Examining the influence of current waveform on the lightning electromagnetic field at the altitude of halo formation

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In this paper, we extend the analysis of Lu (2006) to calculate the electric field (E-field) of lightning return stroke in the region of sprite initiation and halos using a transmission line model that uses various lightning stroke current measured during the triggered lightning experiment as the driving source to examine the individual components (i.e., electrostatic, induction, and radiation) of E-field perturbation. As the altitude increases, the maximum strength of electrostatic and induction field gradually decreases, and the induction field decays slower than electrostatic field above 80 km. The electrostatic and induction field in the region of halo formation have a much larger contribution to the total E-field than the radiation field. Therefore, it is proposed that in addition to the electrostatic field, the induction field (with amplitude more than half of total E-field) is the main component of the total E-field within the first half millisecond directly above the stroke. Our analysis indicates that the induction field might play a significant role in the halo formation and probably also the sprite initiation. The M-component, the longer rising edge, the wavy long tail, and the relatively long time scale of stroke current can increase the amplitude of electrostatic and induction field at the height of halos, and drive the occurrence of halos and the subsequent development of streamers, therefore forming sprites. Our results enrich the understanding on the mechanism of halo production and the lightning electromagnetic field in the middle and high-altitude atmosphere, and also pave the way for future accurate modeling of halo formation.

1. Introduction

The middle and upper atmosphere electrical discharging phenomena, also known as Transient Luminous Events (TLEs), are one of the hot subjects in current study on lightning physics. Early in 1925, C. T. R. Wilson, the Nobel Prize winner in physics, proposed that lightning electromagnetic fields could generate transient luminescence in the lower ionosphere. After red sprite was recorded for the first time in 1989 (Franz et al., 1990), many studies have been conducted on TLEs using low-light and high-speed camera observations and electromagnetic modeling, while the mechanism of discharge luminescence still needs further investigation. Rowland (1998) suggested that three kinds of energy may be the cause of TLEs: (1) electrostatic field generated by the initial charge of thunderstorm before lightning discharge; (2) electromagnetic pulse (EMP) produced by lightning stroke; (3) quasi-electrostatic (QE) field generated by the current flow following the return stroke. In addition, the conductivity of atmosphere was assumed to increase exponentially with height, with different conductivity profiles being used for daytime and nighttime conditions (Tran et al., 2017). The occurrence of TLEs in the upper atmosphere also benefits from the very low air density in the upper atmosphere (Wilson, 1925).

According to its morphological characteristics, TLEs are usually divided into elves, halos, red sprites, blue jets, and gigantic jets (Pasko et al., 2012; Wescott et al., 2001; Miyasato et al., 2002; Liu et al., 2018).
Among them, the halo phenomenon is in the form of a diffusive circular dish, which usually occurs at a height of 75–85 km (Wescott et al., 2001; Miyasato et al., 2002) with a horizontal range of about 40–80 km (Barrington-Leigh et al., 2001; Wescott et al., 2001). When the electric field (E-field) generated by the lightning discharge reaches the breakdown threshold (approximately 120 TD), the halo may be generated (Barrington-Leigh et al., 2001; Wescott et al., 2001; Bering et al., 2002; Moudry et al., 2003; Luque and Gordillo-Vázquez, 2011). Pasko et al. (2012) numerically simulated that the halo is a direct result of the QE field generated by the cloud-to-ground (CG) strokes. Veronica et al. (1999) developed a new two-dimensional cylindrical symmetric electromagnetic model that can give the influence of the QE field and the EMP process. The model can simulate lightning ionosphere interactions on a time scale of several microseconds to tens of milliseconds. Barrington-Leigh et al. (2001) used this model to study the relationship between elves and halos. They suggested that elves are mainly produced by EMP when large changes in charge moments occur over shorter time scale (<1 m), and halos are generated by the QE field. By discussing the EMP breakdown versus QE field breakdown, Fernsler and Rowland (1966) found that in the vertical CG stroke, the EMP can account only for breakdown between 70 and 95 km altitude and can produce only short-lived optical emission, consistent with elves, but not consistent with the longer-lived option emission. The optical radiation of halos usually lasts from 1 to 3 m, and its occurrence is usually related to the positive and negative CG process (Bering et al., 2002, 2004; Frey et al., 2007). Compared to the intra-cloud lightning flash and cloud-to-cloud lightning flash, the return stroke of CG can transfer more charges (Rakov and Uman, 2003; Maggio et al., 2009). Therefore, studying the electromagnetic field at the halos originating zone during the return stroke of CG is of great significance for the study of the halos initiation mechanism and its influencing factors.

