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Key Points:
- Elves were indeed triggered by energetic lightning
- The production efficiency of elves was insensitive to the underlying landform
- The geog. distribution of the elves agrees with that for the most energetic lightning

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Energetics and geographic distribution of elve-producing discharges

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Abstract The major types of transient luminous events (TLEs) are believed to be directly triggered by cloud-to-ground discharges. Intense lightning generally seems to have a higher production efficiency for TLEs, but this observation has not yet been statistically investigated. Two data sets, the upgraded World Wide Lightning Location Network (WWLLN) lightning stroke data and the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) TLE data, were used to investigate the energetics and the geographic distribution of TLE-producing lightning. The global median energy of the strokes that produced the TLEs is at least an order of magnitude higher than the global median stroke energy for WWLLN lightning in the same data window. Furthermore, the energy distributions of the elve-producing strokes exhibit no oceanic and land disparity. These results reveal that the elves are indeed triggered by energetic lightning and the production efficiency of elves with respect to the stroke energy of the causative lightning was insensitive to the underlying landform. Analysis of the spatial correlation between the ISUAL elves and the WWLLN lightning reveals that the geographic distribution of the ISUAL elves agreed well with that for the most energetic 10% of the WWLLN lightning strokes, better than for total lighting. We also found that elve occurrence rates in the apparently reduced detection regions behind the Earth's limb may have been greatly underestimated, partially due to the failure in providing triggers to initiate ISUAL recording or the severity of atmospheric attenuation to the elve emissions that may have caused them to be undetected.

1. Introduction

The first example of a transient luminous event (TLE) in the upper atmosphere, a sprite, was identified in 1989 during the testing of a low-light camera [*Franz et al*., 1990]. Soon, several additional types of TLEs were recognized in succession, for example, elves in 1994 [*Fukunishi et al*., 1996], blue jets and starters in 1995 [*Wescott et al*., 1995], halos in 2001 [*Barrington-Leigh et al*., 2001], and gigantic jets in 2002 and 2003 [*Pasko et al*., 2002; *Su et al*., 2003]. Several models have also been proposed to illuminate the possible physical mechanisms of these discharge phenomena. *Pasko et al*. [1997] proposed a quasi-static electric field model to explain the reason for the occurrence of the sprite, while an electromagnetic pulse (EMP) model was put forward by *Inan et al*. [1991] to predict the existence of elves, even before this type of TLE was observed. *Krehbiel et al*. [2008] proposed an electrodynamic model to illustrate the initiation of the blue and gigantic jets, and *Kuo et al*. [2009] presented a model of a lowered local ionosphere boundary to interpret the dynamic development during the fully developed jet stage of gigantic jets. These fleeting luminous phenomena are closely related to the lightning activity in the parent thunderclouds. Therefore, an investigation of the connection between TLEs and the characteristics of causative discharges is essential and can provide valuable information toward the understanding of TLEs.

Since 1989, the most abundant TLEs in the ground campaign have been reported to be sprites. However, a spaceborne survey carried out by the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) mission on board the Taiwanese FORMOSAT-2 satellite [*Chern et al*., 2003] changed this understanding; and the statistical results revealed the dominant type of TLE to be the elves, which accounts for approximately 80% of the observed TLEs, while sprites contribute only 10% [*Chen et al*., 2008]. Elves are capable of producing free electrons near the lower boundary of the ionosphere at 80–90 km altitudes [*Mende et al*., 2005] that can be sustained for 2 min or more [*Mika et al*., 2006; *Cheng et al*., 2007]. Therefore, elves can act as local lightning-driven electron sources. Elves are triggered by the EMPs emitted by lightning, but not all lightning is capable of producing an elve in the upper atmosphere. For the ISUAL-detected elves, the lower threshold of the elve-producing lightning peak current is inferred to be 80 kA [*Kuo et al*., 2007]. However, by comparing the photometric characteristics of ISUAL far ultraviolet (FUV) events and those of the well-identified elves that occurred before the limb, *Chang et al*. [2010] concluded that these FUV events were faint elves that were not discernible in the ISUAL imager data. The number of elves registered by the ISUAL spectrophotometer (SP) is estimated to be about 16 times higher than that from the imager survey. Furthermore, some FUV events were found to contain multiple peaks; these events are probably induced by the *M* components or the multiple strokes in lightning flashes [*Chang et al*., 2010]. The ISUAL experiment also yields that the ratio of the land to oceanic elves is about 1 [*Chen et al*., 2008], which is much lower than the ratio of 10 for the lightning reported by the Lightning Imaging Sensor experiment (another spaceborne optical observation) [*Christian et al*., 2003], or 5.5 for the ISUAL sprites reported by *Chen et al*. [2008]. Some studies [*Barrington-Leigh and Inan*, 1999; *Kuo et al*., 2007; *Chen et al*., 2008] have also suggested that only intense lightning with a high peak current can produce elves. But a global study on the energy, the occurrence frequency, and the geographic dependency between elves and lightning is still lacking.

The World Wide Lightning Location Network (WWLLN) [see http://wwlln.net] is a long-range VLF network capable of precisely locating global lightning [*Rodger et al*., 2009]. Using the data from the upgraded WWLLN [*Hutchins et al*., 2012a], *Hutchins et al*. [2012b] analyzed the spatial, the temporal, and the energy distribution of lightning as seen by the detection efficiency-corrected WWLLN and reported that the observed median stroke energy being 629 J in 2010, with a 25% average uncertainty in all the measured strokes.

