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Simulation of inverted charge structure formation in convective regions of mesoscale convective system

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Abstract

The charge structure evolution of a mesoscale convective system with anomalous
or inverted charge structure observed in the Severe Thunderstorm Electrification and
Precipitation Study, a field project on the Colorado–Kansas border in summer 2000, is
simulated using the Weather Research and Forecasting (WRF) model coupled with
electrification and discharge processes. Two non-inductive electrification schemes are
used based on liquid water content (LWC) and graupel rime accretion rate (RAR).
The simulation with the LWC-based electrification scheme cannot reproduce the
inverted charge structure with a positive charge region sandwiched by two negative
charge layers, while the RAR-based electrification scheme produces the evolution
process of a normal–inverted–normal charge structure in the convective region, which
is consistent with the observations. In low RAR (< 2 g m⁻² s⁻¹) region, graupel is
mainly negatively charged when it bounces off ice crystals, while the ice crystals take
up positive charge. However, in the zone where the inverted charge structure forms, a
strong updraft (>16 m s⁻¹), high LWC (>2 g m⁻³) and high RAR (>4.5 g m⁻² s⁻¹)
region appears above the height of the −20°C layer, so that a positive graupel charging
region is generated above −20°C layer of the convective region, resulting in a negative
dipole charge structure with negative charged ice crystals above the positive charged
graupel. The negative dipole is superposed on the positive dipole (positive above
negative) charge structure at the lower position to form an inverted tripole charge
structure.

Keywords electrification and discharge model, inverted charge structure, mesoscale
convective system
1 Introduction

Inverted charge structure is closely related to the occurrence of positive cloud-to-ground (CG) lightning (MacGorman and Rust 1998; Guo et al. 2016). It is also found that the hailstorms present dominant positive CG flashes during periods of falling hail in central plains region of U.S. and North of China (MacGorman and Burgess 1994; Liu et al. 2009).

The understanding of the charge structure in thunderstorm has gone through a process from simple to complex. The earliest concept models of thundercloud were dipolar charge structures (Wilson 1920). Then Simpson et al. (1937; 1941) modified the dipole models by proposing a tripole structure, with a positive charge center near the thundercloud base and negative and positive charge centers successively. There were also screening layers existing at the upper and lower cloud boundaries (Vonnegut et al. 1962; Marshall et al. 1989). Numerous detection techniques have been developed to study thunderstorm electricity, and the basic tripole model is considered to be overly simplified for many situations (Krehbiel 1986). Marshall and Rust (1991), Stolzenburg et al. (1998) and Coleman et al. (2003) analyzed the sounding profiles of vertical electric fields in different regions of the United States. They considered that the charge in thundercloud is multi-layered with 4 to 9 layers. The charge structure in the weak updraft region is more complex than the strong updraft region, and the charge structure outside the updraft is more complex than that in the updraft region.