The numerical calculation of lightning electromagnetic field is mostly based on lightning stroke base current models, including double exponential function model (Bruce and Golde, 1942), Heidler function model (Heidler et al., 1999) and impulse function current model (Chen et al., 2002). These models are more focused on the general characteristics of the base current, rather than the real situation. As an extension to the analysis of Lu (2006), in order to study the lightning electromagnetic field in the transmission-line (TL) model (Uman et al., 1975) at height of about 80 km of the height of halos and further find out its possible effect on halos with greater detail, this paper is based on the measured base current of artificial triggered lightning in Shandong in 2013 and 2014, focusing on the analysis of the corresponding electromagnetic components. For the first time, based on the current measurement data of artificial triggered lightning, it can better reflect the characteristics of natural lightning current. The study on the electromagnetic field of lightning return stroke generated at the height of halos helps to reveal the possible mechanism of halos, enrich the physical knowledge of halos, and promote the understanding of TLs.

2. Data and methods

In this section, we describe the method used to calculate the different components of lightning-induced E-field perturbation at mesospheric altitudes. In particular, the lightning stroke current measured during the triggered lightning experiments at Shandong Triggering Lightning Experiment (SHATEL) are introduced into the model as the excitation source in order to investigate the influence of various factors of lightning current on the lightning-induced E-field perturbation.

### 2.1. Model description

In the calculation of electromagnetic field produced by lightning strokes, the TL model is used to simplify the stroke channel, and the lightning channel has no branches and is perpendicular to the ground surface. The lightning stroke channel model is shown in Fig. 1. The height of lightning channel H is 5 km, and v is the constant return stroke speed of 1.8 × 10^6 m/s. The current at the bottom of the channel at \( z^* = 0 \) is \( I(0, t) \), and there is a time delay \( (t-z^*/v) \) between it and the current value of the current element \( I(z^*, t) \) at time \( t \), height \( z^* \) (Rakov and Tuni, 2003).

\[
I(z^*, t) = P(z^*)I(0, t - z^*/v)
\]

where, \( P(z^*) = 1 \), which means the current does not decay with height. The current at the channel top is equal to the current at the bottom of the channel. We compared the E-field calculated by the method used in this paper and the MTLL method where the current at the channel top is 0. Although they have different amplitude, the proportion of total E-field, electrostatic component and induction component is almost same. The method we used is valuable under the condition that we are more care about the ratio between the total E-field and its components in the calculation results.

The horizontal and vertical components of the E-field are calculated respectively as (Uman, 1987):

