Computer simulations on sprite initiation for realistic lightning models with higher-frequency surges

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[1] Computer simulations on transient luminous emissions in the mesosphere and lower ionosphere have been performed for realistic lightning modelings with fast-varying current surges (M components) superimposed on the lightning continuing current (CC). The algorithm used here is an electromagnetic (EM) code, which enables us to estimate self-consistently the reduced electric field, electron density, conductivity, and luminosity as a function of space and time by solving the Maxwell equations. It is found that M components in the CC with small amplitudes, but with a fast-varying EM effect, can initiate or enhance the occurrence of sprites. Even for a return stroke (RS) without CC, subsequent high-frequency current variations (like M components) are found to lead to dramatic changes in the sprite occurrence. The physics underlying these changes is studied by means of, e.g., temporal and spatial variations of luminosity, electron density, and conductivity. As the conclusion, the RS is a fundamental agency for spites, but high-frequency variations as EM effects exhibit an additional essential influence on sprite occurrence. These computational results are used to offer some useful ideas concerning the unsolved problems of sprites and halos, including polarity asymmetry, long-delay characteristics, and morphological shapes of sprites.

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1. Introduction

[2] Transient luminous events (TLEs) are large-scale optical phenomena occurring at stratospheric and mesospheric and lower ionospheric altitudes, which are directly related to the electrical activity in underlying thunderstorms. The most typical category of TLEs is red sprites, which have been studied for over a decade [e.g., *Füllekrug et al.*, 2006]. Results indicate that these sprites are excited mainly by positive cloud-to-ground (CG) lightning discharges [*Lyons*, 2006; *Rycroft*, 2006; *Pasko*, 2006; *Williams et al.*, 2007]. Despite a lot of extensive studies (as summarized by *Füllekrug et al.* [2006]), the following essential questions associated with sprites are far from being well understood: (1) polarity asymmetry of sprite-producing lightning [*Williams et al.*, 2007], (2) presence of long delay of the occurrence of sprites with respect to their parent lightning discharges [*Lyons*, 2006], and (3) morphological characteristics or difference of sprite shapes (carrot type, columniform etc.) [*Cho and Rycroft*, 2001; *Asano et al.*, 2008].

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[3] As regards the polarity asymmetry, *Williams et al.* [2007] have mentioned that beginning with prescient calculation by *Wilson* [1924], considerable evidence has accrued that sprites represent dielectric breakdown in the mesosphere triggered by ground lightning flashes, and the vertical charge moment is the key parameter in the initiation of sprites. The initiation criterion envisioned by *Wilson* [1924] is broadly consistent with recent sophisticated modern computations [*Pasko et al.*, 1995; *Cho and Rycroft*, 1998]. So the initiation threshold is considered to be independent of the polarity of ground lightning discharges. However, most of sprites are caused by ground flashes with positive polarity [e.g., *Lyons*, 2006]. As for the further understanding of polarity effect, *Williams et al.* [2007] have suggested an important role of another type of TLE; the so-called "halo", a quasi-uniform electrical breakdown in the mesosphere. This halo is interpreted as arising from electrostatic stress by lightning [*Barrington-Leigh et al.*, 2001]. *Bering et al.* [2004] have recently found the occurrence of numerous halos associated with negative CG lightning discharges. This circumstance may produce a possible explanation for the sprite polarity paradox, which is the reason why *Williams et al.* [2007] have mentioned this halo as the dark horse in the race to understand TLEs.

[4] The second question on the long delay of sprites behind their parent lightning discharges has been extensively investigated by several workers [*Reising et al.*, 1996; *Bell et al.*, 1998; *Cummer and Füllekrug*, 2001; *Lyons*, 2006; *Hu et al.*, 2007]. These authors suggested the important role of the CC in the delayed sprites. *Cummer and Füllekrug* [2001]

indicated that long CCs are responsible for long-delayed sprites, while *Bell et al.* [1998] conjectured that horizontal currents between clouds are responsible for the charge removal and ensuing mesospheric electric field increase that generates long-delayed sprites. In spite of these speculations related to the CC, the details are poorly understood; for example, (1) in which way the CC is associated with long delay of sprites (simply by increasing the total charge transfer?) and (2) any microprocess in the CC might be involved in the long delay of sprites etc.

[5] The third point is the morphological difference of sprites. There have been already observed different shapes of sprites, and two fundamental ones are carrot types [*Sentman and Wescott*, 1995] and columniform structures (or simply called columns) [e.g., *Wescott et al.*, 1998]. Some other structures have been further observed for winter lightning in the Japan Sea side [*Matsudo et al.*, 2007]. Fine structures within these different kinds of sprite shapes, have been interpreted in terms of the streamer developing model [*Liu and Pasko*, 2004; *Hayakawa et al.*, 2007b]. However, the most fundamental question is what is the main factor in determining the morphological shape of sprites (carrots or columns) [*Cho and Rycroft*, 2001], which is poorly understood and needs further theoretical and experimental studies. Also, is there any relation of this third point with the previous point? That is, is there any relationship between the sprite shape and sprite delay time?

[6] This paper intends to offer some hints on the above mentioned unsolved issues by means of computer simulations for more realistic lightning discharge current model. Having in mind the present situation on the above mentioned three fundamental issues related to sprites, we have to indicate our own position to this problem. In our paper by *Asano et al.* [2008], we have assumed only a single return stroke (RS) and studied the sprite occurrence (initiation) by means of the EM code by solving the Maxwell's equations. By changing different parameters of a RS, we have obtained one important point that the risetime of the RS is extremely important in sprite initiation, indicating an essential role of the EM effect in sprite initiation. Independently, *Yashunin et al.* [2007] have suggested the high-frequency component (like M components) so as to enhance the mesospheric electric field to initiate a sprite. Then, we have considered, for the first time, the coexistence of a RS and fast-varying high-frequency surges (M components) in our EM computer simulations. Finally, the computer simulation results for much more realistic models of lightning discharges are presented, which are extensively discussed in the context of the above mentioned unsolved problems of sprites.

2. Polarity Independence of Sprite Initiation by our Computer Simulations

[7] *Williams et al.* [2007] have summarized the observational (experimental) evidence on the polarity asymmetry of sprite-producing lightning. As is already mentioned in section 1, the initiation threshold of sprites is independent of the polarity of the charge of the parent lightning flash. The initiation criterion envisioned by *Wilson* [1924] is found to be further supported by more sophisticated modern computations by *Pasko et al.* [1995] on the basis of the ES (electrostatic) code. We have further used the more general EM code (this includes the effects observed by ES code) for the sprite problem for a single RS [*Asano et al.*, 2008] and our first important conclusion of *Asano et al.* [2008] is the confirmation of polarity independence in the sprite initiation problem.

[8] Hence, on the basis of these computer simulation results by means of both ES and EM codes, it might be more reasonable for us to attribute the observational polarity asymmetry of sprite-producing lightning as discussed by *Williams et al.* [2007] to the essential differences in the electrical characteristics of parent lightning flashes (positive and negative), including (1) polarity asymmetry in vertical charge moments, (2) impulsiveness of lightning flashes, and (3) polarity asymmetry in the forcing of sprites and halos by lightning, as suggested by *Williams et al.* [2007].

[9] In the next section, we will perform the computer simulations with paying particular attention to different types of positive lightning flashes as a generalization of different lightning currents, and we study the temporal and spatial behaviors of TLEs (sprites, halos etc.) in the mesosphere and lower ionosphere.

3. Classification of Elves, Halos, and Sprites in the Computer Simulation Results

[10] First, we briefly review the model we used here. As in the approach formulated by *Pasko et al.* [1995], the lightning stroke downloads instantly the upper positive (or lower negative) charge of a cloud, so that an electric dipole that is excited prior to the stroke initiation turns into a negative (or positive) monopole. This scheme is preserved even with an account for CC and high-frequency variations.

