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A numerical study of the positive cloud-to-ground flash from the forward flank of normal polarity thunderstorm

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ABSTRACT

This study investigates the electrical conditions favorable to the occurrence of positive cloud-to-ground (+CG) flashes from the forward flank of normal polarity thunderstorm by building a three-dimensional stochastic lightning model and a normal polarity charge structure model. The lightning model well simulated the bilevel branched structure of lightning flash, which has been observed by previous studies. Simulation results indicate that the downshear extension of the charge layer to the forward flank would decrease the electric field of thunderstorm. When only the upper positive charge layer downshear extended to the forward flank, it could not give rise to the occurrence of +CG flashes. When both the upper positive and midlevel negative charge layers downshear extended to the forward flank, if the charge of the negative charge layer was less than the positive charge layer above it in the forward flank of the thunderstorm, that generated sufficient charge imbalance between these two charge layers, +CG flashes could originate from the forward flank; otherwise, IC flashes occur.

1. Introduction

Negative cloud-to-ground (−CG) flashes are common in summer thunderstorms, and they account for about 90% of all cloud-to-ground (CG) flashes worldwide (Rakov, 2003). However, the positive cloud-to-ground (+CG) flashes that neutralized positive charge in clouds will occur at some stages in some regions of certain thunderstorms. Berger (1967) first identified the +CG flashes in strikes to towers on Mount San Salvatore, Lugano, Switzerland. Kuk et al. (2010) measured the current of lightning flashes over the Korean peninsula and found the monthly maximum median peak current of +CG flashes was nearly four times than that of −CG flashes. Existing studies showed the characteristics of +CG flashes with high peak current and long continuous current (e.g., Xie et al., 2013). CG flashes are responsible for a great proportion of the fatalities, injuries, and property loss caused by natural hazards (e.g., Matsangouras et al., 2015). Compared with −CG flashes, +CG flashes are likely to radiate more electromagnetic field energy and cause more damage (e.g., Zhang et al., 2009a, 2009b, 2011a, 2011b). Latham and Williams (2001) considered that since +CG flashes often have higher current, they may be more likely to ignite forest fires than −CG flashes.

Numerous investigations have shown that +CG flashes may be an important indicator of certain phenomena associated with thunderstorms. Carey et al. (2003a) found that the +CG flash rate and percentage of +CG flash in the Spencer supercell increased dramatically while the storm was producing severe tornadic damage. Statistics showed that thunderstorms generating more +CG flashes tended to develop into severe thunderstorms (e.g., Reap and MacGorman, 1989; Branick and Doswell, 1992). The +CG flash-dominated thunderstorms often produced large hail (e.g., Stolzenburg, 1994; Carey et al., 2003a; Feng et al., 2009). However, a more general assessment of Carey et al. (2003b) showed the relationship between the storm severity and frequency of +CG flash varied considerably. The large amplitude, destructive characteristics, and indicating effect of +CG flashes on severe weather phenomenon make understanding the cause of +CG flashes being an important issue.

Charge structures and scenarios giving rise to the production of +CG flash have been investigated extensively (e.g., Brook et al., 1982; Wiens et al., 2005; Kuhlman et al., 2006; Tessendorf and Rutledge, 2007; Qie et al., 2009; Lu et al., 2009; Zhang et al., 2013; Kong et al., 2015). Hypotheses of charge structures causing +CG flash were reviewed by Williams (2001) and Nag and Rakov (2012). One of the hypotheses is the inverted charge structure which has an inverted charge region inside the thundercloud compared to the normal polarity charge

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structure. Observations of the Severe Thunderstorm Electrification and Precipitation Study (STEPS) program (Rust and MacGorman, 2002; Lang et al., 2004; Wiens et al., 2005) suggested the production of dominant +CG flashes during the STEPS were explained by an inverted dipole structure. The presence of the lower positive charge region beneath the main negative charge region is thought to be essential for the production of −CG flash in a tripole charge structure thunderstorm (e.g., Williams, 1989; Qie et al., 2005a, 2005b; Nag and Rakov, 2009). It was also found that a lower negative charge region at the bottom of a thundercloud is needed to facilitate +CG flashes initiating in an inverted charge structure (Mansell et al., 2002; Wiens et al., 2005; Zhang et al., 2006; Kuhlman et al., 2006; Fierro et al., 2006; Tessendorf and Rutledge, 2007). This lower negative charge region in the inverted charge structure plays the same role of the lower positive charge region in the normal tripole charge structure, forming the local strong electric field to initiate lightning.

Observations and simulations revealed that +CG flash can originate from a normal polarity storm (e.g., Rust et al., 1981; Shafer et al., 2000; Mansell et al., 2005; Fierro et al., 2006; Tan et al., 2012; Weiss et al., 2012). In some situations high +CG flash rates tend to originate outside the largest radar reflectivity and in the regions of downshear flank or anvil of the thunderstorm (Rust et al., 1981; Shafer et al., 2000; Fierro et al., 2006; Weiss et al., 2012). Some studies took the tilted charge structure account for that phenomenon, that is, the positively charged upper region of the thunderstorm is displaced downshear to the forward flank due to the strong wind shear, so the negative charge region does not shield the positive charge region overhead from the ground anymore, +CG flash can originate from the displaced positive charge region (Brook et al., 1982). As discussed above, in the inverted tripole charge structure, the presence of the lower negative charge region beneath the main positive charge region is thought to enhance the local electric field, which provides the initiation of positive discharge to the ground (Mansell et al., 2002; Wiens et al., 2005; Zhang et al., 2006; Kuhlman et al., 2006). Also, the model study of Fierro et al. (2006)) suggested that the lower negative charge region under the upper positive charge region in the forward flank of thunderstorm was favorable for the downward propagation of positive leaders. By the observation of an inverted polarity storms, a lower positive charge region is also found under the upper negative charge region on the cloud edge when −CG flashes originated from the anvil (Tessendorf and Rutledge, 2007; Kuhlman et al., 2009), and it can be analogous to the situation of +CG flashes from the anvil of normal polarity storm.