\[
E_x(r, \phi, z, t) = \frac{1}{4\pi\varepsilon_0} \int_0^H \left[ \frac{3r(z - z^*)}{R^3} \int_0^{r(t)} I \left( z^*, \tau - \frac{z^* - z}{v} \right) d\tau \right] dz^* \\
+ \frac{1}{4\pi\varepsilon_0} \int_0^H \left[ \frac{3r(z - z^*)}{cR^3} \int_0^{r(t)} I \left( z^*, \tau - \frac{z^* - z}{v} \right) d\tau \right] dz^* \\
+ \frac{1}{4\pi\varepsilon_0} \int_0^H \left[ \frac{c^2R^3}{c^2R^3} \int_0^{r(t)} \frac{\partial}{\partial \tau} I \left( z^*, \tau - \frac{z^* - z}{v} \right) d\tau \right] dz^* \\
E_z(r, \phi, z, t) = \frac{1}{4\pi\varepsilon_0} \int_0^H \left[ \frac{2(z - z^*)^2 - r^2}{R^3} \int_0^{r(t)} I \left( z^*, \tau - \frac{z^* - z}{v} \right) d\tau \right] dz^* \\
+ \frac{1}{4\pi\varepsilon_0} \int_0^H \left[ \frac{2(z - z^*)^2 - r^2}{cR^3} \int_0^{r(t)} I \left( z^*, \tau - \frac{z^* - z}{v} \right) d\tau \right] dz^* \\
+ \frac{1}{4\pi\varepsilon_0} \int_0^H \left[ \frac{c^2R^3}{c^2R^3} \int_0^{r(t)} \frac{\partial}{\partial \tau} I \left( z^*, \tau - \frac{z^* - z}{v} \right) d\tau \right] dz^* \\
\]

Different return stroke models, such as BG, TCS, MTLL, MTLL, and DU models described by Nucci et al. (1990) will produce different field components by using different current distributions. Once the current is specified, there are four different methods to calculate the electromagnetic field (dipole technique, monopole technique, apparent charge potential, and potential difference technique).
the charge itself (electrostatic field) to the initiation of halo, the influence of induction field induced at high altitude from the process of charge movement on the initiation of halo cannot be ignored, and its attenuation in the halo region may be less than that of the electrostatic component. Therefore, different from the work of Pasko et al. (1995) (using the full-wave method), this paper selects the classical dipole method which can well represent the field components (i.e., electrostatic, induction, and radiation) to study the mechanism of halo formation. However, even though the total E-field from a current or charge distribution is unique, the division of total E-field in the time domain into so-called electrostatic, induction, and radiation components is not unique using the four methods above. As for the fourth method to calculate the electromagnetic field relaying on stationary charges, uniformly moving charges and accelerating charges, the field components calculated are static, velocity, and radiation components. These three components can be converted to the electrostatic, induction and radiation components calculated by dipole method (Cooray and Cooray, 2012, 2019). No matter which of the four methods is used, the ratio between the field components obtained is almost the same, and the difference between them in the far range is negligible (Thottappillil and Rakov, 2001a; 2001b). Even in the fourth method, the proportion of the static, velocity, radiation components is almost the same as proportion of the electrostatic, induction, radiation components in the dipole method (Cooray and Cooray, 2019). Using different methods does not affect the conclusion that the electromagnetic component (induction component) produced by the process of charge movement has a considerable influence on the halo initiation.

By neglecting the curvature of ground and ionosphere that are both viewed as perfect conductors, we set up the parallel-plate capacitor model for further computation showed in Fig. 2. This assumption is valid for the computation confined within a small area, for example, r < 300 km (e.g., Veronis et al., 1999). Recalling that all existing observations (e.g., Sentman and Wescott, 1995; Winckler 1995; Lyons, 1996; Iinan et al., 1997; Barrington-Leigh and Iinan, 1999; Fukunishi et al., 1996; Barrington-Leigh et al., 2001; Neubert et al., 2008; Sào Sabbas et al., 2009, 2010) and most theoretical simulations (e.g., Fernsler and Rowland, 1996; Pasko, 1997; Rowland et al., 1995; Iinan et al., 1991; Luque and Ebert, 2009; da Silva and Sào Sabbas, 2013) show that the sprites, halos and elves appear within the altitude range of 40–95 km. So we set the ionosphere height H₀ to be 95 km, and the height of field point P is in the range of 40–95 km. In our computation, reflections from both ground and ionosphere are incorporated by simply introducing image currents into conductors. According to the principle of mirror image, the electromagnetic field produced by the actual current and the mirror current is calculated by equations (2) and (3) separately, and the superposition principle is used to obtain the total E-field of any point P(r, ϕ, z) in free space at any time. In the equation for calculating the E-field, the total E-field consists of three components: the electrostatic field containing a current integral; the induction E-field contains a current source; and the radiation field contains a current derivative. Both attenuation during propagation and penetration into ionosphere of E-field are neglected, equations (2) and (3) are valid under our assumption. Under these assumptions, we ignore the strong boundary effects and must admit that we overestimate the results. Rowland et al. (1995, 1996), Fernsler and Rowland (1996), and Sukhorukov et al. (1996) have done some work to consider the true conductivity of the ionosphere. However, these studies did not specify the main contributions of the individual E-field components. Zhang et al. (2014) compared the calculation with both the finite-differential time-domain (FDTD) method and our method, their results indicate that our model generally overestimates the lightning-induced E-field at 90 km by a factor of about 4. Although the FDTD method can well consider the nonlinear effects of atmospheric electrical parameters in the middle and upper atmosphere, it cannot effectively distinguish the E-field components. In Section 3.2, we compared the vertical E-field at a horizontal radius of 1 km and an altitude range of 40–95 km based on the calculation method used in this paper and the FDTD method in Zhang et al. (2014) to estimate the error of the results obtained in this paper.