[11] We use again the same EM code, the details of which have already been described by *Cho and Rycroft* [1998] and *Asano et al.* [2008]. Two-dimensional (axisymmetric) computer simulation is adopted, and our code solves Maxwell's equations via the Finite Difference Time Domain (FDTD) method. Hence, we treat all electric field components (static, induction and radiation fields). Once the electric field is known at a given grid point, the reduced electric field, E/N_n where N_n is the neutral density, is calculated. The electron temperature, the ionization rate and the attachment rate are expressed as a function of E/N_n on the basis of the electron swarm data available. The rate equation for the electron density is integrated with respect to time and the electrical conductivity at each grid point is updated using the new electron density and temperature. Finally, Maxwell's equations are integrated in time to give the electric and magnetic fields of the next time step. So that we can determine self-consistently the temporal and spatial evolution of different physical parameters in order to examine the optical emissions and related phenomena; (1) reduced electric field (E/N_n in V m^2), (2) electrical conductivity (σ) (in S/m), (3) luminosity R (in Rayleigh) and (4) electron density perturbation ΔNe (in m^{-3}) (as a difference from the ambient profile).

[12] A few and essential improvements have been done over our previous computation by *Asano et al.* [2008]. The most important point is that we extend very much the computational time from a few ms in the work by *Asano et al.* [2008] to ~30 ms or even more in order to investigate the long-time history. Being closely related to this elonga-

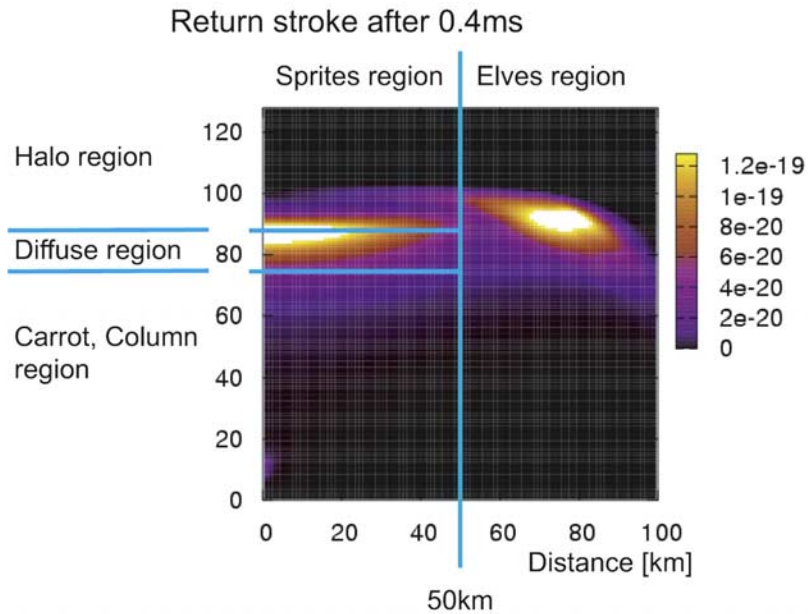

Figure 1. An example of computer simulations on the reduced electric field of TLEs for a RS (Q = +200C, τ = 25 μs, and ds = 10 km). Regions of sprites and elves are defined. Also, the region of sprites is further classified into (1) a halo region, (2) a diffuse region, and (3) a sprite region (carrots, columns, etc.) as a function of height.

tion of computer time, we have adopted Mur's second-order scheme as the absorbing boundaries unlike the previous Mur's first-order scheme as in the work by *Asano et al.* [2008]. Because the computer region is also extended up to the radius of 300 km in this paper, we need to avoid the spurious effect due to unwanted reflected waves. The grid sizes, are Δr and Δz = 1 km (r: radial and z: vertical) just as before.

[13] As in the work by *Asano et al.* [2008], a RS current is expressed as follows.

$$I(z=0,t) = Q\frac{1}{12}\frac{1}{\tau}\left(\frac{t}{\tau}\right)\exp\left(-(t/\tau)^{1/2}\right)$$

In this expression, the whole waveform is determined only by the two parameters Q (charge transfer) and τ (risetime). The peak current Ipeak = I (z = 0, t = 4τ) is observed at t = 4τ, which can be also considered as the definition of τ.

[14] Figure 1 illustrates an example of our computer simulations on the reduced electric field (E/N_n) at 0.4 ms after the onset of a single RS with Q (charge transfer) = +200C, τ (risetime) = 25 μs, ds (charge height) = 10km and the charge radius = 50 km as in the work by *Asano et al.* [2008]. On the basis of the early observations [e.g., *Lyons*, 2006], the spatial extent of sprites is known to be within a radius of 50 km from the overhead of their parent lightning, while elves extend up to a radius longer than 50 km which is now concluded to originate from EM radiation field of lightning flashes [*Nickolaenko and Hayakawa*, 1995; *Inan et al.*, 1996]. So, we define the region with radius smaller than 50 km as the sprite region, while the outer region is defined as the elve region [*Fukunishi et al.*, 1996]. The sprite region is furthermore divided observationally and theoretically into a few regions [*Lyons*, 2006; *Pasko*, 2006]: (1) a halo region as a layer of optical emissions above the altitude of ~85 km [*Barrington-Leigh et al.*, 2001; *Bering et al.*, 2004], (2) a region with diffuse optical emissions in a height of 75~85 km (we call it diffuse region [*Pasko and Stenbaek-Nielsen*, 2002]), and (3) a sprite region with carrots, columns or so on below about 75 km.

4. Computer Simulations on the Realistic Lightning Modelings Simulating Positive and Negative Lightning Flashes

[15] Our latest paper [*Asano et al.*, 2008] has indicated that charge transfer (Q) and the height where the charge is removed (ds) of a RS are key parameters in initiating sprites, which is consistent with the former ES code simulation by *Pasko et al.* [1995]. An additional important finding only by the use of EM code is the important effect of risetime (τ) of a RS. When we suppose only a single RS, its smaller τ is much more effective in initiating a sprite. This theoretical conclusion seems to be inconsistent with the larger risetimes associated with positive ground flashes with CC [*Lyons*, 2006; *Rycroft*, 2006]. So that, in order to dissolve this inconsistency, we have suggested an important role of fast-varying components (like M components) superimposed on a RS. At the same time, *Yashunin et al.* [2007] have indicated an important additional role of M components to enhance the mesospheric electric field by means of an analytical analysis of only electric field for a combination of a RS and radiation field.

4.1. Computer Simulations for a Single RS

[16] Before going into the complicated lightning configuration, we will summarize our previous computer simulations for the simplest case of a single RS [*Asano et al.*, 2008]. We have concluded that there is no polarity asymmetry in the initiation of sprites and that three parameters of