In a further study [*Hutchins et al*., 2013], a global contrast between oceanic and continental lightning energies is presented, based on the expanded WWLLN data. A linear regression method was used to show that strokes over the ocean are stronger on average than those over land, with a sharp boundary along the coastlines. Systematic comparisons among the data of the WWLLN, the Lightning Imaging Sensor, the Optical Transient Detector, and the Earth Networks Total Lightning Network have led to the conclusion that there exists a strong difference in the energetics between land and oceanic thunderstorms that results in a higher fraction of more powerful strokes over the oceans [*Füllekgfrug et al*., 2002; *Hutchins et al*., 2013].

With the characteristics of lightning strokes determined by the WWLLN, we are able to focus on the features of lightning strokes associating with TLEs, especially for the elves, the most abundant type of TLEs. Since TLEs are mostly triggered by intense lightning, the possible threshold of the stroke strength compared to typical lightning has not yet been quantitatively determined. Hence, whether lightning strokes associated with continental and oceanic TLEs also exhibit a similar energy disparity as that reported for lightning is worth investigating. Through systematically analyzing the characteristics of the TLE-producing lightning, the above mentioned question may be answered.

2. Data Sources and Cross Identification

As of January 2013, the WWLLN consists of 70 VLF stations around the world that allows it to detect global lightning with a 5 km location and 15 μs timing accuracy as well as to achieve an estimated overall lightning stroke detection efficiency of 11% [*Hutchins et al*., 2012b; *Abarca et al*., 2010; *Rodger et al*., 2009; *Rudlosky and Shea*, 2013]. An upgrade to the WWLLN implemented in 2009 enables the system to simultaneously measure stroke location and the radiated 6–18 kHz VLF band energy through calibrating the network from a single well-calibrated station with a bootstrapping method [*Hutchins et al*., 2012a]. The measured radiated VLF energy of lightning in WWLLN is calculated based on integration over a 1.33 ms window (0.33 ms pretrigger and 1 ms posttrigger), and an average uncertainty of 17% is reported. This inferred VLF band energy, validated by some selected samples, is found to be proportional to the peak current of the strokes and can act as a proxy of the peak current [*Hutchins et al*., 2012a]. The capability of measuring lightning stroke energy as well as the global coverage of the network makes a global comparison of stroke energy over land and oceanic regions feasible. Since the WWLLN obtains the location and the energy of the lightning through measuring sferics, it is noted that the WWLLN does not determine discharge polarity, which is crucial for mapping sprite-producing flashes that are known to be almost exclusively positive [*Lyons*, 1996; *Williams et al*., 2007]. In this study, the daily WWLLN data from May 2009 to December 2012 are used for the analysis. To generate a data set of TLE-associated WWLLN strokes, the WWLLN data need to be analyzed alongside with the ISUAL TLE data.

ISUAL is the only spaceborne experiment performing a long-term (from July 2004 to the present), global TLE survey. ISUAL contains three bore-sighted sensors: an intensified charge-coupled device imager, a six-channel SP measuring photon fluxes at six preselected bands, and a two-channel, 16 anode array photometer (AP)

Table 1. Matching Ratio of Finding the Causative Discharges for the ISUAL TLEs in the WWLLN Stroke Data

TLE Type	ISUAL Events	Coincident WWLLN Strokes	Matching Ratio
Elve	11,862	5,249	44.25%
Sprite	949	354	37.30%
Halo	854	340	39.81%

providing light variation at different vertical heights [*Chern et al.*, 2003]. An ISUAL event is registered when the SP is triggered by either lightning or TLEs. The ISUAL-recorded TLEs are categorized as sprites, halos, elves, or jets on the basis of their morphological appearance in the imager and with the assistance of light curves acquired by the SP and AP. The features of different TLE types may be simultaneously identified in one captured event and then respectively tallied. The geographic coordinates of an ISUAL TLE are deduced from the imager frame with the assumption that the event or its parent thundercloud top was at certain heights [*Chen et al.*, 2008]. In the past 9 years, more than 20,000 TLEs have been registered along with their trigger time and geolocation. A systematic drift in the ISUAL onboard timer was identified recently, and this glitch renders the accuracy of the ISUAL timestamp to be no better than 25 ms. This inaccuracy in the onboard timer was shown to induce errors when ISUAL events were compared with another lightning-related data set as multiple strokes can occur within 25 ms and the probability of misidentification could become significant. Recently, *Huang* [2013] developed an algorithm to correct for the drift in the onboard timer, reducing the standard deviation of the ISUAL event time from 25 to 2 ms or less. Therefore, a criterion of 5 ms tolerance was chosen to cross-identify the coincident WWLLN events. In addition to a temporal criterion, differences in geographic locations are also taken into account. The geolocation accuracy is approximately 250 km for the ISUAL TLEs observed up to the Earth's limb in the previous study [*Chen et al.*, 2008]; therefore, a second criterion of 250 km geolocation discrepancy is set to seek for ISUAL-WWLLN coincident events. In all, 15,642 TLEs were observed by ISUAL from May 2009 to December 2012, and the cross identification with WWLLN is summarized in Table 1. Previous studies show that only 10–15% of National Lightning Detection Network (NLDN) events can be properly identified by WWLLN [*Abarca et al.*, 2010; *Rodger et al.*, 2009]. We obtained a matching ratio of approximate 40% in the cross identification, and the significantly higher rate implies that the TLEs recorded by ISUAL are, on average, more energetic than typical lightning discharges. This matching is similar to the results in matching Terrestrial Gamma Ray flashes to WWLLN [*Hazelton et al.*, 2009]. The detailed statistical results in the later sections also support this observation.

