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Unusually intense continuing current in lightning produces delayed mesospheric breakdown

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Abstract. Ultra low frequency magnetic field measurements made 500–2000 km from positive lightning discharges show a signature that is consistent with unusually high amplitude cloud-to-ground continuing lightning current. The magnitude of this nearly constant current moment is as large as 60 kA km and can last at half this amplitude for longer than 150 ms, thereby moving 640 C or more (assuming a 7 km vertical channel length) to the ground after the return stroke. This total charge transfer is more than an order of magnitude greater than most previously reported continuing currents in positive discharges. Three cases analyzed show this strong continuing current flows before, during, and after sprites that initiate more than 40 ms after the return stroke. Accounting for this continuing current, quantitative analysis shows that the total vertical lightning charge moment changes are large enough to produce mesospheric electrical breakdown and long-delayed sprites.

1. Introduction

Since the discovery of sprites about 10 years ago [*Franz et al.*, 1990], attention has been focused on the unusually strong (both in peak current and total charge transfer) lightning discharges known to excite these mesospheric optical emissions [*Boccippio et al.*, 1995]. The complete nature of these strong discharges is still not known, as demonstrated by the existence of long-delayed sprites that can initiate more than 100 ms after a return stroke with no clear signature of lightning current in between [*Bell et al.*, 1998; *Reising et al.*, 1999]. Nearly constant continuing currents lasting more than 100 ms have been documented in positive cloud-to-ground (CG) discharges in midwestern thunderstorms [*Rust et al.*, 1981], but there are few quantitative measurements of positive continuing currents. Negative continuing currents of this duration are well-known, but their amplitude rarely exceeds a few hundred amperes [*Uman*, 1987, p. 171]. Higher amplitude positive continuing currents of 1 kA for 40 ms [*Bell et al.*, 1998] and 10 kA for 5 ms [*Brook et al.*, 1982] have been reported, but larger and/or longer currents are thought to be required to move the charge necessary to generate delayed sprites [*Pasko et al.*, 1996]. Very strong continuing currents have been measured in winter thunderstorms in Japan [*Miyake et al.*, 1992; *Goto and Narita*, 1995]. These discharges tend to originate at relatively low altitudes [*Brook et al.*, 1982] and their total charge moment changes are not as large as those reported here.

In this work, ultra low frequency (ULF, here ∼0.1–200 Hz) magnetic field measurements located 500–2000 km from the discharges show a signature between the discharge and sprite that is consistent with high amplitude vertical cloud-to-ground continuing lightning current. Accounting for this continuing current, electromagnetic simulations show that the observed vertical lightning charge moment changes (ΔM_Q) are large enough to produce mesospheric electrical breakdown and long-delayed sprites.

2. Instruments and Data

ULF horizontal magnetic field variations were recorded during the summer of 1998 at ground stations near Santa Cruz, California (STC), Soccoro, New Mexico (SOC), and Saskatoon, Saskatchewan (SKT). The sensors were two orthogonal horizontal induction coils, and GPS timing provided inter-station time synchronization with an accuracy of 20 μs. The coil sensitivity was $\sim$0.1 fT/$\sqrt{\text{Hz}}$ at 100 Hz. National Lightning Detection Network data [*Cummins et al.*, 1998] provided the precise locations of the observed discharges. The nearly stationary 60 Hz noise is removed by subtraction of a synthesized noise waveform, and the <0.1 Hz, non-lightning variations are fit to a polynomial and subtracted. After digital low pass postfiltering, the resulting system frequency response is flat from 0.1–100 Hz and is 20 dB down at 200 Hz.

From the set of ULF data from the summer of 1998, we identified three events associated with sprites that initiated more than 40 ms after any NLDN-recorded return stroke in the surrounding area. Sprite initiation times were determined to ±8 ms from University of Alaska video images. Figure 1 shows the ULF horizontal magnetic field component transverse to the propagation path (B_ϕ) observed at SKT, SOC, and STC for one of the three events. The initial pulse at t=0 is generated by the lightning return stroke, and the pulse at t=160 ms is not a return stroke and is presumed to be generated by the sprite itself [*Cummer et al.*, 1998]. Simultaneous VLF data show that there is no energy above ∼ 1 kHz associated with this pulse, indicating the current rise time is too slow to be an ordinary return stroke. The sprite video also shows that the sprite initiated during a 16.7 ms period containing this subsequent pulse. The third pulse at t=240 ms is an NLDN-recorded positive CG 46 km away from the CG at t=0, and it is not relevant to this analysis. The small time offset in the three signals is

