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# Effect of Earth's Magnetic Field on Prerequisites for Lightning Initiation in Thunderstorm

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## Abstract

In this study, a hypothesis is proposed about the possible effect of Earth's magnetic field (EMF) on the charge structure of thundercloud based on the Lorentz force equation. To prove this hypothesis, a simulation using the 12th International Geomagnetic Reference Field (IGRF) model has been conducted. In this simulation, three scenarios are considered based on updrafts/downdrafts categories of the charge motion to analyze how a change in velocity of hydrometeor could influence the charge structure of a thunderstorm. The results of simulations show that by stronger velocities, the charged hydrometeors will experience higher amounts of magnetic force. In fact, after cloud electrification and creation of individual charged hydrometeors, Earth's magnetic force could push the separated charges. Therefore, the distance between separated charges will increase more and more, that leads to the collection of the same sign charges in some layers, which are called charge layers of thunderclouds. Consequently, the probability of electric field and lightning initiation will increase. Finally, results indicate that the effect of EMF on charged hydrometeors might be one of the mechanisms of forming thundercloud's charge structure and lightning initiation.

**Keywords:** EMF, Hydrometeor, Cloud Electrification, Charge Separation, Thunderstorm, Weather.

## 1. Introduction

Thunderstorms have great influence on human activities and it is astonishing how little our knowledge is about them. A thunderstorm is typically a system of thunderclouds. A cloud type termed cumulonimbus, commonly referred to as the thundercloud, is the primary genesis of lightning. Lightning occurs when the electric field between clouds or clouds and the Earth exceeds a critical value that is an electrical phenomenon inside thunderstorms (Haldoupis, 2018). Soula et al. (2016) indicated that space-based observations have revealed that the highest frequency of lightning on Earth belongs to the Democratic Republic of Congo. Lightning occurs when the electric field between clouds or clouds and Earth exceeds a critical value. In 1752, Lemonnier conducted an experiment and verified Franklin's hypothesis about the electrical essence of thunderstorms and then he discovered fair weather (the fair weather criteria for atmospheric electricity measurements explained by Harrison and Nicoll (2018) atmospheric electrical effects. Further research confirmed that the surface of the Earth is charged negatively whereas the air is charged positively, resulting in a vertical fair weather electric field near the Earth's surface, which is about 100 V $m^{-1}$. Wilson (1921) suggested that the negative charge on the Earth is kept by the thunderstorms' action. The Global Electric Circuit (GEC) is a closed system of electric currents flowing between the ionosphere and Earth (Namgaladze et al., 2018). In fact, the discharge current is fully compensated through a global system of thunderstorm current generators and electrified shower clouds, which act as "global batteries" (Haldoupis et al., 2017). Füllekrug (2004) described the contribution of intense lightning discharges to the GEC. Rycroft et al. (2007) studied the effects of electric discharges in GEC. Tacza et al. (2014) investigated the relationship between the Carnegie curve (daily electric field variation in Universal Time) and the generators of the

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GEC. The worldwide thunderstorm generator is formed by the global stormy weather areas while the fair-weather areas can be considered as a resistive load. Convective clouds which have an important effect on the electric field of the Earth's surface are one of the most influential components that support the GEC (Pustovalov and Nagorskiy, 2018). Slyunyaev et al. (2019) implied that thunderstorm generators operating as voltage sources in GEC. Nicoll et al. (2019) described a GEC monitoring network to increase the knowledge about atmospheric electricity. Worldwide thunderstorm/ lightning activity is the major source of maintenance of atmospheric GEC variations (Victor et al., 2019). Therefore, the important role of thunderstorm and lightning in GEC would justify the need to investigate the charge structure of thunderclouds. The knowledge of the physical processes that occur inside the lightning event is very important (Gunasekara et al., 2018). Detailed features of mechanism of lightning flashes are still unknown (Vayanganie et al., 2018). One of the unsolved issues is the mechanism that will establish areas of locally enhanced electric fields to initiate electrical breakdown in thunderclouds (Cooray, 2015).

Any cloud electrification mechanism requires a process that electrifies individual hydrometeors and a process which separates these charged hydrometeors by their polarity. As a consequence, distances between the charged cloud regions will be of the order of kilometers. Generally, cloud electrification studies (Tessendorf, 2009; Gharaylou et al., 2009; Tsenova et al., 2013; Kulkarni and Siingh, 2014; Bruning et al., 2014; Pegahfar and Gharaylou, 2015; Glassmeier et al., 2018; Dye and Bansemer, 2019) proposed two distinct mechanisms. A comprehensive review about the mechanisms of thunderstorm electrification has been done by Saunders (2008).

Most of the precipitation related mechanisms about charge separation in thunderstorms fall into one of the following categories:

- Inductive (or polarization mechanism, initiated by the ambient fair-weather electric field)
- Non-inductive (connected with electrochemical or thermoelectric particle characteristics)

In Kuettner et al. (1981), the authors concluded that the non-inductive mechanism governs the charge distribution and its polarity, and the inductive mechanism governs the field strength. Rakov and Uman (2003) indicated that there could be other important mechanisms that have not been considered for cloud electrification and charge separation; it is also possible that substantial electrification mechanisms are still unrecognized.

The effect of magnetic field on cloud electrification and charge separation could be one of the above-mentioned unrecognized important mechanisms. In this paper, we try to clarify this mechanism to some extent.

First, it is needed to know some basic points about the magnetic field of Earth. In Lam et al. (2013), it has been reported that the EMF is really complicated but still to a great extent, it can be viewed as a dipole with north and south poles like a simple bar magnet. The magnetic axis of the Earth is inclined at about 11 degrees to Earth's spin axis. At any optional point, the geomagnetic field ($B$) is specified by the direction and field strength. In polar coordinates ($r$ and $\theta$), where $r$ is the radial distance from the center of the Earth, and $\theta$ is the angular distance to the dipole axis, the EMF with the dipole model can be expressed as follows:

$$B = \frac{\mu_0}{4\pi}\frac{M}{r^3}\sqrt{1 + 3cos^2(\theta)} \qquad (1)$$

where $M$ is the Earth dipole moment ($8 \times 10^{22} A.m^2$), and $\mu_0$ is the permeability in the free space. The magnetic field varies from place to place on Earth because the angle $\theta$ varies (Lam et al., 2013).