3. Energies of Typical and TLE-Producing Lightning

Hutchins et al. [2013] reported that in 2010 WWLLN obtained a median lightning stroke energy of 629 J, with a 25% average uncertainty in all measured strokes. We carry out the following analysis in a manner similar to *Hutchins et al.* [2012a, 2013]; therefore, a comparable uncertainty level of 17% is expectable in the derived energies in this study. The histogram of all measured WWLLN lightning strokes from May 2009 to December 2012 is derived and plotted as a gray line in Figure 1. The median energy of all measured WWLLN strokes in this study yields 900 J, approximately 30% larger than the energy of 629 J reported by *Hutchins et al.* [2013] for the WWLLN lightning in 2010. This difference may come from year-to-year variations resulting from, for example, El Niño and La Niña events [*Sátori et al.*, 2009; *Wu et al.*, 2012], or the variable detection efficiency of the network as more stations are added. Previous studies [*Barrington-Leigh and Inan*, 1999; *Cheng et al.*, 2007; *Kuo et al.*, 2007; *Chen et al.*, 2008] have indicated that TLEs, especially elves, are caused by energetic lightning. Thus, the objective of this section is to present a systematic analysis on the energetics of the TLE-associated lightning.

The energy distribution of TLE-associated strokes is shown in Figure 1 as a black line. As one would have expected, the energy histograms show that the energies of the lightning discharges to induce the three major types of TLEs are at least an order of magnitude more energetic than that of the ordinary lightning which are not associated with TLEs. The median energy of the lightning that produced elves, sprites, and halos is 1.26×10^4 J, 6.98×10^3 J, and 1.19×10^4 J, respectively, significantly higher than the global median stroke energy of 9.00×10^2 J observed by WWLLN in the same period. However, the elve is still the dominant type of TLE in this study, accounting for 86% of events. This rate is higher than the value previously reported by *Chen et al.* [2008], *Su et al.* [2008], and *Chen et al.* [2012]. One possible reason is that elves is produced by EMP heating of lightning discharge, and the strong pulse in the sferics is more easily identified within the

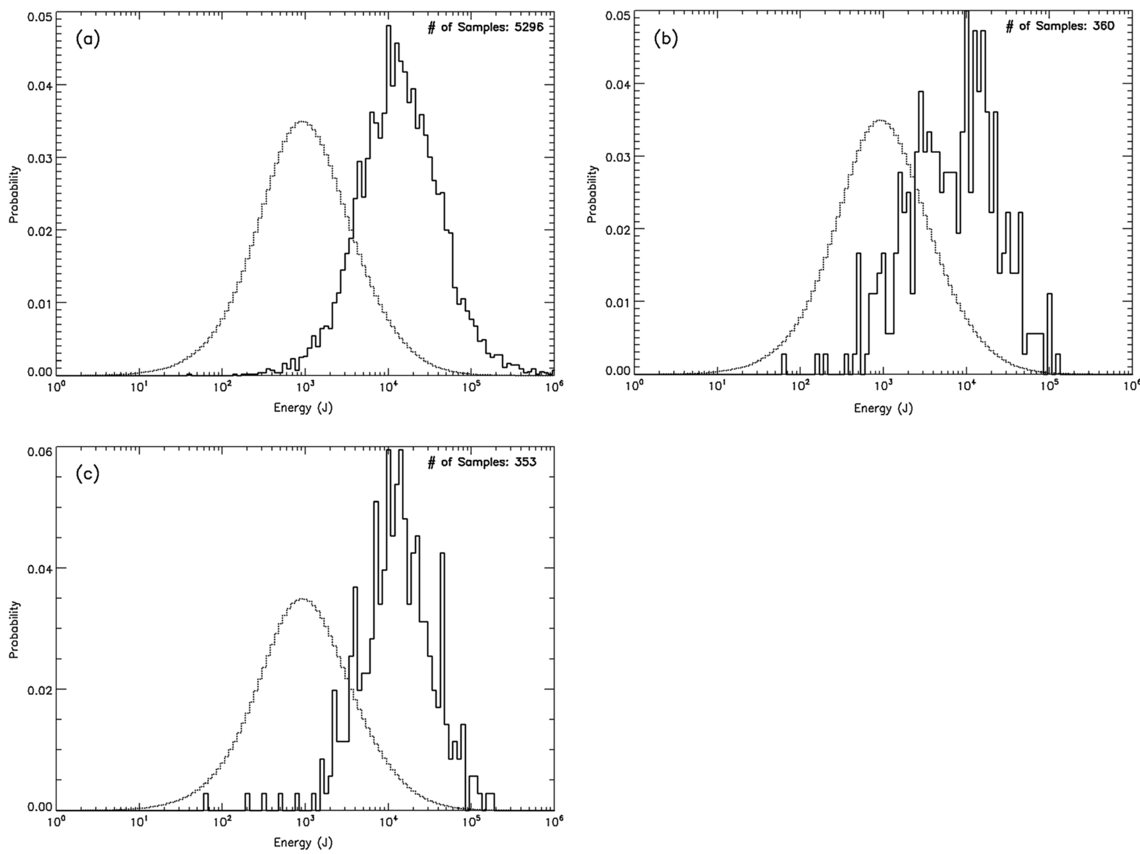

Figure 1. Energy distribution of TLE-producing strokes: (a) elve, (b) sprite, and (c) halo. The median energies for the TLE-producing discharges, respectively, are 1.26×10^4 J, 6.98×10^3 J, and 1.19×10^4 J. The gray curves represent the energy distributions of the total WWLLN lightning reconstructed in this study.

criteria, whereas the parent lightning of sprites, halos, and gigantic jets is often followed by a continuous current and the resulting long duration radio emissions may blur the peak of the sferics and render it difficult to precisely identify under the criterion of 5 ms. This effect may reduce the detection ratio of sprites and halos. This interpretation is supported by the fact that the detection ratios of sprites and halos shown in Table 1 are slightly lower compared to elve detection. The numbers of coincident sprite and halo events (only a few hundred) are insufficient to construct reliable temporal and geographic statistics; therefore, we focus only on elves in the following analysis.