It should be noted that the lightning channel model and the mirror model in Lu (2006) are used in this paper, and most of the parameter settings are consistent with Lu (2006). However, as a further development work of Lu (2006), this paper changed the position of the field point and improved the current input data. The height of the field point in Lu (2006) is 90 km, the height of the creation of elves. While for the height of the halo center is in the range of 70–85 km and the average height is about 80 km (Wescott et al., 2001; Miyasato et al., 2002), in the section 3.1, 3.3 and 3.4, the height of the field point is placed at 80 km to examine the characteristics and contributions of individual E-field components at this altitude to pave the way for the future studies of halo phenomena. In the section 3.2 and 3.5, an altitude range of 40–95 km is set to analyze the change of total E-field, electrostatic components and induction components. As another difference, the current input data will be introduced in the next section.

2.2. Description of the current input data

Artificial triggered lightning has provided an effective way to study the physical mechanism of lightning discharge. Different from that in Lu (2006), the base current data used in this paper comes from artificial triggered lightning experiments in Binzhou, Shandong Province (Jiang et al., 2013). One case is a lightning stroke case with 16 return strokes obtained in summer of 2013 (Sun et al., 2014), another is a case with 6 return strokes in the summer of 2014 (Lu et al., 2016), the peak current is distributed at 5.9–32.7 kA. In fact, the return stroke process of artificial triggered lightning is only similar to the subsequent stroke of the natural lightning (Rakov et al., 1998; Yang et al., 2009), that is, the average peak current (10–17 kA) of the return stroke of a traditional artificial lightning is basically the same as the subsequent stroke of natural lightning (12–18 kA) (Zhang et al., 2007). According to the observations, the subsequent stroke can generate base current with relatively large peak value. In 2016, the maximum stroke base current recorded in 50 artificial lightning strokes in Guangdong is 46 kA (Zhang et al., 2017). According to Chen et al. (2015), based on the combined observation data of 58 flashes of negative polarity, when the height of the grounding point of the natural lightning is greater than 200 m, the peak current of subsequent stroke can reach ~151.4 kA.

