Letter to the Editor Intense oceanic lightning

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Letter to the Editor

Intense oceanic lightning

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Abstract. The electrodynamic properties of intense oceanic lightning discharges are compared to intense continental lightning discharges. Particularly intense negative lightning discharges with absolute charge moments > 2 kC·km occur more often over the oceans than over the continents during April 1998. Intense continental lightning discharges, with negative and positive polarity, and intense positive oceanic lightning discharges primarily occur associated with mesoscale convection in the late evening. The number of intense negative oceanic lightning discharges increases in the early morning hours, probably associated with the resurgence of oceanic mesoscale convection in coastal areas. The day-to-day variability of intense negative oceanic lightning discharges exhibits a five day periodicity, possibly related to planetary waves.

Key words. Meteorology and atmospheric dynamics (lightning; ocean-atmosphere interactions) – Oceanography - general (marine meteorology)

1 Introduction

Climatological studies of synoptic audible thunder observations on ships and at meteorological observatories reported a $\sim$10–30% contribution of oceanic thunderstorms to global thunderstorm activity (Brooks, 1925). A more recent study with more than $\sim 7 \cdot 10^6$ synoptic observations of audible thunder reports similar results, but with $\sim$2 times more oceanic thunderstorms than expected (Trent and Gathman, 1972). Although lightning activity is higher over the continents, lightning flash recordings on board the OTD satellite (Goodman and Christian, 1993) also exhibit considerable lightning activity over the oceans (Christian and Latham, 1998). The occurrence of oceanic and continental lightning discharges at dawn and dusk was estimated with optical recordings on board the DMSP satellites (Turman and Edgar, 1982). At dawn, $\sim$37% of the recorded lightning discharges occur over the oceans and $\sim$63% occur over the continents, while at dusk, only $\sim$15% of the lightning discharges occur over the oceans and $\sim$85% occur over the continents. Oceanic lightning flashes in coastal areas can be detected by their Very Low-Frequency (VLF) electromagnetic radiation, for example, recorded by the National Lightning Detection Network (Cummins et al., 1998). One study from February to March 1986 shows that more lightning flashes occur over the gulf stream, east of the North American coastline, than over the nearby ($\sim$300 km) continent (Biswas and Hobbs, 1990).

The remote sensing of lightning flash electromagnetic radiation, the satellite-based optical recordings of lightning flashes, and the ground-based observations of audible thunder are primarily used to determine temporal lightning flash rates and spatial lightning flash densities. On the other hand, the physical properties of oceanic lightning flashes, such as their polarity and their intensity, are almost unknown. The study of lightning flashes over the gulf stream reports that positive and negative lightning flashes are more intense over the ocean than over the continent (Biswas and Hobbs, 1990). Optical lightning flash recordings on board the Vela satellites detected lightning superbolts with an optical power of $\gtrsim 3 \cdot 10^{12}$ W (Turman, 1977). These lightning superbolts are extremely rare. Only one lightning flash out of $\sim 2 \cdot 10^6$ is intense enough to reach this optical power. The 17 locations of the observed lightning superbolts are tabulated for the years 1972–1975 and they are displayed in Fig. 1. Surprisingly, 11 of the lightning superbolt locations are found in coastal areas ($\sim$65%), whereas 4 occur over the oceans ($\sim$23%) and 2 occur over the continents ($\sim$12%). Therefore, one may hypothesize that the majority of the most intense lightning flashes on planet Earth occur in coastal areas.

2 The polarity of intense oceanic lightning discharges

The Extremely Low-Frequency (ELF) electromagnetic radiation of particularly intense cloud to ground lightning dis-

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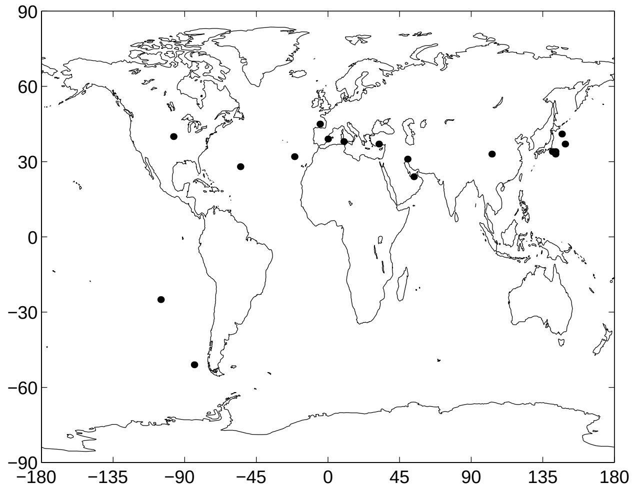

Fig. 1. Lightning discharges with particularly large optical intensities (black dots) occur primarily in coastal areas (Turman, 1977).