The objective of this study is to understand the electrical conditions favorable to the occurrence of +CG flashes from the forward flank of normal polarity thunderstorm. The forward flank here means the transition zone between the convective core and distant downstream anvil of thunderstorm. We discuss this issue through the simulations by building a three-dimensional stochastic lightning model and a normal polarity charge structure model.

2. Model description

2.1. Charge structure model

The charge structure (Fig. 1) within thunderstorm is assumed to be an normal polarity charge structure with an upper positive charge region (P), a midlevel negative charge region (N), and a small lower positive charge region (LP) plus an upper screening charge layer (SC). Such charge distribution has been observed and simulated in previous studies (e.g., Williams, 1989; Wiens et al., 2005; Mansell et al., 2005; Tessendorf and Rutledge, 2007).

The charge structure is built in a three-dimensional Cartesian domain with equidistant grids. The computational domain is 36 km × 36 km × 38 km, with the same horizontal and vertical grid spacing of 500 m. The charge region is assumed to have an ellipsoid

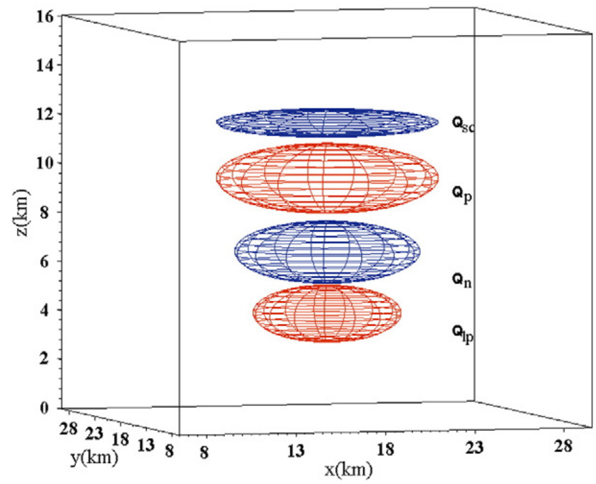

Fig. 1. The normal polarity charge structure with an upper positive charge region (P), a midlevel negative charge region (N), a small lower positive charge region (LP) plus an upper screening charge layer (SC).

shape. Each charge density presents exponential decline from the center to the outer according to

$$\rho = \rho_0 \exp\left[-\left(\frac{(x-x_0)^2}{r_x^2} + \frac{(y-y_0)^2}{r_y^2} + \frac{(z-z_0)^2}{r_z^2}\right)\right] \quad (1)$$

where ρ_0 is a parameter controlling the maximum charge density of the charge region; x_0, y_0, and z_0 represent the position of the charge region center; and r_x, r_y, and r_z determine the horizontal and vertical range of the charge region respectively. The height and the range of each charge region are based on the observation of a storm during the STEPS on 29 June 2000 (Wiens et al., 2005). Many observations suggested the electric field magnitude inside active thunderstorms were typically less than 150 kV/m (Marshall and Rust, 1991), so the maximum electric field of simulation domain is confined to 150 kV/m when determining the value of charge density of charge structure. Values of these parameters are summarized in Table 1. To simulate the downshear extension of the charge to the forward flank from the storm core, x_0 and r_x of the charge region are continuously adjusted, more details will be described in the following section. Charge in the forward flank is considered to originate in the storm core and to be carried to the forward flank by horizontal wind from the electrification region, so when x_0 and r_x of the charge region is adjusted, ρ_0 is also adjusted to keep the total charge unchanged.

By solving Poisson's equation $\nabla^2\phi_{\mathrm{amb}} = -\rho/\varepsilon$ with the SOR algorithm, the electric potential (ϕ_{amb}) and electric field ($E_{\mathrm{amb}} = -\nabla\phi_{\mathrm{amb}}$) in each point of model domain can be obtained. The charge can be calculated by $Q = \sum \rho \Delta V$, where ΔV is the grid cell volume.

2.2. Lightning model

Similarly to Mansell et al. (2002), the lightning model is based on the stochastic dielectric breakdown model proposed by Wiesmann and

Table 1
Geometrical and electrical parameters of the charge structure model.

Charge region	z_0 (km)	ρ_0 (nC/m^3)	x_0 (km)	y_0 (km)	r_x (km)	r_y (km)	r_z (km)	Charge (C)
SC	11.75	1.1	18	18	6.0	6.0	0.5	−19
P	9.75	2.2	18	18	6.0	6.0	1.5	77
N	6.75	3.0	18	18	5.0	5.0	1.5	−73
LP	4.25	1.0	18	18	4.0	4.0	1.5	18