In this paper, the 22 measurements of lightning stroke base current...
are cut out. By comparing and analyzing the waveform parameters of these channel-based current, it is found that some of characteristics of current are different from the characteristics of conventional current commonly used in the former electromagnetic field calculation, for example, in Lu (2006), the double exponential function model with a peak current of 57 kA and time scale of 0.1 ms was used. These 22 measurements of channel-based current are divided into two types: the first is the stroke base current measured after a dart leader connecting thunderstorm clouds with the earth; the second is the stroke base current measured after a dart-stepped leader, with a long time interval after the previous stroke, dart leaders may transform into dart-stepped leaders (Sun et al., 2014). The former type base currents are divided into the traditional base current, base current with M-component and base current with wavy long tail. The falling edge of traditional base current is relatively smooth. The base current with M-component has a subsequent enhancement with millisecond timescale, named type-2 as shown in Fig. 3(b). The rising edge time of the second type base current is significantly greater than that of the first type base current, named type-3 as shown in Fig. 3(c). The falling edge of the base current with wavy long tail still fluctuates after 1 ms, named type-4 as shown in Fig. 3(d). Then, the 22 channel base current normalized by the peak value are aligned at the peak, that is, divide each current value by its peak value, then find the normalized mean of the first type current, the result is shown in Fig. 3(a), named type-1. Since we did not observe the occurrence of halo in the actual artificial experiment, and there is no measured current peak that can induce halo, we assume that the input channel base current with a time scale of 2 ms has a peak value of 100 kA in calculation. The charge moment change for initiation of a sprite is found to be as low as 120 C km (Hu et al., 2002). Huang et al. (1999) analyzed many sprite-producing discharges from one day and found a minimum total charge moment of 300 C km for sprite production. However, Huang et al., (1999) measured the charge moment change for the entire lightning discharge, which by definition exceeds charge moment change responsible for initiating the sprite. Cummer and Lyons (2005) reported impulse lightning charge moment changes (defined as occurring in the first 2 ms after the return stroke onset) in all CG in three storms, and found that the threshold of two nights was approximately 600 C km and on the other it was approximately 350 C km. The charge moment change of the lightning discharge examined in this paper is above 550 C km, which could produce a sprite or halo.

It should be noted that, the “two-wave” theory (Rakov et al., 1995) was not used, and the charge neutralization between the downward and upward waves (Jiang et al., 2013) was not considered when discussing the E-field generated by the type-2 base current at a high altitude, both of them pay more attention to the physical mechanism of M-component. The effect of the two waves in this paper is combined into a current source focusing on the overall current radiation generated by the resultant current, as well as the case with type-3 and type-4. In other words, for all 4 types of current waveforms shown in Fig. 3, regardless of their actual formation mechanism and height profile, the current source was assumed to be at ground level and inject the specified current wave into the vertical channel above it, as per equation (1).

3. Results and analysis

In this section, we apply the method described above to examine the influence of current waveform on the lightning electromagnetic field components at the altitude of halo formation and attempt to reveal the characteristics of lightning-induced E-field perturbation, which will provide more insights into the mechanism of halo production as the electromagnetic coupling between tropospheric thunderstorm and mesosphere.

3.1. Dominance of vertical E-field

This section examines the dominance of the vertical E-field and its three components at an altitude of 80 km directly above the stroke. Based on type-1 current with peak value of 100 kA and time scale of 2 ms, Fig. 4 shows the ratio between the maximum vertical E-field and the maximum horizontal E-field with the radial distance (r ≤ 300 km), where the value of black dashed line is 1. It can be seen from the figure that the vertical component of the electrostatic field (red solid line) dominates in the range of 0–95 km and 150–300 km. The vertical component of the induction field (blue solid line) dominates in the range of 0–60 km and 235–300 km, and stronger within 60 km especially. The vertical component of the radiation field (green solid line) dominates in the range of 75–300 km, and the green solid line in this region is almost in line with the black solid line (vertical total E-field). As mentioned above, the radial diameter of halos ranges from about 40 to 80 km, and the vertical components of the electrostatic field and induction field are completely dominant within 105 km and 60 km, respectively; in addition, since Wescott et al. (2001) found that halos are pretty much centered on the CGs, with the minimum displacement: 4.6 ± 2.7 km, the following discussions will focus on the vertical components of lightning

![Fig. 3. Current used as I(0,t) in equation (1) for E-field calculations below, (a) type-1 current; (b) type-2 current; (c) type-3 current; (d) type-4 current.](image)
E-field to examine the mechanism of halo production.