In general, the magnetic field cannot be ignored as an interface between electrical energy and mechanical (thermal) energy. There are lots of facilities which have been designed with regard to the magnetic field as a medium (Motors, Generators, Transformers, Measurement Devices, etc.). Hence, the important role of magnetic field in different contexts triggers the idea that the EMF could have a vital effect on the GEC, climate, and Earth thermodynamic system.

Electric field increment in thunderclouds that leads to lightning incidence is a result of electrification of hydrometeors and charge separation. Different mechanisms have been introduced for cloud electrification and charge separation, but the exact reason of these phenomena has not been precisely determined. One of these important mechanisms could be the effect of EMF.

In this paper, it is not intended to show that the EMF plays the most important role in cloud electrification and charge separation. The main aim of this paper is to investigate the possible effects of EMF on cloud electrification and charge separation. The structure of this paper is as follows. Section 2 describes some effects of magnetic field related to hydrometeors. Section 3 is dedicated to the data and method. In section 4, simulation results and their analysis are presented. Finally, section 5 provides a brief conclusion of the research.

## 2. Some Effects of Magnetic Field

The general purpose of this section is to investigate the effects of magnetic field on cloud electrification, charge separation, and lightning incidence. Different impacts of magnetic field have been reported in various documents. In this paper, the purpose is to discuss the impact of magnetic field on hydrometeors and linking them to cloud microphysics and atmospheric electrical activities. Moreover, some probable new considerations in cloud electrification theories will be proposed and a novel hypothesis about charge separation in clouds based on the Lorentz force equation and Fleming's Right-hand Rule will be presented.

### 2-1. Effect of Magnetic Field on Charge Separation

The impact of magnetic field on charged moving water vapor investigated by Badru et al. (2015). They reported that the magnetic forces resulted in the coalescence and nucleation of charged cloud droplets in the few seconds during interaction. They observed that this effect facilitated the increase in diameter of condensed charged droplets and reduction in number of condensed charged droplets.

After electrification of hydrometeors (through each mechanism of thunderstorm electrification), the charges in the cloud could be separated via EMF effect based on the Lorentz force equation (Equation 2).

$$\vec{F} = q \,.\left(\vec{V} \times \vec{B}\right) \tag{2}$$

Observations in supercells indicate that they have a more complicated charge structure than the basic tripole of usual thunderstorms. Stolzenburg et al. (1998) used data from various electric field balloons soundings of supercells to indicate that strong updrafts have a simpler charge structure than regions of the downdraft or weak updraft. Pineda et al. (2016) indicated that strong updrafts show the typical three layers (tripole) structure, while weak updrafts represented at least six charge layers, which typically have alternating polarity. These facts are some clues that could show the importance of velocity of hydrometeors. In fact, after electrification of hydrometeors in thunderclouds, positive and negative charge centers could be established by EMF (based on Equation 2). It could be stated that the powerful updrafts ($V$) cause stronger force ($F$), and finally this leads to further separation of positive and negative charge centers (because the positive and negative sign of $q$, causes opposite force direction), and also this leads to a simple charge structure. Putting all together, these explanations could describe the above-mentioned observations (Stolzenburg et al., 1998; Pineda et al., 2016).

Regarding some observations, opposite charge layers are not placed exactly vertically and have a kind of displacement. Ogawa and Brook (1969) and others have shown that the dipole vector within thunderclouds is often at a substantial angle to the vertical. Thunderstorm observations showed that a kind of force could have displaced the charge layers so that the layers are not identical (in vertical positions).

In general, horizontal (east/westward or south/northward) motion of charged hydrometeors will result in a vertical (up/downward) magnetic force and vertical motion of charged hydrometeors will result in horizontal magnetic force. Based on the Equation (2), as the EMF has three different components, it could be stated that in each direction of the charged hydrometeor's motion, the net magnetic force will be nonzero and as the main component of EMF is from south to north, at least it could lead to two kinds of charge separation (vertical and horizontal) depending on the direction and strength of velocity vector of hydrometeor.

### 2-2. Magnetic Field Effects on Relative Diffusional Growth Rates' Theory

Comprehensive thunderstorm charge transfer experiments have been accomplished by scientists in which the magnitude and sign of the charge transfer during ice crystal rebounds from riming graupel have been specified as a function of cloud temperature, graupel temperature, cloud water content, cloud droplet size distribution, impurity content of the graupel, ice crystal size, relative velocity between the colliding particles and their collision and separation probabilities. Saunders (2008) indicated that the relative diffusional growth rate of the interacting ice particle surfaces is the factor that governs the sign of charge transfer. The charge transfer follows the principle that the ice surface that grows quicker by vapor diffusion, charges positively during ice crystal/graupel rebounding collisions. This concept has been shown to be consistent with the results achieved in different laboratories (Saunders, 2008).

In fact, a thunderstorm charging mechanism based on vapor deposition rate, first proposed by Baker et al. (1987). This theory was promoted further by Dash et al. (2001). They claimed that the faster growing ice surface has more negative surface charge attainable for transfer, and therefore charges positively. Two colliding ice surfaces tend to equalize their surface charges so that the quicker grown surface misses a negative charge. The equalization of charges happens on a time scale of μs, which is much less than the estimated 0.1 ms contact time. This supplies inadequate time for the deeper protons in the ice to react during the attainable contact time. When a quicker growing ice crystal rebounds from a gentler growing graupel pellet, the charge and mass exchange during the collision causes the graupel to charge negatively. These consequences are related to thunderstorm conditions where mixing between cloud parcels having various histories will result in quicker, or gentler, growth of ice crystals (Saunders, 2008).