4. Energies of Elve-Producing Strokes Over Land and Ocean

In previous studies, the land-to-ocean density ratios for lightning and TLEs are respectively reported to be about 10 and 1 [*Christian et al*., 2003; *Chen et al*., 2008], and some evidence indicates that oceanic lightning is more intense than land lightning [*Turman*, 1977; *Füllekgfrug et al*., 2002]. To investigate whether the energies of elve-producing strokes above land and ocean are the same or not, the ISUAL-registered elves are separated into land and ocean events, using the definition adopted in *Christian et al*. [2003]. The energy distributions of these two groups are presented in Figure 2, which shows that the energies of elve-producing strokes over the ocean and land are 1.30×10^4 J and 1.17×10^4 J, respectively.

Since the median stroke energies are 8.56×10^2 J and 9.66×10^2 J for all measured WWLLN land and oceanic lightning in this study, there is a 13% difference, and the energy spectra are similar to that shown in *Hutchins et al*. [2013, Figure 1]. The median energy difference between land and oceanic WWLLN lightning is not significant enough to conclude that oceanic lightning is more intense than land lightning. However, *Hutchins et al*. [2013] examined the energy contrast between continental and oceanic WWLLN lightning using a linear regression method for the strokes. The energy differences between land and oceanic lightning strokes, especially in the energy range $10^{3.5}$–10^5 J are clearly discernible in Figure 2a (dotted lines). A linear regression

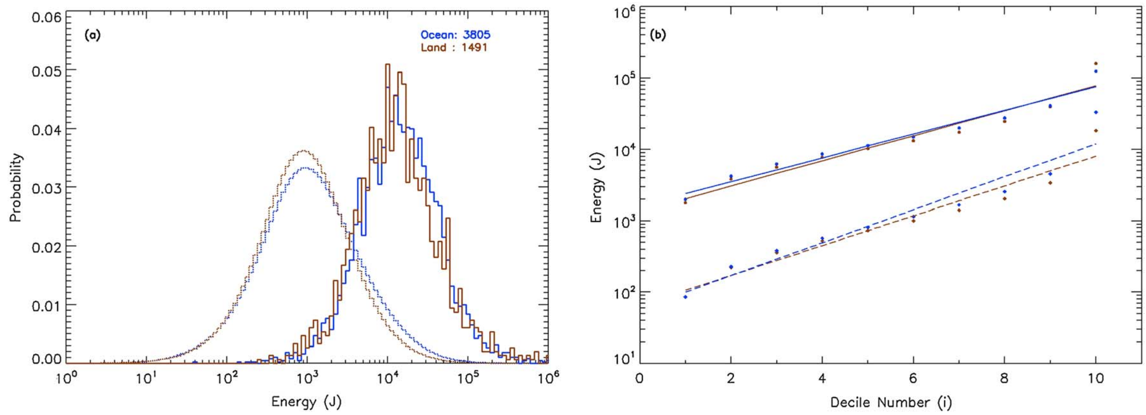

Figure 2. (a) Energy distribution of the elve-producing strokes (solid lines) and the total WWLLN strokes (dotted lines) over the oceanic (blue) and the land (brown) areas. The median stroke energies for elves are, respectively, 1.30×10^4 J and 1.17×10^4 J, whereas the median energies of the WWLLN lightning strokes over these two landforms are 9.7×10^2 J and 8.6×10^2 J. (b) The plot of mean energy in each bin with the linear regression with same legends.

method analogous to the one used in *Hutchins et al*. [2013] was adopted here to quantitatively distinguish this energy difference. The resulting mean stroke energies in the corresponding decile bins for lightning and elve-producing strokes are shown in Figure 2b. The slope of the regression represents the energy change from one decile to the next, and the difference in the slopes between oceanic and continental elve-producing strokes is only 5% (solid lines in Figure 2b), substantially smaller than the 10% difference in the slopes for the overall land and oceanic lightning (see the dotted lines in Figure 2b). Therefore, we did not find a similar energy contrast for oceanic and continental elve-producing strokes as that reported for the total lightning [*Hutchins et al*., 2013]. This result indicates that the stroke energy or the peak current of the lightning is an important factor in driving the production of elves, while this threshold energy shows no significant variation over different Earth landforms.

