC . Results are compared with relevant cases for zero charge transfer in cloud regions with low temperature and liquid water content. The parameterization of cloud charging in regions with supercooled cloud water droplets is based on the Saunders et al. [1991] laboratory results.

NUMERICAL SIMULATIONS AND RESULTS

MésoNH model

The model used in the present study is MésoNH, which is a non-hydrostatic mesoscale model resulting from a joint development of Laboratoire d'Aérologie and Météo-France (http://www.aero.obs-mip.fr/mesonh/). In the model, the charge separation mechanisms are entirely due to rebounding collisions between ice particles – graupel, pristine ice and snow/aggregates. The electric charges carried by each of the five hydrometeor categories (cloud and rain drops, ice crystals, snow and graupel) are transported the airflow and are exchanged according to the various microphysical mass transfer rates. A power law distribution of the individual charges as a function of the particle size is assumed. All the charging rates are obtained after integration over the particle size distribution. A lightning scheme is added to enable a partial neutralization of the charges when the electric field becomes disruptive locally. Recent comprehensive description of the electrical scheme characteristics can be found in Barthe and Pinty [2007] and Barthe et al [2012].

Parameterizations of thunderstorm charging

The cloud electrification parameterizations used for the simulations are based on the equations presented in Saunders et al. [1991]. According to these equations the charge transfer Q per separation event for graupel/ice crystal collision depends on crystal size d and relative velocity V following the equation:

$$Q=Ad^{a}V^{b}q(EW,T) \quad (1)$$

where A, a, and b are constants depending on crystal size and graupel velocity and are tabulated in

Saunders et al. (1991), *q* is the charge determined from the experimentally derived equations linking *EW* (the effective water content) and *T* (temperature) for the positive and negative charging cases. For the purpose of the present study the following parameterizations were used:

1) SAUN: charge separation values according to Saunders et al. [1991], calculated in the temperature range [-40 °C, 0 °C] and at EW > 0.026 gm^{-3} , so there in no charging assumed below -40 °C and below EW<0.026 gm^{-3}

2) SAUN+RGR: same as SAUN, however at EW<0.026 gm^{-3} :

- when the cloud is supersaturated with respect to ice, Si>1:
  q = -0.05 fC
- when cloud is subsaturated with respect to ice, Si<1:
  q = 0.05 fC

This parameterization, proposed in Mitzeva et al. [2006], is based on the Relative Growth Rate hypothesis, according to which the faster growing by vapor diffusion ice surface charges positively. The smaller ice particle will grow faster than the bigger one in supersaturated regions, which will charge the bigger ice particle negatively. Inversely, in subsaturated cloud regions, smaller ice particles will sublimate faster, leading to positive charging of the bigger ice particles.

3) SAUN+LT: same as SAUN, however at -37 °C >T > -47 °C:

q = -0.05 fC

This parameterization is based on the recent laboratory results obtained by Avila et al. [2011].

Results

Three cloud cases C1, C2, and C3 were simulated using the temperature and moisture profiles presented in Figure 1. The simulation domains are respectively 60x60 km for C1, 64x64 km for C2 and 80x80 km for C3. All simulations were run for a duration of 3 hours Model Time (MT), and the preliminary study of microphysical, dynamical and electrical cloud characteristics presented here is based on outputs every 10 minutes. Lightning information is given simultaneously during the simulations.

In Table1 is given some information on microphysical and dynamical characteristics of the simulated cloud cases C1, C2 and C3: the maximum mixing ratios in g/kg of cloud (Rc) and rain (Rr) water, ice crystal (Ri), snow (Rs) and graupel (Rg) and the maximum updraft velocity (W) in m/s, as well the height and the time of their achievements.

