Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

A numerical study of aerosol effects on electrification of thunderstorms

Y.B. Tan [a,b,*], Z. Shi [a,b], Z.L. Chen [a,b], L. Peng [a,b], Y. Yang [a,b], X.F. Guo [a,b], H.R. Chen [a,b]

[a] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China

[b] Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science and Technology, Nanjing 210044, China

ARTICLE INFO

Article history:
Received 24 January 2015
Received in revised form
7 September 2015
Accepted 9 November 2015

Keywords:
Aerosol
Non-inductive charging
Inductive charging
Thunderstorms
Numerical simulation

ABSTRACT

Numerical simulations are performed to investigate the effect of aerosol on microphysical and electrification in thunderstorm clouds. A two-dimensional (2-D) cumulus model with electrification scheme including non-inductive and inductive charge separation is used. The concentration of aerosol particles with distribution fitted by superimposing three log-normal distributions rises from 50 to 10,000 cm^{-3}. The results show that the response of charge separation rate to the increase of aerosol concentration is nonmonotonic. When aerosol concentration is changed from 50 to 1000 cm^{-3}, a stronger formation of cloud droplet, graupel and ice crystal results in increasing charge separation via non-inductive and inductive mechanism. However, in the range of 1000–3000 cm^{-3}, vapor competition arises in the decrease of ice crystal mixing ratio and the reduction of ice crystals size leads to a slightly decrease in non-inductive charge rate, while inductive charging rate has no significant change in magnitude. Above aerosol concentration of 3000 cm^{-3}, the magnitude of charging rate which keeps steady is insensitive to the increase in aerosol concentration. The results also suggest that non-inductive charge separation between ice crystal and graupel contributes to the main upper positive charge region and the middle negative charge region. Inductive graupel–cloud droplet charge separation, on the other hand, is found to play an important role in the development of lower charge region.

1. Introduction

Many studies have been devoted to space charge distributions in thunderstorms, which are closely related to the characteristics of lightning discharges (Carey and Rutledge, 1998; Coleman et al., 2003; Qie et al., 2005; Tan et al., 2006, 2012, 2014a, 2014b). A host of observations of soundings of the electric field demonstrate that the complex charge structure usually including four to ten charge layers in thunderstorms (Marshall and Rust, 1991; Rust and Marshall, 1996). However, it is difficult to fully understand the process of charge structure evolution and the origin of charge generation. At present, many cloud models coupled with charge separation mechanism have been explored to discuss the profiles of space electric field and charge structure in the evolution of a thundercloud (Takahashi, 1984; Rawlins, 1982; Helsdon et al., 2002; Mansell et al., 2005). As all various electrification mechanisms are majorly dependent on environment temperature, hydrometeors concentration and size spectrum (Takahashi, 1978; Jayaratne et al., 1983; Saunders et al., 1991; Ziegler et al., 1991; Saunders and Peck, 1998), the validity of microphysics and hydrometeors is one of the key factors for simulating charge structure. Furthermore, the impacts of aerosols on cloud microphysics and hydrometeors concentration and size spectrum are reasonably well understood (Khain et al., 1999; Yin et al., 2000; Wang, 2005; Fan et al., 2007; Li et al., 2008). Thus, aerosols act as cloud condensation nuclei (CCN) perhaps have greatly effect on the charge structure in thunderclouds.

An in-depth study of storm electrification requires numerical simulations. The parameterizations of charging mechanisms by which hydrometeors acquire charge are involved in cloud model. Most of the related electrification parameterizations based on laboratory studies can be classified into inductive charging parameterization and non-inductive charging parameterization. The drop-ice interaction is considered as a primary inductive mechanism (Aufdermauer and Johnson, 1972; Moore, 1975), and the inductive charge transfer between two particles is connect with particles radius, the falling velocities, collision angle and environmental electric field (Mason, 1988). In addition, non-inductive charge separation can be considered as a primary mechanism in thunderclouds, meanwhile several non-inductive parameterizations based on the laboratory results (Takahashi,

* Corresponding author at: Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China.
E-mail address: ybtan@ustc.edu (Y.B. Tan).

http://dx.doi.org/10.1016/j.jastp.2015.11.006
1364-6826/

1978; Gardiner et al., 1985; Jayaratne et al., 1983; Saunders et al., 1991; Brooks et al., 1997; Saunders and Peck, 1998) are put forward to simulate charge separation via rebounding graupel–ice collisions. Although the comparison of these laboratory-based parameterizations in a full simulation model (with coupled dynamics and microphysics) has revealed significant differences between the results (Mansell et al., 2005), the sign and magnitude of electric charge separated during collisions between ice-phase particles highly generally depends on temperature, relative velocity of the collisions, hydrometeors concentration and the supercooled droplet size spectrum (Takahashi, 1978; Gardiner et al., 1985; Jayaratne et al., 1983; Saunders et al., 1991; Brooks et al., 1997; Saunders and Peck, 1998). In general, charge separation is closely related to microphysics and hydrometeors properties of thunderclouds. It is well-know that aerosols can change dynamical, microphysical, and hydrometeors properties of cloud (Khain et al., 1999; Yin et al., 2000; Wang, 2005; Fan et al., 2007; Li et al., 2008). How aerosols affect electrification process in thunderclouds? However, at present very few previous simulation studies of aerosols effects have been performed in cumulus electrification model.