Although the charge structure in a thunderstorm is complicated, the tripole
charge structure is still considered to be sufficient to describe the main charge layer in a thunderstorm (Williams 1989; 2001). In the normal tripole charge structure, a negative charge region is located from −25 to −10°C sandwiched by two positive charge layers (Krehbiel et al. 1979; 1986). An important finding of the Severe Thunderstorm Electrification and Precipitation Study (STEPS) is the confirmation of the existence of inverted charge structure (Lang et al. 2004). Observations for many case studies indicated that the charge structure is opposite to the normal tripole charge structure, that is, the positive charge appears in the temperature layer of the negative charge, and the negative charge appears in the temperature layer where the positive charge often occurs. This negative–positive–negative charge structure is generally termed ‘inverted’ (Rust et al. 2002; MacGorman et al. 2005; Weiss et al. 2008; Bruning et al. 2014). We considered avoiding the terminology of “inverted” following the arguments of Bruning et al. (2014), but this terminology was used very frequently in the existing literatures, which make it easy to compare and quote the previous studies with the same terminology. At the same time, we also thought about the use of “anomalous”. Although the inverted polarity charge structure appears under relatively special dynamical and microphysical conditions, it still conforms to the basic principle of electrification. Therefore, the terminology of “inverted charge structure” is maintained here. The concepts of positive (negative) dipole, which means that the positive charge layer above negative charge layer (negative above positive), are used to describe the features of dipole charge structure (Black and Hallet 1999; Takahashi and Suzuki 2010).
The Thunderstorm Electrification and Lightning Experiment (TELEX) was organized by the United States National Severe Storms Laboratory (NSSL) to study the formation of inverted charge structure (MacGorman et al. 2008). In general, there are two theories for the mechanism of inverted charge structure formation (Zhang et al. 2014). One theory is associated with microphysical processes. It is believed that due to the strong updraft flow and the growth of cloud condensation nuclei, an abnormally high liquid water content (LWC) appears in mixed-phase regions (Williams et al. 2005) and then a positive graupel charging zone occurs at low temperatures. After collision of different particles, graupel is positively charged and ice crystals are negatively charged, resulting in an inverted charge structure (Williams et al. 2005; Carey and Baffalo. 2007; MacGorman et al. 2008). The other theory attributes the formation of inverted charge structure directly to the dynamical conditions. It is considered that the strong updraft not only changes the charging process within the cloud by affecting the microphysical conditions, but also affects the charge structure through dynamical transport. Therefore, the inverted charge structure could be generated when the mixed-phase region in the cloud is also the negative graupel charging zone. That is, the graupel particles are still negatively charged and the ice crystal particles are still positively charged. However, due to the dynamical transport of flow, the charge redistributes and thus forms the inverted charge structure (Bruning et al. 2010; MacGorman et al. 2011; Xu et al. 2016). This view is called the dynamical-derived mechanism. There is still some controversy about the formation of inverted charge structure. Electrification and discharge models are effective tools to
investigate the formation of inverted charge structure in thunderstorms.

Simulation studies based on cloud models show that different non-inductive charging schemes present significant differences in the formation of charge structures in thunderstorms. Charging schemes based on the graupel rime accretion rate (RAR) easily form inverted charge structures, while charging schemes based on LWC tend to form normal charge structures (Helsdon et al. 2001; Mansell et al. 2005; Li et al. 2012). However, these previous studies focused on the characteristics of the non-inductive electrification scheme and not the formation process of inverted charge structure. The WRF model can reproduce the development of thunderstorms with more realistic atmospheric conditions. Therefore, the use of WRF model to conduct further simulation studies of inverted charge storms can enhance the understanding of inverted charge structure formation.

Xu et al. (2016) used WRF model coupled with electrification and discharge processes to simulate an inverted charge storm in North China. The results suggested that dynamical transport plays an important role in the formation of inverted charge structures in North China. In this study, a mesoscale convective system (MCS) with inverted charge structure observed in the STEPS study is simulated using the same numerical model. Two non-inductive electrification schemes based on the RAR and LWC are used. The evolution characteristics of the charge structure in the MCS are compared with the inverted storm in North China. The stratiform and convective regions of the MCS often show different charge structures (Carey et al. 2005). Although the charge structure of the stratiform region are shown in the results, we
only focus on the formation of inverted charge structures in the convective region.

The rest of this paper is organized as follows. A description of the observations and the model setup are provided in sections 2 and 3, respectively. In section 4, the formation of charge structure in convective regions is examined. A summary and discussion are given in section 5.

2 Observations

An MCS observed on 22–23 June 2000 in the STEPS study in the highlands of the United States was selected. The storm produced >25 mm hail and strong winds of 30 m s\(^{-1}\) (Lang et al. 2004). Substantial positive CG lightning occurred in the development of the MCS and the proportion of positive CG lightning reached nearly 80% in the mature stage of the storm (Lang et al. 2004). Figure 1 shows the evolution of the positive CG lightning ratio observed by the National Lightning Detection Network (NLDN) during the MCS. A description of the related distribution and positioning accuracy of the NLDN can be found in Cummins et al. (1998). Although the storm is dominated by negative CG lightning most of the time, positive CG lightning dominates at certain time intervals, such as from 01:20 to 04:40 on 23 June.

Figure 2 shows the evolution of radar echoes observed by a Doppler radar (KGLD station, based in Goodland, Kansas). After the storm onset, the storm gradually moves eastward and forms a convective line. As the storm develops toward the southeast, the storm shows the characteristics of a trailing stratiform MCS. The radar reflectivities show a lumpy structure overall. Tessendorf et al. (2007) analyzed
the evolution of charge structure during this MCS from 00:00 UTC to 03:00 UTC on
23 June. They showed that the storm displayed an obvious inverted charge structure
using various observations, such as Lightning Mapping Array data.

