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REGRESSION EQUATIONS OF NON-INDUCTIVE CHARGE TRANSFER BASED ON LABORATORY DATA

ATANAS MANCHEV, RUMJANA MITZEVA

Department of Meteorology and Geophysics

Атанас Манчев, Румяна Мицева. РЕГРЕСИОННИ УРАВНЕНИЯ ЗА НЕИНДУКТИВЕН ПРЕНОС НА ЗАРЯД ВЪЗ ОСНОВА НА ЛАБОРАТОРНИ ДАННИ

Чрез стъпков регресионен анализ са получени емпирични уравнения за пресмятане на стойността и знака на отделения товар при неиндуктивно наелектризиране на ледени кристалчета и градови зърна. Основен източник на използваните данни са лабораторните експерименти на Такахаши [1], който представя измерените стойности на отделения товар като изолинии, функции на температурата и водността в лабораторния облак. Като независими променливи освен температурата и водността в облака са тествани различни други променливи, които могат да бъдат пресметнати в числени модели на облак. Най-добро съответствие между измерените и пресметнатите стойности на отделения товар се получава при използване на четири регресионни уравнения в зависимост от границите на изменение на скоростта на обзърняне на градовите зърна. Анализът показва, че представените уравнения могат да бъдат използвани в числени модели на гръмотевичен облак за параметризация на неиндуктивен механизъм на наелектризиране.

Atanas Manchev, Rumjana Mitzeva. REGRESSION EQUATIONS OF NON-INDUCTIVE CHARGE TRANSFER BASED ON LABORATORY DATA

Set of empirical equations for the sign and magnitude of charge transfer at non-inductive rebounding collisions of ice crystal and graupel were obtained using stepwise regression analyses. The original source of data was Takahashi's laboratory experiment [1], who presented measured charge transfer values as isolines, function of cloud temperature and liquid water content. Several independent variables, which may be calculated in numerical cloud model, were tested together with liquid water content and cloud temperature. The best fit of calculated to the measured values of charge transfer was obtained by the use of four regression equations, depending of the range of changes of the graupel rime accretion rate. The analyses showed that the presented empirical equations could be used for the parameterization of non-inductive charging mechanism in numerical model of thunderstorm.

Keywords: non-inductive charge in clouds, stepwise regression analyses, numerical model of thunderstorm

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INTRODUCTION

It is now well accepted that the electric charge separation during non-inductive collisions between graupel and ice crystals is the major charge separation mechanism in thunderstorms. This mechanism, involving collisions between vapor grown ice crystals and riming graupel pellets, has been studied in extensive laboratory simulations by Takahashi [1], Saunders et al. [2], Brooks et al. [3], Pereyra et al. [4], Berdeklis and List [5], and others. One of the main goals of this kind of experiments was to obtaine information for the sign and magnitude of separated charge depending on in-cloud characteristics, which may be used in numerical models for the parameterization of thunderstorm electrification. The results in [2] and [5] are presented as a set of equations for the sign and magnitude of charge, function of effective liquid water content, EW, and cloud temperature, Tc. Based on the results in [3] the revised version of Saunders et al. (1991) equations is suggested by replacing EW by rime accretion rate $RAR = EW \cdot V$. The Takahashi's data however are given only on graph as an isolines of the separated charge, function of liquid water content, LWC and cloud temperature and can not be used directly in numerical models of thunderstorm. Helsdon et al. [6] extracted the values of charge transfer by interpolation of the given in [1] laboratory data and used them in numerical model of thunderstorm electrification. In our opinion the idea to increase the number of data by interpolation between available laboratory data is reasonable, but the use of the data in numerical model as assign values is rather ungainly.

The task of the present paper is to obtain equations for non-inductive charge transfer during rebounding collisions between ice crystals and a riming target, based on the results presented by Takahashi in [1], which may be used in numerical models of the development of thunderstorm electric fields.

