Numerical Simulation of Effect of Lower Positive Charge Region in Thunderstorms on Different Types of Lightning

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ABSTRACT: Combined with the existing stochastic lightning parameterization scheme, a classic tripole charge structure in thunderstorms is assumed in the paper, and then 2-dimensional fine-resolution lighting discharge simulations are performed to quantitatively investigate the effect of lower positive charge (LPC) on different types of lightning. The results show: (1) The LPC plays a key role in generating negative cloud-to-ground (CG) flashes and inverted intra-cloud (IC) lightning, and with the increase of charge density or distribution range of LPC region, lightning type changes from positive polarity IC lightning to negative CG flashes and then to inverted IC lightning; (2) Relative to distribution range of charge regions, the magnitude of charge density of the LPC region plays a dominant role in lightning type. Only when the maximal charge density value of LPC region is within a certain range, can negative CG flashes occur, and the occurrence probability is relatively fixed.

INTRODUCTION

After natural lightning is triggered, why are some lightning channels terminated in the air to form IC lightning and others are able to develop to the ground to become CG flashes? The propagation behavior of lightning channels and the reason for formation of different types of lightning have been difficult problems in lightning scientific research field for a long time. With the development of modern observation and numerical simulation techniques, numerous studies indicated that lightning types, polarity, and propagation behavior may be closely related to the charge distribution of thunderstorms [e.g., Mazur and Ruhnke 1998; Zhang et al. 2006; Krehbiel et al. 2008; Zheng et al. 2010; Akita et al. 2011]. The typical charge distribution of thunderstorms is dipole or tripole charge structure, and the difference between them is whether there is an LPC region [Williams 1989]. However, whether there is a positive charge region at the bottom of thunderstorm and its magnitude may be the critical factors for the formation of negative CG flashes and inverted IC lightning [Qie et al. 2005; Nag and Rakov 2009].

Tessendorf and Rutledge [2007] suggested that the existence of LPC region serves to enhance the electric field at the bottom of the negative charge region, thereby facilitating the launching of a negatively-charged leader toward ground. Liu et al. [1989] found that a large LPC region usually exists at the bottom of the storms, and nearly all the IC flashes appear to occur in the lower portion of the cloud in

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Chinese Inland Plateau. Pawar and Kamra [2004] found that the LPC region plays a dominant role in initiating an IC or CG flash by the surface measurements of electric field and Maxwell current near a tropical thundercloud. Qie et al. [2005] revealed a tripole charge structure with a larger-than-usual LPC region in thunderclouds over the Tibetan Plateau of China, and reported that the large LPC prevents negative CG flashes from occurring and facilitates inverted IC flashes. Nag and Rakov [2009] qualitatively examined the inferred dependence of lightning type on the magnitude of the LPC region. They inferred that when the magnitude of LPC region is abnormally lager (comparable in magnitude to that of main negative charge), inverted IC flashes are expected to occur; when the magnitude of LPC region is even smaller than that of main negative charge region, negative CG flashes are expected to occur. All these have shown that the LPC region in thunderclouds has a great impact on lightning type and the propagation behavior of lightning leaders. Because of the limitation of sounding observation technique, it is difficult to acquire the information about charge structure (including charge density, horizontal and vertical distribution range, and total charge volume) in thunderclouds roundly, so the conclusions are mostly qualitative or inferred, hardly able to understand the effect of LPC on lightning behavior roundly.

So, how does LPC affect lightning types and propagation behavior of lightning leaders in the end? And how do the charge magnitude and distribution range of LPC region affect lightning discharges? To solve these problems, it is necessary to carry out theoretical computing work. Therefore, based on the existing stochastic lightning parameterization scheme [Tan et al., 2006a, 2006b, 2007], the assumption of a tripole charge structure in thunderstorms is used in the paper. The paper will quantitatively analyze the effect of LPC on lightning discharges through sensitive experiments of numerical simulation, and will put emphasis on the analysis of the effect of charge magnitude and distribution range of LPC region on lightning types.

SIMULATION METHOD

Tan et al. [2006a, 2006b, 2007] developed a fine-resolution lightning parameterization scheme based on the work of Mansell et al. [2002]. On the basis of the work, to carry out sensitive simulation experiments conveniently, the assumption of a tripole charge structure in thunderstorms is used in the paper. The space charge distribution provided by the charge structure is used as background field to carry out the following experiments of lightning simulations.