3 Model description

The WRF-Electric model coupled with the physical processes of electrification
and discharge (Xu et al. 2012; 2014) is used in this study. The electrical processes
were coupled with the Milbrandt two-moment microphysical scheme in the
WRF-Electric model. An electrical WRF model also has been developed by using the
NSSL two-moment microphysical scheme (Fierro et al. 2013). However, the
WRF-Electric model used in this study was developed in a parallel effort to Fierro et
al. (2013).

The location of the three study domains and the terrain height are shown in
Figure 3. The terrain of the simulated area shows high elevation in the west and low
elevation in the east. The horizontal resolutions of three domains are 9 km, 3 km, and
1 km, respectively, with two-way interactive nesting. The mesh sizes of the three
domains are 208 × 208, 361 × 361, and 511 × 511, respectively, with the center of the
grid at 40° N, 102° W. In the vertical direction, 43 uneven σ levels were used for all
the meshes as in Zhang et al. (2011). The simulation time is from 06:00 UTC on 22
June to 12:00 UTC on 23 June with a total of 30 hours. The time steps for the three
domains are 30 s, 10 s, and 3.33 s, respectively. The simulation results are outputted
hourly.
The physical schemes used in the experiment are as follows. The Milbrandt two-moment microphysical scheme (Milbrandt et al. 2005a, 2005b) coupled with the electrical processes is used in the three study domains. Other model physics processes include the RRTM (Rapid Radiative Transfer Model) longwave radiation scheme (Mlawer et al. 1997), the Dudhia shortwave radiation scheme (Dudhia, 1989), and the YSU (Yonsei University) planetary boundary layer (Hong et al. 2006). The Kain–Fritsh cumulus parameterization scheme (Kain 2004) is only applied to the 9 km mesh.

Two non-inductive electrification schemes are used based on LWC and RAR. The LWC-based scheme is adapted from the research by Gardiner et al., (1985), Ziegler et al., (1991) and Tan et al., (2014) (hereafter TGZ). Under this scheme, when graupel particles (or hail) collide with ice crystal particles (or snow), the polarity of charge obtained by graupel/hail depends on the liquid water content and the ambient temperature. As shown in Fig. 4a, the black solid line represents the reversal temperature, which determines the sign of charge transfer when graupel (or hail) collides with the ice and snow. The graupel would charge positively when bounced-off ice crystals in the regions where reversal temperature is smaller than environment temperature, while the ice crystals would charge with opposite polarity. These regions can be defined as positive graupel charging zones, while the regions where reversal temperature is greater than environment temperature can be defined as negative graupel charging zones.

The RAR-based scheme is from Saunders and Peck (1998) (hereafter SP98). The
RAR is equal to the EW multiplied by V (where V is the relative velocity between the
droplets and graupel). EW is called the effective liquid water, which is the LWC
multiplied by the collection efficiency of the riming particle. RAR is considered an
important variable because the sign and magnitude of charge transfer between
rebounding ice crystals and a graupel surface is controlled by the riming surface
diffusional growth rate, which itself is dependent on temperature while being heated
by accreted, freezing, droplets. Saunders and Peck (1998) constructed a curve of
critical RAR (RARcrit) at which the charging of graupel changes sign for a particular
temperature (negative at lower RAR and positive for higher). The critical RAR curve
for the SP98 scheme delineates the positive and negative graupel charging zones as a
function of RAR and temperature. It is shown in Fig. 4b.

The TGZ scheme takes into account the collisional charging processes between
graupel and ice crystals and between hail and ice crystals and snow, whereas the SP98
scheme only considers the non-inductive charging process between graupel and ice
crystals.

