GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 3, PAGES 333-336, FEBRUARY 1, 2000

Global Triangulation of Intense Lightning Discharges

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Abstract. A global network of three electromagnetic measurement instruments is used to simultaneously record time series of globally observable Extremely-Low-Frequency (ELF) magnetic field disturbances which propagate with little attenuation around the globe within the Earth-ionosphere cavity. The triangulation of individual lightning flashes results in a picture of the temporal evolution of intense lightning discharge occurrences on the planetary scale during April 1998. The lightning flash charge moments are calculated with the short pulse approximation of the normal mode expansion. The majority of the triangulated lightning discharges exhibit charge moments with a potential to excite mesospheric sprites and ~5-20 % may account for air breakdown at sprite altitudes in ~50-70 km height.

Introduction

Space shuttle based observations [*Boeck et al.*, 1995] of transient optical emissions in the mesosphere above thunderstorms [*Franz et al.*, 1990], denoted sprites [*Sentman et al.*, 1995; *Lyons*, 1996], reported many sprite appearances all around the Earth. Sprites are generally preceeded by positive cloud-to-ground discharges associated with particularly large Extremely-Low-Frequency electromagnetic field disturbances [*Boccippio et al.*, 1995; *Reising et al.*, 1996], possibly related to electrical current in the body of the sprite [*Cummer et al.*, 1998; *Pasko et al.*, 1998]. Remote sensing of these electromagnetic field disturbances from the Antarctic has been used as a proxy indicator for sprite occurrence in North American thunderstorms with an estimated 83 % detection probability [*Reising et al.*, 1999]. At frequencies <100 Hz, the electromagnetic waves of cloud-to-ground discharges can propagate with little attenuation around the globe, guided within the Earth-ionosphere cavity [*Holzer and Deal*, 1956]. Constructive interference of these globally circum propagating electromagnetic waves results in Earth-ionosphere cavity (or Schumann) resonances [*Sentman*, 1995], which are used to radio locate sprite-associated lightning flashes in North America with an estimated 80 % detection probability [*Füllekrug and Reising*, 1998]. Consequently, it has been suggested that discrete ELF magnetic field disturbances may be used to predict promising regions of sprite-associated lightning flash occurrences on a global scale. In this way, sprite occurrences in Japan have been confirmed (Takahashi, pers. comm.) and the southern side of the Pyrenees and Alps have been determined as promising regions of sprite occurrences in Europe [*Füllekrug and Reising*, 1998].

Lightning flash triangulation

In this contribution, we make use of horizontally oriented induction coil magnetometers to continously record simultaneously occurring ELF magnetic field disturbances in the frequency range 4-200 Hz at Silberborn, Germany (51.8° N, 9.5° E), and 4-19 Hz at Hollister, California (36.8° N, 121.4° W), and at Lameroo, Australia (35.5° S, 140.6° E), during April 1998. Note that the bandwidth of the measurements at Hollister and Lameroo (15 Hz) is relatively small compared to the broadband recordings (196 Hz) at Silberborn. Discrete ELF magnetic field disturbances which exceed the natural noise background by two standarad deviations at all locations, are detected and used for further analysis. Figure 1 displays for example discrete excitations of Earth-ionosphere cavity resonances at the network of measurement stations on April 16. The resonant signal of ~8 Hz at Silberborn is preceeded by the sharp ELF magnetic field disturbance from the lightning flash, seen as a result of the large instrumental bandwidth. The network of measurement stations recorded 52510 globally observable discrete ELF magnetic field disturbances during April 1998. Note that globally observable light-

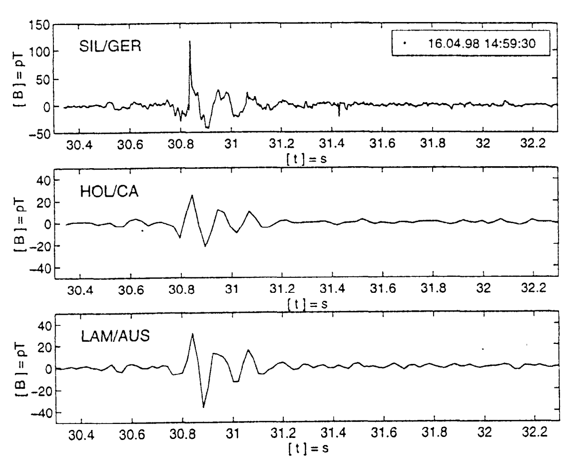

Figure 1. Simultaneously recorded discrete excitations of Earth-ionosphere cavity resonances at Silberborn, Germany (SIL/GER), Hollister, California (HOL/CA), and at Lameroo, Australia (LAM/AUS).