Assumption of distribution of charge structure in thunderstorms

In order to reproduce the lighting spatial form that can be compared to the natural lightning channel diameter, 2-dimensional Cartesian coordinate system with fine resolution is used. The simulation domain is 76 km×20 km, and resolution is 12.5 m×12.5 m. The charge distribution in thunderclouds is assumed to be a tripole structure [Williams 1989] with an additional negative screening charge layer at the top of storms, so the vertical distribution of the charge structure from up to down is: negative screening charge region (S), upper positive charge region (P), main negative charge region (N), and lower positive charge region (LP) (as shown in Figure 1). Stolzenburg et al. [1998] revealed this basic charge structure with four charge regions within convective updrafts in thunderstorms, and a negative screening layer usually exists at the top of storms [Bruning et al. 2007]. So, it is more close to actual situation to use the charge structure, and Krehbiel et al. [2008] simulated upward electrical discharges from thunderstorms with the charge distribution. The charge regions are assumed to be ellipse, which are centered on x_0 and z_0, and regard r_x

and r_z as the long and short half axis. The charge density distribution in charge regions is assumed to have a Gaussian spatial distribution, which has the maximal charge density in the center of charge regions. Bell et al. [1995] used the same charge density distribution in their 2-D dipole-charge model of quasi-electrostatic field. The specific charge density distribution in positive and negative charge regions is determined by the following formula:

$$\rho = \rho_0 \exp(-(2\phi)^2) \quad , \qquad (1)$$

$$\phi = \sqrt{\frac{(x-x_0)^2}{r_x^2} + \frac{(z-z_0)^2}{r_z^2}} \qquad (2)$$

The ρ_0 in above formula is used to control the maximal charge density of positive and negative charge regions, and it represents the magnitude distribution of charge density in charge regions. From the above formula, we know that the charge density magnitude and distribution range of charge regions are determined by the five parameters: ρ_0, x_0, z_0, r_x, r_z. In this paper, we focus on the discussion of the effect of LPC region on lightning behavior, so only r_x and ρ_0 in LP are varied in process of simulation, and other parameters are fixed. The distribution range values of charge regions follow the model of Krehbiel et al. [2008], and the specific values of these parameters are shown in Table 1. To discuss it conveniently, we define $D_x=2r_x$ as the horizontal distribution range of charge regions and ρ_{0x} as the maximal charge density of charge regions, and the subscript x can be S, P, N, and LP, which corresponds to different charge regions. What needs to explain especially is when we discuss different cases, ρ_0, r_x and corresponding D_x in S, P and N will also vary, and how they vary will be described in detail in the following section.

Table1 Geometrical and electrical parameters of thundercloud charge regions

Charge regions	ρ_0 (nC/m^3)	x_0 (km)	z_0 (km)	r_x (km)	r_z (km)
S	-1.0	38	12	4	1
P	2.2	38	9.5	4	1.5
N	-3.3	38	6.5	3	1.5
LP	Variation	38	4	Variation	1

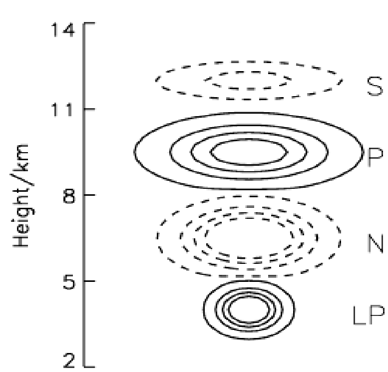

Figure 1 Schematic of classic tripole charge structure in thundercloud

Lightning parameterization scheme

With regard to lightning parameterization scheme, Mansell et al. [2002] developed a lightning scheme based on the stochastic dielectric breakdown model with the concept of bidirectional leaders [Kasemir 1960], and they successfully simulated IC lightning channels with bi-level branched structure and CG flashes. However, the resolution (500 m) is not fine and the method to adjust the overall charge neutrality is not well rationed. In addition, a flash was presently classified as a CG flash when a leader branch reached down to 1.5 km altitude. Tan et al. [2006a, 2006b, 2007] tested an improved lightning scheme with runaway breakdown and bidirectional stochastic propagation, and performed IC lightning simulation in fine resolution (12.5 m). The simulation results produced a bi-level branched channel structure in agreement with observation data. Tao et al. [2009] also modified the stochastic lightning scheme with a new CG treatment scheme, and simulated CG flashes whose leaders can reach ground directly for the first time. This paper applies the existing stochastic lightning parameterization scheme [Tan et al. 2006a, 2006b, 2007; Tao et al. 2009].