4 Results

4.1 Evolution characteristics of charge structure simulated by TGZ scheme

Figure 5 shows the evolution of the simulated radar composite reflectivities in
the MCS. After the storm onset, the storm mainly moves eastward and gradually
forms a multicell storm with a line structure. With the development of the storm, the
radar echo shows an MCS structure with convective and stratiform regions. The storm
moves southeastward during the later period of development. Compared with the observed radar echoes, the simulated storm shape and direction of movement are basically consistent with the observations. The main deviation of the simulation from the observations lies in the fact that the MCS appears farther north and the simulated storm forms the convective line structure earlier. Note that the southeast side of the storm is the moving direction and is called the front side of the storm. The low-level winds in front of the storm are dominated by inflows (figure not shown). Four representative vertical cross-sections A1–A2, B1–B2, C1–C2, and D1–D2 are selected from Figure 5 to compare the charge structure of the storm at different locations at different times. The representativeness of the selected cross-sections is explained in the discussion part (section 5). The evolution characteristics of the charge density are mainly analyzed in the vertical cross-sections. An observation study of this MCS (Tessendorf et al. 2007) suggested that the storm at 00:00 UTC displays an inverted charge structure, corresponding to the B1–B2 and C1–C2 vertical cross-sections (Fig. 5c).

Figure 6 shows the evolution of the simulated total charge density. The four cross-sections A1–A2, B1–B2, C1–C2, and D1–D2 correspond to those identified by the same letters in Fig. 5, (a)–(d) are the results based on the TGZ scheme and (e)–(h) are the results based on the SP98 scheme. The main convective regions locate at 20 km–40 km in A1–A2, 60 km–120 km in B1–B2, 40 km–70 km in C1–C2 and 220 km–280 km in D1–D2. The simulation results with the TGZ scheme are analyzed first. During the initial stage of the storm, the cloud is weakly charged. The upper level of
cloud in the convective region is a positive charge layer. In the lower level, a negative charge layer appears between −25°C and −10°C. A positive dipole charge structure with a positive charge layer above a negative layer forms in the cloud (Fig. 6a). With the development of the storm, the total charge density in the cloud gradually increases and the charge structure is a positive dipole structure (Fig. 6b–c). At the later stage, a positive charge region forms near and below 0°C in the convective region, forming a positive–negative–positive tripole charge structure (Fig. 6d). In the TGZ scheme, the convective region is dominated by a positive dipole or tripole charge structure, and an inverted charge structure is not found in the simulation.

In the vertical cross-sections that pass through both the convective and stratiform regions, the main negative charge layer is significantly tilted from the convective region to the stratiform region (Fig. 6c–d). Compared with the convective region, the height of the negative charge layer (above the −25°C layer) is clearly higher in the stratiform region. Underneath the main negative charge layer of the stratiform cloud, there is a distinct positive charge layer. Thus, a negative dipole charge structure with a negative charge layer above a positive charge layer dominates in the stratiform region. At some points, there is also a thin layer of positive charge above the main negative charge layer in the stratiform region (Fig. 6c). The main positive charge region of the stratiform cloud lies in the region of −25 to −10°C, which is close to the temperature layer of the main negative charge layer in the convective region.

4.2 Evolution characteristics of charge structure simulated by SP98 scheme
The evolution of the charge structure simulated by the SP98 scheme is significantly different from that simulated by the TGZ scheme. At the initial stage of the storm, the convective region exhibits a positive dipole charge structure (Fig. 6e), which is similar to the results of TGZ scheme. Then the storm gradually develops into a trailing stratiform MCS. The cells of the convective line show an inverted charge structure. There is a main positive charge layer, sandwiched by two negative charge layers (Fig. 6f–g), which is different from the TGZ scheme. As the storm develops, the inverted charge structure in the convective region disappears and becomes a normal charge structure (Fig. 6h). The charge structure in the stratiform region simulated by the SP98 scheme is similar to that simulated by the TGZ scheme. There is also an obviously higher main negative charge layer with a main positive charge region below. A negative dipole charge structure is shown in the stratiform cloud region (Fig. 6g–h).

In summary, the convective cells always show a positive dipole or tripole charge structure with the TGZ scheme, whereas with the SP98 scheme, the charge structure shows a normal–inverted–normal evolution. The appearance of an inverted charge structure with the SP98 scheme is consistent with the observations. Is the formation of this inverted charge structure associated with dynamical transportation or the inverted polarity charging process?

The simulation results of the two non-inductive electrification schemes show that the stratiform and convective regions of the MCS show different charge structures. The WRF-Electric do not include a melting-related charging mechanism. This makes
it difficult to conduct the stratiform charge structure analysis since melting is widely understood to have a major influence on stratiform charging near 0 °C (Shepherd et al. 1996, Evtushenko and Mareev 2009). In the following, only the charge structure formation in the convective regions of the MCS is discussed.

