A MODELLING STUDY OF THE EFFECT OF CLOUD SUPERSATURATION ON NON-INDUCTIVE CHARGE TRANSFER IN THUNDERSTORM ELECTRIFICATION

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ABSTRACT: Numerical studies are under way into the impact of cloud supersaturation on the sign of non-inductive charge transfer during graupel/ice crystal interactions in thunderstorms. Results from laboratory studies have 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. The ice crystals grow by vapour diffusion in a supersaturated environment while the graupel surface may grow by diffusion under low accretion rate conditions, but will sublimate when heated sufficiently by riming. The graupel surface is also influenced, even under net sublimation conditions, by the vapour released to it from droplets freezing on its surface. In a cloud, the diffusional growth rates are also affected by ventilation as the supercooled droplets and their local environment flow past the riming surface.

The model is used to investigate the influence of supersaturation on the diffusional growth of riming graupel particles, then the sign of electric charge transferred during ice crystal collisions is determined according to the concept of relative vapour diffusional growth rates of the colliding particle surfaces, according to *Baker et al.,* 1987. The variable parameters available in the model may be adjusted to represent the environmental supersaturation conditions in various laboratory experiments and are used to determine charge sign sensitivity to supersaturation, temperature and the rate of rime accretion.

INTRODUCTION

The laboratory studies of *Reynolds et al.* [1957], *Takahashi* [1978], and *Jayaratne et al.* [1983], indicated how particle charging in thunderstorms may be associated with collisions between riming graupel and vapour grown ice crystals. Of importance to the present study is the conclusion from these studies that the sign of the charge transferred to a riming graupel pellet depends on the cloud temperature and LWC of the cloud. Later, *Jayaratne and Saunders* [1985] noted the importance to charge transfer of the liquid water captured by the graupel, known as the effective liquid water content, EW. The findings from the laboratory studies differed in detail; however, they all confirm that at cloud temperatures typically below about –10°C, with values of EW around 1 g m^{-3}, graupel tends to charge negatively. They all noted that an increase in EW at constant cloud temperature can reverse the sign of graupel charge to positive. This charge sign reversal, as a function of EW and T may help account for the observed charge structure in thunderstorms. A possible explanation of this charge sign reversal, the subject of this paper, may help lead to an understanding of the differences in results obtained in various laboratory simulations of this charging process.

Baker et al. [1987] suggested that the relative diffusional growth rates of the interacting graupel and crystals could control the sign of the charge transfer, such that the faster growing ice surface charges positively. The origins of this idea come from the many laboratory observations of non-riming ice particle collisions in which growing ice surfaces charge positively while sublimating ice surfaces charge negatively. *Baker et al.* considered the effect of vapour transfer to the local graupel surface from captured supercooled droplets freezing on the surface; the enhanced diffusional growth rate of the surface compared to that of the ice crystals leads to positive graupel. They also noted that, according to standard theory, a small ice crystal in a droplet cloud grows by diffusion at a higher rate than does a larger graupel surface, which favours negative graupel charging. Differences in surface characteristics and droplet freezing time under various cloud conditions were invoked to account for a change in charge transfer from one charge sign regime to the other.

Williams et al. [1991] pointed out that an effect of the freezing of supercooled droplets on the graupel is to heat it by latent heat release. The resulting decrease in the graupel diffusional growth rate below that of the colder, faster growing ice crystals may account for the negative charging of graupel. Laboratory studies of the charge transfer to artificially heated, but riming, ice surfaces (*Avila et al.* 1996, and *Saunders et al.* 1999) confirmed the effect. It was not clear from the work of *Williams et al.* how an increase in EW could reverse graupel charging to positive as noted in the laboratory experiments. Based on equations from *Baker et al.*, *Williams et al.* calculated that the vapour from a droplet freezing at 0°C on the graupel surface influences only a small local area of the colder graupel and that the chance of an ice crystal encountering this faster growing area during the brief droplet freezing time is very low.

Subsequent work by *Saunders et al.* [2001] suggested an important influence on the sign of charge transfer, driven by ice surface growth rates, of the water vapour content (saturation ratio) in the laboratory cloud. Experiments by *Saunders et al.,* [2003] also show how cloud supersaturation and cloud particle history can influence the charge sign reversal line, so that under appropriate conditions the line location on an EW/T plot may fit the laboratory determined charge reversal lines of *Takahashi* [1978], *Jayaratne et al.* [1983] and *Pereyra et al.* [2000]. Figure 8 shows the principal reversal line from *Saunders et al.* [1991] as an example.