DATA AND REGRESSION EQUATIONS

Wojcik [7] extracted values of charge transfer by interpolation between isolines of charge values presented in Fig. 1 in [1]. He obtained 930 values for charge transfer at LWC between 0.01 and 30 $\mathrm{g\,m^{-3}}$ and cloud temperatures between 0°C and −30°C. For the aim of our paper we used part of his sample. The data at LWC greater than 10 $\mathrm{g\,m^{-3}}$ and at cloud temperature higher than −10°C were excluded from the sample used in our paper. The reason for elimination of the data at LWC >10 $\mathrm{g\,m^{-3}}$ is the fact that in a real clouds the measured LWC is less than 10 $\mathrm{g\,m^{-3}}$. The charge values at $Tc > -10$°C in Takahashi's measurements [1] were positive for all LWC and the correlation coefficient between predicted and measured charge transfer were lower when the sample contains values at $Tc > -10$°C. In such a way the obtained equations will be valid at cloud temperaturelower than −10°C. This restriction is acceptable because in real clouds at $Tc > -10$°C there are no ice crystals and graupel, or their number is insignificant during the growth stage of thunderstorms when the non-inductive mechanism plays a major role in the build up of electric field of thunderstorms. As a result the truncated sample used at our analyses contains 588 charge values Q at temperatures between $-10°$C and $-30°$C and LWC between 0.01 and 10 $\mathrm{g\,m^{-3}}$. The idea for data used by us gives Fig. 1 where isolines of charge transfer as a function of cloud temperature Tc and LWC are shown. One can see that the charge is positive at low and high LWC and negative at intermediate values of LWC, and that the maximum magnitude of negative charge is at temperature $-14°$C to $-15°$C and $LWC = 2$ $\mathrm{g\,m^{-3}}$. The dependence of charge transfer on LWC at different temperatures is more pronounced at Fig. 2. The shape of the graphs at different temperatures is similar but the transition from positive to negative and then to positive charge is at different values of LWC.

To obtain empirical equation for charge transfer as a function of in-cloud characteristics several parameters and their combination, which may be calculated principally in numerical cloud models, were tested as independent variables in stepwise regression analysis. It is worth to be mentioned that based on [3] instead of LWC we used rime accretion rate RAR as more meaningful parameter for charge transfer than LWC, where

$$RAR = E_c \cdot LWC \cdot V,$$

E_c is collision efficiency, and V is graupel velocity. Since we used constant values for $E_c = 0.8$ and V =9 m/s (the corresponding fixed values were used in [1]), RAR is practically LWC multiplied by 7.2. This means that the charge in our sample will depend in one and the same way on LWC and on RAR. In the cloud models, however, E_c and V vary in space and time and according to (3) the use of RAR in the charge transfer equations is more reasonable than the use of LWC.

Due to the complicated changes of sign and magnitude of charge at different RAR and Tc the efforts to describe the behavior of charge transfer as a function of in-cloud characteristics with one equation failed.

One of the best set of equations (with higher correlation coefficients between predicted and measured values) for charge transfer obtained in our analysis is:

At $RAR \leq 12$ $\mathrm{g\,m^{-2}s^{-1}}$

$$\begin{aligned} Q = {} & 207.033 + 38.785Tc + 2.617Tc^2 + 0.079Tc^3 + 0.000899Tc^4 \\ & + 4.152RAR - 0.867RAR^2 + 0.0544RAR^3 - 0.000977RAR^4 \\ & - 53.67P + 51.702P^2 - 15.421P^3. \end{aligned} \tag{1}$$

At $12 < RAR < 60$ $\mathrm{g\,m^{-2}s^{-1}}$

$$\begin{aligned} Q = {} & 58.12 + 5.51Tc + 0.209Tc^2 + 0.00276Tc^3 \\ & - 4.22RAR + 0.256RAR^2 - 0.00549RAR^3 + 0.00005RAR^4. \end{aligned} \tag{2}$$