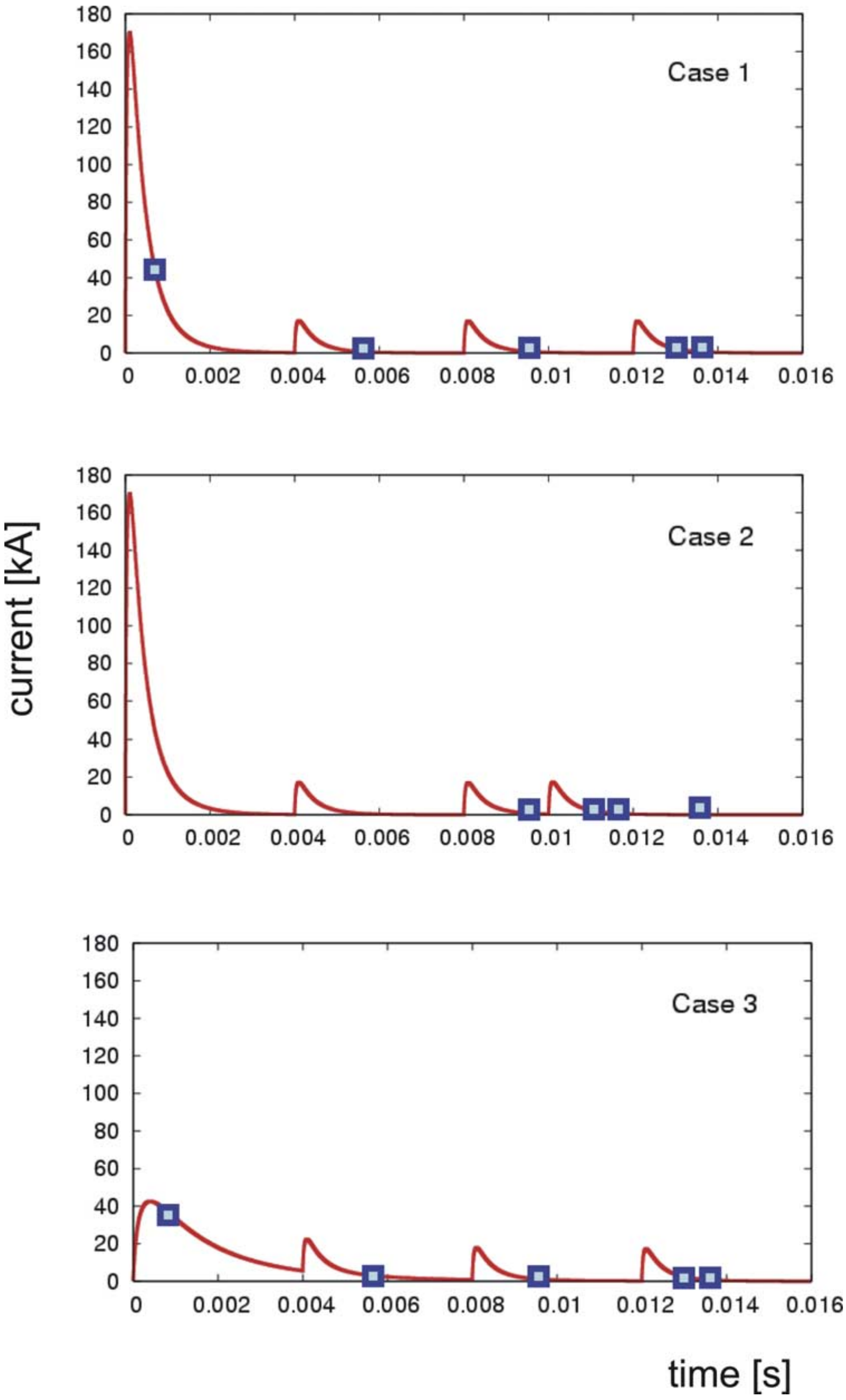

Figure 2. Three cases of our computations, case 1 to case 3. Cases 1 and 2 are the situations in which pseudo M components followed the RS, but the succession manner of pseudo M components is different. The electrical parameters of a RS are Q = +100C, τ = 25 μs, and ds = 10 km, while those of each pseudo M component are Q_M = +10C, τ_M = 25 μs, and ds_M = 10 km. Case 3 simulates the situation with a long CC (Q = +100C, ds = 10 km, but τ = 100 μs) and with a series of M components (the parameters for M components are the same as before). The boxes in each case indicate the observational times when the computational results are illustrated in Figures 3, 6, and 7.

a RS (that is, Q, ds and τ) are both important in the sprite initiation. When Qds > 400 C km and τ is small enough of the order of a few tens μs, there is observed a rather narrow width region just above the underlying lightning (r$\simeq$0) where the reduced electric field intensity is strong enough for the dielectric breakdown [*Asano et al.*, 2008]. This might be a very possible candidate for generating a simple sprite structure (or columniform sprite) just at r$\simeq$0 for a lightning discharge without any CC.

4.2. Computer Simulations for More Realistic Lightning Models

[17] When we have a larger risetime (τ) for a positive RS as in the previous lightning waveform, it is likely to have an associated long tail, just like a CC. Higher-frequency surges (M components) are likely to be superimposed on such CCs [e.g., *Rakov and Uman*, 2003]. The mechanism of M components is not well understood, but probably as manifestation of processes of unknown nature, e.g., branching inside the could [*Kitagawa et al.*, 1962]. Almost all of the literature on M components is based on negative lightning discharges (triggered and natural) [*Rakov et al.*, 1992; *Fisher et al.*, 1993; *Thottappillil et al.*, 1990, 1995; *Campos et al.*, 2007], and it seems that there are no papers on the characteristics of M components for the positive lightning. So that, there must be some uncertainties in modeling these M components in the positive lightning discharge. According to a recent work by *Ballarotti et al.* [2005], 28% of the negative strokes are followed by some kind of CCs (long (>40 ms), short (10–40 ms) or very short (<10 ms)). But, there have been scarce information on the M components for positive lightning discharges. Of course, it seems likely that this percentage would be significantly higher than that of negative discharges by *Ballarotti et al.* [2005]. A recent paper by *Campos et al.* [2007] has summarized other properties of M components for negative natural lightning, including CC waveform, the time of an M component behind a parent RS, the duration of M components, the interval of successive components etc. Again we do not know whether these characteristics apply for the positive lightning as well, but in our modeling we have to reply on the information in the paper by *Campos et al.* [2007] even though these are the results for negative lightning.

[18] Figure 2 summarizes our lightning current models studied in this paper, which combine a RS and a few M pulses. Three cases are treated (case 1 to case 3). The last case of case 3 well represents the situation most likely reflecting the positive lightning case with M components. As is seen for case 3 in Figure 2, we have the following electrical properties of an RS and M components. For the RS, Q = +100C, ds = 10 km and τ = 100μs, which results in the lightning current waveform in Figure 2 with the presence of CC. This general current waveform seems to be well supported by the recent paper by *Campos et al.* [2007] for negative lightning, because they have found that the two type of CC (more or less exponential decay and low intensity plateau) constitute 60% of the combinations of RS and CC. As regards the M components, we have always adopted the following values for the electrical parameters: τ_M = 25μs, Q_M = +10C (one tenth of that of the RS), ds_M = 10km. Since most of the literature shows M component risetime to be hundreds of μsec [e.g., *Rakov and Uman*, 2003], we have changed τ_M in a wide range of 25 μs, 100 μs and 200 μs, After having confirmed that the similar results are obtained, we present only the results for τ_M = 25 μs. Cases 1 and 2 indicate the RSs without any CC, but by performing quantitative estimation of high-frequency surges, we want to suggest that the presence of higher-frequency surges (like M components) exhibits significant influence on the initiation of sprites. Though these two cases (cases 1 and 2) might be unrealistic for the actual lightning. M components are defined as the high-frequency surges only present during the CC phase, so that we use the terminology of pseudo M components as the higher-frequency surges in cases 1 and 2. The electrical parameters of the RS are the same as follows in cases 1 and 2. The electrical parameters of the RS are fixed as follows in cases 1 and 2: Q = +100C, ds = 10 km and τ = 25 μs. Ten km for ds seems to be the extreme bound of likely size ranges, and much smaller values are expected for winter lightning [*Hayakawa et al.*, 2004, 2005, 2007a; *Asano et al.*, 2008]. The characteristics of pseudo M components are chosen in an analogy to those of M components described above. Actually few workers have recently noticed significance of higher-frequency components in association with sprite occurrences or sprite morphology [*Ohkubo et al.*, 2005; *van der Velde et al.*, 2006; *Suzuki et al.*, 2006; *Matsudo et al.*, 2007].