SIMULATION RESULTS

The charge magnitude of LPC region is jointly determined by the charge density magnitude and the distribution range of charge regions when the charge distribution form is fixed, and the two variables are independent from each other. Therefore, this paper will investigate the effect of LPC region on lighting types and propagation behavior from the two aspects respectively. As the variation of vertical distribution range is limited,the distribution range here is designated as the horizontal distribution range.

Effect of charge density magnitude of LPC region on lightning discharges

Figure 2 shows lightning channel structures and space charge distributions from different charge density magnitudes of LPC region. The charge configuration is the same in Figure 2(a), (b), (c), and (d), and r_x of LP is 1.5 km. The difference in Figure 2(a), (b), (c), and (d) is the magnitude of ρ_{0LP}, which is 1.5 nC/m^3, 3.0 nC/m^3, 4.0 nC/m^3, and 4.5 nC/m^3 respectively. As shown in Figure 2, with the increase of charge density of LPC region, the lightning type changes from positive polarity IC flashes to negative CG flashes and then to inverted IC flashes: 1) When the charge density of LPC region is small (Figure 2a、2b), lightning initiates between upper positive and negative charge regions of thunderstorms. Positive and negative leaders tend to propagate vertically from the initiation point at first, then negative leaders tend to extend horizontally after propagate upward to pass through the accumulative region of positive charge, and positive leaders also tend to extend horizontally after propagate downward to pass through the accumulative region of negative charge. There are a significant number of branches inside the high charge density zone and a few branches inside the low charge density zone, and the whole intracloud lightning channel presents a bi-level branched structure [Shao and Krehbiel 1996]; 2) When the charge density of LPC region is large (Figure 2c), lightning initiation point changed. The lightning initiates between positive and negative charge regions of the lower portion of cloud, and it is a negative CG flash. The negative leaders reach ground after propagate downward to pass through the positive charge region. The negative leaders in positive charge region with multiple branches, and tend to propagate alone after pass through the positive charge region. The propagation characteristics of positive leaders are similar to those of IC flashes. Mansell et al. [2005] also found that negative polarity CG flashes occurred when the LPC region had sufficient charge density to cause high electric fields; 3) When the charge density of LPC region is abnormally large (Figure 2d), lightning also initiates between positive and negative charge regions of the lower portion of cloud, but it is an inverted IC flash. The propagation features of the inverted IC flash leaders are consistent with those of normal IC flash, and only the initiation point and polarity changed. With regard to the two types of IC lightning, Zhang et al. [2002] revealed that in the case of a tripole charge structure, IC flashes not only occur between upper positive charge region and middle main negative charge region, but also can occur between middle main negative charge region and LPC region by using the observation data of lightning VHF radiation source. Qie et al. [2009] further confirmed that only the tripole charge structure with a larger-than–usual LPC region in thundercloud will facilitate the occurrence of IC lightning within the upper dipole and lower dipole regions. These observation facts also have proved the rationality of our simulation result.