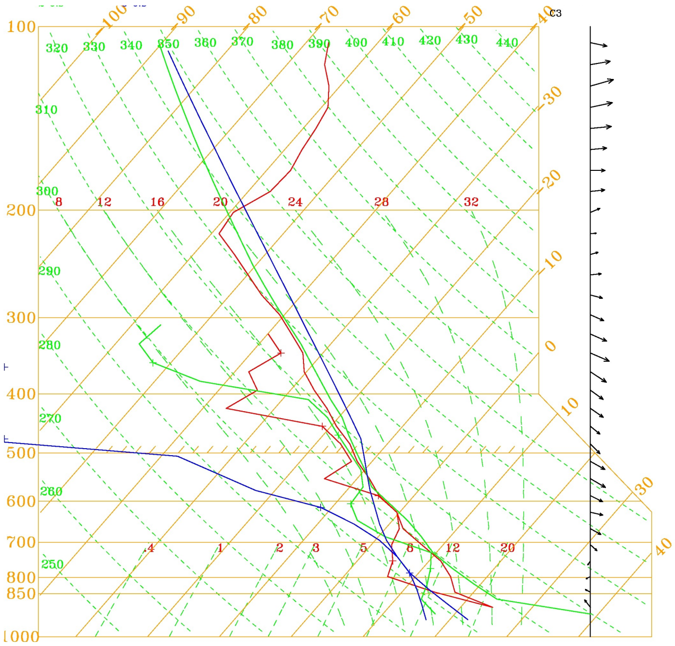

Figure 1. Temperature and moisture profiles used for the simulations of cloud cases C1 – in red, C2 – in green, C3 – in blue.

Table1: Maximum mixing ratios (in g/kg) of cloud (Rc) and rain (Rr) water, ice crystal (Ri), snow (Rs) and graupel (Rg) and the maximum of the updraft velocity (W m/s) with information of the height and the time of their achievements in the simulated cloud cases C1, C2 and C3.

	C1	C2	C3
Rc_max	4 g/kg at 3.8 km, 30min	4.5 g/kg at 5.2 km, 20min	4.3 g/kg at 3.8 km, 40min
Rr_max	0.5 g/kg at 4 km, 40min	2 g/kg at 2.6 km, 50min	7.6 g/kg at 2.6 km, 30min
Ri_max	1.2 g/kg at 8.8 km, 30min	1.5 g/kg at 10.2km, 30min	0.8 g/kg at 9 km, 70min
Rs_max	0.9 g/kg at 3.8 km, 20min	0.8 g/kg at 8.6 km, 40min	2.1 g/kg at 3.8 km, 50min
Rg_max	7.6 g/kg at 8.4 km, 30min	9 g/kg at 9.4 km, 20min	12 g/kg at 7.2 km, 30min
W_max	37 m/s at 7.6 km, 30min	40 m/s et 9.6km, 20min	35.5 m/s at 7 km, 70min

From the table one can see that at least for the maximum cloud particle mixing ratios, the three considered cloud cases are quite similar. However, in C3 the maximum ice crystal mixing ratio is lower, while the maximum of the snow mixing ratio is higher in comparison to the other two cloud cases.

In Table 2 some electrical characteristics of the simulated cloud cases C1, C2 and C3 with the three parameterizations SAUN, SAUN+RGR and SAUN+LT are systematized.

Table2: Maximum negative Qtot_min and positive Qtot_max charge densities, number of flashes and time interval of the lightning activity for the three simulated cloud cases C1, C2 and C3 with SAUN, SAUN+RGR and SAUN+LT parameterizations of charging

Cloud Case	Parameterization	Qtot_min [nC/m^3]	Qtot_max [nC/m^3]	Number of flashes	Duration of lightning activity
C1	SAUN	-0.8 at 5.2km, 50min	0.8 at 6.2km, 50min	76	2377.5 s – 4010 s
	SAUN+RGR	-2.1 at 5.2km, 50min	0.7 at 6.6km, 50min	93	2500 s – 3765.5 s
	SAUN+LT	-2.2 at 5.2km, 50min	0.8 at 6.2km, 50min	62	2715 s – 3842 s
C2	SAUN	-1.7 at 5.6km, 80min	1.3 at 7.2km, 90min	1534	2262 s – 10730 s
	SAUN+RGR	-1.9 at 4.2km, 90min	1.8 at 6.2km, 90 min	1486	2250 s – 10712.5 s
	SAUN+LT	-2 at 3.8km, 90min	1.9 at 6.8km, 90min	1504	2265 s – 10737.5 s
C3	SAUN	-3.5 at 4.6km, 30min	2.6 at 6.2km, 40min	1079	1510 s - 10800s
	SAUN+RGR	-3 at 4.4km, 30min	2.8 at 6.2km, 40min	882	1510 s - 10800s
	SAUN+LT	-2.8 at 4.2km, 30min	2.8 at 6.2km, 40min	1053	1510 s – 10800 s