4.2.1. Results for Case 1

[19] As is shown in case 1 of Figure 2, three high-frequency components (pseudo M components) are supposed to take place regularly with the same time internal of 4 ms. Figure 3 illustrates a series of the computational results for the luminosity (approximately corresponding to the reduced electric field (E/N_n)) at several observation times denoted by boxes in Figure 2 (case 1) (time t is counted from the onset of a RS), and we use t = 0.6 ms (just after the RS), t = 5.5 ms (after the onset of first pseudo M component), t = 9.5 ms (after the occurrence of 2nd pseudo M component) and t = 13.0 and 13.5 ms (at two successive times after 3rd pseudo M component). Each image covers the radius up to 50 km and height range 60 to 110 km, in order to investigate the spatial structure of optical emissions as well. You will be surprised with dramatic changes in the images of luminosity (or reduced electric field, E/N_n) in Figure 3 as significant consequences of having the fast variations. White parts in Figure 3 indicate that the luminosity exceeds the upper bound of the color code. Let us look at the series of pictures in Figure 3. At t = 0.6 ms just after the RS onset, we find a rather faint and diffuse layered optical emission in the height range 80–90 km, which can be defined as a "halo". This kind of halos is found to appear 0.6–1.0. ms after the largest current peak of the RS and to last only for $\sim$ 1 ms. As the time goes, this halo goes down and its brightness also reduces. As is shown by *Asano et al.* [2008], when t = 1.3$\sim$2.0 ms, we can observe a sprite only just above the underlying lightning at r?0 (this is not clearly seen in Figure 3a for t = 0.6 ms). When there is only the RS, these phenomena would just relax. During this relaxation phase we introduce a pseudo M pulse, which results in the enhancement (clearly seen just along the r = 0 axis in Figure 3b) of the sprite (h = 70–80 km) just above the lightning and also to have excited a faint, diffuse emission in the height of 80–85 km. Four ms after the 1st pseudo

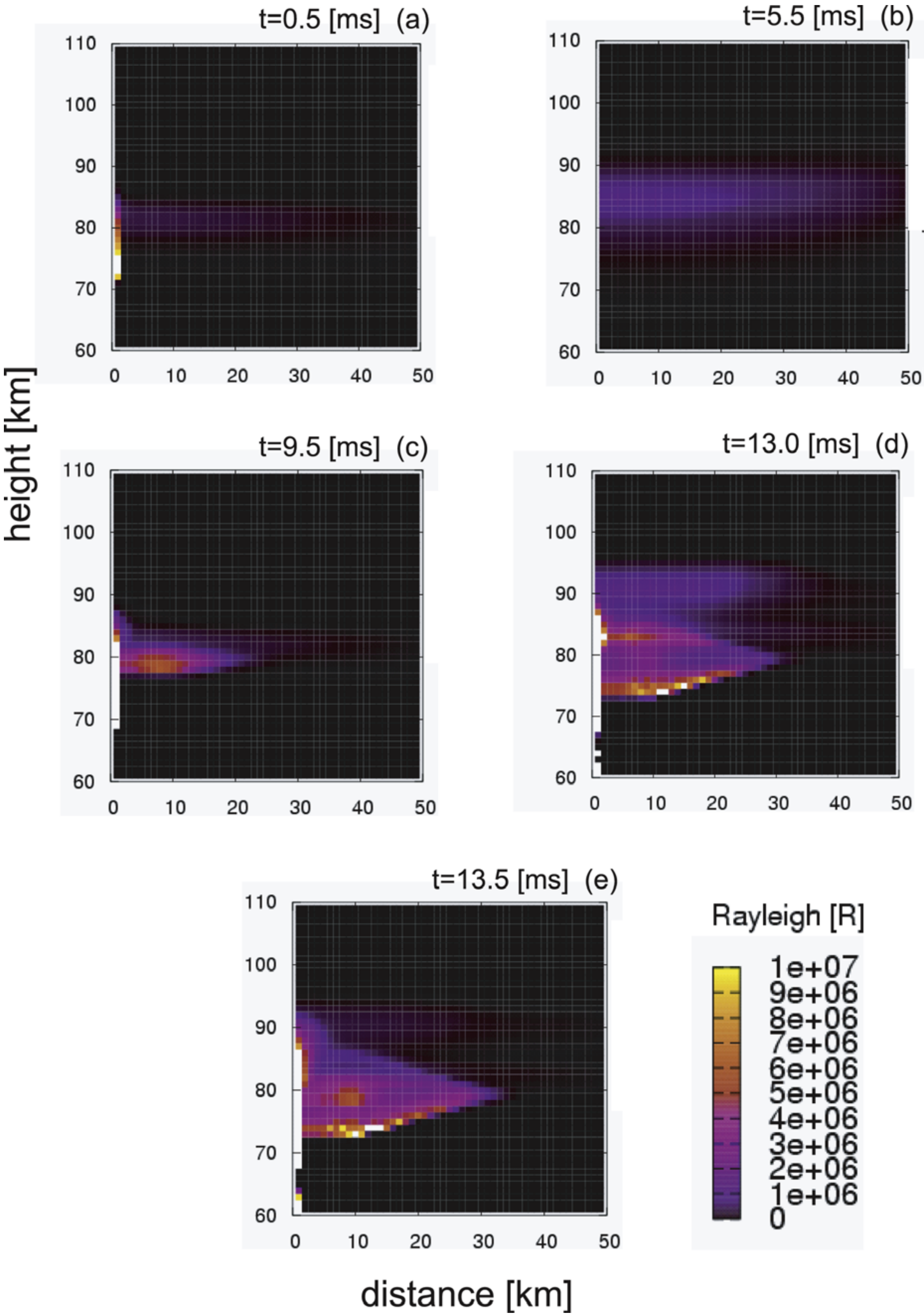

Figure 3. Computational results on the spatial distribution of luminosity for case 1 at different observation times (indicated by boxes given in Figure 2). Regular occurrence of pseudo M components is every 4 ms.