In recent years, considerable progress has been made in understanding aerosols, their microphysical properties, and the factors that enable them to act as cloud condensation nuclei (CCN) (Twomey, 1974; Albrecht, 1989). As a result, aerosols exert a substantial influence on the microphysical properties of warm and cold clouds. Some observations and numerical simulations reveal that greater concentrations of aerosols result in the production of more small cloud droplets and reduced collision efficiencies, which can delay the formation of raindrops (Brenguier et al., 2000; Durkee et al., 2000; Yin et al., 2000; Nakajima et al., 2001; Ramanathan et al., 2001; Feingold, 2003; Jirak and Cotton, 2006). On the other hand, aerosol concentrations have a substantial impact on mixed convective clouds (Khain et al., 1999; Lynn et al., 2005; Seifert and Beheng, 2006; Wang, 2005; Fan et al., 2007; Li et al., 2008). Increase in the concentration of aerosol particles leads to higher vertical velocities; more super-cooled liquid water and increases in large ice-phase hydrometeor particles concentrations (Van den Heever et al., 2006; Yang et al., 2011). Aerosols, therefore, not only affect the microphysical development in clouds but also have influence on the physical characteristics of hydrometeor particles. As the mechanisms of thunderstorm electrification is intrinsically linked to microphysics and hydrometeor particles, the possible effects of aerosols particles on thunderstorm electrification should be studied with cloud models.

Some models have discussed below include aerosols and electrification process. A study by Takahashi (1984), who used a spectral bin dynamic model to study the effects of maritime (low) CCN and continental (high) CCN on electrification, suggested that aerosols might be responsible for significant enhancement for electrification for the continental CCN. Mitzeva et al. (2006) performed a 1D bulk-water model to investigate differences between the early electrical development of maritime and continental thunderstorms, and found that updraft enhancement, greater ice production, and stronger electrification with continental aerosol content compared to maritime. The influence of IN (ice nuclei) bacteria on thunderstorm structure and lightning formation has been studied using a regional atmospheric model, and a relationship between lightning rates and maximum cloud updraft was taken into account on the storm dynamics (Gonçalves et al., 2012). A recent study by Wang et al. (2011) revealed the impact of aerosols on precipitation and lightning under polluted aerosol and clean aerosol conditions with a two-moment bulk microphysical scheme. In addition, another recent numerical study by Mansell and Ziegler (2013) investigated the responses of storm precipitation, electrification and lightning to increasing aerosol concentrations using a 3-D bulk cloud model.

The aim of this paper is to present sensitivity studies of aerosol concentration on thunderstorm microphysics and electrification. For this purpose, a two-dimensional cumulus model with detail cloud microphysics and electrification scheme is used. Numerical experiments are mainly tested for the relationship between aerosol concentration and electrification in thunderstorms.

2. Simulation method

2.1. Thundercloud model and simulation background

This study used a 2-D Cartesian cumulus model, developed by the Chinese Academy of Meteorological Sciences (Hu and He, 1987). It is a non-hydrostatic cumulus model. Prognostic equations are included for momentum, pressure, potential temperature, and cloud droplet spectral width which is used to calculate the conversion of cloud droplet to rain. There are also conservation equations for mass ratio and concentration ratio of hydrometeors. The microphysics package is a multi-category, double moment scheme. It has five hydrometeor categories, which are cloud droplet, rain, ice crystal, graupel and hail. These particles are all assumed to have a gamma function distribution of diameter (See Appendix A).

The main cloud physical processes are condensation and evaporation, collision, autoconversion, nucleation and multiplication, melting and freeze, and the model includes 27 kinds of microphysical processes of cumulus. The 27 kinds of microphysical processes are: condensation and evaporation of ice crystal, rain, cloud droplet, graupel, and hail; collision between cloud droplet and ice crystal, rain, graupel, as well as hail; collision between rain and ice crystal; collision between rain and graupel, and hail; collision between ice crystal and graupel, and hail; nucleation and multiplication of ice crystal; autoconversions of cloud–rain, ice–graupel, and graupel–hail; freeze of rain into hail; melting of graupel, hail, and ice into rain; collection of ice, collection of rain, and welt growth of graupel.

To better understand the effect of aerosol on cloud microphysical processes, we made some improvements to the model. As

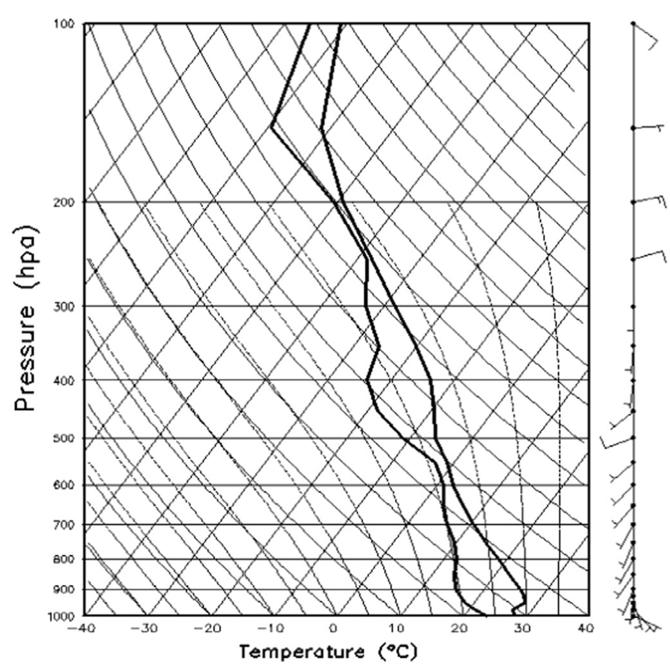

Fig. 1. Environmental sounding used for the simulation of thunderstorm clouds.

Please cite this article as: Tan, Y.B., et al., A numerical study of aerosol effects on electrification of thunderstorms. Journal of Atmospheric and Solar-Terrestrial Physics (2015), http://dx.doi.org/10.1016/j.jastp.2015.11.006