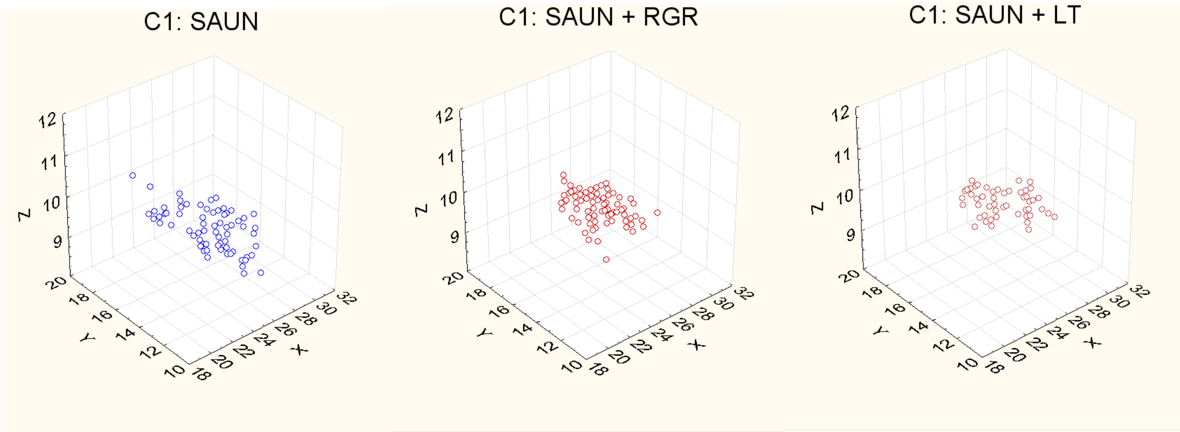

Figure 2. Cloud case C1: Spatial location of lightning flash initiation obtained with SAUN, SAUN+RGR and SAUN+LT parameterizations

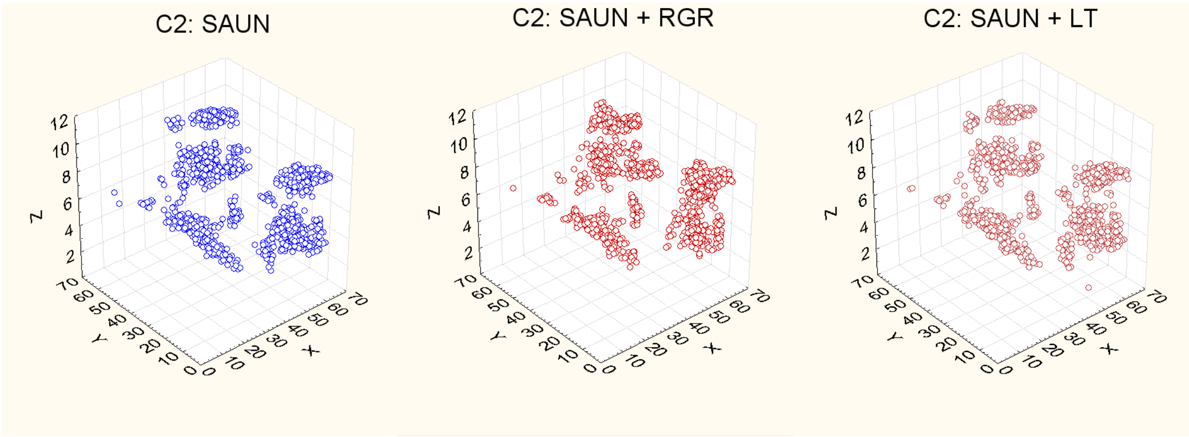

Figure 3. Cloud case C2: Spatial location of lightning flash initiation obtained with SAUN, SAUN+RGR and SAUN+LT parameterizations