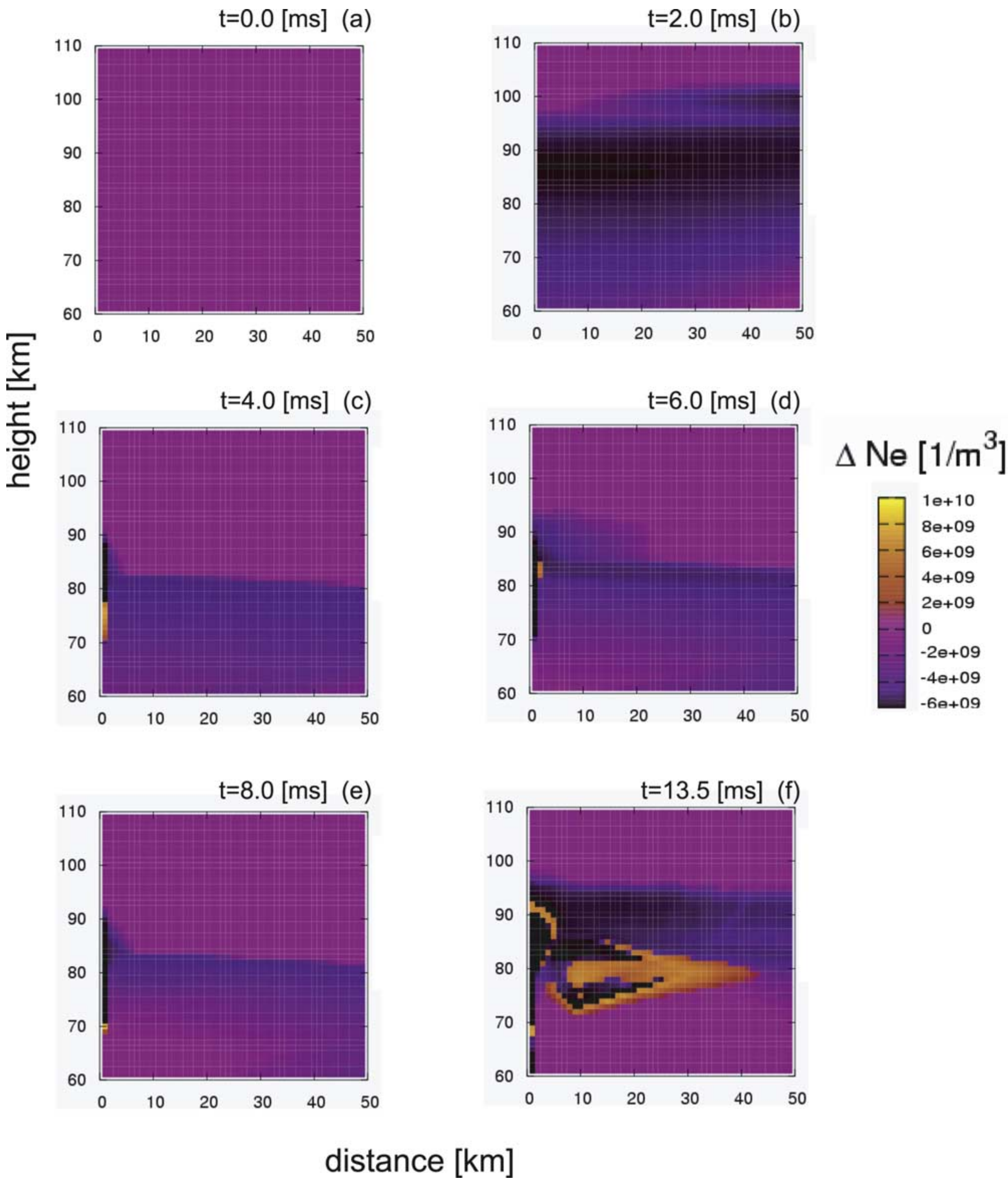

Figure 4. The temporal evolution of ΔNe (m^{-3}) for case 1 at different observation times (0.0, 2.0, 4.0, 6.0, 8.0, and 13.5 ms after the RS onset). ΔNe is change in electron density with respect to the assumed ambient profile.

M component we assume a 2nd pseudo M component, and 1.5 ms after the onset of 2nd pseudo M component (t = 9.5 ms) we find a clear enhancement of the sprite lasting from t = 5.5 ms just above the lightning and also an enhancement in brightness of the diffuse part. The preexisting sprite just above the lightning is seen to be enhanced and extended in height range at t = 13.0 and 13.5 ms (as seen in Figures 3d and 3e). Further, we notice a conspicuous enhancement in the optical emissions in the height range of 70–85 km and also in a wide radial distance up to 30 km. The lower boundary of possible sprite region at t = 13.0 ms in a radial distance from 10 to 30 km, seems to be increasing

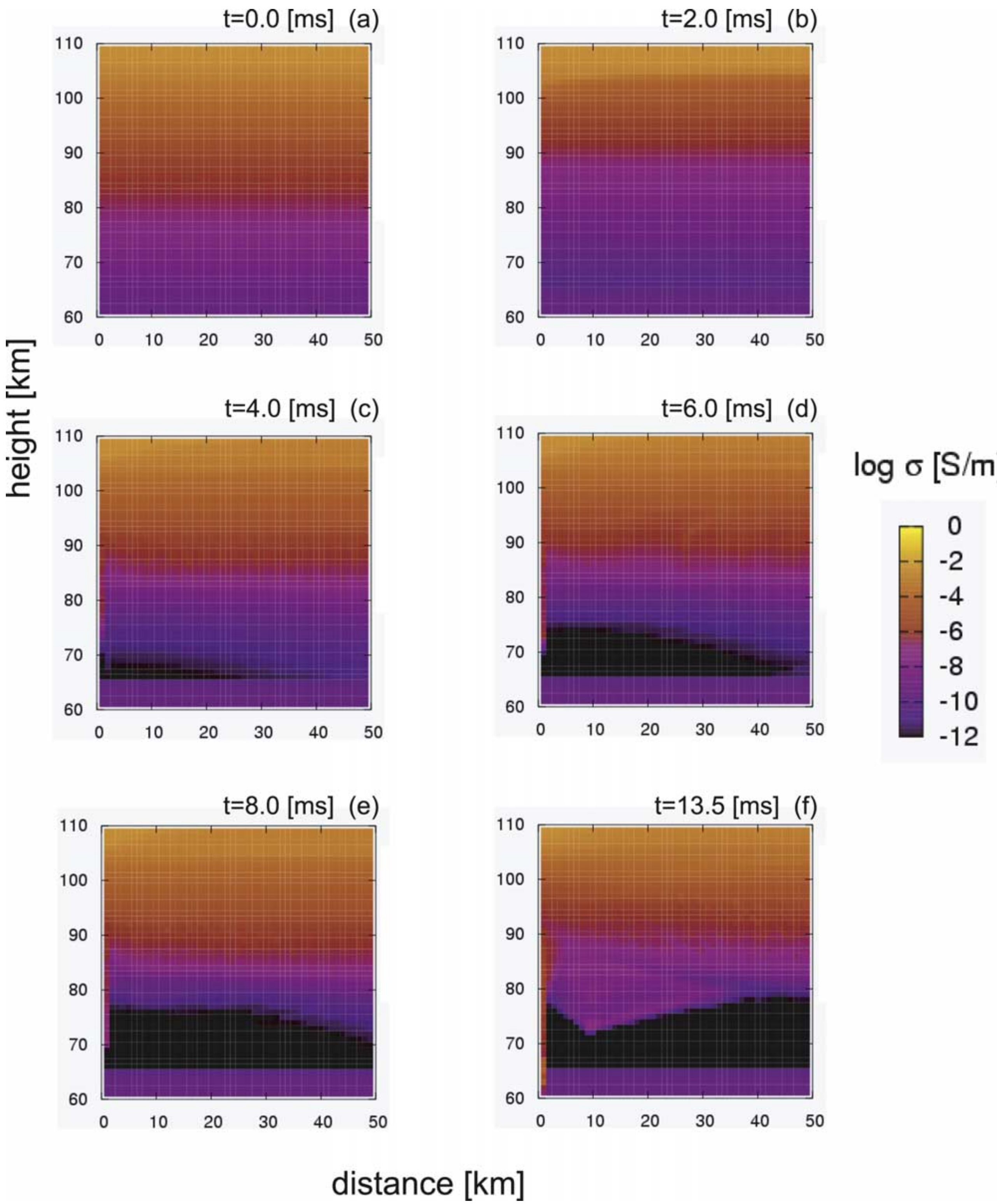

Figure 5. The same as Figure 4 but for conductivity (log σ(S/m)). The conductivity σ is expressed by 10^{α}, and this power index (α) is plotted in color.

in height, as the apparent consequence of significant effect of EM (radiation) field as analytically suggested by *Yashunin et al.* [2007]. The time t = 13.0 ms (Figure 3d) is one ms later than the onset of 3rd pseudo M component, so that we see again the halo region in the upper altitude (85–95 km).

[20] To better understand the phenomena observed in Figure 3; that is, to study the fundamental physical processes underlying in the optical phenomena in Figure 3, we have presented the temporal behaviors of two relevant plasma parameters (ΔNe (change in background electron density;

difference from the assumed background electron density profile) (in m^{-3}) and conductivity σ (in S/m)) for case 1 (corresponding to Figure 3) in Figures 4 and 5. In Figures 4 and 5 the observation times are a little different from those in Figure 3 (t = 0.0, 2.0, 4.0, 6.0, 8.0 and 13.5 ms). In Figure 5, the conductivity σ (z, r) is plotted in color in a logarithmic scale (10^{α}), and this power index (α) is illustrated. While, ΔNe is positive when the electron density is increasing with respect to the background value, while ΔNe is negative for decreasing the electron density with respect to the background. We compare corresponding observation times in Figures 4 and 5. At t = 2.0 ms, the electron density is seen to be decreased. This is due to the fact that even though the quasi-electrostatic (QE) field is generated by a RS, the value of E/N_n does not exceed the breakdown threshold. Because when E/N_n is not above the threshold, the electron attachment is exceeding the ionization. The conductivity σ is found to exhibit the same behavior, a decrease just as the case of ΔNe because E/N_n does not exceed the threshold. Especially, above the altitude of 65 km, the conductivity σ is dominated by the effect of electron density, so that both of the conductivity and electron density decrease. At the times of t = 4.0 ms (when we had the 1st pseudo M component), t = 6.0 ms and t = 8.0 ms (when we had the 2nd pseudo M component), the E/N_n is enhanced so as to exceed the threshold, so that we expect an increase in electron density. This is because the ionization becomes dominated over the electron attachment. In the regions where the E/N_n exceeds the threshold, the conductivity is enhanced because of the enhanced electron density. While, in the regions where the E/N_n is below the threshold, the electron density is decreased, and the conductivity remains low. At t = 13.5 ms (after the 3rd pseudo M component at t = 12.0 ms), we find different regions with high E/N_n in a wide spatial range, probably because of the EM effect of successive occurrence of pseudo M components. The increase in electron density is found to have a significant influence on the conductivity when E/N_n exceeds the threshold. When the conductivity is high, the rate of increase in electron density is also large, but the rate of subsequent decrease in density is also large. While, if the conductivity is lower when E/N_n exceeds the threshold, then we expect slower increase in density and also slower subsequent decrease in density. These behaviors might have resulted in extremely complicated spatial distributions.