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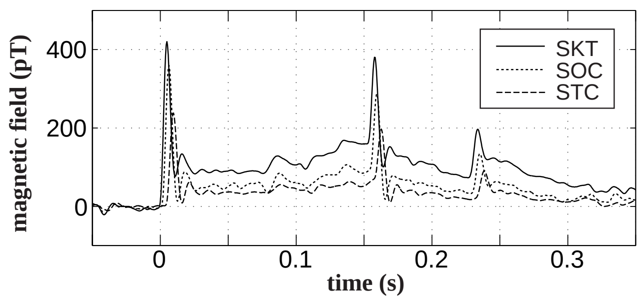

Figure 1. Horizontal transverse magnetic field waveforms recorded at SKT, SOC, and STC for a sprite associated lightning discharge on July 15, 1998. Note the elevated field between the return stroke (t=0) and the sprite (t=0.16). The time t=0 corresponds to 05:09:11.381 UT.

due to the different propagation distances from the source to each receiver.

The unusual part of these data is the 40–150 pT elevated field level between the return stroke and the sprite, indicating that significant electric current is flowing somewhere in the system. In Section 3, we measure this current with numerical techniques. But assuming this current is vertical and slowly varying, we can estimate its magnitude from a quasi-static calculation. Provided the sensor is much farther from the source than the ground-ionosphere distance, the series of current elements formed by the lightning channel and its images in the conducting ground and ionosphere produces the same field as an infinite vertical current [*Wait*, 1970, p. 134]. The equivalent uniform vertical current $I_u = Ih_s/h_i$, where I is the actual vertical current, h_s is the length of the vertical current, and h_i is the height of the ionosphere. From magnetostatics, the horizontal magnetic field at a distance r from this source is $B_\phi = \mu_0 I_u / 2\pi r$. The distances from the discharge to SKT, SOC, and STC are 1211 km, 1647 km, and 2473 km, respectively, and the nearly constant magnetic fields of 90, 50, and 35 pT all correspond to an equivalent uniform current of ∼500 A. Assuming an ionospheric altitude of 80 km and a discharge length of 7 km, the observations imply strong continuing currents of ∼5.7 kA that last, in this case, for more than 200 ms. We can rule out horizontal currents inside or between clouds as the source of these fields because the ground image currents are opposite in direction to a horizontal source current, making them very weak radiators. Calculations using the waveguide mode model described by *Cummer and Inan* [2000] show that the horizontal current (assuming a 10 km long discharge) required to produce the observed field amplitude at 50 Hz is an unrealistic factor of 300 larger.

From the ULF data alone, we cannot determine whether this current is vertical CG or vertical intracloud (IC), since equal currents in both configurations will generate essentially equal remote magnetic fields. Since the slow current immediately follows a CG return stroke, it is likely that this continuing current is CG. However, the implications for mesospheric breakdown and sprite generation are the same whether the current is IC or CG.

The standard method of measuring continuing currents from slow electric field variations is usually limited to observations within a few tens of km because of the $\sim 1/r^3$ dipole field decay with distance. These data show that continuing currents can be detected with slow magnetic field variations much farther from the source due to the $\sim 1/r$ field decay, provided the instrument is sufficiently sensitive.

3. Quantitative Analysis

The magnetic field data was analyzed to extract the vertical lightning current that radiated the observed fields using a technique described by *Cummer and Inan* [2000]. An electromagnetic propagation model, in this case a full-wave time domain finite difference electromagnetic simulation, is used to calculate the fields at the known propagation distance produced by an impulsive lightning discharge. This simulation accounts for the anisotropy of the ionosphere and also implicitly includes the fields generated by post-discharge dielectric relaxation currents [*Greifinger and Greifinger*, 1976] which can be significant at ULF even at long distances from the source. Linearity and time invariance of the propagation problem are assumed, thus the remote fields are simply the convolution of the propagation impulse response and the source current moment. The source current moment can therefore be determined from a deconvolution of the measured remote fields and the simulated propagation impulse response. This technique has been used to quantitatively characterize sprite-producing lightning discharges using higher frequency (∼50–1000 Hz) magnetic and electric field measurements [e.g., *Cummer and Inan*, 1997; *Bell et al.*, 1998].

