VLF/ELF sferic evidence for in-cloud discharge activity producing sprites

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1. Introduction

[2] Transient luminous events in the mesosphere, designated as sprites, are found to occur in association with intense positive cloud-to-ground (+CG) lightning discharges [e.g., Boccippio et al., 1995; Sentman et al., 1995] with a few ms time delays from the onset of CG [Cummer and Stanley, 1999]. The thunderstorm system producing the parent +CG discharges of sprites above the Great Plains in the U.S. is identified as the mesoscale convective complex system with large horizontal intracloud channels [Lyons, 1996]. +CG discharges are followed by continuing currents which are responsible for large charge transfer [Uman, 1987], and that positive charge layers are considered as a main source of the charge transfer with horizontal current channels [Krehbiel et al., 1979]. The quasi-electrostatic (QE) model of sprites proposed by Pasko et al. [1997] indicates that sprites occur just above the CG discharges with a time delay of a few ms. However, some horizontal displacements of sprites as far as 50 km away from the location of the parent CG discharge is often observed [Wescott et al., 2001; Füllekrug et al., 2001] and long time delays more than 100 ms from the parent CG to the onset of sprites are occasionally observed [Bell et al., 1998; Füllekrug and Reising, 1998]. These experimental results suggest that the evolution of horizontal intracloud channels and horizontal currents in lightning discharge processes play an important role in the sprite generation mechanism, as theoretically predicted by Valdivia et al. [1997]. However, observational results in support of this are not available currently.

[3] In this study, we have investigated the relationship between the broadband ELF/VLF waveform data and optical data of sprite events observed during the 2003/2004 winter sprite campaign in Japan. The distance between the sprite occurrence region and the ELF/VLF measurement sites is the order of several hundred km.

2. Observations

[4] We have carried out a sprite campaign in Japan during the 2003/2004 winter season. For optical measurements of sprites, an image intensified CCD camera (II-CCD) sensitive to the visible wavelength range and two sets of multi-anode array photometers (MAPs) were employed at Iitate Observatory (37.7°N, 140.7°E). These instruments are the same as those have been used for the past winter sprite campaign [Takahashi et al., 2003].

[5] Images from II-CCD are recorded continuously on SVHS videotapes at a frame rate of 60 fields/sec with time stamps synchronized with the IRIG-E code from the GPS receiver with the accuracy of ±16.7 ms. Sferic measurement in the VLF range was made with a 2-m vertical dipole antenna and crossed loop antennas with an isosceles triangle shape (1.6 m on leg and 1.7 m on base) aligned in the geographic N-S and E-W directions. Signals from this antenna system are amplified and band pass filtered for 1–40 kHz range. Output signals are recorded as an event trigger method with a sampling rate of 100 kHz using a 16-bit A/D board. Furthermore, we use ELF magnetic field data recorded at Onagawa Observatory (38.43°N, 141.48°E) [cf. Sato and Fukunishi, 2003]. Output signals from the two-component (geomagnetic N-S and E-W) search coil magnetometer are amplified and band pass filtered for the range of 1–100 Hz and are recorded continuously with a sampling rate of 400 Hz using a 16 bit A/D board.

[6] During the campaign period from December 15, 2003 to February 15, 2004, we have obtained 40 sprite events. Out of these events we have analyzed 21 sprite events observed on December 15, 2003. Figure 1 shows the location of observation sites and the locations of sprite events which occurred mostly near the coast of the Sea of Japan. The distances from the observation sites to the causative CGs are in the range of 250–600 km. The locations of sprites are estimated from the azimuth and elevation angles determined using the background star field identified on each image by assuming the top height of sprites as 82.5 km. Based on the analysis using which lightning detection network data and imager data, the accuracy of this method is estimated to be ±30 km.

3. Results

[7] Sprite events on December 15, 2003 were captured by the II-CCD camera for 6 hours from 12:00 to 18:00 UT above the thunderstorm system located along the coast of the Sea of Japan. Figure 2 shows a sprite image taken at