Paper number 1999GL003684.
0094-8276/00/1999GL003684$05.00

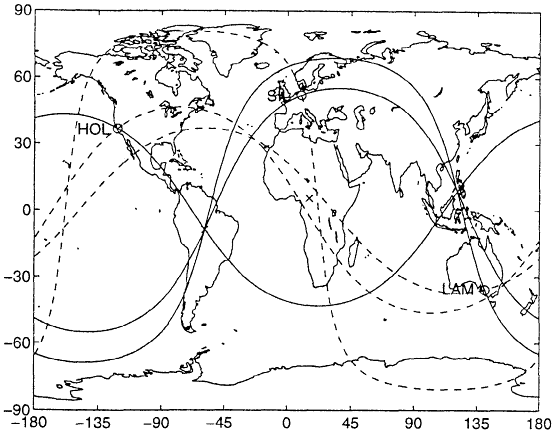

Figure 2. The Poynting vector orientation at each station defines a great circle with intersections at a unique source location (solid lines) or a most likely source location at the inscribed circle center (×) of a spherical triangle (dashed lines).

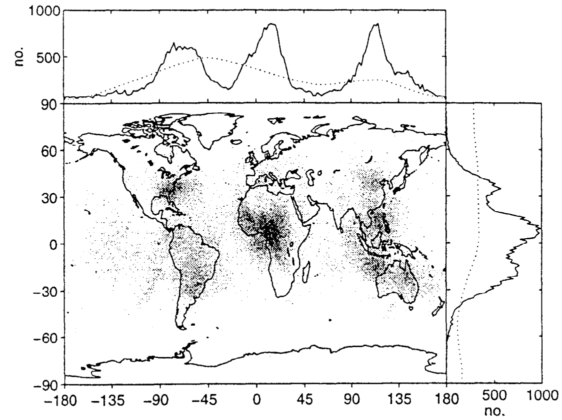

Figure 4. The global distribution of lightning flash occurrences during April 1998 is centered in America, Africa and South-East Asia within the latitudinal band ±60°. The relative sensitivity of the network maximizes in the northern Atlantic and minimizes in the southern Pacific (dotted lines).

ning flash occurrences (~1/40 s) represent only 1 out of 4000 ordinary lightning flash occurrences (~100/s) since the detection efficiency of lightning flashes at frequencies <100 Hz is biased towards the rarely occurring positive lightning flashes [*Füllekrug and Reising,* 1998; *Boccippio et al.,* 1998]. The orientation of the Poynting vector at all stations define three great circles on the globe with intersections at two conjugate points in opposite hemispheres (see Figure 2, solid lines). This hemispheric ambiguity of the lightning flash location is resolved by taking into account the time of arrival difference between two measurement stations, introduced by the electromagnetic wave propagation at ~0.8 c. The anisotropic conductivity of the nighttime ionosphere usually results in a triangulation error [*Füllekrug and Sukhorukov,* 1999] and three great circle intersections in either hemisphere which define a spherical triangle on the globe (see Figure 2, dashed lines). In this contribution, we make use of the inscribed circle center of this spherical triangle as the most likely lightning flash location. The triangulation accuracy is verified with times and locations of lightning flashes reported by the VLF time of arrival difference system of the British Meteorological Office [*Lee,* 1986] in Europe, Africa, eastern North America, and South America (see insert in Figure 3). The distribution function of the triangulation error exhibits a sharp maximum with a mean accuracy ~1 Mm (see Figure 3, solid line), in agreement with previous estimates [*Füllekrug and Sukhorukov,* 1999, and references therein]. The constant part of the distribution towards larger triangulation errors results from random simultaneous occurrences of ELF magnetic field disturbances. The cumulative distribution indicates that ~80-90 % of simultaneously recorded ELF magnetic field disturbances have self consistent Poynting vector orientations (see Figure 3, dashed line).