We applied this technique to each of the measured field waveforms in the three cases studied. In all cases, the variability in the three extracted current amplitudes for a single event was at most 20% up to the times of the sprites. Because the ionosphere partially controls the signal attenuation with distance, this site-to-site variability may be due to

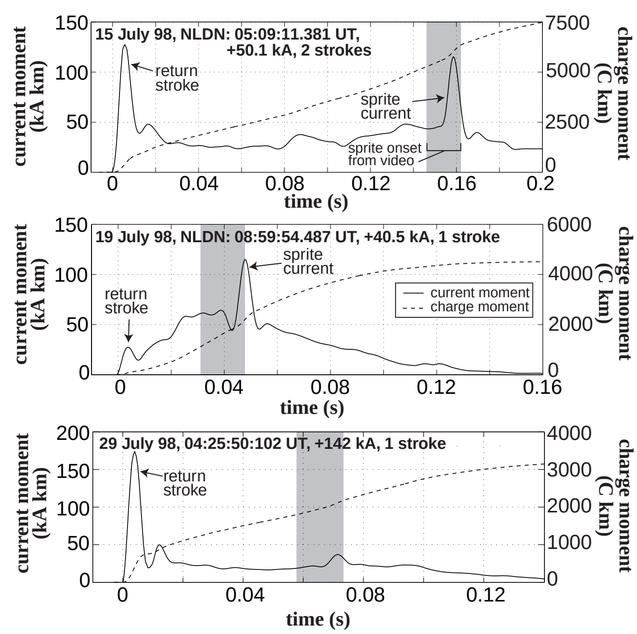

Figure 2. Extracted current moment and charge moment variations for the three events analyzed. NLDN stroke data is given for each. The sprite onset times determined from video (with 16.7 ms uncertainty) are shaded. The first two events contain apparent sprite current during the sprite onset period. In all cases, there is high amplitude continuing current between the return stroke and sprite.

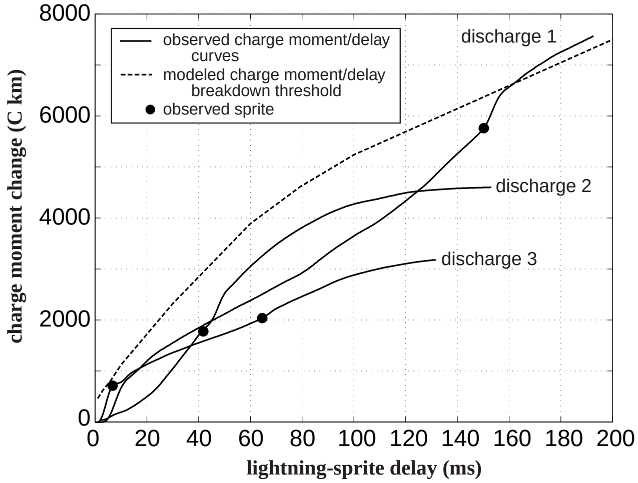

Figure 3. Comparison of theoretical and observed ΔM_Q required to initiate mesospheric breakdown as a function of lightning-sprite delay. The three observed charge moment variations are shown and the sprite current onset times are marked by dots.

large scale ionospheric differences between the paths, which are expected because of the different geomagnetic latitudes of each path. The absolute magnetic field calibration uncertainty is $\sim$5%, giving a $\sim$25% uncertainty for the amplitudes of the extracted currents and charges, which does not affect the findings and conclusions of this work.

Figure 2 shows the extracted current moment and charge moment waveforms for the three events. The NLDN-recorded parameters for each of these positive CGs is given on the plots. Each curve is the average of the three individual measurements for each event. The second pulses in the first two events are sprite current (confirmed by the lack of VLF return-stroke radiation). We are not able to determine the origin of the small pulse at t=70 ms in the third event because it is not distinct in the ELF-VLF data. Although it occurs within $\pm$8 ms of the sprite, the ΔM_Q associated with this pulse is insignificant compared to that in the previous return stroke and continuing current. We conclude that the previous return stroke and continuing current are the primary generators of the observed sprite.

As expected from the rough calculation in Section 2, each event shows a post return stroke continuing current from 20–60 kA km that lasts at least 100 ms and in one case longer than 200 ms. The current channel length cannot be determined from these measurements, but it is unlikely that this differs from the assumed 7 km by more than a factor of two. A charge altitude of 7 km gives a continuing lightning current magnitude (3–9 kA) and duration (>100 ms) of the observed constant lightning current that is significantly larger than most previous reports of positive CGs. Analysis of Schumann resonance measurements in terms of exponentially decaying currents has shown that discharges with 32 kA km peak current moment and decay times of 32 ms occur routinely around the globe [*Burke and Jones*, 1996], but their two parameter interpretation does not have sufficient time resolution to clearly determine the continuing current amplitude and duration.