Emersic and Saunders (2010) presented a derivation of the crystal growth rate equation expressed as:

$$\frac{dm}{dt} = \frac{4\pi\, C\, \sigma_s}{\frac{L_s^2}{\kappa\, R_v\, T} + \frac{R_v\, T}{e_i(T)\, S}} \quad (3)$$

The parameters of this equation are described in Table 1. They could be affected by EMF and could be interpreted as a function of EMF. Therefore, it could be stated that the EMF impacts the relative diffusional growth rates' theory. Changes in dielectric permittivity of water after magnetic field treatment show that the capacitance of water (liquid droplet, ice, graupel or snow) is dependent on the magnetic field (Ibrahim, 2006; Pang and Shen, 2013). Also latent heat of sublimation is a function of magnetic field because hydrogen bonding will be affected by the magnetic field application (Smirnov, 2000; Pang, 2014). Moreover, by application of a homogeneous magnetic field, the thermal conductivity of water will decrease (Semikhina and Kiselev, 1988; Hasaani et al., 2015). Hence, it could be stated that the thermal conductivity could be affected by magnetic field. In addition, as the saturation vapor pressure is a function of surface tension, and surface tension is affected by a magnetic field (Toledo et al., 2008; Cai et al., 2009), it could be stated that magnetic fields could alter the saturation vapor pressure.

**Table 1.** Parameters of crystal growth rate equation (Equation 3).

| Parameters | Description |
|---|---|
| C | Electrostatic capacity of the crystals |
| $\frac{dm}{dt}$ | Rate of change of crystal mass |
| $e_i(T)$ | Saturation vapor pressure over ice |
| κ | Thermal conductivity of air |
| $L_s$ | Latent heat of sublimation |
| m | Mass of ice crystal |
| $R_v$ | Gas constant for water vapor treated as an ideal gas (461.5 J kg$^{-1}$ K$^{-1}$) |
| S | Supersaturation |
| $\sigma_s$ | Experienced supersaturation |
| T | Temperature |

Therefore, it could be suggested that the relative diffusional growth rates of the interacting ice particle surfaces, which is the factor that controls the sign of charge transfer, is a function of magnetic field because at least four elements of Equation (3) depend on the magnetic field. Hence, magnetic field plays an important role in determining the sign of charge transfer through variation of hydrometeor's microphysical parameters (effect of EMF on non-inductive process).

## 3. Data and Method

In order to study the effect of velocity vector of hydrometeors on charge separation in thunderclouds in the presence of EMF based on the Lorentz force equation and Fleming's Right-hand Rule, a simulation using 12th IGRF model has been conducted using MATLAB software.

The IGRF model is a standard mathematical description of the large-scale structure of EMF. It was created by fitting parameters of a mathematical model of the magnetic field with measured magnetic field data from surveys, observatories and satellites across the globe. The IGRF has been produced and updated under the direction of the International Association of Geomagnetism and Aeronomy (IAGA) since 1965, and it is the product of a collaborative effort between magnetic field modelers and the institutes involved in collecting and disseminating magnetic field data from satellites, observatories and surveys around the world (Thébault et al., 2015). The 12th generation of IGRF is the latest version of a standard mathematical description of the EMF.

The geocentric components of the geomagnetic field in the northward, eastward, and radially inwards directions (*X*, *Y* and *Z*) could be obtained from IGRF model (Thébault et al., 2015).

The function of IGRF model is located in Aerospace Toolbox of MATLAB software. Using this function, the EMF and its secular variation could be calculated at a specific location and time. Input arguments of this function are:

- Height (from the surface of the Earth)
- Latitude (north latitude is positive, south latitude is negative)
- Longitude (east longitude is positive, west longitude is negative)
- Time

Output arguments of this function are:

- Magnetic field vector, in nanotesla (nT).

$B_x$ : Northward component of the magnetic field.

$B_y$ : Eastward component of the magnetic field.

$B_z$ : Downward (vertical) component of the magnetic field (+ve down).

- Horizontal intensity, in nT.
- Declination, in degrees (+ve east).
- Inclination, in degrees (+ve down).
- Total intensity, in nT.
- Secular variation in magnetic field vector, in nT/year.
- Secular variation in horizontal intensity, in nT/year.
- Secular variation in declination, in minutes/year (+ve east).
- Secular variation in inclination, in minutes/year (+ve down).
- Secular variation in total intensity, in nT/year.

In this article, because the simulation is conducted based on IGRF model, the Cartesian coordinate system is selected (in which *x*, *y*, and *z* represent northward, eastward, and radially inwards directions respectively), and the usual meteorological directions (in which *x* represent eastward direction) are not used. Therefore, in this article, these directions (*x*, *y*, and *z* for northward, eastward, and radially inwards directions respectively) are used for magnetic field, velocity and force.

From observations of thunderstorm electrification, it could be concluded that both the intensity and the direction of velocity of hydrometeors significantly affect the electrical properties of thundercloud (for example, the charge structure of thundercloud). In order to study the effect of velocity of hydrometeors on the charge structure of thunderclouds in the presence of EMF, a simulation with three scenarios is done to analyze how a change in velocity of hydrometeors could influence the occurrence of lightning initiation. Three simulation scenarios are considered based on strong, moderate and weak updrafts/downdrafts categories of the charge motion. Thermodynamic and hydrodynamic forces acting on charges are neglected for simplicity.

Vonnegut (1963) stated that an intense thunderstorm has sufficient electrical energy to power a tornado. Moreover, he implied that the electrification could cause extraordinarily intense winds. Vonnegut believed that the convective motions will give rise to potential gradients as the result of electromagnetic induction in the EMF.

Krasilnikov (1997) introduced the electromagnetohydrodynamic (EMHD) model, explaining the processes of energy conversion in tropical cyclones, hurricanes, and tornadoes. He explained the EMHD mechanism for the formation and intensification of the primary circulation in these vortices. However, he did not consider the effect of EMF on the processes of energy conversion in tropical cyclones, hurricanes, and tornadoes.

The magnetic force could be in any direction $(\vec{x}, \vec{y}, \vec{z})$ but the gravity and the electric field's force is in vertical direction ($\vec{z}$ ). An electric field will attract or repel a charged particle in the direction of the field, depending on the charge of the particle. Therefore, as both gravity and electric force are in vertical direction, the amount of vertical component of magnetic force in comparison with gravity and electric force is negligible. It should be noted that the effect of horizontal component of magnetic force is so important and the main core of this paper is this concept. In fact, the north/southward and east/westward components of Earth's magnetic force could play an important role in charge separation and charge structure of thunderclouds.