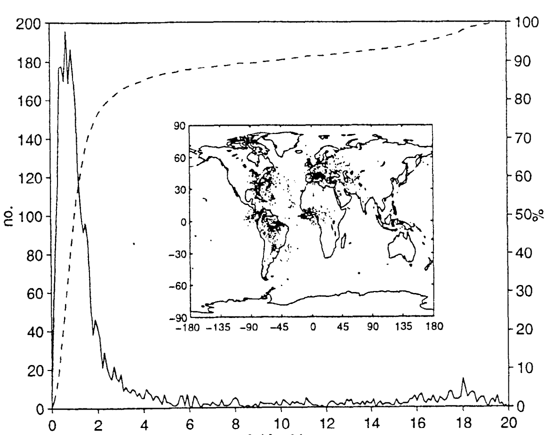

Figure 3. Lightning flash locations reported by the British Meteorological Office (inserted Figure) are used to estimate a mean triangulation accuracy (d) ~1 Mm (solid line). The cumulative distribution function indicates that ~80-90 % simultaneously recorded ELF magnetic field disturbances exhibit self consistent Poynting vector orientations (dashed line).

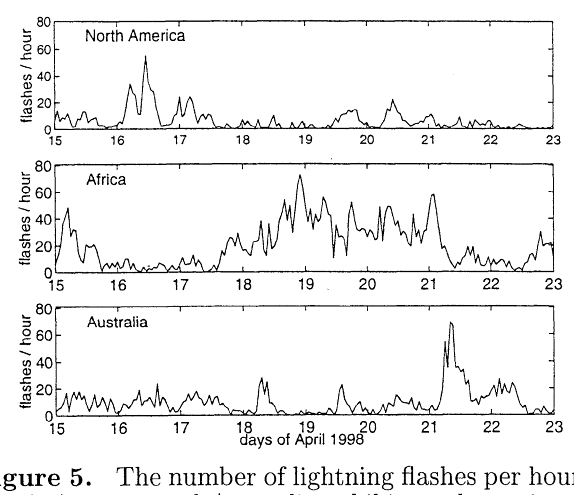

Figure 5. The number of lightning flashes per hour in North America and Australia exhibits a sharp rise and a decay within one day, while the lightning activity in Africa persists for several days.

The triangulated lightning flash locations during April 1998 are summarized in $1^{\circ}\times 1^{\circ}$ large grid cells on the globe and they are averaged over the longitude and latitude (see Figure 4). The latitudinal distribution shows that most lightning flashes are centered within the latitudinal band $\pm 60^{\circ}$ with a maximum around the equator. The longitudinal distribution exhibits three distinct maxima which correspond to the major centers of global lightning activity: America, Africa, and South-East Asia. The network of measurement instruments has a detection efficiency which is constrained by the maximum source-receiver distance. This relative sensitivity is averaged over the latitude and longitude (see Figure 4, dotted lines) and varies by a factor of two around the globe. The network is most sensitive to sources in the northern hemisphere at Atlantic longitudes and least sensitive to sources in the southern Pacific. The continous magnetic field recordings during April 1998 make possible a study of the temporal evolution of individual thunderstorms and their spatial migration (see http://www.geophysik.uni-frankfurt.de/˜fuellekr/glas.html). Figure 5 shows for example the number of lightning flashes per hour in the three different geographic areas North America, Africa and Australia during April 15-23. The thunderstorms in North America and Australia exhibit a sharp rise of the flash rate and a decay within one day, while the high flash rate in Africa persists for 3-4 days and may be associated with one or more mesoscale convective systems [*Laing and Fritsch,* 1997], or many individual thunderstorm cells.