If the calculated by Eq.(2) charge is negative, then at $RAR > 12$ $\mathrm{g\,m^{-2}s^{-1}}$

$$\begin{aligned} Q = {} & 58.12 + 5.51Tc + 0.209Tc^2 + 0.00276Tc^3 \\ & - 4.22RAR + 0.256RAR^2 - 0.00549RAR^3 + 0.000051RAR^4. \end{aligned} \tag{3}$$

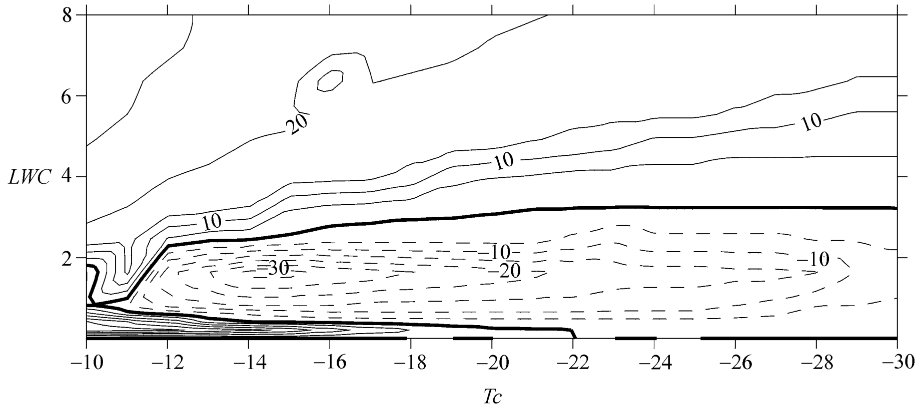

Fig. 1. Laboratory charge values as a function of liquid water content, LWC and temperature, Tc for the sample used in the study. Solid lines—positive charge, dashed lines—negative charge

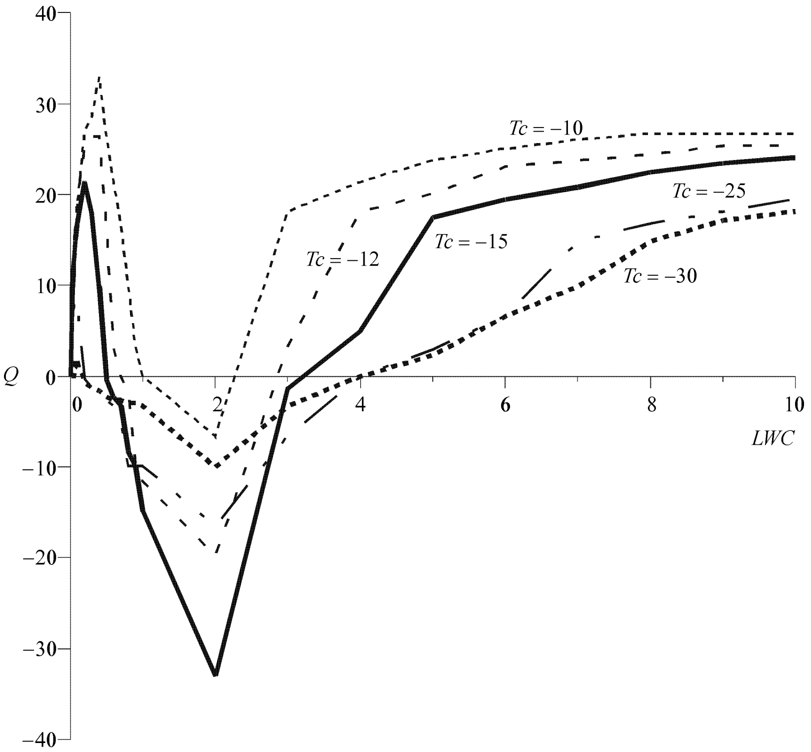

Fig. 2. Laboratory data for the charge as a function of LWC at different cloud temperatures Tc for the sample in the study