4.2.2. Results for Case 2

[21] Figure 6 shows the computational result for case 2, and four observation times are studied (t = 9.5, 11.0, 11.5, and 13.5 ms). Especially, we concentrate on the effect of closely spaced (separated in time only by 2 ms, unlike 4 ms in case 1) pseudo M components in this case. Figure 6a for t = 9.5 ms is nearly the same as the situation of Figure 3c. At t = 11.0 ms, 1 ms after the onset of 3rd pseudo M component (Figure 6b), a few points are clearly recognized because of close occurrence of the pseudo M components. First, the sprite luminosity just above the lightning (i.e., very close to r $\simeq$ 0) is found to be extremely enhanced and extended in height. Because the observation time (t = 11.0 ms) is 1 ms after the 3rd pseudo M component, we can observe a clear layered halo with radial extension of 40 km or so. Then, the most significant effect is a dramatic enhancement in the reduced electric field (or optical emission) below 80 km and enrichment in complexity of its structures. At later observation times of t = 11.5 ms (Figure 6c) and t = 13.5 ms (Figure 6d), the phenomena exhibit just relaxation.

4.2.3. Results for Case 3

[22] The risetime of the RS in this case is taken as τ = 100 μs, so that this RS seems to be representing well a long CC, corresponding to the observed CC by *Campos et al.* [2007] (more or less exponential or low-intensity plateau in their definition). A few conventional M components are assumed to take place during the CC stage. The repetition period of M components is assumed to be 4 ms, which is a little bit smaller than the average value by *Campos et al.* [2007], but is not so unrealistic. Also, the duration of M components in our model appears to be a typical value (a few ms) obtained by *Campos et al.* [2007]. Figure 7 is the corresponding computational result. At t = 0.6 ms (Figure 7a) we can notice a halo, but a very weak one because of a large τ effect as it was already found by *Asano et al.* [2008]. As compared with case 1, the luminosity of halo in Figure 7 is extremely weak. At the observation times of t = 5.5 ms (Figure 7b) and t = 9.5 ms (Figure 7c) (each 1.5 ms after the 1st and 2nd M components, respectively) we notice no significant changes in halo, except an appearance of a sprite just above the lightning (r $\simeq$ 0) as the accumulated consequence of a few M components (definitely the QE field). A third M component is found to have significant effects on the images in Figure 7d; (1) enhancement of the sprite just above the lightning, (2) an additional region for sprites in the height from 75 to 82 km and with a radius of ~25 km, and (3) a halo, a layered structure in the height of 80–85 km, seen as a background of the former sprite region.

[23] The underlying physics can be studied by plotting the similar graphs on electron density change, conductivity etc. as in Figures 4 and 5 for case 1. Though we have the results, we will not show them because we can understand the physics easily in analogy to Figures 4 and 5 for case 1.

5. Summary of EM Code Computational Results and Some Hints on the Unsolved Sprite Problems

[24] The EM code in this paper [*Asano et al.*, 2008] can be used to study both the QE and lightning radiation (or EM) field in the sprite problem, and actually *Asano et al.* [2008] have found that both of these two fields are equally important in the sprite problem, by suggesting an additional importance of a fast-varying effect (small τ values) to the QE field. Of course, it is already widely accepted that EM field of lightning is the source of elves [e.g., *Nickolaenko and Hayakawa*, 1995; *Inan et al.*, 1996].

[25] Another point of view of our present computational study is based on the hypothesis that the unsolved three important issues on sprites and halos in section 1, are related to the asymmetrical nature of the forcing of TLEs by positive and negative flashes. So the present paper has presented the 1st attempt of TLEs using a much more realistic lightning modeling than the previous works based on only a simple and single RS [*Pasko et al.*, 1995; *Cho and Rycroft*, 1998; *Asano et al.*, 2008].

[26] We have introduced fast-varying higher-frequency components (like M (or pseudo M) components) superimposed on the single RS waveform. This assumption is

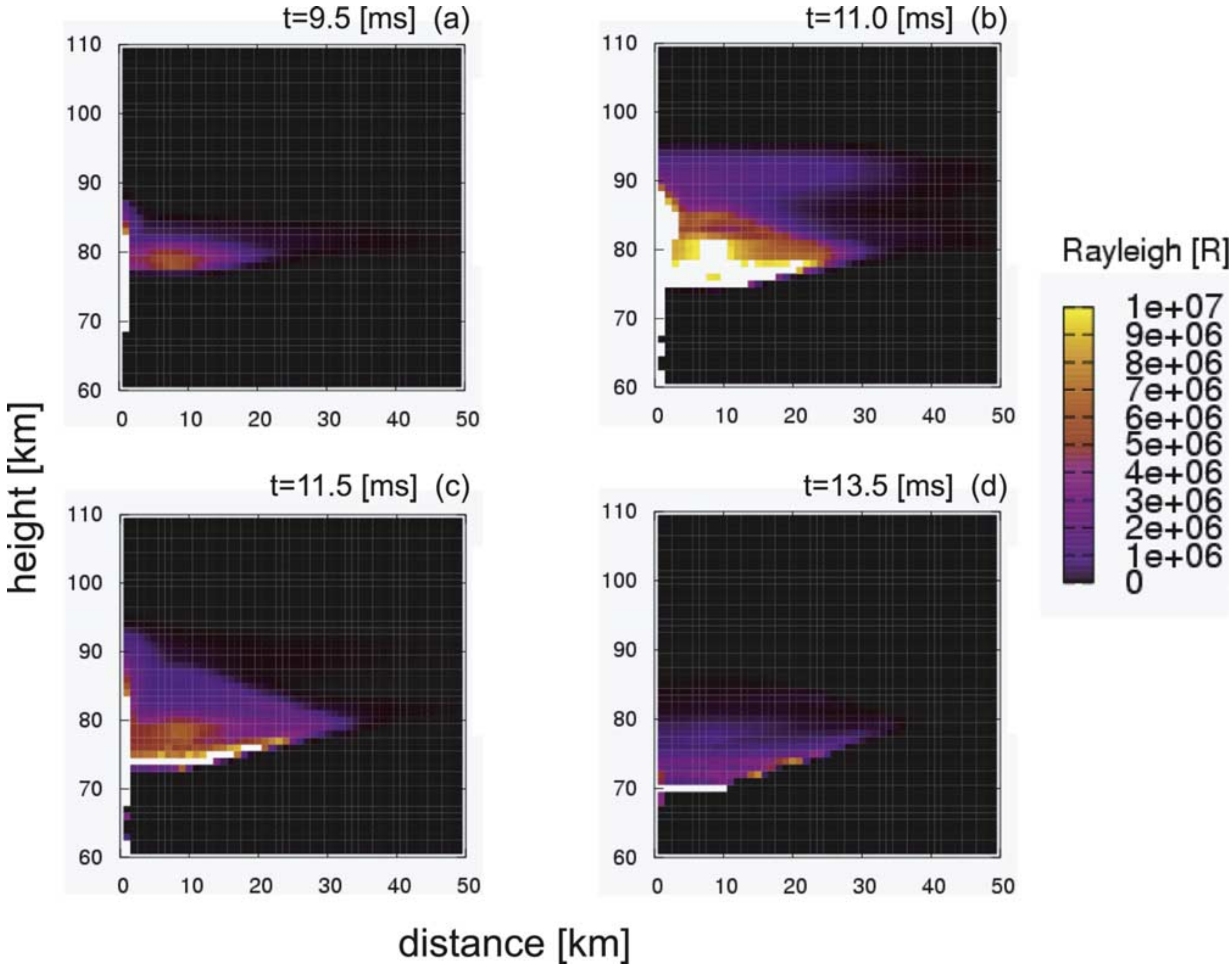

Figure 6. The same as Figure 3 but for case 2.