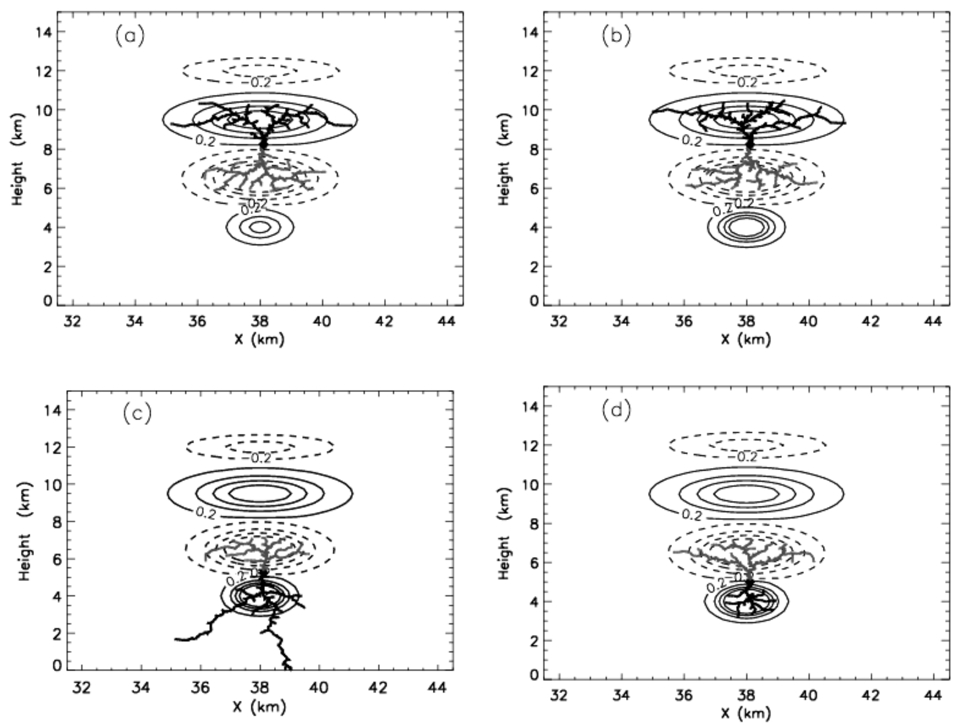

Figure 2 Lightning channel structure and space charge distribution from different charge density magnitudes of LPC region

Horizontal ordinate is the horizontal distance of simulation domain, ordinate is the height from ground, and solid is for positive charge density contour and dashed is for negative charge density contour. The charge density contour is equal to ±0.2， ±0.7，±1.2，±1.7 nC/m^3 in turn, the black diamond is for initiation point, and gray and black lines are for positive、negative leader respectively.

Effect of distribution range of LPC region on lightning discharges

Figure 3 shows lightning channel structures and space charge distributions from different distribution ranges of LPC region. The ρ_{0LP} of LP is 3.2 nC/m^3 in Figure 3(a), (b), (c), and (d), and the only difference between them is r_x of LP, which is 1.5 km, 2 km, 2.5 km, and 3 km respectively. As shown in Figure 3, under the same charge density distribution, the lightning type and propagation behavior of leaders can also have great changes with the increase of distribution range of LPC region. When r_{LP} equals 1.5 km (Figure 3a), lightning initiates between upper positive and negative charge regions of thunderstorms, and it is a positive polarity IC flash; when r_{LP} equals 2 km and 2.5 km (Figure 3b, 3c), lightning initiates between positive and negative charge regions of the lower portion of cloud, and they are negative CG flashes. Comparing the propagation behavior of negative leaders in Figure 3 (b) and (c), we find that the grounded negative leaders reach ground mainly in a vertical downward manner in Figure 3(b), but the grounded negative leaders will propagate a horizontal distance (about 3 km) first, and then bend to reach ground in Figure 3(c), which makes the horizontal distance between ground stroke point and initial point to be 4.5 km. Akita et al. [2011] found that the negative leaders of negative CG flashes propagated a horizontal distance about 10 km in cloud first, and then bent to reach ground, but they did not give an explanation. From the simulation results, we believe that the horizontal propagation of negative leaders may be the cause of a large horizontal distribution range of LPC region in thunderstorms; when r_{LP} equals 3 km (Figure 3d), lightning initiates between positive and negative charge regions of the lower portion of thundercloud, and it is an inverted IC flash. The negative leaders pass through positive charge region but do not reach ground. Qie et al. [2005, 2009],and Nag and Rakov [2009] indicated that a large distribution range of LPC region facilitates the occurrence of inverted IC flashes, and all these have confirmed the rationality of our simulation results.