Krasilnikov (2002) proposed a method of volume electric charge neutralization of powerful clouds. This method results in the decrease in an electric field, a sudden increase in precipitation, and subsequent degradation of powerful clouds.

Dehel et al. (2007) implied that the Lorentz force and the electric force, acting on charged particles that exist in atmospheric vortex phenomena, plausibly contribute to the set of physics that will explain tornados and other atmospheric vortex phenomena. However, they only considered the fine charged particles, which have the maximum possible charges.

Individual positive and negative charges are considered that EMF will exert a magnetic force on them. Based on Equation (2), in a thundercloud, when positive or negative charge (charged hydrometeor) moves in EMF, a magnetic force will be experienced by the charge (in a direction that is perpendicular to EMF and velocity vector). A mechanism of cloud electrification acts on hydrometeors and creates charged particles in thunderclouds. After electrification of hydrometeors (through each mechanism of thunderstorm electrification), the charged hydrometeors (positive and negative charges) could be separated via magnetic force originated from EMF (based on Equation 2). The stronger velocity of charged hydrometeors causes stronger magnetic force, which finally leads to the separation of positive and negative charge centers.

Many suggestions have been made as to the physical mechanism, by which thunderstorms become so highly charged, with the mechanism found to best fit observations being due to the presence of both supercooled liquid droplets and ice crystals within the cloud (Bennett, 2008). The mixed-phase region of thundercloud is where charging happens and the charged areas of the cloud tend to place between three to ten kilometers above the ground (Schultz and Vavrek, 2009). The charge transfer that occurs per each collision is thought to be in orders of $10^{-15}$ C (Kuettner et al., 1981). Charges of about $10^{-10}$ C were commonly observed on particles around 1 mm in size (Latham, 1981) and this charge is considered for this simulation.

In charge transfer by collision (in the non-inductive process), it is assumed that the charge transfer occurs at −15 ◦C and a height of about 6 km (Rakov and Uman, 2003). Therefore, in this simulation, it is supposed that initial charges exist at 6 km elevation. Although, as Krehbiel (1986) and Li et al. (2017) concluded, the height of the border of main positive and main negative charge layers depends on temperature. The observations suggest that the typical space charge distribution of a mid-latitude thunderstorm consists of a dipole with the main positive charge centered between -20 and -40°C and located above the main negative charge centered between -5 and -25°C (Kuettner et al., 1981; Saunders, 1994). As Vonnegut (1994) indicated, usually the cloud's electrified state is maintained for many minutes by charged regions could reach up to tens of coulombs, positive in the upper, and negative in the lower part of the cloud.

In order to describe our hypothesis comprehensively, two states of charged hydrometeors' velocity vector are assumed. First, an example will be presented in which it is supposed that charged hydrometeors only have horizontal motion (west to east or vice versa). Then, another example with regard to the vertical motion of charged hydrometeors will be presented.

Simply, it could be supposed that in a certain region, the direction of EMF is from south to north. If a situation is considered in which the movement (velocity vector) of charged hydrometeor is from west to east and the updraft/downdraft is neglected, then based on Equation (2) the direction of magnetic force will cause the charges to separate and place them in different elevations with regard to Fleming's Right-hand Rule. In fact, EMF will establish a magnetic force that is in vertical direction and it causes separation of positive and negative charge centers (layers) from lower to upper levels or vice versa. Hence, the positive (negative) charge will be pushed to higher (lower) elevations by magnetic force. However, it should be noted that if the charges (velocity vector) move from east to west, the direction of magnetic force will be inversed and as a result, the positive (negative) charge will be pushed to lower (higher) elevations. It could be stated that this feature of EMF (and the resulted magnetic force) might be a cause of observed normal dipole ($\pm$) and inversed dipole ($\mp$) charge structures in clouds. Furthermore, as west to east motion of hydrometeors (eastward winds) is prevailing, the constitution of normal dipole ($\pm$) charge structure in clouds is expected to be overcoming. Therefore, horizontal component of velocity vector with regard to EMF leads to vertical magnetic forces (vertical separation of charged hydrometeors).

If only the updraft movement of charged hydrometeor (vertical velocity vector) is considered and horizontal component of velocity vector is neglected, EMF (which is supposed to be from south to north) leads to a magnetic force that is westward (or vice versa depending on the charge sign of the electrified hydrometeor). This magnetic force will cause positive and negative charges to separate in horizontal directions based on the Fleming's Right-hand Rule. Therefore, updraft/downdraft component of velocity vector with regard to EMF leads to horizontal magnetic forces (horizontal displacement of charged hydrometeors). Hence, after electrification of hydrometeors, the displacement between positive and negative charge centers in horizontal direction could be caused by Earth's magnetic force.

With regard to IGRF model, EMF has three different components ($B_x$ , $B_y$ , $B_z$) in each point of troposphere. Therefore, based on the Equation (2), it could be stated that in each direction of the charged hydrometeor's motion, the net magnetic force will be nonzero. Therefore, magnetic forces originated from EMF could result in two kind of charge separation (vertical and/or horizontal) depending on the direction and strength of velocity vector of hydrometeor.

Some studies (Barthe et al., 2016; Miller et al., 2001) described a strong link between updraft or graupel fall speed, and lightning activity. Therefore, the velocity of charged hydrometeors has a key role in thundercloud's charge structure formation and lightning initiation.

In this simulation, the velocity vector of charged hydrometeors has three components ($V_x$ , $V_y$ , $V_z$). In fact, $V_x$ represents the northward component, $V_y$ stands for the eastward component, and $V_z$ represents the up/downward component of charged hydrometeors' velocity vector. As Bluestein (1992) indicated, updrafts/downdrafts could be classified in three categories (with regard to the velocity) including strong, moderate, and weak. Therefore, three scenarios are considered based on updrafts/downdrafts categories to investigate our hypothesis. In first scenario of simulation, it is intended to simulate the motion of charged hydrometeors from west to east, not only with a feeble horizontal motion ($V_y$ = 10 m s$^{-1}$) but also with a powerful horizontal motion ($V_y$= 20 m s$^{-1}$), and simultaneously investigating the effect of weak updrafts/downdrafts ($V_z$= $\pm$10 m s$^{-1}$). Second and third scenarios are the same as the first one, but the effect of moderate updrafts/downdrafts ($V_z$= ±20 m s$^{-1}$) are investigated in the second scenario, and finally in the third scenario of simulation the effect of strong updrafts/downdrafts ($V_z$= ±30 m s$^{-1}$) are studied. The sign of updraft motion is considered negative (−) while the sign of downdraft velocity is considered positive (+).