3.2. Comparison of E-fields calculated by TL and FDTD

Take the type-1 current with peak value of 100 kA as the input current, the contrast of the vertical E-field at a horizontal radius of 1 km and an altitude range of 40–95 km based on the calculation method used in this paper and the FDTD method in Zhang et al. (2014) with a grid size of 0.5 km × 0.5 km is shown to estimate the error of the results obtained due to the spatial conductivity in this paper. The atmospheric conductivity profile used in the FDTD calculations is given in Fig. 5a, among them, the influence of lightning E-field on spatial conductivity is considered above 60 km. The other parameters in both models are set the same.

As shown in Fig. 5b, at altitude of 40–80 km, the E-fields calculated by TL and FDTD method are almost consistent. While the simulation results of the FDTD method are smaller than that of TL above 80 km, because when the nonlinear influence of the middle and upper atmosphere electrical parameters is considered, the medium becomes dissipated, a portion of the electromagnetic energy is dissipated by collision ionization and thermal ionization. At the heights of 85 km and 90 km, the simulation results of FDTD are reduced by about 1/4 and 3/4, respectively, comparing with TL. When the height reaches 95 km, the simulated E-field of FDTD has even decreased to zero, and the simulated E-field value of TL is still comparable to the simulation result at 90 km. In summary, the method used in this paper is effective at altitude range of 40–80 km, and the influence of the spatial conductivity on the E-field must be considered when the height exceeds 80 km, where the simulation result of TL is invalid. The E-field value given by the FDTD method cannot distinguish the electrostatic, induction and the radiation components, while it can give a more accurate value of E-field, the calculation results of TL above 80 km will be corrected by FDTD.

3.3. Vertical E-field calculated for four kinds of base current

Based on the four types of base current with a peak of 100 kA and a timescale of 2 ms, Fig. 6 shows the waveforms of vertical components of the electrostatic, induction, and radiation fields, as well as the total E-field at different radial distances r (1 km, 50 km, 200 km) at an altitude of 80 km.

From Fig. 6a, b, c, and d (r = 1 km), it can be seen that for the vertical E-field directly above the stroke, the induction components are the main components of the peak of total E-fields (with amplitude more than half of the total E-field) within the first half millisecond of all the discharges. Except in Figure b, the induction components appear two big peaks with time difference, according to the calculation, the second one is superposition effect of ionosphere reflection with time delay of propagation; as time goes on, the proportion of the electrostatic field gradually increases; the radiation component is the weakest directly above the stroke (almost zero), which is consistent with the results of Barrington-Leigh et al. (2001).

Fig. 7a, b, c, d show the waveform of vertical components at a radial distance r = 50 km. The figures show that although the magnitude of induction component has become smaller, its contribution to the peak of the total E-field is still the largest; the amplitude of radiation field...
The radiation component, vertical radiation component is reversed when the vertical induction based on type-3 current; (d) based on type-4 current. The altitude of 80 km: (a) based on type-1 current; (b) based on type-2 current; (c) based on type-3 current; (d) based on type-4 current.

Interestingly, it can be clearly seen that the polarity of the vertical radiation component is reversed when the vertical induction component has an extreme value. From a mathematical point of view, in the radiation component, \( \frac{d}{dt}I(z, t - \frac{z}{c} - \frac{z}{c}^2) \) is the differential of \( I(z, t - \frac{z}{c} - \frac{z}{c}^2) \) in the induction component with respect to time \( t \). When the induction component has an extreme point, the radiation component at that moment is zero.

Fig. 5a, b, c, d show the waveform of vertical component at a radial distance \( r = 200 \) km. In the figure, the polarity of induction field is reversed, and the amplitude is small. According to formula (3), it can be calculated that when the horizontal distance \( r \) is about 136 km, the value of the vertical induction component of this field point is approximately 0, when \( r \) is greater than this critical value, the value of the vertical induction component will be less than 0; the value of electrostatic field is almost zero; the radiation component contributes the most to the total E-field at this horizontal distance.