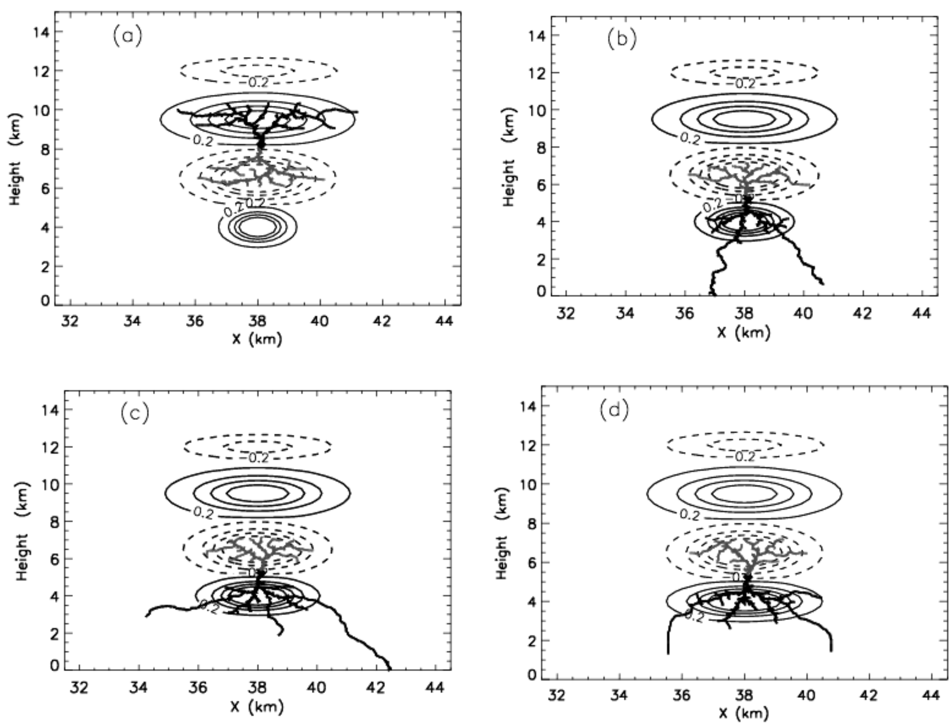

Figure 3 Lightning channel structure and space charge distribution from different distribution ranges of LPC region.

Quantitative simulation results of the relationship between LPC and lightning type

It is not hard to find that the effect of LPC in thunderstorms on lightning type is the result of common effect of charge density and distribution range of LPC region, but the effect degree from the two is different, and the effect of charge density magnitude of LPC region on lightning type is more prominent, so lightning type is determined mainly by the charge density magnitude of LPC region. To further research the effect of charge density and distribution range of LPC region on lightning type and give a quantitative result, the sensitive simulation experiments are designed in the paper, and the experiment program is as follows: 1) The initial value of ρ_{0LP} is 0.4 nC/m^3, and increases in steps of 0.4 nC/m^3, and the maximal value is 6.4 nC/m^3, which is consistent with the cloud charge density range (0—6.7 nC/m^3) through in situ balloon measurements by Marshall and Stolzenburg [1998]; 2) The initial value of D_{LP} is 1 km and increases in steps of 0.5 km, and the maximal value is 6 km. We ensure $D_{LP} \leq D_N$, mainly considering the distribution range of LPC region is smaller than that of main negative charge region [Krehbiel et al. 2008; Nag and Rakov 2009]. Each group (ρ_{0LP}, D_{LP}) can conduct a simulation experiment, and it has 176 groups in all. For each fixed ρ_{0LP}, 11 times of lightning simulations with different D_{LP} are conducted. To discuss it conveniently, this paper makes statistic for each fixed ρ_{0LP} respectively: the proportion of positive polarity IC flashes in these 11 times of lightning (R_1); and the proportion of negative CG flashes in these 11 times of lightning (R_2); and the proportion of inverted IC flashes in these 11 times of lightning (R_3). The base map in Figure 4 is the statistical results by simulation.

As shown in the base map of Figure 4, 1) When ρ_{0LP} < 2.4 nC/m^3, lightning are all IC flashes, and the proportion of positive polarity IC flashes accounts for 100%, and with the continued increase of ρ_{0LP}, the proportion of IC flashes tends to decrease monotonously; 2) When ρ_{0LP} > 2.8 nC/m^3, inverted IC flashes begin to occur, and its proportion increases monotonously with the increase of ρ_{0LP}; 3) Only when 2.4 nC/m^3<ρ_{0LP}<4.8 nC/m^3, can negative CG flashes occur, and its proportion presents a single peak distribution within this charge density range. To get a more accurate charge density range, within the charge density range of 2.4—4.8 nC/m^3, we make the above-mentioned step of ρ_{0LP} to 0.1 nC/m^3 and repeat the simulation experiments, and the results are shown in the small window figure of Figure 4. As shown in the small window figure, only when 2.6 nC/m^3≤ρ_{0LP}≤4.5 nC/m^3, can negative CG flashes occur, and the proportion of negative CG flashes essentially unchanged (2.8—4.2 nC/m^3), which is probably in the range of 27% to 36%. Only in the starting part (2.6—2.8 nC/m^3) and ending part (4.2—4.5nC/m^3), does its proportion present a rapid change.