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16:05:42.58 UT and concurrent VLF sferic waveform (electric field component), its spectrogram and ELF waveform (magnetic field component). The spectrogram is calculated by short time series analysis and is displayed in the frequency range from 500 Hz to 50 kHz with a logarithmic axis. The ELF magnetic waveform shows the component tangential to the direction of estimated sprite locations (phi component) and here positive enhancements correspond to positive downward currents. Vertical dashed lines represent the ambiguity (±16.7 ms) of sprite onset time due to the CCD exposure time. The VLF waveform shows that occurrence of a large transient burst (shown by green arrow) is followed by a small pulse train (~20 ms duration (designated as a red bar). From the spectral analysis, the frequency range of the large transient burst is found to have a lower frequency component extending ~1 kHz with its peak at ~5 kHz, whereas that of the weak pulse train has a higher frequency component (above around 5 kHz) with its peak around several tens of kHz. The characteristic of the large burst is similar to that of the return stroke (as mentioned in the discussion) and this pulse train is similar to sferic clusters observed by Johnson and Inan [2000]. Simultaneous to the VLF sferics, ELF waveform demonstrates the onset of a transient positive perturbation indicating the existence of a continuing positive downward current in the causative lightning discharge. In addition, after the occurrence of the sferic cluster, intermittent pulses (designated as a blue bar) are found to appear after the decay of the sferic cluster and persist for ~100 ms. These pulses would be related to the same lightning flash because the return stroke, the sferic cluster, and the intermittent pulses occur sequentially.

[8] Another example is shown in Figures 3 in the same format as Figure 2. This example shows the sprite event with much longer delays than that shown in of Figure 2. A sprite image taken at 15:31:23.24 UT displays a faint diffuse glow termed as a sprite halo and a carrot-shaped sprite with a horizontal displacement at least ~30 km from the center of the sprite halo to the carrot-shape sprite, which is deduced from their aspect angles in the image. After 25 ms from the onset of the return stroke (denoted by green arrow), a sferic cluster (a red bar) is found to occur with a duration of 80 ms. The ELF waveform at the bottom demonstrates a double onset of positive perturbations. The first onset is coincident with the return stroke and shows a small amplitude perturbation. The second onset coincides with the onset of the sferic cluster and exhibits large amplitude and long lasting perturbation. From these temporal relationships, this sprite event is considered to be generated by intense electric fields induced during the sferic cluster event accompanying a continuing current rather than electric field induced by the return stroke. Similar to the case of Figure 2, intermittent pulses (a blue bar) are also generated over 150 ms after the sferic cluster.

[9] On the night of December 15/16, 2003, we have succeeded in recording VLF waveforms for 17 out of the 21 sprite events. All VLF data show coincident occurrences of sferic clusters and sprites. The sferic clusters are character-
ized by a long durations (10 to 100 ms) and a higher frequency component than that of return strokes. Among the 17 events, VLF data of 7 events show significant time delays (more than 16.7 ms) from the onset of the return strokes to the initiation of sferic clusters. In addition, ELF data show positive transient perturbations for all events just coinciding with the occurrence of sferic clusters. Moreover, these event waveforms show intermittent pulse continuing over 100 ms after the decay of sferic clusters. The average charge moment change of these events is 422 C-km estimated using the method of Sato and Fukunishi [2003] and ELF data obtained from Showa station (69.0°S, 39.5°E).

Among the 21 sprite events, we have succeeded in capturing temporal variations of sprite luminosities for 3 events with array photometer (MAP). The MAP data are not available for the rest events due to contamination of cloud flash. One of these events is displayed in Figure 4. Four sequential sprite images labeled from (A) to (D) are taken at 15:07:22.87, 22.89, 22.90, and 22.92 UT, respectively. A dotted rectangular window in each image represents the field-of-view of the MAP channel in which most of the sprite elements are observed. The luminosity variation of sprites captured by this photometer channel is shown in Figure 4 (bottom). A signature of exponential relaxation (pointed by arrows) is identified as the temporal variation of sprites. This sprite event consists of a cluster of structured elements, which are numbered from #1 to #9 in the Figures 4a–4d. Considering the temporal development of each sprite element and the ambiguity of the stamped time of sprite images, it is suggested that two elements (#3, #4) in Figure 4b correspond to the first sprite luminosity enhancement represented by an arrow in Figure 4 (bottom), whilst elements from #5 to #9 (mainly two elements #5 and #6) in Figures 4c and 4d correspond to the second sprite luminosity enhancement. The concurrent VLF waveform data show the occurrences of both the return stroke and the sferic cluster. The return stroke occurred simultaneously with the strong scattered light emission (saturated in this range) identified in the MAP data. After that, the sferic cluster is found lasting ~60 ms. The ELF data shows positive transient perturbations with two distinct peaks, i.e., the first peak would correspond to the return stroke immediately followed by the sferic cluster and the first luminosity enhancement of sprites due to elements #3 and #4, whilst the second one coincides with the second luminosity enhancement mainly due to elements #5 and #6 and the intensity enhancement of sferic clusters.

