Atmospheric Research 153 (2015) 376–391

Contents lists available at ScienceDirect

Atmospheric Research

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

The effects of aerosol on development of thunderstorm electrification: A numerical study

Pengguo Zhao [a,b], Yan Yin [a,b,*], Hui Xiao [b]

[a] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing 210044, China
[b] Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science & Technology, Nanjing 210044, China

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form 28 August 2014
Accepted 29 September 2014
Available online 7 October 2014

Keywords:
Mesoscale model
Aerosol effects
Electrification
Charge structure

ABSTRACT

The effects of aerosol on electrification of an idealized supercell storm are investigated using the Weather Research and Forecasting model coupled with electrification and discharge parameterizations and an explicit treatment of aerosol activation. It is found that the microphysical and electric processes of the thunderstorm are distinctly different under different aerosol background. Enhancing aerosol loading increases growth rate of snow and graupel particles, and leads to higher concentration of ice particles. Increasing aerosol concentration also results in enhancement in electrification process, due to more ice particles participating in the electrification process in the polluted case. In the clean case, the charge structure maintained dipolarity throughout the simulation, while in the polluted case the charge structure transformed from dipolarity at the initial stage of charging separation to the structure of a negative charge region above the main positive and the main negative charge centers at the later stage. A detailed analysis of the microphysical processes shows that increasing aerosol loading led to more liquid water content and higher rime accretion rate above the freezing level, which was in favor of graupel charge positively and ice crystal and snow charge negatively in this region. In a word, increasing aerosol loading leads to increased cloud water content, resulting in a new negative charge region developed above the main positive charge center.

1. Introduction

The effects of aerosol on cloud microphysical processes and precipitation have attracted much attention during the last decades (Rosenfeld, 1999; Yin et al., 2000; Li et al., 2011). Some observations (Pinto et al., 2004; Bell et al., 2008; Rosenfeld et al., 2012) showed that aerosols may play a primary role in enhancing lightning activities, while the effects of aerosol on electrical processes of thunderstorm have been rarely discussed in model simulations. In this study, the evolution of electric processes and microphysics under different aerosol background are discussed with the Weather Research and Forecasting (WRF) model coupled with an explicit aerosol activation scheme and electrification and discharge processes.

Laboratory investigations (Reynolds et al., 1957; Takahashi, 1978; Saunders et al., 1991) and simulation studies (Takahashi, 1983; Helsdon et al., 2001; Mansell et al., 2005) confirmed that the main charging process of thunderstorm is caused by rebounding collisions between ice crystals and graupel particles in the mixed-phase region. Numerous microphysical characteristics affect the polarity and magnitude of the electrification processes of thunderstorm. Baker et al. (1987) proposed the Relative Diffusional Growth Rate theory to explain charge transferring mechanisms, and indicated that ice particles with greater surface growth rates would charge positively during collision separation processes. The growth

* Corresponding author at: Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science & Technology, 219 Ningliu Road, Nanjing 210044, China. Tel.: +86 25 58731207.
E-mail address: yinyan@nuist.edu.cn (Y. Yin).

http://dx.doi.org/10.1016/j.atmosres.2014.09.011
0169-8095/

rate of ice crystals is inversely proportional to the particle size, hence the charging positively temperature range of graupel collided and separated with larger ice crystal increases (Emersic and Saunders, 2010). Keith and Saunders (1990) showed that the magnitude of charge transferred to graupel is positively correlated to the size of ice crystals, while the positive charge of graupel particles is closely related to the larger ice crystals of irregular shapes (Avila et al., 2005). Laboratory study (Emersic and Saunders, 2010) showed that increase in cloud droplets could lead to negative graupel charging at higher temperature. The model study by Mitzeva et al. (2005) showed that increasing effective liquid water content lead to the sign of graupel charge reversing from negative to positive, while Avila et al. (1999) indicated that droplet size also influences charge transfer. Graupel particle charges positively under smaller droplet environment all the time, while charges negatively at temperatures below −18 °C under larger droplet environment. Saunders et al. (2001) showed that the ice crystal and graupel sublimate when liquid water content is low, and ice particles which sublimate fastest charge negatively. Aerosol connects with the above-mentioned microphysical properties, therefore, it can affect the electrification process of thunderstorm.