In all scenarios, it is supposed that the motion of charged hydrometeors is from west to east, with both feeble and powerful horizontal motions, and simultaneously investigating the effect of weak, moderate and strong updrafts/downdrafts. The magnetic force resulted from EMF could have three components ($F_x$ , $F_y$ , $F_z$) based on Equation (2) with regard to different velocity vectors. The combination of northward and eastward components ($F_x$ , $F_y$) makes the horizontal magnetic force, while the upward/downward component ($F_z$) represents the vertical magnetic force. The downward component of vertical magnetic force is considered positive while the upward component of vertical magnetic force is considered negative. The results of three scenarios are illustrated and discussed in next section.

## 4. Results

The results of first, second, and third scenarios of simulation are illustrated in Figures 1, 2, and 3. In each figure, different components of magnetic force are illustrated when a charged hydrometeor with a charge of +100 pC moves in troposphere with a specified velocity vector (components of velocity vector of hydrometeor are showed in each figure based on simulation scenarios). In fact, each figure shows that if an electrified hydrometeor with a specified velocity vector moves in 6 km elevation on prime meridian in different latitudes (from south pole to north pole), how much magnetic force will be experienced by the charged hydrometeor. In each figure, vertical axis shows the components of magnetic force (*N*) that is experienced by charged hydrometeor and horizontal axis is dedicated to the latitude (degree). The northward component of magnetic force ($F_x$) is illustrated in red color and also the blue color is dedicated to eastward component of magnetic force ($F_y$). Finally, the vertical (downward) component of magnetic force ($F_z$) is showed with green color.

The results of the first scenario of simulation (weak updraft/downdraft) show some important points which are described below. From the results of part (a) and part (b) of Figure 1, it could be concluded that as the northward component of velocity of hydrometeor is neglected ($V_x = 0$), by changing the direction of vertical velocity ($V_z$) from downdraft to updraft, the sign of eastward magnetic force ($F_y$) will be reversed. Besides, it could be stated that in part (a) and part (b) of Figure 1, as the magnitude of eastward and vertical velocities are equal ($|V_y| = |V_z| = 10$) and the northward component of velocity of hydrometeor is neglected ($V_x = 0$), the magnitude of eastward and vertical components of magnetic force are the same.

It is clear that the northward component of the magnetic force in updraft case (Figure 1 - b) is stronger than that of in downdraft case (Figure 1 - a). As a consequence, the stronger magnetic force on charged hydrometeors leads to more charge separation and electric field development. Therefore, the probability of lightning initiation increases.

Furthermore, the vertical magnetic forces (in part a, and part b of Figure 1) are equal, which resulted from the same horizontal velocity vectors ($V_x = 0, V_y$= 10 m s$^{-1}$).

The results of part (a) and part (c) of Figure 1 show that as the magnitude of vertical velocities are equal ($|V_z| = 10$) and the northward component of velocity of hydrometeor is neglected ($V_x = 0$), the magnitude of eastward component of magnetic forces are the same in both figures. Furthermore, with the same vertical velocities ($|V_z| = 10$), the more powerful eastward velocity establishes greater vertical and northward magnetic forces. As a result, charge separation will occur faster. Therefore, it could be stated that EMF (and resulted magnetic force) has an effect on separation of charged hydrometeors and on forming the charge layers of thunderclouds. In fact, based on Fleming's Right-hand Rule horizontal components of velocity vector ($V_x, V_y$) with regard to EMF lead to vertical magnetic force ($F_z$), which will cause the charges to separate and will place them in different elevations. In fact, after electrification of hydrometeors in cloud, positive and negative charge centers could be established by Earth magnetic force, and it could be stated that the more powerful hydrometeors' velocity vectors cause stronger magnetic forces and finally this leads to better separation of positive and negative charge centers (because the positive and negative sign of $q$ causes opposite magnetic forces).