To investigate the potential of the triangulated lightning flashes to excite mesospheric sprites, it has been suggested to analyze the lightning flash charge moment [*Huang et al.,* 1999]. Cloud-to-ground discharges correspond to a vertical current which is proportional to the magnetic field intensity $B_h = \sqrt{B_{\mathrm{NS}}^2 + B_{\mathrm{EW}}^2}$ and the source-receiver distance. Figure 6 shows for example

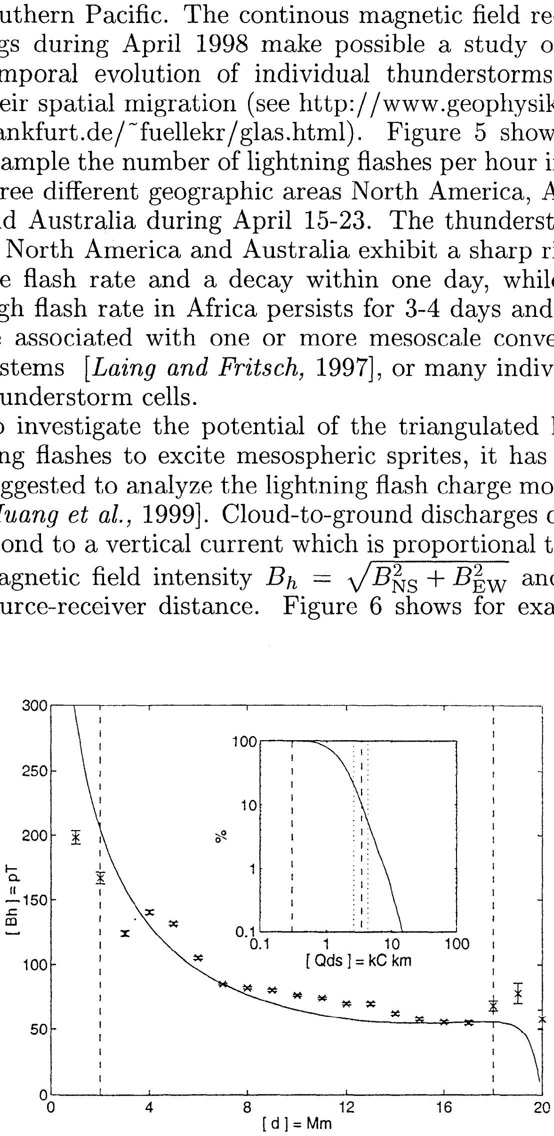

Figure 6. The experimentally determined source-receiver distance (d) dependent peak horizontal magnetic intensity B_h ($\times$) is compared to the short pulse approximation of the normal mode expansion (solid line) within 2-18 Mm (dashed lines). The cumulative distribution of all charge moments (inserted Figure) indicates that the majority exceeds ~0.3 kC km and ~10 % exceed 3.5 kC km (dashed lines).

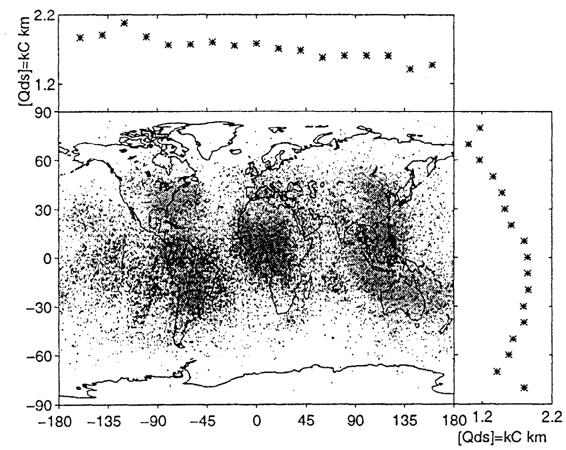

Figure 7. The mean global distribution of charge moments exhibits an equatorial maximum and a decrease towards eastern longitudes which introduce a geographic bias in the charge moment estimation.

the experimentally determined source-receiver distance dependence of the peak horizontal magnetic itensity derived from the broadband recordings at Silberborn, Germany. Analytical descriptions for the electromagnetic radiation of individual lightning flashes have been developed [*Jones and Kemp,* 1970; *Kemp and Jones,* 1971; *Sentman,* 1996] and used to determine a minimum charge moment threshold ~0.3 kC km for sprite detection [*Huang et al.,* 1999]. In this contribution, we make use of the short pulse approximation of the normal mode expansion [*Burke and Jones,* 1996]

$$B(f,\vartheta) = \frac{Qds\mu_0}{4\pi a h} \sum_n \frac{2n+1}{n(n+1)-\nu(f)(\nu(f)+1)} P_n^1(\cos\vartheta),$$

