Lightning-Induced Extensive Charge Sheets Provide Long Range Electrostatic Thunderstorm Detection

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By combining electrostatic measurements of lightning-induced electrostatic field changes with radio frequency lightning location, some field changes from exceptionally distant lightning events are apparent which are inconsistent with the usual inverse cube of distance. Furthermore, by using two measurement sites, a transition zone can be identified beyond which the electric field response reverses polarity. For these severe lightning events, we infer a horizontally extensive charge sheet above a thunderstorm, consistent with a mesospheric halo of several hundred kilometers' extent.

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Introduction.—Terrestrial lightning discharges show considerable variety, occurring within a single cloud, between clouds, between a cloud and Earth's surface below or upper atmosphere above, or directly to surrounding air. Lightning can be detected by its emission across a broad electromagnetic spectrum from radio to optical, acoustic waves, or through quasielectrostatic field changes [1]. Peak lightning discharge currents between 1 and 500 kA are typically observed, which, when passed through natural or engineered structures can cause significant damage, leading to fires or system failures [2]. Advance warning of lightning through remote detection techniques can reduce the threat to human endeavour, as well as heralding hazardous weather associated with thunderstorms [3]. Electrostatic detection of lightning conventionally assumes an inverse-cube relationship between a lightning flash and its transient distant electrostatic field change [4–6]. Such a strong dependence however also restricts the maximum electrostatic detection range to about 100 km, in contrast to lightning detection over thousands of kilometers from ionospheric reflection of low radio frequency energy. Electrostatic detection has an additional advantage that all charge reconfigurations can be detected, irrespective of the charge transfer process. If the charge configuration above and within a thundercloud is favorable, detection becomes possible well beyond 100 km.

Thunderstorm detection instrumentation.—New electrostatic thunderstorm detector (TD) instruments have been constructed to monitor electrostatic field changes from distant thunderstorm activity. Two such detectors were installed at different U.K. sites on 29 May 2012. One (TD1), was at Reading University Atmospheric Observatory, U.K. (51.442°N, 0.938°W) and the other (TD2) approximately 120 km west at Biral headquarters in Portishead, U.K. (51.483°N, 2.769°W). The detectors are identical, each employing an isolated spherical antenna of 0.3 m diameter stainless steel at 2.5 m above the ground, mounted on heated PTFE insulators with a rain shield at the base. The spherical antenna generates a current in response to the rate of change of the local electric field, which is measured using an electrometer current amplifier [7] embedded within the supporting PTFE insulator. The amplifier's 100 MΩ input resistor and $\sim$17 pF sphere self-capacitance gave a time constant of $\sim$2 ms, and the output was digitized at 16 bit resolution (1 V $\approx$ 10 nA or 1130 V m^{-1} s^{-1}). dc currents were removed by a 1 Hz high pass filter stage, and, as only the electrostatic component of the field change was of interest, a 200 Hz low-pass filter stage was used to attenuate the electromagnetic component above $\sim$1 kHz. Such radiative field components are, however, small compared to the electrostatic component at close range [6,8]. Both instruments sampled continuously at 100 Hz to resolve the total electric field change from distant lightning. Measurements were stored by a SD card, time stamped in UTC using a crystal oscillator clock synchronized once daily to GPS time. Between synchronizations, however, drift in the crystal oscillator (not originally designed for accurate time keeping) caused a −100 to 900 ms absolute timing uncertainty. Because U.K. lightning flash rates are relatively low, even this 1 s timing uncertainty allowed unambiguous comparison of lightning flashes with the radio frequency detection methods available.

Reference values of lightning peak current, type (cloud-to-ground, CG or cloud-to-cloud, CC), number of return strokes (multiplicity), and geographical location were obtained from the LINET radio frequency detection network. This dense VLF lightning location network uses receivers throughout Europe, and has high regional detection efficiencies and location accuracies [9]. For six days in 2012 (30 May, 11 and 29 July, 5, 15, and 25 August—the reference "summer data set") when significant lightning activity was observed within 100 km of TD1, distances from TD1 to the LINET flash detections were calculated. A LINET flash was considered coincident with TD1 (or TD2) if it occurred within −100 to 900 ms of the electrostatic detection. (Multiple flashes were rare, but in those cases the flash nearest in time to the other detection was used.)