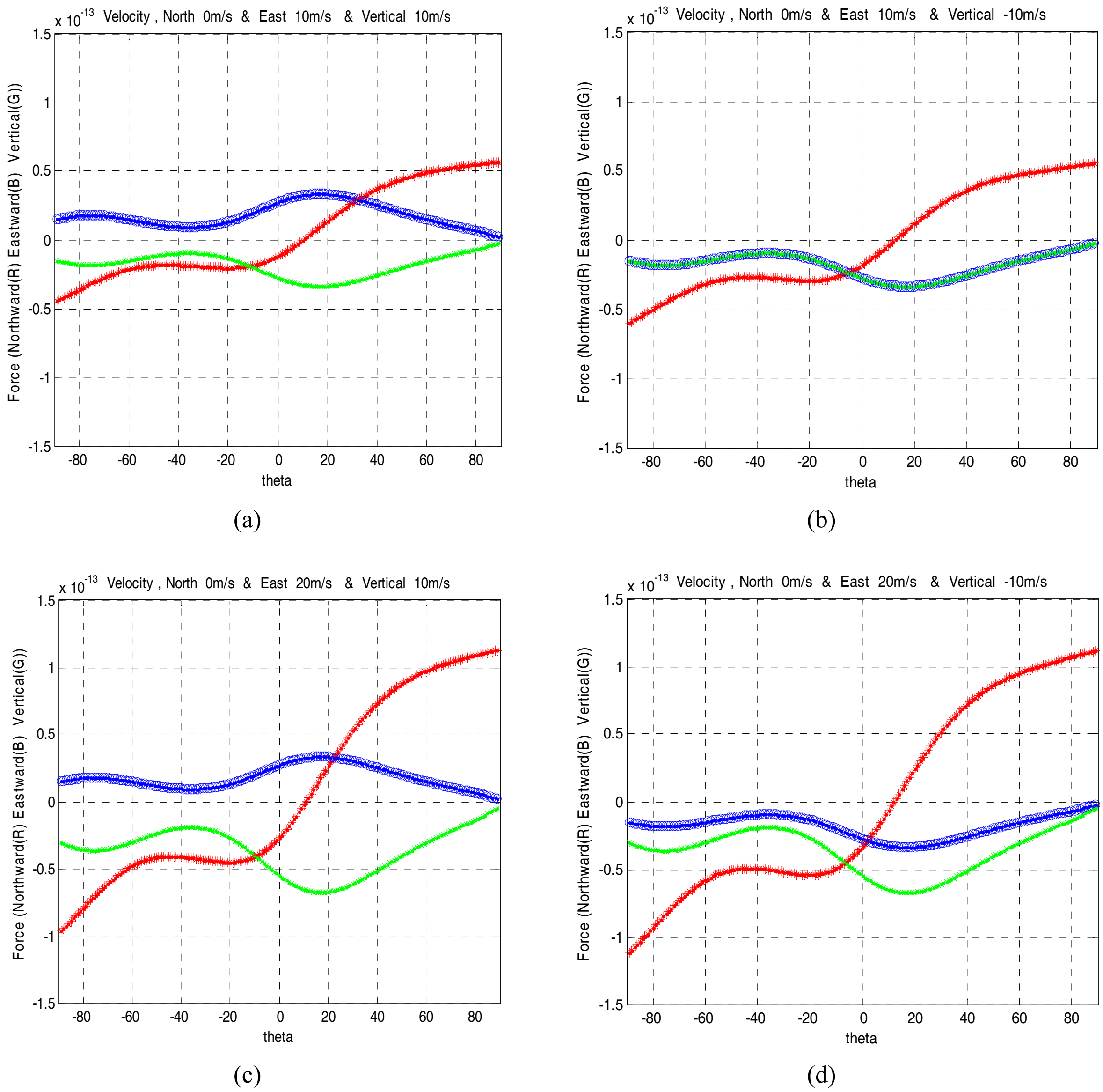


**Figure 1.** Results of the first scenario of simulation. Magnetic force resulted from the effect of EMF on moving charged hydrometeors. Vertical and horizontal axis shows magnetic force (N) and latitude (degree) respectively. Velocity vector characteristics are shown in each part. The sign of updraft motion is considered negative while the sign of downdraft velocity is considered positive. The northward, eastward and vertical (downward) components of magnetic force are illustrated in red, blue and green color respectively.

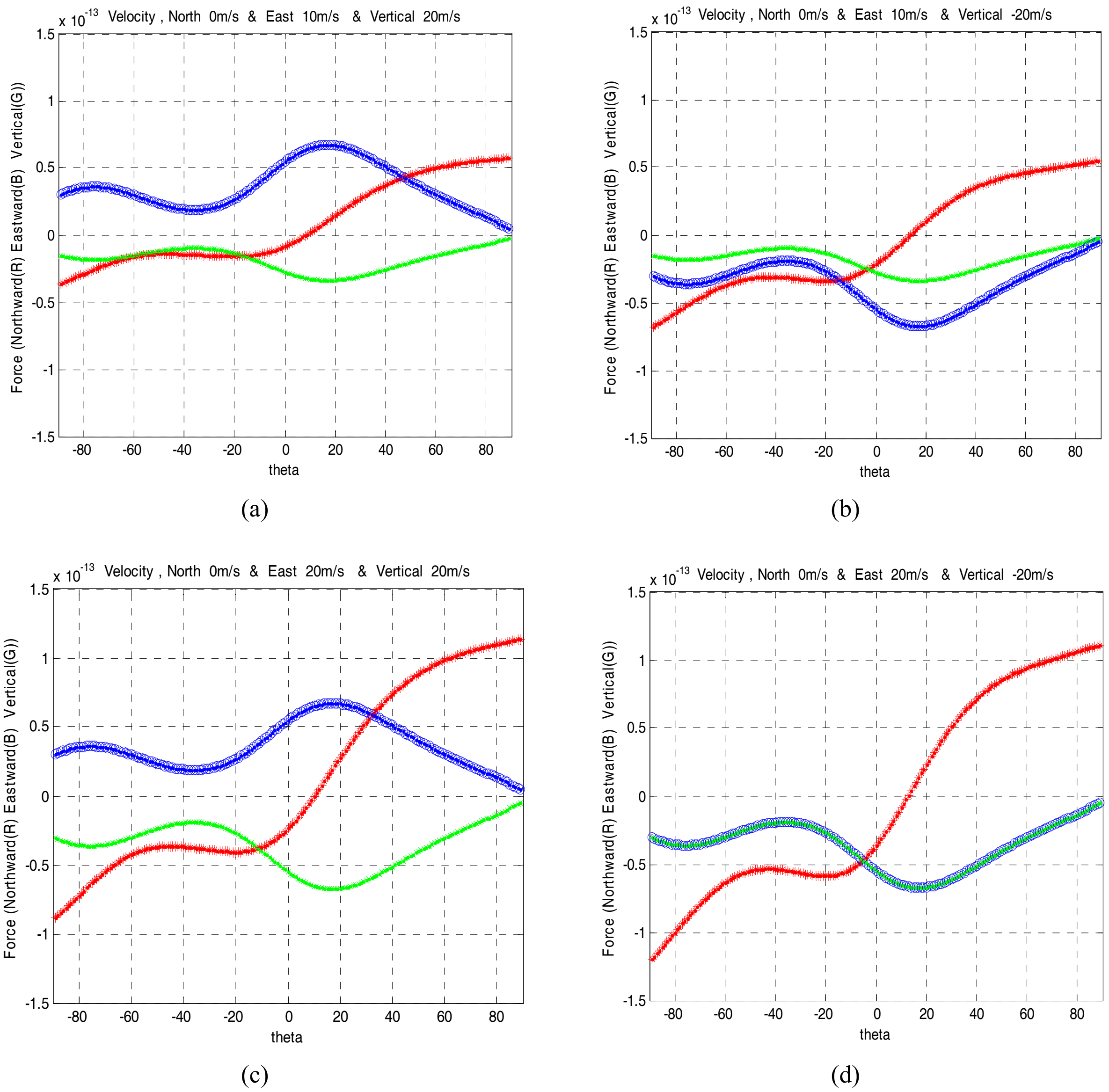


**Figure 2.** Results of the second scenario of simulation. Magnetic force resulted from the effect of EMF on moving charged hydrometeors. Vertical and horizontal axis shows magnetic force (N) and latitude (degree) respectively. Velocity vector characteristics are shown in each part. The sign of updraft motion is considered negative while the sign of downdraft velocity is considered positive. The northward, eastward and vertical (downward) components of magnetic force are illustrated in red, blue and green color respectively.