These observations have important implications for the generation of long-delayed sprites. Higher frequency magnetic field data from similar events show no distinct field signature between the discharge and sprite [*Reising et al.*, 1999], and it has been conjectured that horizontal currents between clouds are responsible for the charge removal and ensuing mesospheric electric field increase that generates long delayed sprites [*Bell et al.*, 1998]. It is likely that the ULF sensitivity of the receivers used in these studies was insufficient to distinguish any long ($\gtrsim$30 ms) continuing currents. The lower frequency observations reported here show that, in these events, the CG current does not turn off between the return stroke and the sprite but instead continues to move substantial charge to the ground. Further data and analysis are required to determine whether long continuing currents are always responsible for long-delayed sprites. The total charge moved to ground during these discharges varies from 300 to more than 850 C, for a 7 km channel length.

Detailed simulations of mesospheric electrical breakdown [*Pasko et al.*, 1996] have shown that, because of dielectric relaxation at higher mesospheric altitudes, sprites that initiate tens of ms after a return stroke require a larger ΔM_Q and do so at lower altitudes than do minimally delayed ($\lesssim$ 5 ms) sprites. Figure 2 shows that these three sprites began after 2000–6000 C km of lightning ΔM_Q, which is at least a factor of 2 more than most short-delayed sprites [*Cummer and Stanley*, 1999] and closer to the recently observed daytime sprites [*Stanley et al.*, 2000], which also likely initiate at lower altitudes.

To test the consistency of these new observations with predictions of breakdown theory, we used a fully electromagnetic finite difference simulation (similar to that of *Pasko et al.* [1998]) that accounts for the ionosphere (using the conductivity profile σ_1 of *Pasko et al.* [1998]) to calculate the mesospheric electric fields $E_{\rm sim}(r,z,t)$ in response to a unit step lightning current discharging a point charge distribution at 7 km altitude. This source is equivalent to a linearly increasing $M_{Q\rm sim}(t)$, and approximates the observed M_Q curves in Figure 2. Defining $E_k(z)$ as the altitude-varying breakdown electric field [*Raizer*, 1991, p. 343], the quantity $M_{Q\rm sim}(\tau)[\min_z(E_k(z)/E_{\rm sim}(0,z,\tau))]$ is the minimum M_Q required to force $E(0,z,\tau) \geq E_k$ at some altitude. This operation scales the source M_Q to the minimum value necessary to initiate breakdown at $t=\tau$, and therefore gives the ΔM_Q required to generate a sprite as a function of time from lighting discharge onset.

This time-varying theoretical sprite initiation threshold is plotted in Figure 3. Also shown are the observed charge moment variations for the three discharges in Figure 2 with the time of sprite onset marked on each. Note that two temporally distinct sprite clusters were observed in response to discharge 3. If model and observation agreed perfectly, the sprites would initiate at the times when the charge moment curves crossed the theoretical threshold curve. The observations fit the expected trend of increasing charge moment for increasing sprite delay expected from electrical breakdown theory with a quantitative deviation from theory of 10–50%. Possible sources of this deviation are uncertainty in the mesospheric conductivity altitude profile, which dictates the electric field relaxation time and therefore strongly controls the electric field, and differences in the assumed (linear) and actual (not quite linear) ΔM_Q variations. Another is the possible contribution of horizontal charge motion (which is not measurable with the technique used here) to the mesospheric electric field. However, the good quantitative agreement between simulation and observation for the extreme case (the largest ΔM_Q and longest delayed sprite) supports non-relativistic electrical breakdown (as opposed to runaway electron breakdown [*Roussel-Duprè et al.*, 1998]) generated by vertical continuing current as the primary mechanism for these long-delayed sprites.

4. Conclusions

ULF magnetic field observations show distinctly elevated field levels between the CG return stroke and the onset of long delayed ($\gtrsim$ 40 ms) sprites. The intensity and continuity of these fields after the return stroke shows them to be produced by vertical CG currents and essentially rules out horizontal incloud processes. Inverse analysis of the fields with an electromagnetic simulation shows that the current moments in these continuing currents are of the order of a few tens of kA km and can last for longer than 100 ms, thereby moving as much as 850 C in 150 ms in a single discharge. These continuing current charge moment changes are almost an order of magnitude larger than those previously reported in positive or negative discharges. The integrated total vertical charge moment change in the discharges is approximately that expected to produce electrical breakdown in the mesosphere.

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