At $RAR \geq 60\ \mathrm{g\,m^{-2}s^{-1}}$

$$Q = 31.405 + 0.7687Tc - 0.00465Tc \cdot RAR + 0.000012Tc \cdot RAR^2. \qquad (4)$$

Here $P = e_i(Tc) - e_w(Tc)$, where $e_w(Tc)$ and $e_i(Tc)$ are saturation vapor pressure at temperature Tc with respect to water and ice, respectively, measured in hPa. Eq.(1) describes the positive charge at $RAR < 12\ \mathrm{g\,m^{-2}s^{-1}}$ and gives the transition from positive to negative sign of charge transfer. Eq.(2) gives the positive charge values at $12 < RAR < 60\ \mathrm{g\,m^{-2}s^{-1}}$ and transition from negative to positive charge. If according to Eq.(2) charge is negative one has to use Eq.(3). Eq.(4) has to be used at $RAR > 60\ \mathrm{g\,m^{-2}s^{-1}}$ and it gives always positive charge.

DISSCUSSION AND CONCLUSIONS

On Fig. 3 the measured (solid line) and calculated by Eqs (1–4) charge transfer as a function of RAR at different cloud temperatures is presented. The results show that the critical values of RAR, at which the sign of charge changes, determined by the empirical equations (from positive to negative—Eq.(1), from negative to positive—Eq.(2)) coincide with the measured values for all cloud temperatures higher than -10°C. The magnitude of positive charge transfer is also well determined by empirical equations. The magnitude of negative charge calculated by the equations is underestimated for temperatures $Tc < -25$°C and it is overestimated for $Tc < -25$°C. The maximum of the magnitude of the measured negative charge is at -14 to -15°C, while the maximum calculated by the equations is at $Tc = -12$°C. Eqs. (1–4) give the magnitude and sign of charge transfer to one graupel by collision with one ice crystals with diameter $d = 40\ \mu$m (which is the average ice crystal size in [1]). In numerical models the magnitude of charge will be bigger at higher concentration of ice crystals and graupel. Since there is only insignificant amount of ice crystals and graupel at temperatures $Tc \leq -10$°C, it is expected that the influence of the discrepancy between measured and calculated charge at $Tc = -10$°C on the net charge will be also insignificant. The effect of overestimation and underestimation of the magnitude of negative charge given by regression equations on the net charge in thunderstorm can not be supposed. For the estimation of this effect one can compare the outputs of numerical simulations of cloud cases with parameterization of non-inductive charging based on Eqs. (1–4) and with parameterization in which Eq.(3) and Eq.(4) are multiplied or divided by proper factor depending on the cloud temperature. The study in [8] showed that the empirical equations in which the graupel surface temperature T_g (rather than Tc) was used for the calculations of saturated vapor pressure over ice (i.e. $e_i(T_g)$ instead of $e_i(Tc)$) give negative charge values closer to laboratory data and the maximum magnitude of negative charge was at $Tc = -15$°C. However, in most numerical models the graupel surface temperature is not calculated, so the equations presented here are more general than the equations in which the graupel surface temperature is used. When the Eqs. (1–4) are used for the parameterizations of