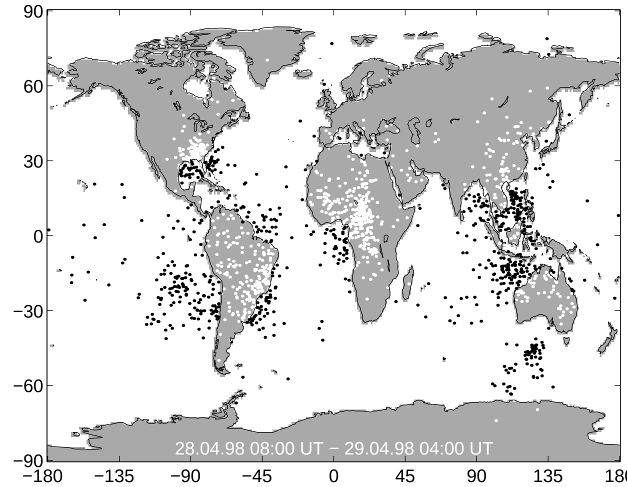

Fig. 2. Particularly intense oceanic (black dots) and continental (white dots) lightning discharges are displayed over the land masses (gray patches) from 28–29 April 1998. Many lightning discharges occur in the coastal areas and over the oceans.

charges is recorded with a global network of three magnetometers. The polarization of the electromagnetic wave is used to triangulate the lightning discharges on the planetary scale (Füllekrug and Constable, 2000). The polarity and the charge moment Ql of the intense lightning discharges is inferred from the measured magnetic field B_m with the normal mode expansion and frequency dependent ionospheric heights

$$Ql(\omega, \vartheta) = B_m(\omega, \vartheta) \frac{4\pi a^3 h_1(\omega)\varepsilon_0}{\sum_n \frac{2n+1}{(\omega-\omega_n)(\omega+\omega_n^*)} P_n^1(\cos\vartheta)} \qquad (1)$$

(Sentman, 1996; Füllekrug, 2000). In this approach, the geometric spreading of the electromagnetic wave is described with the associated Legendre polynominals $P_n^m(\cos\vartheta)$ of degree n and order $m = 1$ at an angular distance ϑ from the lightning discharge on a spherical earth with radius a. The ionospheric transfer function is characterized by the frequency dependent conduction boundary $h_1(\omega)$ and the complex modal frequencies ω_n. The resulting charge moment Ql describes the amount of charge Q lowered from cloud to ground within a lightning channel of length l (Burke and Jones, 1996; Sentman, 1996; Huang et al., 1999). The minimum and maximum intensity of all detected cloud to ground lightning discharges is 0.1 kC·km and ∼9.0 kC·km, respectively, with a mean intensity of ∼1.6 kC·km. Since a typical cloud to ground lightning channel length is ∼4–6 km and cannot exceed the height of the tropopause at ∼10–15 km, the mean cloud to ground charge transfer is >110–400 C and exceeds the mean charge transfer of lightning discharges by a factor of >5–20 (Uman, 1987).

Figure 2 displays, for example, the globally triangulated lightning discharges from 28–29 April 1998. In addition to the dominant continental lightning activity (Orville and Henderson, 1986), many oceanic lightning discharges are observed over the Gulf of Mexico, west of the South American coast, and over the maritime continent in Southeast Asia.

Table 1. The total numbers of negative and positive oceanic lightning discharges during April 1998 are compared to continental lightning discharge occurrences

occurrences	negative	positive	sum
oceans	9743	14281	24024
continents	8963	19523	28486
sum	18706	33804	52510

Most of the oceanic lightning discharges occur in coastal areas and only some lightning discharges occur over the open oceans. The proximity of oceanic lightning discharges to the continent presumably results from the advection of their parent thunderstorm systems across the western continental coastline by the prevailing easterly winds in the latitude range from ∼30°S to ∼30°N. However, the oceanic thunderstorm south of Australia is most likely initiated over the open ocean. To discriminate between intense oceanic and continental lightning discharges, the surface of the earth is divided into oceanic and continental areas with a 1°×1° resolution (Fig. 2). A continental grid box is defined when it includes any fraction of continental land masses. The total number of intense negative and positive oceanic lightning discharges during April 1998 is summarized in Table 1, and they are compared to intense continental lightning discharges. It is evident from this statistical analysis that the number of positive continental lightning discharges exceeds the number of negative continental lightning discharges by a factor of ∼2 in agreement with the work of Burke and Jones (1996), and Füllekrug and Reising (1998). But the relative amount of all intense oceanic lightning discharges is ∼45% and is larger than expected. Moreover, intense negative lightning discharges are more likely to occur over the oceans than over the continents. This simple discrimination between in-