where a is the radius of the Earth, h ~80 km the height of the ionospheric reflection boundary, μ_0 the magnetic permeability, $\nu(f) = 1.64 - 0.1759 \ln f + 0.01791 (\ln f)^2 - i\, 0.34587 f^{0.64}$ the complex propagation constant at frequency f [*Huang et al.,* 1999], $P_n^1(\cos\vartheta)$ the associated Legendre polynominal of order n and first degree, and ϑ the co-latitude. The normal mode expansion relates the observed magnetic field intensity $B(f,\vartheta)$ to the charge moment Qds which describes the amount of charge Q, lowered to ground within a lightning channel of length ds ~5 km. Integration of $B(f,\vartheta)$ over the frequency range 4-200 Hz of the measurement instrument at Silberborn results in theoretical source-receiver distance dependent horizontal magnetic intensities, calculated for a charge moment Qds =1.6 kC km for comparison with the experimental estimation (see Figure 6, solid line). The model calculation and the experiment agree well at source-receiver distances 2-18 Mm (see Figure 6, dashed lines). Near the source location and at antipodal distances, the finite number of modes may affect the theoretical model calculation [*Sentman,* 1996], or the small number of detected lightning flashes may affect the experimental estimation. However, the majority of lightning flash locations is found in the source-receiver distance range, where the normal mode expansion may be applied. The cumulative charge moment distribution indicates that the majority of the triangulated lightning flashes exceed the charge moment threshold

~0.3 kC km for sprite detection (see insert in Figure 6). Moreover, ~10 % of the lightning flashes exhibit charge moments >3.5 kC km required for conventional air breakdown at sprite altitudes in ~50-70 km height [*Huang et al.,* 1999].

Discussion and Summary

A global network of three ELF magnetic measurement stations is used to triangulate self consistent source locations of particularly intense lightning discharges on the planetary scale with a mean accuracy ~1 Mm. This accuracy is determined by the two stations in California and Australia with an effective bandwidth of only 15 Hz. Since the bearing deviation introduced by the ionospheric anisotropic conductivity decreases with increasing frequency [*Füllekrug and Sukhorukov,* 1999], three similar broadband instruments may considerably improve the triangulation accuracy. The calculated charge moment may be underestimated since we make use of peak magnetic field intensities instead of time integrated magnetic field values. On the other hand, the charge moment may be overestimated since it scales proportional to the variable effective reflection height of the day- and nighttime ionosphere. To estimate possible wave propagation effects, we investigate the mean geographic charge moment distribution. The charge moments from 0.3-4.2 kC km are summarized in $1^o \times 1^o$ large grid cells on the globe and they are averaged over the longitude and latitude (see Figure 7). The longitudinal distribution shows a decrease towards eastern longitudes. Therefore, the charge moments of lightning flashes west of the measurement instrument may be overestimated since lightning activity occurs in the late afternoon and nocturnal ELF wave propagation is less attenuated. Self consistent charge moment estimates require consideration of electromagnetic wave attenuation in the day- and nighttime hemispheres. The equatorial maximum of the global charge moment distribution may indicate a dependence on meteorological conditions. Since the charge moment Qds is the product of the amount of charge Q and the lightning channel length ds, tropical lightning may either lower more charge to ground, or it may be associated with longer lightning channels as a result of higher tropopause levels in equatorial latitudes. Both effects may rely on the latitudinal dependence of the short wave solar radiation input. However, the derived charge moments exhibit a maximum geographic bias on the order of ±25 % which constrains the accuracy of the charge moment estimates. From their cumulative distribution, it is infered that 5-20 % of the recorded lightning flashes (see insert in Figure 6, dotted lines) have the potential to cause conventional air breakdown at sprite altitudes.

Acknowledgments. This research was sponsored by the Deutsche ForschungsGemeinschaft under Grant No. Fu 285/3-1 and Fu 285/3-2. The magnetic field measurements at Hollister were kindly provided by the Department of Materials Science and Mineral Engineering, and the Seismological Laboratory at UC Berkeley. The authors thank the British Meteorological Office for access to selected periods of lightning data, G. Dawes at the University of Edinburgh, Scotland, G. Heinson at Flinders University, Australia, H. Kreilein at the Universität Göttingen, Germany, and B. Santer at Lawrence Livermore National Laboratory/California for logistic support of this project.

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(Received September 27, 1999; revised November 30, 1999; accepted December 3, 1999.)