The present work investigates numerically the effect on the relative growth rates of interacting graupel and crystal surfaces of the droplet cloud saturation ratio as a function of EW and temperature, involving the effect of rime heating, ventilation, and the enhanced capture of vapour from freezing droplets.

THE MODEL

The relative diffusional growth rate is calculated from the difference between the growth rate 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. The cloud temperature T_a remains constant throughout the run and the cloud equilibrium vapour density with respect to water, ρ_a, is also constant. The droplet cloud in the experiments is influenced by the presence of ice crystals, but may be replenished from a vapour source. In order to test the effect of cloud supersaturation, the Saturation Ratio with respect to water, Sw, may be assigned values and is used as a multiplier of ρ_a.

The far field diffusion equation is $\frac{dM}{dt}(\mathrm{f}) = F_f 4\pi C D_v \left(\rho_a(T_a) - \rho_i(T_g)\right)$ where F_f is the far field ventilation coefficient defined below, C is the shape factor with the particles assumed to be spherical, D_v is the vapour diffusion coefficient, $\rho_i(T_g)$ is the equilibrium vapour density over the graupel ice surface as a function of graupel temperature as influenced by the droplet accretion determined from EW and diffusional growth heating. The local vapour field growth equation is $\frac{dM}{dt}(1) = F_l 3 D_v \left(r_d . \sqrt[3]{2}\right)\left(\rho_a(T_m) - \rho_i(T_g)\right)\left(\frac{3 S_g . V . EW}{4\sigma_w . r_d^3}\right)\tau_f$

where F_l is the local field enhancement factor, r_d is the droplet radius, S_g is the graupel projected area, V the velocity, σ_w is the density of water. The droplet freezing time, τ_f, (from Pruppacher and Klett) is given by

$$(2\pi . f_h (L_v D_v (\rho_{wo} - \rho_w) - KT_a))\tau_f - \left(T_g K_i r_d \sqrt{\frac{\pi . c_i \sigma_g}{K_i}}\right)\sqrt{\tau_f} - \frac{2\pi}{3} r_d^2 \sigma_w L_m c_w T_a = 0$$

where K_l is the thermal conductivity of ice, σ_g is the density of the graupel and f_h is a ventilation coefficient calculated as $f_h = 1 + 0.108(Sc^{1/3}\,\mathrm{Re}^{1/2})^2$ if $Sc^{1/3}\,\mathrm{Re}^{1/2} < 1.4$ and $f_h = 0.78 + 0.308(Sc^{1/3}\,\mathrm{Re}^{1/2})$ if $Sc^{1/3}\,\mathrm{Re}^{1/2} \geq 1.4$. The ventilation coefficient for the growth rate of graupel from the far field f_f is assumed to equal f_h.

The graupel temperature is determined from the heating due to droplet accretion, *Macklin and Payne* [1967]. $EW_c V \frac{\left[L_f + c_w(T_a - T_m) + c_i(T_m - T_g)\right]}{4} = \chi \mathrm{Re}^{0.5} \frac{\left[\mathrm{Pr}^{1/3} K(T_g - T_a) + Sc^{1/3} D_v L_v (\rho_g(T_g) - \rho_a(T_a))\right]}{2R_g}$. The left hand side of the equation represents heat release and the right side is heat dissipation. χ is the numerical factor in the heat transfer coefficient and is determined from laboratory studies by *Castellano et al.* [1999]; $\chi = 0.6 + 0.83\exp(-5.17\ 10^{-7}\ d^4\ V)$ where d is the mean droplet volume diameter and v is the velocity. The crystal growth rate from the far field is $\frac{dM_{cr}}{dt} = \frac{4\pi R_{cr}(S_i - 1)}{\frac{L_s^2}{K R_v T_a^2} + \frac{R_v T_a}{E_{icr} D_v}}$ taking into account the heating effects associated with crystal growth.

Assuming that the graupel and ice crystals are spherical, linear growth rates, which are the controlling influence on charge transfer, are determined from: $\frac{dR_{(g/cr)}}{dt} = \frac{1}{4\pi R_{(g/cr)}\sigma} . \frac{dM_{(g/cr)}}{dt}$.