4.3 Formation of charge structure in convective region of the MCS

This section investigates the formation of the charge structure in the convective region of the MCS by analyzing the charge density of different particles, updraft, and LWC in the cloud. The vertical distributions of the mixing ratio and charge density of graupel and ice crystals under the TGZ scheme are shown in Figs. 7a–d and 8a–d, respectively. The noninductive charging rates of graupel at the same time as Fig. 7 for the TGZ scheme are shown in Fig. 9a–d. The non-inductive charging processes between graupel and ice crystals play an important role in this simulation. At low temperatures (below −15°C), the charging processes between different particles in the convective region mainly occur in the negative graupel charging zone. In this region, graupel is negatively charged (Fig. 7a–c) and ice crystals are positively charged (Fig. 8a–c), which is the common charging process in the mixed-phase zone in cloud. Comparing the mixing ratio of the two particles, the horizontal distribution of the ice crystals is wider and the position is higher than that of graupel. The positive charge region composed of ice crystals is slightly higher than the negative charge region composed of graupel. The main charged particles exhibit a positive dipole charge structure with positive above and negative below in the convective region. In the later
stage of development of the MCS there is a small positive charge region composed of
hail in the vicinity of 0°C and below (Fig. 7d), thus forming a positive–negative–
positive tripole charge structure in the cloud. Negatively charged ice crystals appear in
the corresponding position (Fig. 8d). This is due to collisions between ice crystals and
hail (graupel) near the layer of −15 to 0°C. During this process, the ice crystals are
negatively charged, while the hail particles are positively charged. The falling of hail
causes a reduction of charge in the positive charge region in the lower part of the
cloud until it reaches the ground. In this case, >25 mm hail was indeed observed.
From this analysis, we can explain the formation of charge structure simulated by the
TGZ scheme. However, for this example, the charge structure simulated by the SP98
scheme is more consistent with the observations.

The vertical distributions of the mixing ratio and charge density of graupel and
ice crystals under the SP98 scheme are shown in Figs. 7e–h and 8e–h, respectively.
The noninductive charging rates of graupel at the same time as Fig. 7 for the SP98
scheme are shown in Fig. 9e–h. At the initial stage of the storm, the non-inductive
graupel–ice charging process mainly occurs in the negative graupel charging zone
(Fig. 9e). The positive charge layer formed by ice crystals and the negative charge
region formed by graupel constitute a positive dipole charge structure (Figs. 7e and
8e). During the period when the inverted charge structure appears, there is still a
negative graupel charging zone in the convective region (Fig. 9f–g). However, a
positive graupel charging zone also appears in the upper level of cloud at lower
temperature. After the particles have collided and bounced, graupel is positively
charged (Fig. 7f), while ice crystals are negatively charged (Fig. 8f–g). The graupel and ice crystals in the upper level of the cloud show a negative dipole charge in the positive graupel charging zone, while a positive dipole charge structure forms in the negative graupel charging zone in the lower position, which together form an inverted tripole charge structure. Since the noninductive charging rate of the graupel in the upper level of the cloud is positive (Fig. 9g), positively charged graupel should also exist in the same region in Fig. 7g, which may not be present due to the selection of the cross-section. In the cross-section D1-D2, the positive graupel charging zone in the upper level of the cloud becomes weak in the convective region (Fig. 9h) and a positive dipole charge structure still appeared in the cloud (Figs. 7h and 8h). At the bottom of the cloud, there is also a graupel positive charging region appears, which makes the charge structure in the cloud complicated.

In the SP98 scheme, the height of the main positive charge layer (−30—−20°C) of the inverted charge structure in the convective region is higher than that of the common positive charge layer of the inverted charge structure (−25—−10°C) (Krehbiel et al. 1979; Krehbiel 1986; Rust and MacGorman 2002). This is due to the fact that the inverted charging process at low temperature only occurs in the upper level of the cloud in the simulation. If the cloud in the region of −25—−10°C has a sufficiently high RAR value, these regions could also show a positive graupel charging zone. Accordingly, the position of the main positive charge layer is lower in the inverted charge structure.