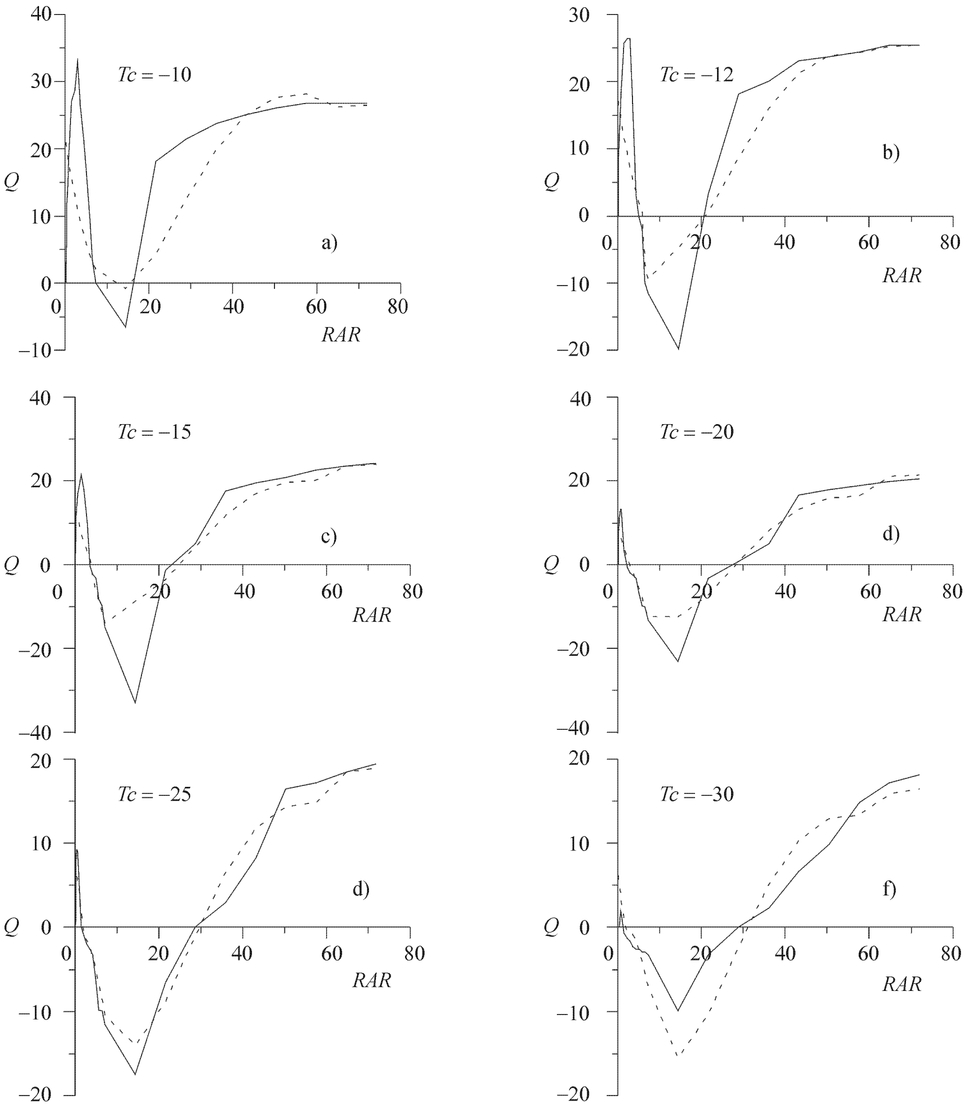

Fig. 3. Charge values, Q [fC], as a function of RAR [$\mathrm{g\,m^{-2}s^{-1}}$] for different cloud temperature, Tc. Solid line—laboratory Takahashi's 1978 data (interpolated by Wojcik, 1995), dashed line—calculated by the regresion equations

non-inductive charging, one has to take into account that the regression equations proposed in this paper are valid for the condition of laboratory experiments in [1]. According to [2] the magnitude of charge depends on crystal diameter d, and graupel velocity V in a following way:

$$Q = B \cdot V^a d^b q,$$

where a and b are different constants depending on crystal size d, and q is the normalized charge transfer function of in-cloud characteristics. This means that before using the above equations in numerical models, B and Q should be estimated, taking into account that the laboratory experiments in [1] were carried out with $V = 9\ \mathrm{m\,s^{-1}}$ and the average volume ice crystal diameter was $d = 40\ \mu\mathrm{m}$.

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Rumjana Mitzeva
St. Kliment Ohridski University of Sofia
Faculty of Physics
Department of Meteorology and Geophisics
5 James Bourchier Blvd.
BG-1164 Sofia, Bulgaria
E-mail: rumypm@phys.uni-sofia.bg