based on the recent few papers by *Hiraki and Fukunishi* [2006], *Yashunin et al.* [2007] and *Asano et al.* [2008]. *Hiraki and Fukunishi* [2006] have studied the occurrence criteria of sprites (and halos) in terms of major lightning parameters (charge moment and discharge time scale) even on the basis of ES code, and pointed out that sprites can be initiated by an impulsive current during the M component stage. In the latter paper by *Asano et al.* [2008] we have found that the risetime (τ) of the RS is also very important in addition to the important values of charge transfer (Q) and charge height (ds). That is, small τ values are favorable for initiation of sprites, which have led them to consider that fast-varying or high-frequency components might play an essential role in the sprite initiation. Independently, *Yashunin et al.* [2007] have suggested an important role of EM field of M components in the sprite initiation by means of their analytical analysis.

[27] On the basis of our results for three cases, case 1 to case 3, we can summarize new and interesting inferences here. It is quite uncertain which case among the three studied (cases 1 to 3) represents very well a real positive lightning. However, case 3, in which there is a combination of a RS and its CC, seems to be a typical case for positive lightning, which is supported by some observational results [*Reising et al.*, 1996; *Bell et al.*, 1998; *Cummer and Füllekrug*, 2001]. Conventional M components (or pulses) are superimposed on the CC in case 3, as is actually observed by *Campos et al.* [2007] for negative CGs. Cases 1 and 2 correspond to the situation when there is an isolated RS without any CC, but even in this situation there may happen some high-frequency current variations (named pseudo M components in this paper) as a generalization of conventional M components. These two cases are used to indicate that such a high-frequency current variation during the relaxation phase of the RS might play an important role in the sprite problem. These information would be of extreme importance for the general sprite problems. Spatial extent (height and radial extension) observed of optical emissions will also be used to offer some hints to the morphological features of sprites (3rd unsolved problem). Though, of course, we imagine that there is uncertainty whether the spatial scale of optical emission is the only parameter in determining the morphological shapes (carrot; column etc.), we believe that it has an important and definite information on the sprite morphology to some extent. We will summarize below what we have obtained from our computer simulations.

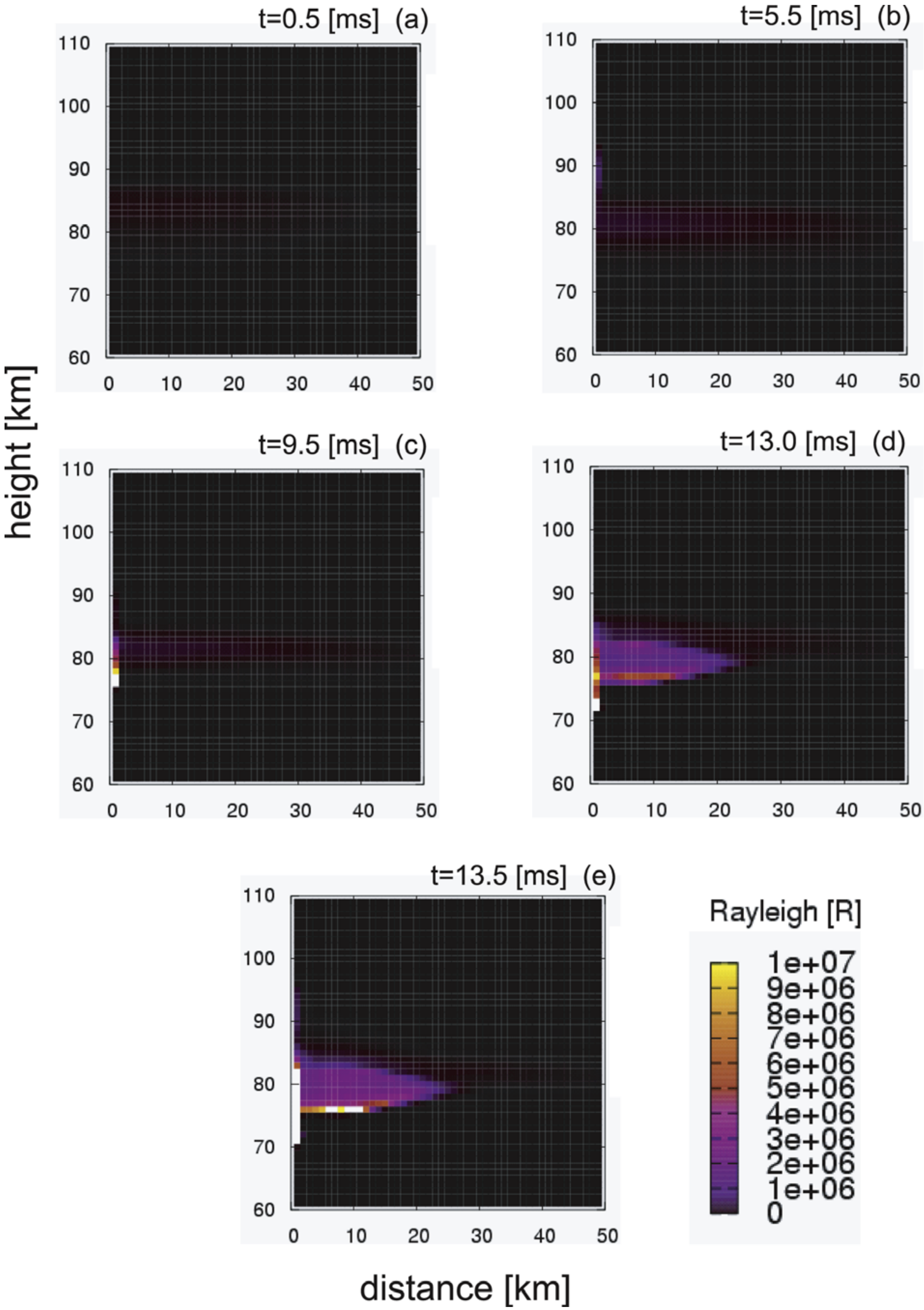

Figure 7. The same as Figure 3 but for case 3, which seems to be a typical case for positive lightning with CC.

5.1. Key Parameters (Q_M, τ_M, ds_M) for a Single M Component

[28] Whenever only one M (pseudo M) component happens after a RS, we have found that the charge transfer (Q_M) (though this is much smaller than Q of the RS) and charge height (ds_M) (assumed to be the same as the RS (ds_M = ds)) are equally important just as those of the RS. When either Q_M or ds_M is small (just like the case of Japanese winter sprites [e.g., *Hobara et al.*, 2001, 2006; *Hayakawa et al.*, 2004, 2005; *Suzuki et al.*, 2006]), the optical emission occupies a small region and its luminosity is low. Any significant difference is not expected in the effect of an M component occurring at any time after the RS so long as its occurrence time is within the relaxation time of the mesosphere (~100 ms).