Similar to *Hutchins et al*. [2013, Figure 5], the ratio of the oceanic and land energy distributions for elve-inducing lightning strokes is shown in Figure 3 as black solid lines. In addition, the ratio of the oceanic and land energy distributions for WWLLN lightning strokes is also presented as a blue solid line for comparison. The fraction of lightning strokes is approximately 0.7 within the 15th and 85th energy percentiles, almost identical to the previous study since we extend the data window from 1 year to 3.67 years. Unlike lightning strokes, within the 15th and 85th percentile levels, the ocean-to-land ratio for elve-inducing strokes exhibits a growing trend and yields an average ratio of approximately 2.6. This ratio for elve-inducing strokes is significantly higher than that for lightning within the same percentile or energy range. Because the bins beyond the 15th and 85th percentile levels contain only a few dozen elves, the ratios in the low- and high-energy tails become highly scattered and are not statistically meaningful. It is noted that the areal ratio of the land and ocean has not been taken into account. The oceanic and land grids respectively cover 69.9% and 30.1% of the Earth's surface [*Pidwirny*, 2006]; therefore, the areal ratio of the ocean and land is approximately 2.3, so the area-normalized ocean-to-land ratio for elve-inducing strokes becomes 2.6/2.3 = ~1.13. This result agrees well with the occurrence density ratio of 1.1 for the ocean-to-land ratio of elves that was reported by *Chen et al*. [2008]. Moreover, in this study we identified 1491 continental elves following the definition of landmass adopted in *Christian et al*. [2003]. If we separate the coastal grids from the land grids using the more restricted definition reported in *Chen et al*. [2008], the numbers of land and the coastal elves are 796 and 695, respectively. However, the coastal grids cover 4.3% of the Earth's surface, only one sixth of the pure land grids. The computed occurrence density over the coastal area is 5.2 and is 1.8 times higher than that over land or ocean. This ratio does agree well, however, with the results listed in *Chen et al*. [2008, Table 2], implying that elves have a higher probability of occurrence over coastal areas.

As indicated in Figure 1, the lowest stroke energy associated with ISUAL-recorded elves can be as low as a few hundred joules, in line with that for the typical lightning. However, it is not easy to identify a clear cutoff for the trigger threshold of elve-producing strokes from the lower end of the energy distribution, because this distribution is also masked by the detection efficiency of the WWLLN network. Some elve-inducing strokes that are only a few hundred joules over the low detection regions (e.g., over central Africa) are probably missed by WWLLN and thus obscure the cutoff at the lower end of the elve energy distribution. But a reasonable estimate still can be inferred

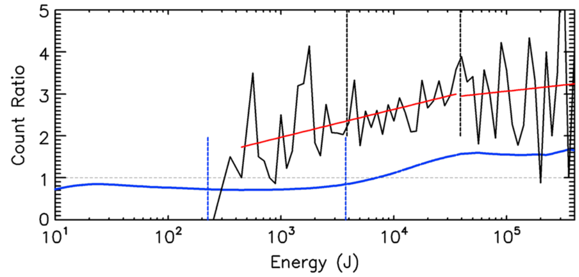

Figure 3. The ratio of oceanic to land events versus stroke energy for the elve-producing (black solid line) and the total WWLLN lightning (blue solid line). The dashed horizontal line is the ratio of unity. The vertical dashed lines, respectively, denote the 15th and 85th percentile values for the energy distribution of the elve-producing (black) and the total WWLLN strokes (blue). The red lines are visual guides.

from Figure 1a, and the threshold of the energy to induce elves is found to be ~800 J. Using *Hutchins et al*. [2012a, equation 2], we can convert this 1.33 ms windowed energy to find a peak current (I_{peak}) of 37.8 kA as the lower limit for lightning strokes to produce elves. This I_{peak} is consistent with the value reported by *Barrington-Leigh and Inan* [1999] that 52% of the NLDN flashes with a peak current over 38 kA exhibited the telltale signature of an elve. Unlike most sprites that are triggered by positive cloud-to-ground discharges [*Lyons*, 1996; *Williams et al.*, 2007], lightning of both polarities are able to induce elves [*Frey et al.*, 2005].

5. Energy and Geographic Distributions of TLE-Inducing Lightning Strokes

Evidence, including the energy distribution shown in the previous section, suggests that elves are triggered by intense lightning strokes, but whether the global distribution of elves follows all or the energetic lightning strokes needs to be determined. We will first quantitatively define the "energetic" lightning via the energy spectrum. A cumulative probability, from low to high, for the lightning energy distribution based on the red curve in Figure 1 is calculated. The lower-bound energy for the top 10% lightning (energetic lightning hereafter) is 5.39×10^3 J. We divide the Earth's surface into 0.5° × 0.5° grids, and the lightning with energies exceeding the above value are sorted into the grid bins to construct a global distribution of energetic lightning. However, the detection efficiency of the WWLLN is not uniform everywhere because not all stations are operational all the time and the high attenuation rate of VLF propagating over land and ice has to be taken into account [*Hutchins et al*., 2012b]. The relative detection maps reported in *Hutchins et al*. [2012b] are constructed by the WWLLN team, and thus the global occurrence of all WWLLN lightning and the energetic lighting shown in Figures 4 and 5 is also produced using the reported daily relative detection efficiency maps in a manner similar with *Hutchins et al*. [2012b]. However, it has to be noted that this correction may be able to compensate for the bias in the lightning occurrence caused by the detection efficiency but cannot amend their contribution to the energy distribution because the detection efficiency should be a function of lightning energy and the relative correction efficiency we used here is an average over all lightning energies. Moreover, the seasonal variation of the lightning and elves is very significant [*Christian et al*., 2003; *Chen et al*., 2008], but the hot zones of elve occurrence and the lightning activity may not exhibit the same seasonal variations. Therefore, all data are divided into four seasons to separately inspect for the variation of elves and energetic lightning with season. The seasonal distributions of all and the energetic lightning are presented in Figures 4 and 5, the elve events in each season are marked by black dots in these figures.