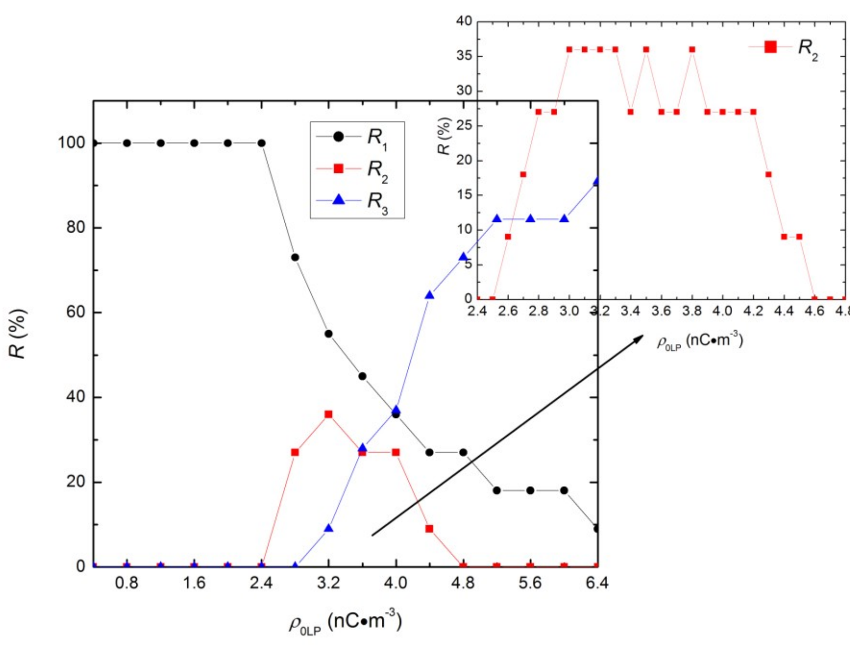

Figure 4 Proportion of three types of lightning under different values of ρ_{0LP}

ρ_{0LP} (nC/m^3) is the maximum charge density of LPC region, the charge density interval in base map of lower left corner is 0.4 nC/m^3, and the charge density interval in window figure of top right corner is 0.1 nC/m^3; R(%) is percentage of the three types of lightning, and R_1, R_2, R_3 is the proportion of positive polarity IC lightning, negative CG flashes, inverted IC lightning in total lightning number (11 times) simulated from each fixed ρ_{0LP}.

The actual distribution of charge structure in thunderclouds is ever-changing, in order to obtain a more universal law, we repeat the simulation experiments by changing ρ_{0x} and D_x of upper charge regions (specific value see in Table 2). The results are shown in Table 3. The parameter R_P in Table 3 is the ratio of absolute value of ρ_{0LP} to the sum of absolute value of ρ_{0P} and ρ_{0N} when negative CG flashes can occur, that is $R_P = |\rho_{0LP}| / (|\rho_{0P}| + |\rho_{0N}|)$. From Table 3 we know: under different cases, the range of ρ_{0LP} is variable when negative CG flashes occur, but the value of R_P follows certain law, and the value of R_P basically within 0.48±0.01—0.79±0.06 when negative CG flashes occur.

Table 2 Parameter value of charge regions of different cases

Cases	S		P		N	
	D_S(km)	ρ_{0S}(nC/m^3)	D_P(km)	ρ_{0P}(nC/m^3)	D_N(km)	ρ_{0N}(nC/m^3)
1	8	-1.0	8	2.2	6	-3.3
2	6	-1.0	6	2.7	4	-3.9
3	14	-0.8	14	1.8	12	-2.3
4	7	-1.2	7	2.4	7	-2.8
5	9	-1.5	9	2.0	8	-2.6
6	10	-1.0	10	1.9	7	-2.7

Table 3 Value range of R_P under different cases

Cases	value range of ρ_{0LP} (nC/m^3) under negative CG	Value range of R_P
1	2.6—4.5	0.47—0.82
2	3.2—5.6	0.48—0.85
3	2.0—3.0	0.49—0.73
4	2.5—3.8	0.48—0.73
5	2.2—3.5	0.48—0.76
6	2.2—3.7	0.48—0.80

CONCLUSIONS

The main conclusions obtained from the simulation are as follows:

(1) The LPC plays a key role in generating negative CG lightning and inverted IC lightning, with the increase of charge density or distribution range of the LPC region, lightning type changes from positive polarity IC flashes to negative CG flashes and then to inverted IC flashes, and such change comes from the change of lightning initiation point and electric potential in thunderclouds.

(2) The effect of LPC in thunderstorms on lightning type is the result of common effect of charge

density and distribution range of LPC region, but relative to distribution range of charge regions, the charge density magnitude of LPC region plays a dominant role in lightning type. Only when R_P is within 0.48±0.01—0.79±0.06, can negative CG flashes occur, and its proportion is relatively fixed, which is about 27%—36%.

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