5.2. Parameters of a Multiple of M (or Pseudo M) Components

[29] For a more frequent occurrence of M (or pseudo M) components, we have found that their effect would be more significant in the following way. With higher occurrence frequency, the diffuse region in Figure 1 is found to exhibit dramatic changes in such a way that the region with higher optical emissions expands very much radially, leading to the appearance of high-luminosity optical emissions The spatial distributions of E/N_n and luminosity, are found to exhibit a rather complicated structure inside the region, as a definite consequence of a combined effect of QE and EM fields (as suggested by *Yashunin et al.* [2007]). As inferred from these complicated structures, it is highly likely to expect rather complicated structures like big carrots, hair or so. But, the duration of the optical emissions is short, of the order of ~1 ms. On the other hand, the situation seems to be considerably different in the lower-altitude carrot column region in Figure 1. However, there is one effect of elongation of the region with higher intensity for the higher occurrence of M (or pseudo M) components, leading to the consequent enhancement in sprite duration. The sprite shapes would be carrots [*Sentman and Wescott*, 1995], V-shaped [*Matsudo et al.*, 2007], or so.

[30] Next we go to the effect of repetition period of M (pseudo M) components. A shorter repetition period of successive M (or pseudo M) components is found to have the similar influence as the higher occurrence frequency of M (or pseudo M) components.

5.3. Timing of the Occurrence of a M (or Pseudo M) Component

[31] When we have a single RS with sufficient Q and ds (e.g., Qds$\gtrsim$1000 C km), the computation simulations by *Asano et al.* [2008] have indicated that a sprite is expected only 1.5~2.0 ms after the onset of a RS. However, the observational facts on the delay by *Lyons* [2006] have suggested that the average delay is of the order of 10 ms, and sometimes 50–100 ms. In this paper, we have found that a small amplitude, but fast-varying (enhanced EM radiation effect) M (pseudo M) component has increased the probability of sprite initiation. These M components are likely to be very universal for positive lightning flashes with CC, and case 3 in our paper seems to indicate this situation. The statistics of M components with respect to their parent RSs indicate the similar values as used in this paper; average delay etc. [*Campos et al.*, 2007] though for negative lightning. As the conclusion of these considerations, the delayed effect of sprite occurrence can be satisfactorily explained in terms of the above lightning modeling with M components. Column-like simple shapes of sprites are found to take place 1–2 ms just after a single RS, so that we can suggest smaller delay time for column sprites, but much larger time delays for complicated or spectacular structures (carrots or so) because of possible involvement of M components.

[32] By making full use of the computer simulation results obtained above, we address to the three unsolved fundamental issues related to sprites. First of all, we discuss the second issue of long-delay sprites. As is summarized above as the Point (3), the occurrence of M components in the CC is of essential importance in triggering a sprite as in case 3. So, when a RS is strong enough to have a sufficient Qds, there will be a sprite with small delay. But, when a RS is not so strong enough, but not so weak, the occurrence characteristics of M components seem to control the delay of a sprite. Even without a CC as in cases 1 and 2, the high-frequency variation (called pseudo M components here, but a generalization of higher-frequency, fast-varying components in the lightning current) plays a significant role in sprite initiation. Any delay of sprites is feasible, just depending on the occurrence of high-frequency variations.

[33] Next the first issue of polarity asymmetry of sprites is discussed. As is mentioned in Section 2, the condition of initiation of sprites with all the electrical parameters (Q, ds, τ) being the same for both polarity, our computer simulation indicates no polarity asymmetry in sprite initiation. The key for this problem would be the fact that positive lightning over the land is absolutely much more frequent than negative lightning (the ratio being about 9:1) when specifying the condition of exceeding 500C km, as already indicated by *Williams et al.* [2007]. Also, as is found in terms of more enhanced impulsiveness of current moment spectra for negative lightning by *Williams et al.* [2007], it is likely that negative lightning tends to have only a RS without any CC, unlike the positive lightning. So that, it is highly required for a single negative RS itself to have sufficient Qds for sprite initiation, while the CC contributes to the increase in total charge transfer for positive lightning case. We have found the important role of high-frequency surges after the RS in sprite initiation, which cannot be easily detected by ELF measurement, but can be detected by higher-frequency observation [*Suzuki et al.*, 2006; *Matsudo et al.*, 2007]. It is feasible that there might be additionally a difference in the characteristics of high-frequency current surges between + and – CGs. These together would be a possible reason for the polarity asymmetry.

[34] We here further comment on the usefulness of Qds (charge moment changes) as observed by ELF waves [e.g., *Williams et al.*, 2007]. When we have a single RS and a sprite, the observed Qds by means of the ELF method surely provides us with the exact information on the lightning. However, when we have a few M components and a sprite, the situation is significantly changed. Because the ELF data would provide only the lower-frequency information on Qds, we have the following scenario. The charge transfer by an M component is not so large as that by a RS, but we have to understand a significant contribution of total

M components to the estimation of Qds. That is, the Qds deduced by ELF data does not seem to reflect the actual situation. The higher-frequency effect of M components is of essential importance in the initiation of sprites, which suggests a combined use of ELF and high-frequency information of lightning discharges [e.g., *Matsudo et al.*, 2007]. In future we are obliged to think that Qds values by ELF method are not so serious a parameter as before, but we can say that it still keeps its importance to some extent.

[35] In our previous paper by *Asano et al.* [2008], we have presented the following threshold criterion by *Hiraki and Fukunishi* [2006].

$$(\mathrm{Ids})(\mathrm{Qds}) = 1.6 \times 10(\mathrm{A\ km})(\mathrm{C\ km})$$

This condition is based on the assumption that a single RS is able to excite a sprite. This concept can be generalized to above cases with including M (or pseudo M) components. The 2nd factor in the above equation (we name it "sprite factor" in the work by *Asano et al.* [2008], suggesting the effect of QE field and CC), while the 1st factor (we call it "elve factor" in the work by *Asano et al.* [2008]) refers to the EM effect. The QE effect acts as a seed (or embryo) to prepare the upper environment to be ready for sprites, and the elve factor (fast variations like M components) act as a trigger of sprites. In this case, the threshold value on the right hand side of the above equation seems to have no serious significance. Former studies on the lowest threshold of Qds have suggested the value of ~200–300 C km [*Huang et al.*, 1999; *Hu et al.*, 2002; *Cummer and Lyons*, 2005] and 600 C km [*Lyons et al.*, 2003] for summer sprites in the U.S.. While, Japanese results for winter sprites indicate ~200–300 C km [*Hobara et al.*, 2001; *Hayakawa et al.*, 2004, 2007a]. As was noted before, the Qds values found by using ELF methods do not always reflect the reality, especially when the (pseudo M) pulses occur. Even so, those observed lowest thresholds seem to be significantly far below either one of any thresholds (conventional breakdown, positive and negative streamer [*Pasko*, 2006]) for a single lightning. Taking into account these all, we will be again led to an idea that M components play an important role in the sprite problem.

[36] We here discuss the last problem of sprite shapes (morphology). Much finer structures with the order of less than 0.1 km, like streamer propagation [*Liu and Pasko*, 2004; *Hayakawa et al.*, 2007b], are beyond the scope of the present computer simulation. Our spatial computational results as shown in Figures 3–6 with the spatial resolution of 1 km, would provide us with a lot of information on the sprite shape (carrot, column or complicated ones). The spatial size of the higher electric field, is surely indicative of higher possibility of more complicated or spectacular structures. The last topic related with this morphological characteristics of sprites, is the presence of lateral displacement of sprites with respect to a parent lightning. *Lyons* [1996, 2006] summarized that the position of a sprite is distributed within a radius of about 50 km from a parent lightning, which we will try to interpret this. As is seen from Figures 3, 4, and 5 for case 1, Figure 6 for case 2 and Figure 7 for case 3, there seems to exist a certain region with the most enhanced electric field at a lateral distance of r = 10–20 km from the parent lightning. This oblique phenomenon is apparent to be a combined effect of the QE field and EM radiation field, which has been analytically suggested by *Yashunin et al.* [2007]. This oblique effect as obtained in this paper would give us a theoretical support to the earlier observational evidence of lateral displacement being up to ~50 km [*Lyons*, 1996].

[37] Finally, the present computer simulations have provided us with some useful information on the relationship between sprite shapes and delay of a sprite behind its parent CG, though there have been published very few reports on this particular subject.

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