WWLLN is a worldwide, continuous recording network, while ISUAL only conducts observations during the nighttime and basically covers the region between the 40°S and 40°N latitudes. ISUAL coverage also varies with the Sun's projection on the Earth's surface; in addition, ISUAL is turned off when it flies over the South Atlantic Anomaly region (see *Chen et al*. [2008, Figure 2]) for the safekeeping of its high-voltage detectors. Thus, some lightning hot zones (e.g., south of the island of Madagascar and southern Brazil) are not fully covered in the current ISUAL TLE survey. So to avoid the possible confusion, only the regions with sufficient ISUAL observation time, more than 10% of the average observation time, are shown in the above figures.

In Figure 4, it is evident that the elve distribution does not vary in phase with lightning for most regions; in some regions lightning activity is relatively low whereas elve occurrence is relatively high. For example, the WWLLN lightning frequency exceeds ~5 ($10^{0.7}$) strokes/yr/km^2 in eastern America for all seasons, but elve activity in this region is lower than that in other regions, say, the South Pacific Ocean or north of Madagascar where lightning occurrence is relatively less frequent, with the lightning occurrence lower than ~1 (10^0) strokes/yr/km^2.

The threshold of 5.39×10^2 J for energetic lightning is used to construct an intense lightning distribution. This threshold is corresponding to a peak current of 122.6 kA, converted using equation (2) in *Hutchins et al.* [2012a]. The geographic distribution of elves in Figure 5 coincides well with the distribution of energetic

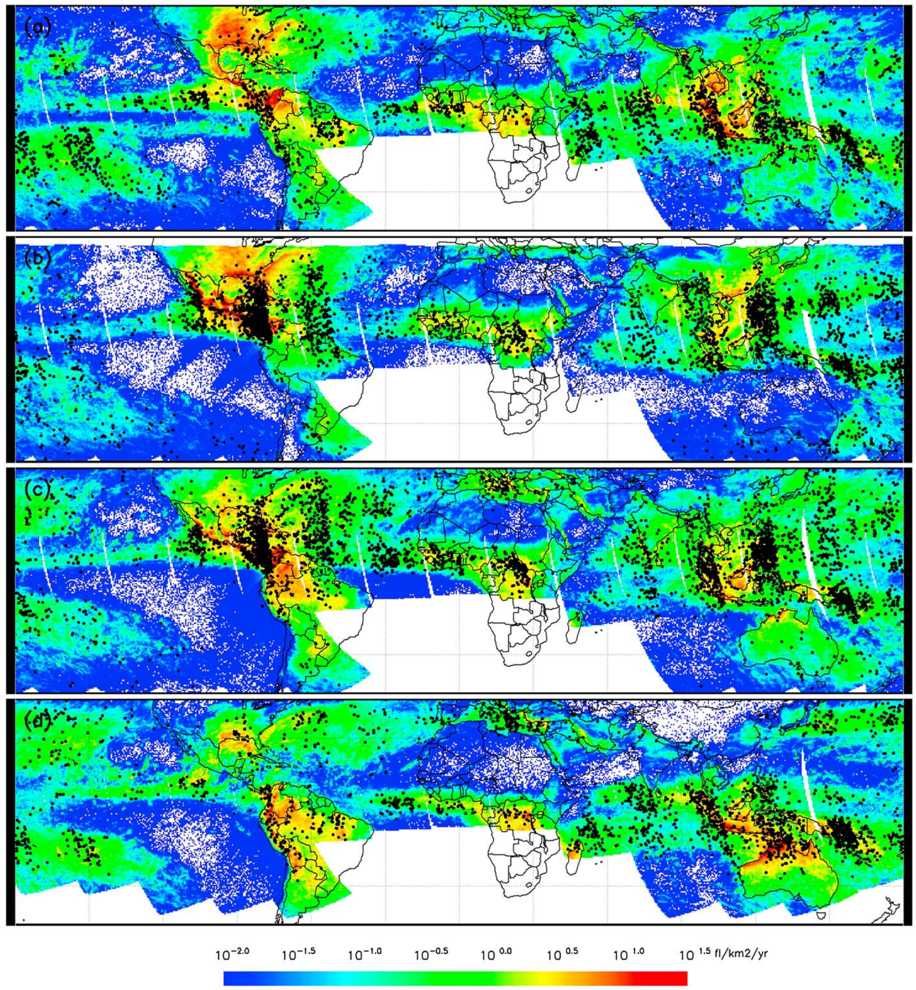

Figure 4. The seasonal distribution of the WWLLN lightning: (a) December, January, and February (DJF) season, (b) MAM season, (c) JJA season, and (d) SON season. The elves captured by ISUAL in each season are marked by black dots.

lightning, and the occurrence of elves become significant when the occurrence density of the energetic lightning exceeds ~0.2 ($10^{-0.7}$) strokes/yr/km^2. For example, the energetic lightning in eastern America is not as active as the total lightning in the March, April, and May (MAM) and June, July, and August (JJA) seasons (Figures 5b and 5c), and the elve occurrence roughly follows the occurrence variation of the energetic lightning, not the total lightning in this region. A clear boundary can be identified along the northern coast of the Gulf of Mexico in the JJA season (Figure 5c). Another example is the regions in the North and the central Atlantic Ocean, about 30°W, 30°N, and 30°W along the equator. Many elves were observed there in the September, October, and November (SON) season, when the lightning activity was not particularly high. Compared with Figure 5d, we can identify these regions as hot zones of energetic lightning that well coincide with the distribution of elves.