The formation of the inverted tripole charge structure in the convective region of
the MCS in Fig. 6f–g is due to the occurrence of positive graupel charging process in
the upper level of the cloud. Why does inverted electrification occur only at specific
locations and what are the dynamical and microphysical characteristics associated
with it? Figure 10 shows that the inverted charging process occurs only when the
updraft is strong and the LWC and RAR are abnormally high.

High vertical velocity is mainly located in the convective region. In the
convective region where the inverted charge structure is generated (Fig. 10b–c), there
is a broad and strong updraft in the cloud with a maximum vertical velocity exceeding
16 m s\(^{-1}\). The high-value region of the vertical velocity (>12 m s\(^{-1}\)) is mainly
distributed above the height of the \(-20^\circ\)C layer. The spatial distribution of the LWC
shows that in the region where the inverted charge structure appears, the LWC
exceeds 2 g m\(^{-3}\) above the height of the \(-20^\circ\)C layer (Fig. 10f–g). During the period
when no inverted electrification occurs, the high-value region of LWC is below the
height of the \(-20^\circ\)C layer, although there is a strong updraft above the height of the
\(-20^\circ\)C layer (Fig. 10h). This indicates that the high-value area of vertical velocity
does not match the high-value region of LWC. The RAR value is the product of LWC
and the relative velocity between different particles, which is closely related to the
updraft in the cloud. The abnormal high RAR regions (Fig. 10j) is more consistent of
the positive graupel charging zone (Fig. 9f–g) in low temperature (<\(-20^\circ\)C). In fact,
the influence of RAR is more direct than LWC and vertical velocity in the charge
separation process for the SP98 scheme. These conditions for the formation of the
inverted charging process are consistent with the theory proposed by previous studies.
(Williams et al. 2005; Carey and Buffalo 2007; MacGorman et al. 2008). However, in this study, the position where the inverted charging process takes place is higher and the temperature of the main positive charge region in the inverted charge structure is lower.

From the previous analysis, it can be seen that the region where the inverted charge structure appears is accompanied by high vertical velocity, LWC and RAR value. In the same condition, why does only the SP98 scheme produce inverted charge structure?

By analyzing the noninductive charging rate of graupel for the TGZ scheme (Fig. 9a–d), it can be seen that the low-temperature region (< −13.8°C) is the negative graupel charging region, while the high-temperature region (> −13.8°C) is the positive graupel charging region. In this case, only a normal tripole charge structure can be formed. It means that the LWC is not high enough to produce a positive graupel charging region in the low temperature region. From the charging zones of the TGZ (Fig. 4a), it can also be seen that when the temperature is lower than −13.8°C, the LWC value required for graupel particles to obtain positive charges in collisions is higher as the temperature decreases. For instance, the 2.24 g m⁻³ LWC is required for −20°C, and the 4.24 g m⁻³ LWC is required for −30°C. Therefore, the lower the temperature, the harsher the conditions for graupel particles to acquire positive charges after collision. This makes it difficult to form a positive graupel charging region in the upper level of the cloud.

In contrast, although the main body of the cloud simulated by SP98 scheme is
still dominated by the graupel negative charging regions, a positive charging region of graupel particles appears in the upper level of the cloud (Fig. 9f–g), thus forming a negative tripole charge structure. From charging zones of the SP98 scheme (Fig. 4b), it can be seen that in the region where the temperature is greater than −10°C, the condition for graupel to obtain a positive charge is that the RAR value is higher than about 1 g m⁻² s⁻¹. With the gradual decrease of temperature, the critical RAR gradually increases. However, when the temperature is lower than −23.7°C, the critical RAR starts to decrease. Therefore, the conditions for graupel particles to obtain positive charges at low temperatures are not harsh. The RAR value (Fig. 10j–k) above the temperature layer of −23.7°C even exceeds 4.5 g m⁻² s⁻¹, which makes the graupel particles obtain positive charges under low temperature and form a negative tripolar charge structure together with the lower graupel negative charging region. It seems that the SP98 scheme is easier to form an inverted charge structure than TGZ scheme.