4. Discussion

[11] It is widely agreed that most sprites are produced by strong positive CG discharges. However, the present result suggests that sferic clusters observed in the VLF range are strongly related to the generation of sprites. One of the keys for understanding the source of the sferic cluster is its characteristic in the frequency domain. Two types of lightning strokes can be identified from the VLF sferic waveform, i.e., a return stroke and a bipolar discharge [Warber and Field, 1995]. The return stroke is one of the CG discharge processes associated with strong electromagnetic radiation whose spectral peak in intensity is around several kHz in the power spectrum. The bipolar discharge means a group of small strokes occurring within the thundercloud system radiate smaller electromagnetic energy whose spectral peak is centered around 50 kHz. In this analysis, we found that spectral peaks of sferic clusters are in the range of several tens of kHz with smaller amplitudes than those of the return strokes. These characteristics are coincident with bipolar discharges, i.e., in-cloud lightning activity within the single lightning flash.

[12] Another characteristic for understanding the source of sferic clusters is the evidence of occurrences of intermittent pulses after the sferic clusters. This characteristic is shown in Figures 2 and 3 besides other 5 events (not shown). An example of the intracloud flash as a result of electric field measurement using slow and fast antennas can be found in the work of MacGorman and Rust [1998, Figure 5.19]. Since the field change data show similar properties in active and final stages as we observed as sferic clusters and intermittent pulses, the sferic clusters would correspond to the lightning discharge process within the thundercloud in active stage. Moreover a new lightning
observation based on VHF techniques has confirmed that discharges in the active stage occur in the upper positive charge layer [Shao and Krehbiel, 1996]. On the other hand, our results should be interpreted as the process of +CG flashes because of the precedent occurrences of the return stroke. Kawasiki and Mazur [1992] investigated +CG flashes during winter storms in Japan and showed the relationship with the regeneration of negative leaders and continuing currents. Occurrences of sferic clusters and simultaneous ELF perturbations would correspond to their observation results. In spite of CG flashes or IC flashes, the VLF sferic clusters would be interpreted as the lightning discharge process within the thundercloud termed as the negative leaders in the positive charge layer. However, considering the coincident ELF perturbations indicating the continuing currents, it is likely to interpret our results as the CG flash.

[13] The importance of the redistribution of charge within the thundercloud (i.e., in-cloud lightning activity) after the intense CG strokes has been suggested as the cause of time delays of sprite generations [Bell et al., 1998]. In addition, as discussed by Füllekrug et al. [2001], this lightning evolution might solve the problem of second current enhancement as observed in the ELF range. Since occurrences of VLF sferic clusters and coincident ELF perturbations are interpreted as the in-cloud lightning activity associated with continuing currents in this study, our results are the first experimental evidence that lightning evolution predicted by Bell et al. [1998] is actually associated with delayed sprite events. As shown in Figures 3 and 4, 7 events have delays more than 16.7 ms with a similar evolution of sferic waveforms in both VLF and ELF data. In addition, the winter thunderstorms producing sprite events are found to have a horizontally extended structure connecting some thunderstorm cells identified by the radar echoes [Hayakawa et al., 2004].

[14] There exists a big difference between our results and previous ELF/VLF magnetic field measurements associated with sprite optical observations [Cummer et al., 1998], which reported the electromagnetic radiation from the sprite body. They found that secondary ELF perturbations with time delays about 5 ms form the parent CG onset coincidently with sprite luminosity as verified by high-speed photometer recordings. They ascribed the absence of VLF radiation at the time of sprite formation to electromagnetic radiation from the sprite itself. Our results of sferic clusters, however, indicate the occurrence of VLF radiation at the time of sprite initiation. This disagreement can be explained by a difference in distances from the observation site to sprite locations. The distances in their observation are about 2000 km, whereas in ours are in the range of several hundred kms. Since the previous measurement of sferic clusters [Johnson and Inan, 2000] verified its high attenuation rate with propagation distance, our short-distant observations made it possible to record these VLF sferic waveforms.

5. Conclusion

[15] VLF sferic clusters and simultaneous ELF perturbations associated with the sprite-producing winter lightning in Japan provide the first evidence that the in-cloud lightning discharge processes are responsible for the generation of sprites. Our results also indicate that the long time delays from the return stroke to the sprite formation can be explained by the time evolution of the intracloud lightning discharge process.

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References


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