Zipser et al. [2006] investigated the locations of the most intense thunderstorms on Earth using the Tropical Rainfall Measuring Mission data, the results indicate that there is a strong preference for extreme events to be located over land. However, in this study, the energetic lightning are found to distribute almost equally over land and ocean. This indicates that the distribution of the most energetic lightning does not coincide with the most intense storms. The indicator they used to gage the storm intensity was the lightning flash rate, not the energy of the lightning flashes. For intense thunderstorms, the high lightning flash rate, or the short repetition time of the discharges, also means the thundercloud may not have sufficient time to accumulate energy to produce energetic lightning. But the relatively smooth ocean surface could have inhibited the corona discharges from occurring and thus the oceanic thunderstorms tend to have a low lightning flash rate. In

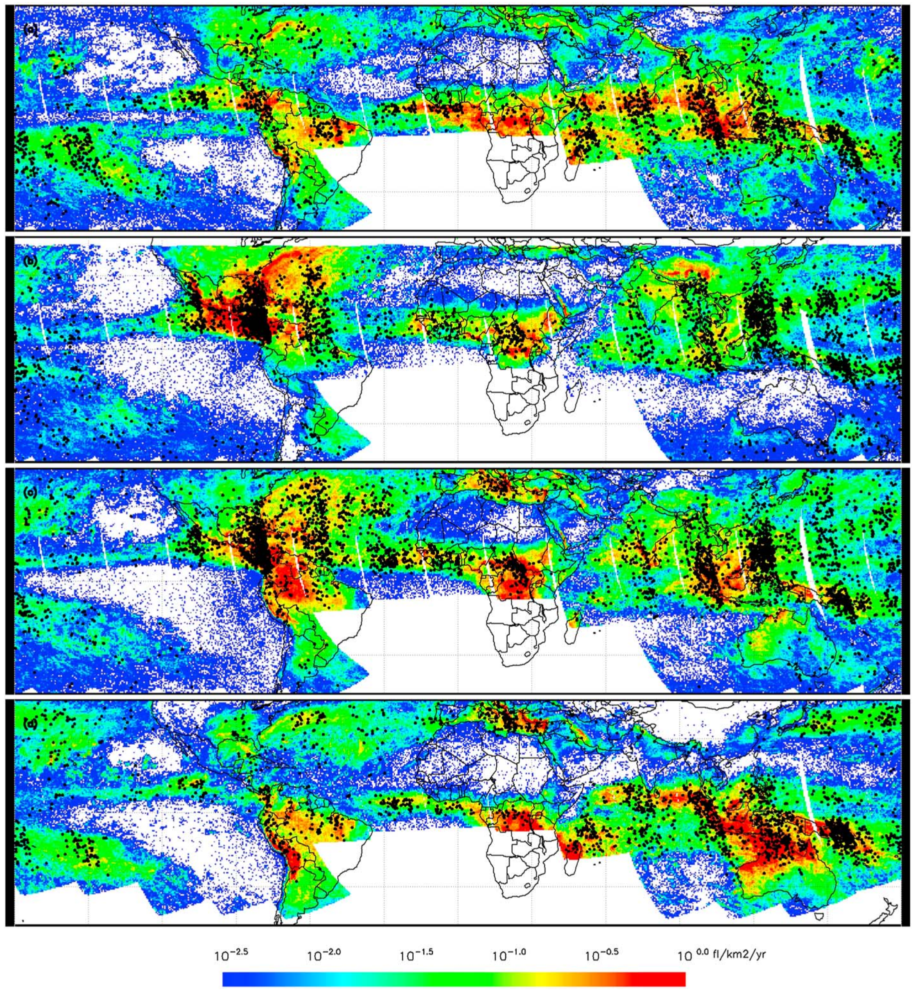

Figure 5. The seasonal distribution of the energetic above the 90th energy percentile of WWLLN lightning strokes with the energy greater than 5.39×10^3 J: (a) DJF season, (b) MAM season, (c) JJA season, and (d) SON season. The elves captured by ISUAL in each season are marked by black dots.

turn, oceanic storms thus may have ample time to pile up energy to produce energetic discharges. Therefore, the disparity in the distributions of intense storm and energetic lightning is understandable and thus can be explained.

There are relatively few elves in some regions, for example, East India, which are longitudinally adjacent to other elve hot zones. The occurrence of energetic lightning in these gaps is sufficiently high, so plenty of elves should have been produced there. After a careful investigation, we conclude that these regions of reduced elve detection were not caused by the nature of the lightning but by the bias in the ISUAL observation. The FORMOSAT-2 satellite has 14 Sun-synchronized daily orbits with an altitude of 891 km, and the ISUAL imager view angle for observing the solid Earth limb points 27.5° down from the local horizon at the satellite. The straight line view distance to the limb at the 100 km altitude tangent point is approximately 3190 km away. But the TLEs in the upper atmosphere are still observable even if they occur behind the Earth's limb. As an illustration, the elve shown in Figure 6 may be referred. The Earth's limb is denoted by the red line, the ground coverage in front of the Earth's limb is shaded in cyan, and a luminous transient event extending above 90 km would still be observable in the yellow-shaded region. In this illustrative case, the observed elve is identified as a behind-the-Earth's-limb event because its parent lightning is not discernible in the image; furthermore, the location projection also places it in the yellow-shaded region. Thus, the ground coverage shown in *Chen et al.* [2008, Figure 2] not only includes the directly viewable area (cyan-shaded) but also extends into the regions beyond the Earth's limb (yellow shaded) as depicted in Figure 6. Some events with faint elves in front of the