Observations.—931 flashes were coincident between LINET and TD1 in the summer data set. The integrated antenna voltages for each event are plotted against distance in Fig. 1, which are almost entirely consistent with the inverse-cube relationship. Individual deviations are likely to arise from differences between the LINET location and the most influential region of charge neutralization to affect the electric field at TD1, such as cloud-to-cloud flashes of large horizontal extents [10].

Unusual transients were recorded by TD1 and TD2 around 1–2 November 2012, when no local thunderstorms were identified. These transients were usually a single sample, i.e., of duration <10 ms, and were concluded to be of remote origin, as many were coincident at both TD1 and TD2, despite the 120 km detector separation. The transients' amplitudes appeared to imply lightning only ~50 km away using the inverse-cube relationship, but meteorological radar and satellite imagery showed no convective cloud within the small geographical region (up to 100 km) expected from the summer data set. The transients' short durations were also uncharacteristic of nearby lightning, which typically lasted ~200 ms from the combined effect of predischarge leaders, intracloud activity, and multiple return strokes.

Analysis of LINET data in a radius of 500 km around TD1 during 1–2 November indicated that, out of the 2485 flashes (mostly over the English Channel), most of the 222 transients from both detectors coincided with a remote flash, and 24 were also unambiguously coincident in both detectors. Locations of the LINET flashes are shown in Fig. 2. (The integrated voltages and distances to coincident flashes were also plotted in Fig. 1.)

The November coincident flashes showed large peak current (median 206 kA), compared to the summer data set (median 16 kA). For the November flashes to be consistent with the summer inverse cube relationship, the charge moments required would be greater, ~24 times larger than the summer flashes; hence, the difference in current, assuming the same proportional difference as for the peak current statistics, does not account for the discrepancy in Fig. 1. Distributions of bipolar peak currents observed during the November events are summarized in Fig. 3(a); most currents have magnitudes below 100 kA.

Figure 3(b) suggests coincident flashes generally had a greater peak current than noncoincident ones. A slight bias is also evident towards coincident flashes being positive (lowering of positive charge) compared to the noncoincident population.

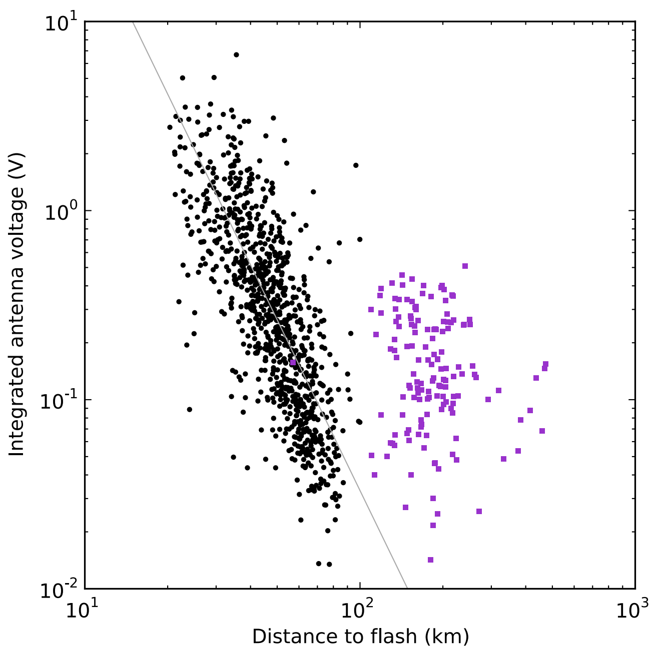

FIG. 1 (color online). Integrated antenna voltage magnitude versus distance to lightning flash for TD1, with the distance obtained from the radio frequency (LINET) lightning location measurement for TD1 events which were time coincident. Black circles represent the summer data set (during May–August 2012), and purple squares 1–2 November 2012 data. The gray line indicates an inverse-cube relationship passing through the May–August data set.