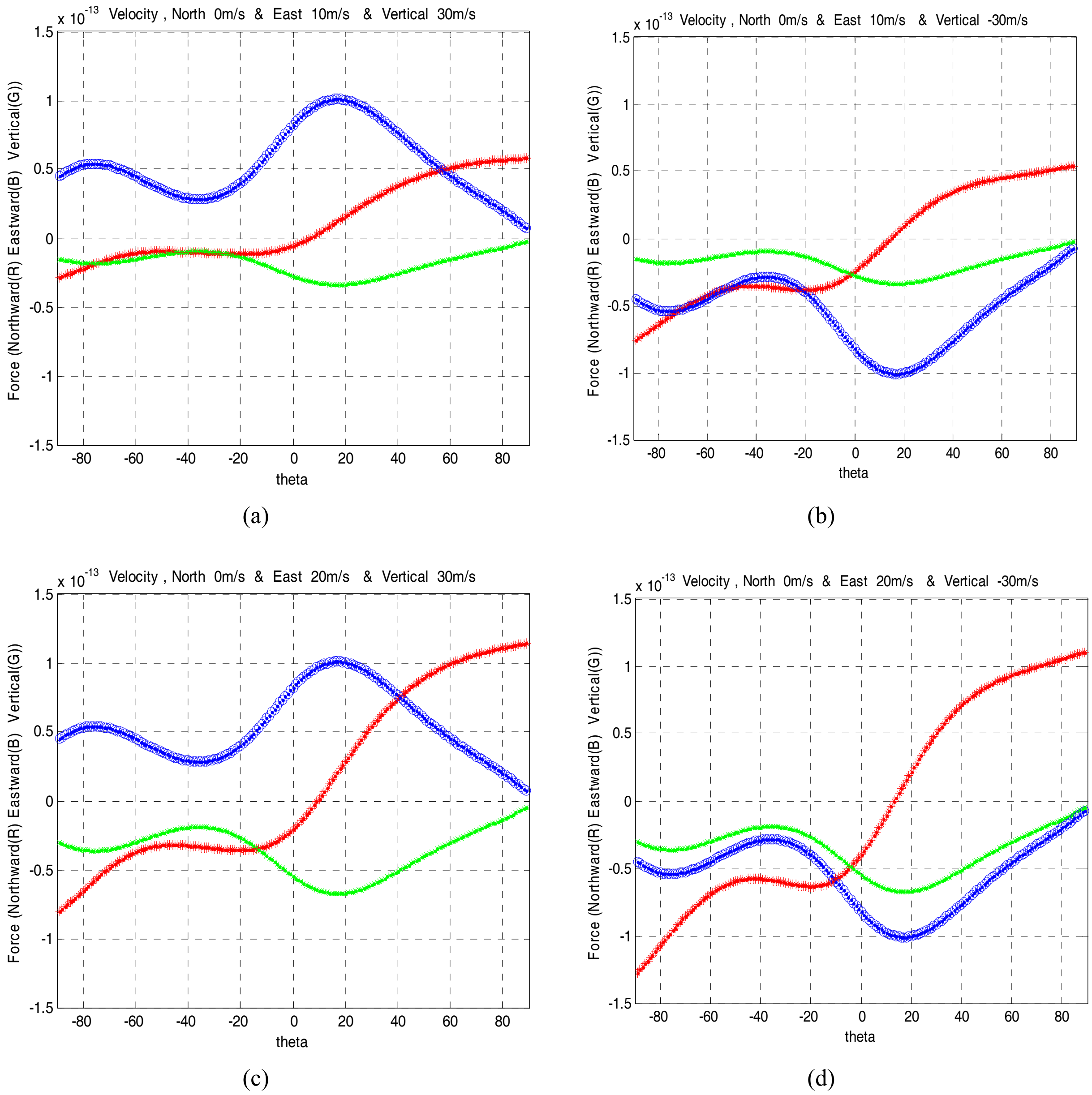


**Figure 3.** Results of the third scenario of simulation. Magnetic force resulted from the effect of EMF on moving charged hydrometeors. Vertical and horizontal axis shows magnetic force (N) and latitude (degree) respectively. Velocity vector characteristics are shown in each part. The sign of updraft motion is considered negative while the sign of downdraft velocity is considered positive. The northward, eastward and vertical (downward) components of magnetic force are illustrated in red, blue and green color respectively.

From the results of different parts of the second scenario (Figure 2) and the third scenario (Figure 3), the same conclusions could be obtained. Based on the Lorentz force equation and the results of these scenarios, it could be stated that the vertical component of magnetic force depends on horizontal (eastward and northward) component of hydrometeors' velocity vector. Moreover, the horizontal (eastward and northward) magnetic force depends on vertical component of the velocity. For instance, if weak, moderate, and strong updrafts (part (b) of Figure 1, Figure 2, and Figure 3) are compared, it is obvious that the eastward component of magnetic force increases respectively. In fact, as the horizontal components of velocity vector are the same, it could be stated that in strong updraft case, the effect of horizontal magnetic force is more powerful than weak (and moderate) updraft case. Therefore, the horizontal magnetic force depends on both the direction (updraft or downdraft) and the intensity of vertical component of velocity. Furthermore, the results of the scenarios show that the eastward magnetic force in latitudes from -10° (south) up to 50° (north) has stronger intensities and its maximum occurs in about 15° (north). Moreover, the northward magnetic force in latitudes about 5° (north) up to 15° (north) has a near zero intensity and its sign reverses in this range of latitudes.