RESULTS

All the calculations have been made for the laboratory simulations of *Saunders et al.* [1991] with R_{gr}=2.5 mm, R_{cr}= 100 μm, V=3 m s^{-1} and r_{drops} =8 μm corresponding to Figure 8. Figures 1 and 2 show the diffusional growth rate of the graupel from the far and local vapour fields taking into account the ventilation factors as calculated above. A typical ventilation factor is around 11 and this value is applied to both far and local vapour fields. Figure 3 combines these rates. Figure 4 is the ice crystal growth rate while Figure 5 is the difference in growth rates between the graupel and ice crystals taking into account ventilation and assuming that the local factor, fl, equals the far field factor, ff. In these figures the effects of cloud vapour content is given in terms of the initial saturation ratio before riming starts, Sw, with respect to water. (Rime heating reduces the actual value of Sw but the cloud vapour content is assumed constant). Higher values of Sw increase the growth rates. Figure 5 shows entirely negative rimer charging; the crystals grow faster than the rimer everywhere. Figure 6 shows the effect of the graupel and crystals growing in diffusion fields with different vapour contents; this may simulate conditions under which local droplet growth is unhindered by crystal growth and the crystal may be growing in a separate local region with its own saturation ratio. The coming together of two interacting particles from different cloud growth conditions may be relevant to laboratory simulations as well as to specific regions in thunderclouds.

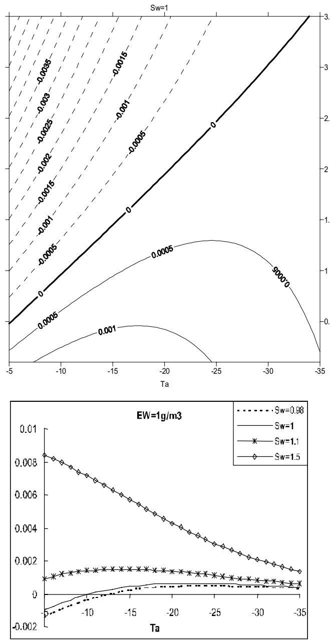

Fig 1. Far field graupel growth rate, dR_f/dt, as a function of T_a, *EW* and *Sw*. Rimer positive corresponds to positive rates in lower figure and solid lines in upper figure.

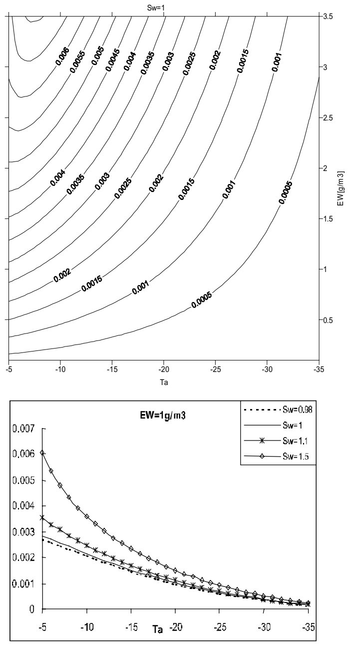

Fig 2. Local graupel growth rate dR_l/dt as a function of T_a, *EW* and *Sw*. Rimer positive in all cases.

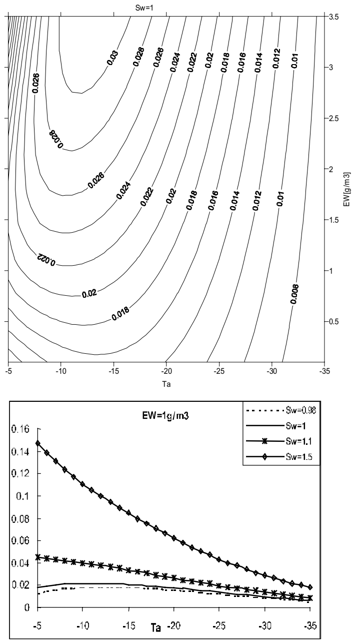

Fig 3. Graupel far and local field growth rate combined. Rimer positive in all cases.

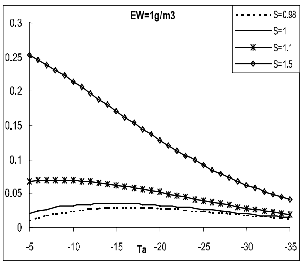

Fig 4. Growth rate of an ice crystal as a function of T_a, *EW* and *Sw*.