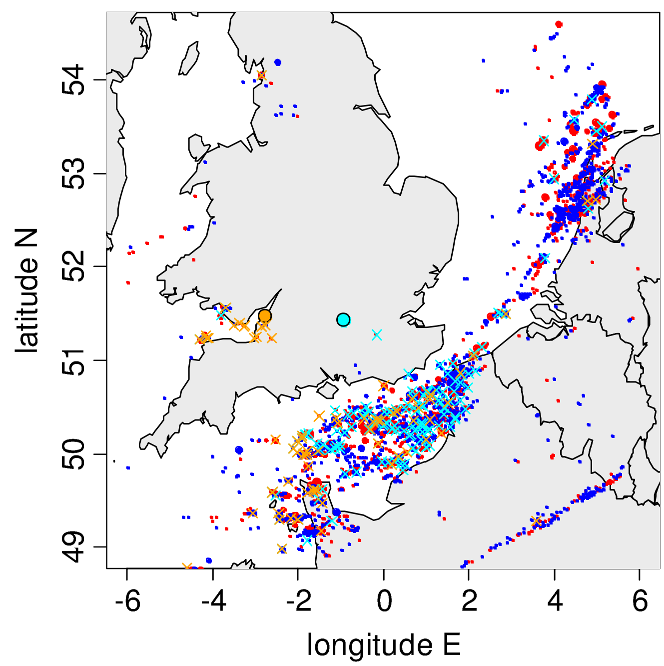

FIG. 2 (color online). Map of LINET lightning flash locations for 1–2 November 2012 within 500 km of TD1 (cyan circle). Red and blue circles indicate positive and negative polarity flashes, respectively, with the circle diameter proportional to peak current. The cyan crosses represent flashes coincident with TD1 detections. The location of TD2 is shown as an orange circle, with orange crosses identifying flashes coincident with this detector.

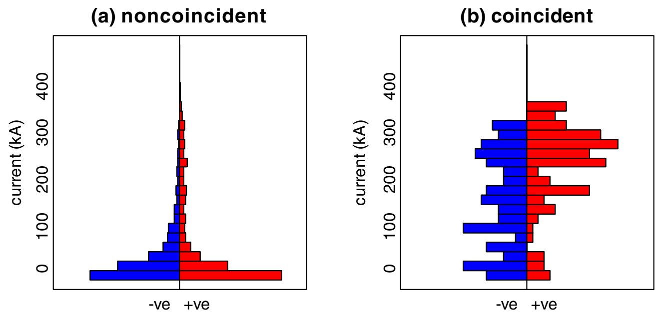

FIG. 3 (color online). Normalized probability densities in 20 kA bins plotted vertically and back to back of peak flash current magnitudes for negative (blue) and positive (red) measured by LINET, during events which are (a) noncoincident and (b) coincident between LINET detections and either TD1 or TD2, and within 500 km of TD1.

For the coincident transients occurring between TD1 and TD2, the majority had the same polarity. Figure 4(a) shows a coincident pair of opposite polarity when one of the sites was 65 km from the flash, which is not possible if the electric field changes related to a simple power law with distance. Figure 4(b) is also contrary to inverse cube expectations since a strong signal is seen from a flash at the more distant station (199 km) yet hardly any signal is identified at the closer station (72 km). No other flashes were identified by LINET occurring within several seconds of these events, so the prospect of flash misallocation is considered unlikely. Figure 4(c) shows a long range signal, with the coincident flash located 318 km from TD1, much further than would be detectable from conventional lightning. The greatest range when both detectors registered a transient was from a -292 kA CG flash at 390 km from TD2.

Discussion.—The amplitude-distance relationship for summer lightning (when peak currents were generally <100 kA) followed an inverse-cube relationship, characteristic of a point-source tropospheric charge transfer above a conducting surface. A different amplitude-distance relationship existed for flashes of both polarities which occurred during 1–2 November. While the median absolute peak current from the coincident November flashes was large (206 kA), some were of more modest currents <100 kA and were usually negative. The lowest peak current from a flash generating coincident transients recorded by both TD1 and TD2 was only -27 kA, despite being 170 and 288 km from TD1 and TD2, respectively. Such flashes would not conventionally be electrostatically detected >80 km away.