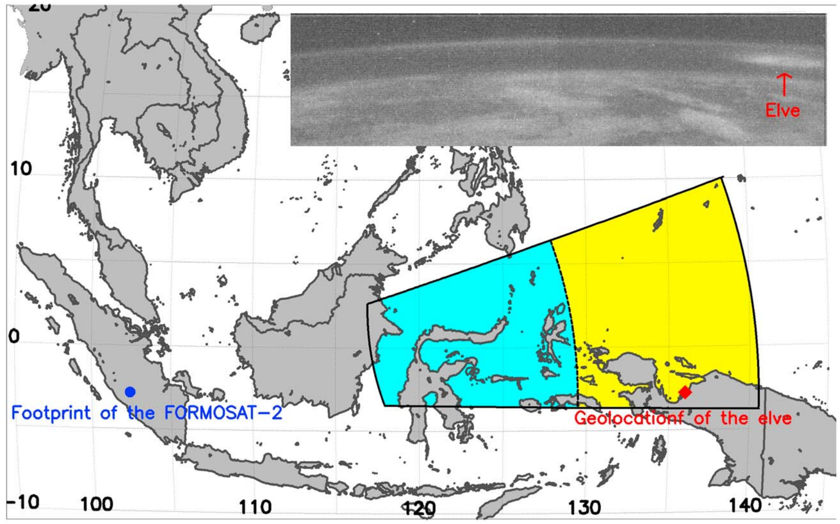

Figure 6. An illustrative event, an elve indicated by the red arrow and located between the bright airglow emission and the Earth's limb in the image taken by ISUAL, occurred on 11 May 2009 14:44:05.643443. The WWLLN stroke energy is $8.47 \times 10^5 \pm 4.51 \times 10^5$ J, and the temporal and the geographic differences for this ISUAL elve are $\Delta d = 8.73$ km and $\Delta t = 2$ ms, respectively. The parent lightning is not visible on the image; hence, the lightning stroke that triggered this event was behind the Earth's limb. The elve location is denoted by a red diamond. The position of FORMOSAT-2 at the time of the event is represented by the filled blue circle, and the Earth's limb is marked by the dashed line. The region in cyan can be directly observed by ISUAL, while for the yellow region, only events having luminous structures in the upper atmosphere are observable by ISUAL.

Earth's limb are triggered by the photons emitted by causative lightning, not elves. These events may become undetectable due to the lack of a trigger for the ISUAL to store these events, since their parent lightning is blocked by the Earth's limb. Thus, it is conceivable that many behind-the-limb elves have gone undetected in the ISUAL TLE survey.

Furthermore, the tangent point for the photons from behind-the-limb elves would become lower in altitude and the elve photons must travel through a thicker atmosphere as the elves occur farther away. Even if the photons emitted by elves are able to trigger the ISUAL, the absorption and scattering of the intervening atmosphere could have severely attenuated the elve emissions and rendered the distant elves from being discernible in the imager frames. These reduced elve detection regions in Figures 4 and 5 are found to be located behind the Earth's limb in the ISUAL global observations. On the other hand, even if elves that occurred behind the limb indeed have gone unaccounted for in the ISUAL survey, the missing event number is hard to estimate. Using energetic lightning as the template, it is reasonable to conjecture that the elve occurrence in the regions of reduced elve detection could be as high as that in the adjacent hot zones. In addition, some lightning-active regions with sufficient energetic events, for example, the southern Indian Ocean near Madagascar, are not observed by ISUAL due to their proximity to the South Atlantic Anomaly region. Therefore, it may be conjectured that the true elve occurrence rate should be at least 2–3 times higher than the reported values [*Chen et al.*, 2008; *Hsu et al.*, 2009; *Chen et al.*, 2012] if accounting for these missing factors.

6. Conclusions

In this paper we use two data sets, the upgraded WWLLN lightning stroke data and the ISUAL TLE data, to investigate the energetic and the geographic distributions of TLE-producing lightning. With a new algorithm to correct the ISUAL event time, the matching ratio for finding the coincident events between these two data sets is found to be 37–44%, which is higher than previous studies using the NLDN data [*Rodger et al.*, 2009; *Abarca et al.*, 2010]. The energy spectra of the lightning strokes that induced the major types of TLEs, i.e., elve, sprite, and halo, reveal that, in general, the energies of the TLE-producing strokes are at least an order of magnitude higher than that of the typical lightning strokes. Previous studies had suggested that oceanic lightning is more intense than the land lightning. However, the energy distribution of the elve-producing strokes exhibits no significant oceanic and land difference. These results indicate that elves are indeed triggered by energetic lightning and the production efficiency of elves with respect to the stroke energy of the causative lightning is insensitive to the underlying landform. The lower limit of the peak current to produce elves is inferred to be approximately 38 kA, using the stroke energy to the peak current conversion proposed in *Hutchins et al*. [2012a]; this result agrees well with that reported in *Barrington-Leigh and Inan* [1999] which was derived using selected elve events recorded in ground campaigns.

Analysis of the spatial correlation between the ISUAL elves and the WWLLN lightning indicates that the geographic distribution of the ISUAL elves agrees well with that for the most energetic top 10% of the WWLLN lightning strokes, the match clearly is better than that for the total lighting. We also found that elve occurrence rates in the regions of reduced elve detection, located behind-the-limb area, may have been underestimated by at least a factor of 2 or 3, in part due to the failure of these events in providing triggers to initiate ISUAL to store these events, or the severe atmospheric attenuation to the elve emissions may have rendered them indiscernible. Based on the uncorrected occurrence rate of elves, *Chen et al*. [2008] reported that the global free electron contribution from elves is approximately 1%, while the elve contribution to the free electron content above elve hot zones could be as high as 5%. After taking the contribution of the reduced elve detection zone into account, the charge impact of elves to the lower ionosphere could be much more significant.

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