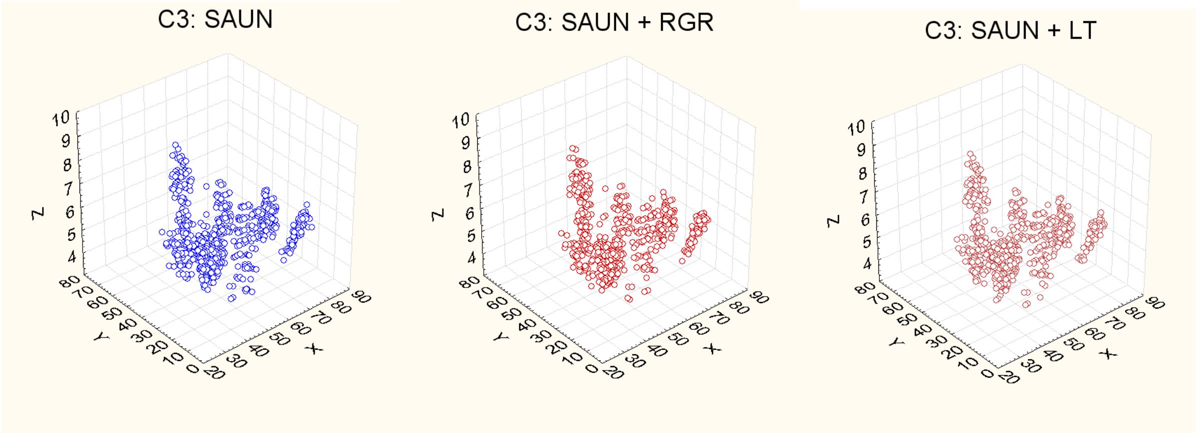

Figure 4. Cloud case C3: Spatial location of lightning flash initiation obtained with SAUN, SAUN+RGR and SAUN+LT parameterizations

Figures 2, 3 and 4 give an idea of the spatial locations of lightning flash initiations obtained with SAUN, SAUN+RGR and SAUN+LT parameterizations for cloud cases C1, C2 and C3 respectively.

Considering the results from Table 2 and Figures 2, 3 and 4 , one can see that the inclusion of the parameterizations at low liquid water content (SAUN+RGR), as well as low cloud temperatures (SAUN+LT) may affect as the maximum of the positive and negative total charge densities, as well as the lightning activity in the simulated cloud cases. However, the effect is in different directions. For example, the use of SAUN+RGR parameterization leads to a pronounced increase/decrease of the number of flashes in C1/C3 respectively and to an insignificant increase in C2. For case C1, using SAUN+RGR and SAUN+LT parameterizations does not affect the maximum positive total charge density, while the maximum negative total charge density is more than two times higher when the parameterizations that take into account the charging at low temperatures and effective water contents are used. This tendency is not observed for the other two clouds, where maxima of positive and negative total charge densities are comparable for the different parameterizations used. From the spatial locations of lightning initiations, shown in Figures 2, 3 and 4, it is seen that in case C1 (Figure 2), with the original SAUN parameterization, the region of flash initiation is wider in comparison to SAUN+RGR and SAUN+LT. All lightnings in this case are initiated above 9km (at cloud temperatures below -40ºC). With the SAUN+RGR parameterization the flash number is higher by about 20% than with SAUN (93 and 76 flashes respectively), but with SAUN+LT, it is lower with 20% (62 flashes). From Figure 3, it is clear that in case C2 flashes are triggered at the highest levels in the cloud when the SAUN+RGR parameterization is used (at above 10 km), while with SAUN+LT – at the lowest levels (at about 3km, which in fact is the only Cloud-to-Ground lightning obtained during the numerical simulations). Figure 4 does not show any visible differences in the spatial distribution of flash initiation for case C3 with the different parameterizations used. However, from Table 2 it is seen that the flash number obtained with SAUN+RGR decreases by 18% compared with SAUN (882 and 1079 respectively). A more detailed analysis showed that after 90 min MT, lightning triggered with SAUN+RGR are about 2 times fewer than with the other two parameterizations. During this period, their spatial location is at about 6 km height, which is in the temperature interval between -20 and -15 ºC, where parameterizations taking into account the charging at low temperatures or low effective water content should not affect the charging.

It is obvious that the impact of the charging in the glaciated cloud regions is very sensitive to the microphysical conditions in the cloud. It has to be stressed that at least for the three considered cloud cases, the effect of the use of SAUN+RGR and SAUN+LT parameterizations is more visible in lower altitude cloud regions than, as was expected, the upper regions, due to the intensive motions in the clouds, accompanied by mass transfers and then by electric charge exchanges.

CONCLUSIONS

In the present study the effect of the charge separation that may occur in glaciated cloud regions on thunderstorm electrification is evaluated. Two different parameterizations that take into account the charging at low effective cloud water content (Mitzeva et al. 2006) and at low cloud temperatures (Avila et al. 2011) are tested and results are compared with the results for cloud electrification obtained with the original parameterization of cloud charging with riming proposed by Saunders et al. [1991]. Three idealized cloud cases were simulated with MésoNH. The main conclusion that might be drawn from the preliminary evaluation of the results is that the impact of the charging in the glaciated cloud regions is very sensitive to the microphysical and dynamical cloud conditions. Its effect is more visible at lower altitude cloud regions, due to intensive motions in the clouds, accompanied by mass transfers and then by electric charge exchanges.

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