Importantly, events in the November data set also showed a polarity reversal distance ~70 km from the detector [e.g., Fig. 4(b)]. Because of the sampling rate, the absolute magnitudes of the anomalies cannot be determined, although there is no reason to suspect their polarities. While polarity reversal is commonly observed close to CC flashes due to the presence of both lower and upper charge neutralization, their range is approximately 1.4 times the height of the center point of the vertical discharge [3]. Given a ~10 km cloud top this limits the reversal distance to less than 14 km from the flash, much greater than the 70 km reversal distance observed here. In comparison, charge transfer several tens of km above the thunderstorm could, however, explain this observation, such as that provided by sprites, which extend up to ~80 km [11].

The generally accepted quasielectrostatic method of sprite generation [12,13] requires an initial charge located near the cloud top (typically positive) overlaid by a layer of charge of opposite polarity and similar magnitude (screening layer charge). The screening charge is then transferred to the conductive lower ionosphere at 80 km when the cloud top charge is neutralized, e.g., from a cloud-to-ground flash. The electric field at the Earth's surface associated with this charge geometry is represented in Fig. 5, (see Supplemental Material [14] for relevant theory). It is evident that although a reduction of electric field is produced at a distance of ~20 km by this configuration, it cannot generate a 70 km polarity reversal distance without significantly increasing the amount of charge in the upper (80 km) source. Such intensification is not justified from charge conservation, as the upper atmospheric charge source derives from the

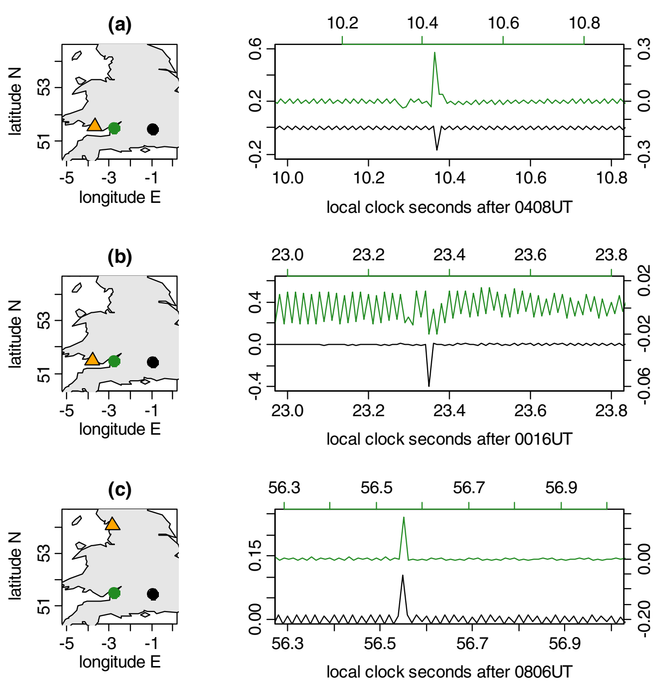

FIG. 4 (color online). Currents (relative scale) detected by TD1 (Reading, black) and TD2 (Portishead, green), on 2 November 2012 for events within one second of a LINET reporting event (location given on left-hand panels by orange triangle) for (a) single stroke -281 kA flash over southern Wales, 191 km from Reading and 65 km from Portishead, (b) a further nearby single stroke 267 kA flash over the Bristol Channel, 199 km from Reading and 72 km from Portishead, and (c) a distant single stroke 267 kA flash over North West England, 318 km from Reading and 286 km from Portishead.