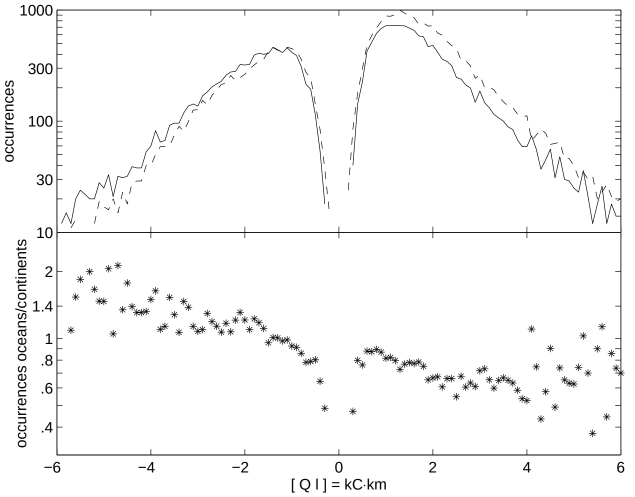

Fig. 3. The charge moment distribution functions of particularly intense oceanic (solid lines) and continental (dashed lines) lightning discharges indicate that negative oceanic lightning discharges are more likely to occur than negative continental lightning discharges (upper panel). The ratio between the oceanic and the continental charge moment distribution function is linearly related to the charge moment (lower panel).

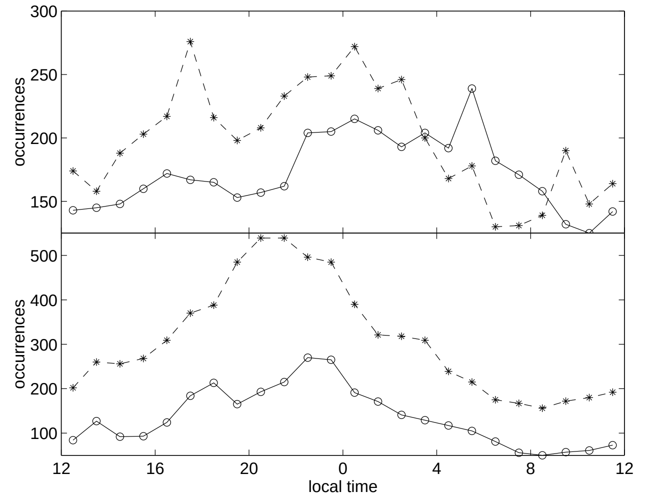

Fig. 4. The diurnal variation of negative (solid lines) and positive (dashed lines) lightning discharge occurrences over the oceans (upper panel) and the continents (lower panel) are similar except for negative oceanic lightning discharge occurrences.

tense negative oceanic and continental lightning discharges strongly indicates further differences in their electrodynamic properties.

3 The charge moment of intense oceanic lightning discharges

To investigate the electrodynamic properties of intense oceanic lightning discharges in more detail, the inferred charge moments are summarized in 0.1 kC·km large charge moment bins for the oceans and the continents (Fig. 3, upper panel). The observed decrease in lightning discharge occurrences with small absolute charge moments $|Ql| < 0.5$ kC·km results from the detection efficiency of the global network of magnetometers, which is only sensitive to the most intense lightning discharges around the planet Earth (Füllekrug and Constable, 2000). The calculated charge moment distribution functions confirm that negative lightning discharges are more likely to occur over the oceans than over the continents, in particular for the large charge moments from –2 kC·km to –6 kC·km. Similarly, positive lightning discharges are more likely to occur over the continents than over the oceans for the extremely large charge moments from +2 kC·km to +6 kC·km. This latter result is in qualitative agreement with Berger et al. (1975), who showed that the extreme 5% peak current is $\sim$250 kA for positive lightning discharges and only $\sim$80 kA for negative lightning discharges.

It is possible to estimate the relative amount of oceanic versus continental lightning discharges by calculating the ratio between the oceanic and continental charge moment distribution function (Fig. 3, lower panel). The calculated ratio exhibits a large scatter for small absolute charge moments $|Ql| < 0.5$ kC·km and extremely large charge moments $|Ql| > 4$ kC·km, as a result of the small total number of observed lightning discharges (Fig. 3, upper panel). Nevertheless, the ratio between oceanic and continental lightning discharge occurrences depends linearly on the charge moment and it is more pronounced for extremely intense lightning discharges. Oceanic lightning discharges with charge moments from –4 kC·km to –2 kC·km and from +2 kC·km to +4 kC·km represent $\sim$130–140% and $\sim$60–70% of the respective continental lightning discharge occurrences. The latter small percentage of intense positive oceanic lightning discharges may result from a partial dissipation of the stratiform region of oceanic mesoscale convection. But the former large percentage of intense negative oceanic lightning discharges is unexpected.