By comparing Figs. 6–8, it can be seen that the total field always has two similar sections with different amplitudes, it is found that the latter section is the production of reflection of ionosphere. As the same of Lu (2006), for the lightning-induced E-field changing at high altitude, the ionospheric mirror effect increases the lightning-induced E-field intensity at high altitudes and extends its time scale. Except it, the M-component, the longer time rising edge of type-2 current, and the existence of wavy long tail increase the amplitude of the electrostatic component with main characteristics of current integration and the induction component with current source compared with the vertical E-field and its components based on type-1 current. Especially in the vertical E-field based on type-3 current, the amplitude is almost doubled. Asano et al. (2009) found that small amplitude M-components with rapidly changing EM effects in lightning continuous current can trigger and enhance sprites. Yashunin et al. (2007) also made the similar conclusion that M-components serve to enhance the E-field at high altitudes, and as a result, may increase the probability of sprite (halo) initiation. In addition to the increase in amplitude, the wavy long tail of base current cause similar fluctuations in the tails of their respective vertical E-fields and component waveforms. From a mathematical point of view, in the case where the horizontal distance \( r \) at the field point is the same, the differences of the waveforms of vertical E-field and its three components based on the current in four types mainly comes from the integral of the mathematical expression \( I(z, t - \frac{z}{c} - \frac{z}{c}^2) \) on the height, and the M-component and the longer time rising edge in the current increase the integration value in the calculation, thereby increasing the peak of the corresponding vertical electrostatic component and induction component. As for type-4 current, the increase peak value of the vertical electrostatic component and the induction component in this paper is only due to the fact that the integration value of type-4 current is greater than that of type-1 current before 0.5 ms, which can be clearly seen from the current waveform diagram, however, the current fluctuation after 1 ms of type-4 current does increase the amplitude of the vertical electrostatic component and the induction component.

Pasko et al. (2012) suggested that halos are a direct consequence of the QE field generated by lightning discharges. According to our results, in addition to the contribution of electrostatic field, the contribution of induction field is more important within a radial range of 50 km. As the induction field is the main component of the total E-field (with amplitude more than half of the total E-field) within the first about 0.5 ms directly above the stroke, our analysis indicates that the induction field makes significant contribution to the halo formation. The M-component, the longer time rising edge, and the wavy long tail of stroke current can all increase the amplitude of electrostatic and induction field at the height of halos, and excite the occurrence of halos and possible subsequent development of streamers, therefore forming sprites.

### 3.4. Maximum vertical E-field for four kinds of base currents

Based on the four types of base current with peak current of 100 kA and time scale of 2 ms, Fig. 9 shows the variation in the maximum vertical component of the total E-field and its electrostatic, induction and radiation components within a range of 0-300 km from the vertical lightning channel at an altitude of 80 km. In the figures, the curves of the maximum electrostatic and induction components both show a downward trend, within the radial distances of 20 km, 25 km, 30 km, and 27 km are the main components of the total E-field, respectively. The amplitude of the electrostatic field is slightly higher than that of the induction field right above the lightning stroke. Subsequently, as the radial distance increases, the maximum induction field exceeds the electrostatic field at 34 km, 75 km, 10 km, and 62 km respectively. Since the origin of halos generally occurs within a radius of 20 km directly above the stroke, this result again supports the conclusion that the induction field above is also one of the causes of halos. By comparing these four figures, it is found that the presence of M-component, long rising edge time and the wavy long tail all increase the maximum amplitude of electrostatic field and the induction field compared with that based on type-1 current. Especially in the vertical E-field based on type-3 current, the amplitude has increased about twice. Within the radial distance of 30 km, the amplitude of the induction field exceeds the electrostatic field at a distance of less than 10 km, and has a more obvious contribution to total E-field.
induction component, the characteristic and main contributions of the electrostatic, induction, and radiation components have been calculated, and our analysis indicates that:

3. Conclusions

The data of lightning stroke base current of artificially triggered lightning in 2013 and 2014 were analyzed. Based on the four types of base current, the characteristics and main contributions of the electrostatic, induction, and radiation components have been calculated, and our analysis indicates that:

3.5. Variation of maximum vertical electrostatic and induction fields with height

Based on type-1 current with time scales of 2 ms and 3 ms, respectively, and the peak current of 100 kA, Fig. 10 shows the curve of absolute maximum vertical electrostatic and induction field over a radius of 20 km from the lightning channel changing with altitude (40–95 km). Based on the results of section 3.2, the value of $E$-field above 80 km have been corrected. The figure shows that at a height of 40 km, the maximum electrostatic field is higher than that of the induction field. As the height increases, the maximum electrostatic component and induction component gradually become smaller and the speed of decreasing behaves from fast to slow below 80 km, while in the altitude range of 80–95 km, the induction component decreases slower than the electrostatic component, and it catches the electrostatic field at approximately 84 km. As the increasing of altitude, although the amplitude of single peak of induction component is decreasing, the time difference between the two peaks is increasing due to the propagation effect of time delay of ionosphere reflection, and which leads to a superposition of the two peak value and an increase in the maximum value of induction component. For TLs that originate within a height range of 70–95 km, the contribution of electrostatic and induction components to their inception cannot be ignored. Even within a certain range, the induction field may contribute more than the electrostatic field. In addition, when the time scale of the base current extends to 3 ms, the maximum electrostatic field and the induction field are significantly increased, the induction component has a slower decreasing speed than the electrostatic component above 80 km. The lightning currents with various time scales have different effects on the middle and upper layer. As the time scale becomes longer, it will be more favorable for the development of streamers from the ionization region (e.g., Hiraki, 2010; Qin et al., 2013), forming sprites with a more vertically structured features (Pasko et al., 1997; Luque and Ebert, 2009; da Silva and São Sabbas, 2013). The longer the timescale of the base current, the more significant the contributions of the electrostatic and induction fields.

4. Conclusions

The data of lightning stroke base current of artificially triggered lightning in 2013 and 2014 were analyzed. Based on the four types of base currents, the characteristics and main contributions of the electrostatic, induction, and radiation components have been calculated, and our analysis indicates that:

1. It is found that not only the $M$-component, but also the long time rising edge and the wavy long tail of the current waveform may increase the amplitude of the electrostatic field and induction field at height of 80 km, which will more easily promote the occurrence of halos, especially the long time rising edge of type-3 current.

2. Within the first about 0.5 ms, the induction field is the main component of the total $E$-field (with amplitude more than half of the total $E$-field) directly above the stroke. Our analysis indicates that the induction field might play a significant role in the halo formation.

3. Above altitude of 80 km, the amplitude of induction field decreases slower than electrostatic field, and exceeds the electrostatic field at 84 km due to the ionosphere reflection and time delay of propagation. It can be inferred that the contribution of induction field may be more obvious at the formation altitude of elves above 84 km, which is consistent with the conclusion by Lu (2006) that the induction field may be one of the causes of the initiation of elves at an average height of 85 km.

There are still some shortcomings for the work presented in this paper. Due to the limited spatial conductivity, in addition to reflection, the low ionosphere and the ground can absorb and leak some of the electromagnetic waves. In the calculation of lightning $E$-field, we correct the value of electrostatic and induction components of TL method by comparing error between results of total $E$-field of TL and FDTD methods. However, as the resulting error only represent the error of the total $E$-field between the two methods, we cannot get the accurate value of electrostatic and induction components with the spatial conductivity taken into account. As the induction component is the main component of the total $E$-field directly above the stroke, its attenuation after taking spatial conductivity into account is almost equal to that of total $E$-field. Therefore, to get a better conclusion, in our future work, it is necessary to consider the more accurate reflection effect of the lower ionosphere, including frequency response.

Acknowledgments

This work is supported by the National Key R&D Program of China (2017YFC1501501); "The One Hundred Talent" Program (2013068) of Chinese Academy of Sciences; National Natural Science Foundation of China (41622501, 41875006); Beijing Meteorological Service Science and Technology Project (BMBK201705002) and Beijing Natural Science Foundation (8184096). We acknowledge to the staff of Binzhou City Meteorological Bureau of Shandong Province and Jiushan Village Salt


H. Ren et al.