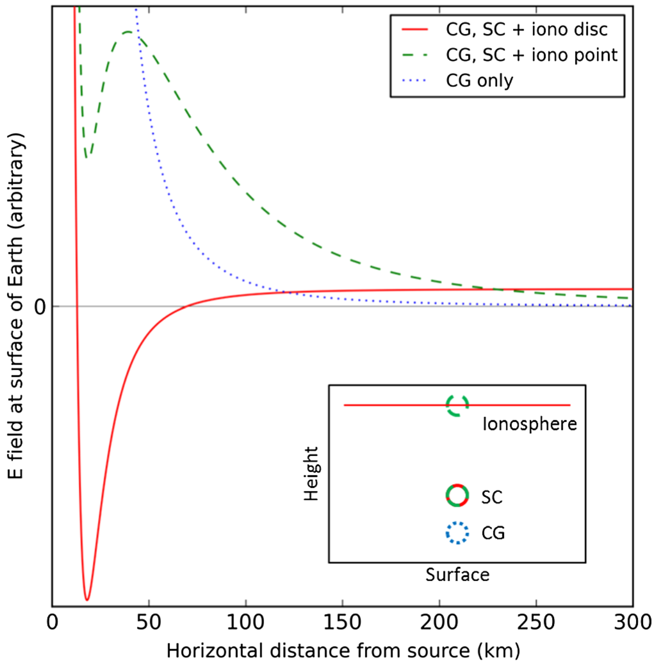

FIG. 5 (color online). Relationship between surface electric field and distance from different charge configurations [see also Supplemental Material [14], Eqs. (1)–(4)]. The blue dotted line shows the inverse-cubed relationship from a single point source at 8 km altitude, representing the charge neutralized by a cloud(top)-to-ground flash. The green dashed line is for a tripole configuration, with equal magnitude point sources at 8, 10, and 80 km altitude (the 10 km being of opposite polarity). This represents cloud top CG charge, screening charge (SC) 2 km above and the upper termination of a sprite. The red line is for the same configuration as the green (sprite) model except the upper charge is spread into a 600 km disc of uniform charge density. The insert indicates the different charge configurations considered.

screening layer and would be approximately equal in magnitude to the cloud top charge to which it was attracted. Modeling the sprite electrostatic field as a vertical line charge [15] would also not be able to account for the observed reversal distance or consistently high transient amplitudes at ranges >200 km. Surface electric field enhancement from this upper atmosphere charge can be achieved if the charge is distributed as a horizontally extensive uniform sheet instead of a point source. Such geometry produces a uniform vertical electric field component throughout the atmosphere beneath of sufficient strength to produce the observed surface field reversal. A charge disc of radius ~600 km was sufficient to produce a reversal distance at the observed ~70 km, as shown in Fig. 5. The disc radius represents the charge density required over an extensive horizontal region centered above the flash where the charge density radial gradient is small.

A transient uniformly charged disc of radius ~600 km could also account for the anomalously high electric field changes at large distances where the electric field from the CG flash would be negligible (Fig. 5). A horizontally extensive disc of charge is consistent with optical observations made of halos, known to occur both with, and without, sprites [16], with transient changes modeled in the ionosphere above [17]. The disc radius calculation is relatively insensitive to cloud top height but is most sensitive to the height of the screening layer above the cloud top charge. The screening charge height is assumed here to coincide with the cloud top boundary, where the conductivity gradient is strongest. Assuming height differences between 1 and 5 km, the corresponding radius for a uniformly charged disc producing a 70 km reversal distance would be approximately 390 km for 5 km height difference ranging to 850 km for a 1 km difference. The lower radius limit represents the longest range where transients were recorded simultaneously at both detectors, which is still somewhat larger than from optically observed halos, at less than 150 km.

The relatively high conductivity of the lower ionosphere would account for the rapid radial spreading of charge from the source, with such currents attributed to the optical effect of halos. The anomalous electric field change with distance observed during the 1–2 November storms may therefore result from rapid charge redistribution in the lower ionosphere associated with halos. Given that sprite halos are strongly biased towards positive cloud-to-ground flashes [18], but our results show similar effects for both polarities [Fig. 3(b)], it seems likely that both sprite and spriteless halos produced the anomalies [13]. 70% of weaker (< 100 kA) flashes producing the transients were negative, with approximately equal numbers of both polarities present for higher peak current flashes [Fig. 3(b)]. This is consistent with findings of a negative polarity bias to flashes which have produced halos [16,19], shown to occur even with relatively weak lightning flashes [16].

The observed electrostatic change with distance from halos is consistent with the quasielectrostatic theory of their generation. Halo charge transients may also offer a possible electrostatic mechanism for the observed synchronization of lightning flashes displaced at considerable distances [20], given the ability of the halo to efficiently project electric field changes to storms hundreds of kilometers from their parent flash, at millisecond time scales.

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