The results of three scenarios show that by stronger velocities, the positive and negative charges (electrified hydrometeors) will experience higher amounts of magnetic force. Therefore, the distance between separated charges will increase more and more, that leads to the collection of the same sign charges in some layers, which are called the charge structure of thunderclouds. Therefore, the probability of electric field development and lightning initiation increases.

In fact, it could be stated that after cloud electrification and creation of individual charged hydrometeors (positive and negative charges on ice crystals and graupel pellets) magnetic forces resulted from EMF could push the separated charges. These magnetic forces could gather the same sign charges in layers and finally create the thundercloud's charge structure.

As Saunders (1988) mentioned, some storms are highly sheared and the horizontal separation between the charge centers can extend to some kilometers. Thus the positive/negative charge center could be out on its own ahead of the storm and discharges directly to ground (Saunders, 1988). In fact, updraft/downdraft component of velocity vector with regard to EMF leads to horizontal magnetic forces (horizontal displacement of charged hydrometeors). Hence, EMF and the resultant magnetic force could clarify the reason of the aforementioned observations (Ogawa and Brook, 1969; Saunders, 1988; Stolzenburg et al. 1998; Pineda et al. 2016) to some extent.

Finally, based on the Lorentz force equation, the magnetic force in Cartesian coordinate system could be expressed as follows:

$$\begin{cases} F_x = q\,(V_y B_z - V_z B_y), & \textit{Northward Magnetic Force} \\ F_y = q\,(V_z B_x - V_x B_z), & \textit{Eastward Magnetic Force} \\ F_z = q\,(V_x B_y - V_y B_x), & \textit{Downward Magnetic Force} \end{cases} \quad (4)$$

Regarding the above equation, the cause of different results of scenarios could be interpreted. It should be noted that in these scenarios just eastward and vertical components of the velocity vector have been considered ($V_y$ , $V_z$), and the northward component of the velocity has been ignored ($V_x$ =0). Besides, it is important that the amount of each EMF component ($B_x$ , $B_y$ , $B_z$) depends on the location of hydrometeor in troposphere and these components are acquired from IGRF model.

Therefore, with regard to the above-mentioned simulation results, the direction and magnitude of the charged hydrometeors' velocity are noteworthy to consider EMF effect on the charge structure of thundercloud. It could be stated that the velocity vector of charged hydrometeors plays an important role in determining the magnetic force's direction and intensity. Therefore, magnetic force could gather the same sign of charges in a region and establish the cloud's charge structure (positive and negative charge layers). In fact, the simulation results show that in presence of charged hydrometeors, the effect of EMF on charge separation in clouds might be a mechanism of forming thundercloud's charge structure that could result in electric field development and lightning initiation in thunderclouds.

## 5. Summary and Conclusion

Electric field increment in clouds that may lead to lightning incidence is the result of cloud electrification and charge separation, while the exact reason of cloud electrification and charge separation has not been specified yet. The important role of the magnetic field in different contexts (as an interface between electrical energy and mechanical energy) triggers the idea that EMF could have a vital effect on GEC, climate, and Earth's thermodynamic system. The goal of this study was to gather some evidences to introduce new horizons about the effects of EMF on cloud electrification and charge separation in thunderclouds, which finally could result in lightning incidence.

To this end, some possible effects of EMF on hydrometeors' electrification have been presented. The relative diffusional growth rates of the interacting ice particle surfaces, which is the factor that controls the sign of charge transfer, is a function of the magnetic field because at least four elements of the crystal growth rate equation (capacitance of water, latent heat of sublimation, thermal conductivity of water, and saturation vapor pressure) are depended on the magnetic field. Hence, the magnetic field plays an important role in determining the sign of charge transfer through the variation of hydrometeor's microphysical parameters.

Moreover, based on the Lorentz force equation, the most transparence effect of EMF on charged hydrometeors is charge separation, but it has not been taken into account yet. In fact, a hypothesis is proposed about the effects of EMF on the charge structure of thundercloud based on the Lorentz force equation and Fleming's Right-hand Rule. To prove this hypothesis, a simulation using the12$^{th}$ IGRF model has been conducted.

Based on the results of scenarios, it could be stated that the vertical component of the magnetic force depends on the horizontal (eastward and northward) component of hydrometeors' velocity vector. Moreover, the horizontal (eastward and northward) magnetic force depends on the vertical component of the velocity. In fact, with the same horizontal components of the velocity vector, it could be stated that the effect of horizontal magnetic force is more powerful in strong updraft case rather than weak (and moderate) updraft case. As a matter of fact, the horizontal magnetic force depends on both the direction (updraft or downdraft) and the intensity of vertical component of the velocity.

The results of the three scenarios show that by stronger velocities, the positive and negative charges (electrified hydrometeors) will experience higher amounts of magnetic force. In fact, after cloud electrification and creation of individual charged hydrometeors (positive and negative charges on ice crystals and graupel pellets) magnetic forces resulted from EMF could push the separated charges. Therefore, the distance between separated charges will increase more and more that leads to the collection of the same sign charges in some layers, which are called charge layers of thunderclouds. Therefore, the probability of electric field development and lightning initiation increases.

With regard to the simulation results, the direction and magnitude of the charged hydrometeors' velocity are noteworthy to consider EMF effect on the charge structure of thundercloud. It could be stated that the velocity vector of charged hydrometeors plays an important role in determining the magnetic force's direction and intensity. Therefore, the magnetic force could gather the same sign of charges in a region and establish the cloud's charge structure (positive and negative charge layers). Both gravity and electric force are in vertical direction and the amount of vertical component of the magnetic force in comparison with them is negligible. In fact, the north/southward and east/westward components of Earth's magnetic force (horizontal magnetic force) could play an important role in charge separation and charge structure of thunderclouds. Finally, simulation results show that in the presence of charged hydrometeors, the effect of EMF on charge separation in clouds could clarify the reason of some real thunderstorm observations to some extent and this effect might be a mechanism of forming thundercloud's charge structure that could result in electric field development and lightning initiation. This hypothesis is a theoretical investigation through a numerical simulation, and it should be tested and verified using experimental apparatus in future.

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