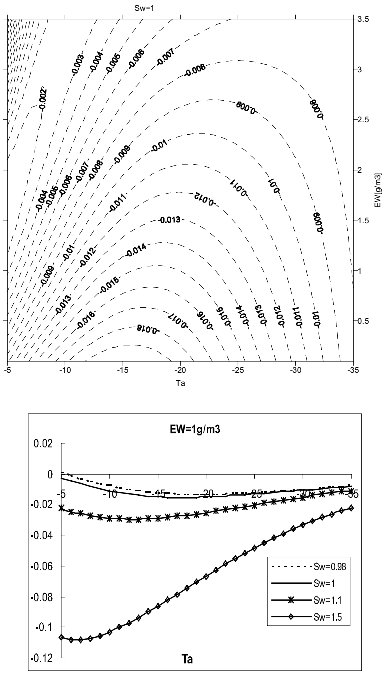

Fig 5. Relative growth rate of graupel and crystals as a function of T_a, *EW* and *Sw*. Crystals grow faster than graupel, which charges negatively (dashed lines).

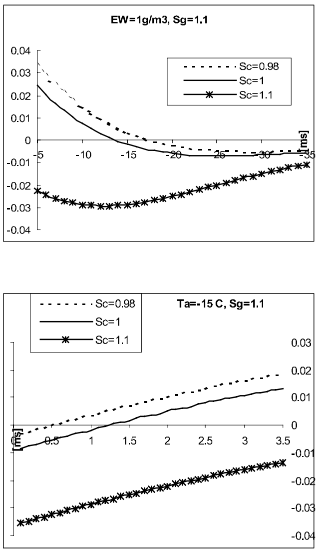

Fig 6. Relative growth rates of graupel and crystals for Swgraupel =1.1and various Swcrystals.
Upper graph – against temperature.
Lower graph – against EW.

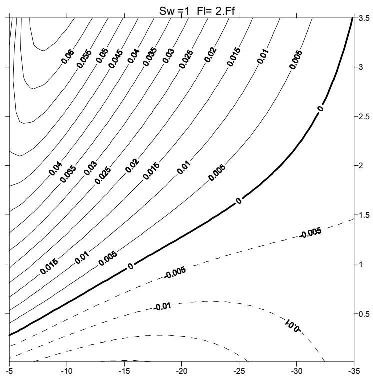

Fig 7. Relative growth rates of graupel and crystals against temperature and EW. Enhanced local vapour supply to rimer compared with Figure 5.

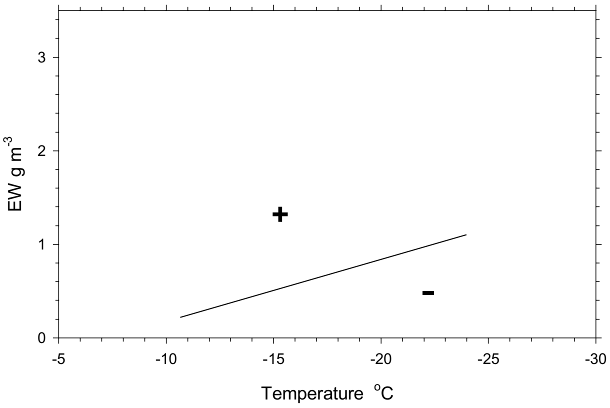

Fig 8. Charge transfer reversal line from Saunders et al. [1991] Above the reversal line graupel grows faster than the crystals and charges positively. Below the line, graupel grows slower than the crystals and charges negatively.

Figure 7 shows the effect of enhancing the local vapour field from the freezing droplets by allowing the graupel surface to capture additional vapour released in directions at small angles away from the rimer surface. This ensures that the graupel surface grows faster than the ice crystals and so charges positively. The resulting figure shows zones of relative growth rate that are similar in form to those obtained in laboratory studies of charge transfer, as shown in Figure 8 from *Saunders et al.* [1991]. Differences at low temperature may be attributed to non-modelled effects. Fine adjustments to the ventilation factors will improve the agreement.

CONCLUSIONS

Figures 7 and 8 show that a measure of agreement between the charge sign boundary as a function of cloud temperature and EW may be achieved by adjusting the far and local vapour diffusion fields affecting graupel growth. By suitable choice of ventilation factors it should be possible to model the charge reversal lines noted in other laboratory studies and hence help determine the cloud conditions critical to thunderstorm electrification.

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