It is well-known that aerosol and thermal condition might be responsible for the differences in electrification process between maritime and continental thunderstorm (Christian et al., 2003). The concentration of cloud droplets in maritime clouds are significantly smaller than that in continental clouds. The large maritime cloud-droplet size is beneficial to warm rain process, while the more numerous but smaller size of cloud droplets in continental clouds had lower efficiency of collision–coalescence and can be risen up to mixed-phase region with updraft (Williams and Stanfill, 2002; Williams et al., 2004). Mitzeva et al. (2006) discussed the differences of early electrical processes between continental and maritime thunderstorms by a 1D cloud model. The results showed that there was more liquid water in the mixed-phase region and more ice particles enhancing the charging process of thunderstorm. Other researches (Khain et al., 2008, 2010; Rosenfeld et al., 2012) reported that an increase in aerosol concentration might intensify the lightning activities in tropical cyclones.

The lightning activities over and downwind of urban area is stronger than that over suburb, and a positive linear correlation is found between lightning frequency and a higher concentration of SO_2 and PM_{10}, supporting that aerosols play a key role in the increase of liquid water content and ice particles in the mixed-phase region and lightning activity (e.g., Orville et al., 2001; Naccarato et al., 2003; Pinto et al., 2004; Kar et al., 2009; Farias et al., 2009). By analyzing long-term TRMM data, Bell et al. (2008) found a positive correlation between surface aerosol concentration and thunderstorm activities during summer weekday in the northeastern United States. The study of Stallins et al. (2013) indicated that there is a greater amount of cloud to ground (C–G) flash around the urban region in weekdays with higher anthropogenic aerosol concentration. Statistical analysis by Wang et al. (2011) about lightning flash and visibility from 2000 to 2006 over the Pearl River Delta in China showed that lightning density is negatively correlated to visibility. Their simulations indicated that aerosol loading enhanced the lightning potential index. Middey and Chaudhuri (2013) and Chaudhuri and Middey (2013) found that increasing the surface pollution in a near thunderstorm environment resulted in magnified lightning flash rate by analyzing the relation between pollution and lightning activities over Kolkata. Siingh et al. (2014) also showed the positive correlation between aerosol concentration and total lightning frequency in different areas of India. Strikas and Elsner (2013) indicated a threefold enhancement in C–G lightning occurrence near coal plants and highway as a result of pollutant emission. Yuan et al. (2011) adduced satellite-based evidence that increasing aerosols loading resulted in enhanced lightning and inconspicuous variation in the meteorology. Takahashi (1984) showed dramatic enhancement in electrification and precipitation with larger CCN concentration by an axisymmetric model.

Mansell and Ziegler (2013) used an empirical expression ($N = CCN \times S^k$) for aerosol supersaturation activation spectrum to study the evolution of electric processes under the transition from low to high CCN concentration. This empirical expression of aerosol activation neither consider the connection between the number of droplet nucleated and fundamental aerosol parameters such as mean size of aerosol and aerosol number nor felicitously describe the number of droplet nucleated under low concentration aerosol or high updraft velocity environment because of the relation between number of droplet nucleated and supersaturation is not consistent with the simple activation spectrum (Abdul-Razzak et al., 1998). Mansell and Ziegler (2013) focused on the sensitivity of graupel initiation, graupel density, electrification and lightning with the transition of CCN concentration from low to moderate and moderate to extremely high (50–5000 cm^{-3}). They found that the higher CCN concentration (1500 cm^{-3}) results in stronger lightning activity, while further increases (2000–5000 cm^{-3}) lead to reducing the electrification and lightning activity.

The previous studies rarely discussed the aerosol effects with considering explicit activation and electrification in the model simultaneously. The reasonability of initial CCN concentrations without considering observed results was dubious. Some previous studies (Mitzeva et al., 2006; Mansell and Ziegler, 2013; Wang et al., 2013) focus on discussing the effect of aerosol on enhancing lightning activities, rarely discussing the effect of aerosol on charge structure and analyzing the reasons.

In this study, we employed a more accurate parameterization (Abdul-Razzak et al., 1998) of aerosol activation to connect the number of aerosol activated immediately with the fundamental features of aerosol and environment such as aerosol size, total aerosol concentration and supersaturation. We coupled the explicit aerosol activation and electric processes with the WRF model to investigate the impact of the different aerosol environment on electrical development of the thunderstorm. Based on the aerosol activation and electric processes, we focus on the microphysical processes under different aerosol background and the effects of microphysical processes on electric characteristics such as charge density and charge structure.

2. A brief description of the model

The WRF (version 3.4) model coupled with an aerosol activation scheme and two-moment bulk mixed-phase microphysics scheme (Morrison et al., 2005; Morrison and