Studies that considered the formation of inverted charge structure to be due to inverted electrification mostly analyzed thunderstorms in the United States. In the simulation of a hailstorm system in North China (Xu et al. 2016), although a wide and strong updraft could be produced, the LWC was small in both range and magnitude. The LWC was less than 1 g m⁻³ above the height of the −10°C layer. Regardless of the scheme used (TGZ or SP98), the microphysical conditions for inverted charge structure are not formed in the inverted storms in North China. The low-temperature regions in the upper level of the cloud are all in the negative graupel charging zone,
even when the updraft is strong enough. In contrast, in the simulation of the MCS in STEPS, the area where the LWC exceeds 2 g m\(^{-3}\) reaches the \(-30^\circ\text{C}\) layer (Fig. 10f–g). This shows that the highlands of the United States may easily form a high-LWC environment in low-temperature regions, creating microphysical conditions for the inverted charging process, but it is more difficult for a high-LWC environment to form in North China. The formation of a dynamical-derived inverted charging process in North China may be more likely.

5 Summary and Discussion

This study used the electrification and discharge model (WRF-Electric) to simulate the inverted charge structure of an MCS in the STEPS study conducted in the highlands of the United States. Two non-inductive electrification schemes, TGZ and SP98, were used in the simulations. We mainly focused on the formation of inverted charge structures in the convective region. The main findings are as follows.

The convective region of the MCS is dominated by the negative polarity charging of graupel. The charge structure in the convective region simulated with the non-inductive electrification scheme based on the RAR is consistent with observations. With the development of the storm, the charge structure in the convective region shows a normal–inverted–normal evolution. In the region where the inverted charge structure appears, a strong updraft (>16 m s\(^{-1}\)), a high LWC (>2 g m\(^{-3}\)) and a high RAR (>4.5 g m\(^{-2}\) s\(^{-1}\)) are all present above the height of the \(-20^\circ\text{C}\) layer, leading to an inverted charging process above the layer. During the collision of large
and small particles, graupel obtains a positive charge and ice crystals obtain a negative charge. The negative dipole charge structures formed by the positive polarity charging of graupel in the upper level of the cloud are superposed on the positive dipole charge structures at the lower positions, which together constitute an inverted tripole charge structure.

The non-inductive electrification scheme based on LWC forms a positive dipole or tripole charge structure in the convective region of the MCS, where the main negative charge layer is located at the temperature layer of \(-25\)–\(-10\)°C. As the negative polarity charging of graupel is predominant in the cloud, negative graupel and positive ice crystal particles form a normal charge structure in the convective region after the collision and sedimentation of different particles. In the later period of development of the MCS, ice crystals and hail collide in the relatively high temperature layers \((-15\)–\(0\)°C) and a small amount of positively charged hail particles or graupel are formed near the temperature layer of \(0\)°C. Together they form a normal tripole charge structure in the convective region along with positive dipole charge structures.

In the inverted severe storm in the highlands of the United States, the positive polarity charging of graupel is likely to form in the upper level of the cloud. The inverted charge structure tends to be formed by microphysical processes. In contrast, MCSs are more likely to form an inverted charge structure through a direct dynamical transportation process in inverted storms in North China. However, as the analysis in this study is based on only one case, this finding may not be universally applicable. To
further confirm the existence of such differences in the formation of inverted charge
structure, more detailed analyses are needed from the background of synoptic scale.

In fact, the source of charge in the stratiform region also should be further
analyzed through numerical simulations. The updraft core in the cloud was the
predominant region of active charging (Calhoun et al. 2014). As the vertical velocity
in the stratiform region is relatively weak, it is considered that there is a lower
possibility of local non-inductive electrification (Yair 2008). Positive ice crystals and
negative graupel in the stratiform cloud region are likely transported from the
convective region. However, some studies considered that the charge transport and
localization of electrification in the stratiform region both play an important role
(Hodapp et al. 2008). Hence, the source of charge in the stratiform cloud region is still
not clear.