4 The temporal evolution of intense oceanic lightning discharge occurrences

The meteorological properties of the thunderstorms which produce the relatively large number of intense negative oceanic lightning discharges are further investigated with the diurnal variation and the day-to-day variability of oceanic and continental lightning discharge occurrences with negative and positive polarity. The diurnal variation of negative and positive continental lightning discharges and positive oceanic lightning discharges exhibit similar diurnal variations with maxima in the late evening (Fig. 4). Therefore, it is evident that large horizontally extended stratiform regions of mesoscale convection (Laing and Fritsch, 1997; Lyons et al., 1998) provide the charge reservoir for particularly intense lightning discharges to occur (Williams, 1998). These mesoscale convective systems may provide less pos-

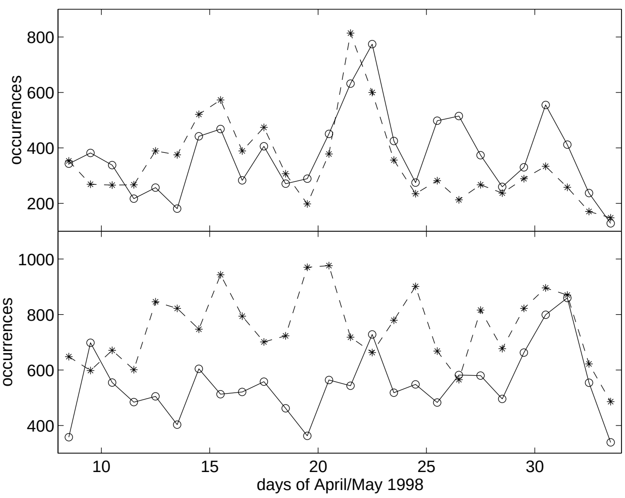

Fig. 5. The day-to-day variability of negative (solid lines) and positive (dashed lines) lightning discharge occurrences over the oceans (upper panel) and the continents (lower panel). The negative oceanic lightning discharge occurrences exhibit an approximate five day periodicity.

itive lightning discharges after midnight. Alternatively, the increase in negative oceanic lightning discharge occurrences in the early morning hours is probably associated with a different meteorological process. For example, nocturnal thunderstorms may be inititated by the radiative cooling from the cloud tops of the mesoscale convective systems. In this picture, the relatively small updraft velocities in the resurgent oceanic mesoscale convection would lead to the observed increase in negative lightning discharge occurrences.

The oceanic and continental lightning discharge occurrences with negative and positive polarity exhibit some day-to-day variability (Fig. 5). In particular, the negative oceanic lightning discharge occurrences exhibit a pronounced day-to-day variability with an approximate five day periodicity. The number of negative oceanic lightning discharges from 24 April to 4 May 1998 is ~ 2 times larger than the number of positive oceanic lightning discharges during the observed five day periodicity, possibly associated with planetary waves.

5 Summary and discussion

The electrodynamic properties of intense oceanic lightning discharges are compared to intense continental lightning discharges. The charge moment distribution functions of intense oceanic and continental lightning discharges indicate unexpectedly that intense negative oceanic lightning discharges occur more often than negative continental lightning discharges during April 1998. The intense negative and positive continental lightning discharges associated with mesoscale convection occur in the late evening. The decrease in intense positive lightning discharges over the oceans after midnight may result from a partial dissipation of the stratiform region of oceanic mesoscale convection. Alternatively, wind shear within continental (Engholm et al., 1990) and coastal (Levin et al., 1996) thunderstorms may result in a modification of the fraction of positive lightning discharge occurrences. The number of intense negative oceanic lightning discharges increases in the early morning hours, probably associated with a resurgence of oceanic mesoscale convection in coastal areas, initiated by radiative cooling or an offshore land breeze. The observed five day periodicity of intense negative oceanic lightning discharges is possibly associated with planetary waves (Harth, 1982), which may modulate the number of observed lightning discharges. It may be argued that the globally triangulated lightning discharge location accuracy of ~ 1 Mm (Füllekrug and Reising, 1998; Füllekrug and Constable, 2000) may influence the statistical analysis. But a random statistical scatter around the mean location would rather blur the results, since the coastal areas where most of the oceanic lightning discharges occur are not well resolved. Consequently, it will be particularly interesting to investigate in the future the electrodynamic properties of intense oceanic lightning in coastal areas with an improved lightning discharge location accuracy.

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