It is also necessary to discuss the representativeness of the vertical cross-sections
in section 4. The grids with composite reflectivity exceeding 45 dBZ were selected as
core convective region, and the total charge density in these grids is averaged in a
horizontal range to obtain the vertical profile of the mean total charge density. Figure
11 shows the evolution of the mean charge density profile with time under TGZ and
SP98 schemes. In the TGZ scheme, the evolution of the charge structure is relatively
simple, and the overall charge structure changed from dipole to positive tripole (Fig.
11a). While in the SP98 scheme (Fig. 11b), the electrical structure exhibits a positive
tripole structure before 16h. During the period of 17-21 h, negative charge region
appeared obviously at 12 km and above and the inverted charge structure was present.
After 22 h, the overall charge structure exhibits the negative bipolar charge structure. Although the basic evolution trend of the charge structure can be distinguished in the SP98 scheme, the charge density profiles display a relatively complex situation.

The red triangles in Fig. 11 indicate the time (15 h, 18 h, 23 h) of the selected cross-sections. The three moments can represent the different stage of the charge structure evolution in the TGZ and SP98 schemes. Therefore, the cross-sections used in the paper are representative from the perspective of the overall charge structure. In such a multi-cell storm, some cells exhibit inverted polarity charge structure and some cells exhibit normal polarity charge structure, which make the mean charge structure profiles more complex. Therefore, the formation process of the inverted polarity charge structure can be captured relatively clearly from the selected cross-sections.
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References


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**Figure Captions**

**Fig. 1.** Proportion of positive CG lightning observed by the NLDN during the evolution of an MCS from 18:00 UTC on 22 June to 12:00 UTC on 23 June.

**Fig. 2.** Radar composite reflectivity observed by NEXRAD (Next Generation Weather Radar) Doppler radar. (a)–(h): 22:00 on 22 June 22 to 05:00 on 23 June UTC at one hour intervals; units: dBZ. t=16~23h indicates the relative time to 06:00 on 22 June.

**Fig. 3.** Terrain height and locations of the three study domains.

**Fig. 4.** Charging zones of the noninductive charge separation schemes. (a) The reversal temperature curve (solid black line) used in the TGZ scheme. (b) The critical rime accretion rate curve (solid black line) used in the SP98 scheme. The positive/negative symbols represent the positive/negative graupel charging zones.

**Fig. 5.** Simulated composite radar reflectivity in domain 2. (a) 21:00 on 22 June, (b) 23:00 on 22 June, (c) 00:00 on 23 June, (d) 02:00 on 23 June, (e) 04:00 on 23 June, (f) 05:00 on 23 June. The letters A1–A2, B1–B2, C1–C2 and D1–D2 denote the positions of the four vertical cross-sections.

**Fig. 6.** Vertical cross-sections of total charge density (nC m⁻³; shaded) along the black lines shown in Fig. 5. (a)–(d) show the simulation results with the TGZ scheme and (e)–(h) show the simulation results with the SP98 scheme. The horizontal lines represent the isotherm lines of −20, −10 (dashed lines), and 0°C (solid line). The solid line labeled “5” represents the contour line of 5 dBZ.

**Fig. 7.** As in Fig. 6, but for the graupel mixing ratio (g kg⁻¹; shaded), charge density of graupel (nC m⁻³; red contours of ±0.1, ±0.2, ±0.3, and ±0.5 nC m⁻³), and charge
density of hail (nC m$^{-3}$; green contours of ±0.1, ±0.2 nC m$^{-3}$). Solid lines indicate positive values and dashed lines indicate negative values.

**Fig. 8.** As in Fig. 7, but for the ice mixing ratio (g kg$^{-1}$; shaded) and charge density of ice (nC m$^{-3}$; red contours of ±0.1, ±0.2, ±0.3, and ±0.5 nC m$^{-3}$).

**Fig. 9.** As in Fig. 7, but for the graupel noninductive charge separation rates (pC m$^{-3}$ s$^{-1}$ shaded)

**Fig. 10.** Vertical velocity (m s$^{-1}$; shaded), liquid water content (g m$^{-3}$; shaded) and RAR (g m$^{-2}$ s$^{-1}$; shaded) for the cross-sections in Fig. 5.

**Fig. 11.** The time evolution of the mean total charge density profiles. (a) In the TGZ scheme and (b) in the SP98 scheme. The red triangles indicate the times of the cross-sections used in section 4.
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Fig. 8. As in Fig. 7, but for the ice mixing ratio (g kg$^{-1}$; shaded) and charge density of ice (nC m$^{-3}$; red contours of ±0.1, ±0.2, ±0.3, and ±0.5 nC m$^{-3}$).
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