Global distributions and occurrence rates of transient luminous events


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[1] We report the global transient luminous event (TLE) distributions and rates based on the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) experiment onboard the FORMOSAT-2 satellite. ISUAL observations cover 45°S to 25°N latitude during the northern summer and 25°S to 45°N latitude during the northern winter. From July 2004 to June 2007, ISUAL recorded 5,434 elves, 633 sprites, 657 halos, and 13 gigantic jets. Surprisingly, elve is the dominant type of TLEs, while sprites/halos are a distant second. Elve occurrence rate jumps as the sea surface temperature exceeds 26 degrees Celsius, manifesting an ocean-atmosphere-ionosphere coupling. In the ISUAL survey, elves concentrate over the Caribbean Sea, South China Sea, east Indian Ocean, central Pacific Ocean, west Atlantic Ocean, and southwest Pacific Ocean; while sprites congregate over central Africa, Japan Sea, and west Atlantic Ocean. The ISUAL experiment observed global rates of 3.23, 0.50, 0.39, and 0.01 events per minute for elves, sprites, halos, and gigantic jets, respectively. Taking the instrumental detection sensitivity and the restricted survey area into account, the corrected global occurrence rates for sprites and elves likely are a factor of two and an order of magnitude higher, respectively. ISUAL observations also indicate that the relative frequency of high peak current lightning (>80 kA) is 10 times higher over the oceans than over the land. On the basis of the corrected ISUAL elve global occurrence rate, the total electron content at the lower ionosphere above elve hot zones was computed to be elevated by more than 5%.


1. Introduction

[2] A serendipitous discovery in 1989 provided the first direct evidence for the existence of cloud-top flashes [Franz et al., 1990], and opened up a research field to intensely study these phenomena now carrying the names of sprite [Sentman et al., 1995; Boeck et al., 1995; Lyons et al., 1996; Su et al., 2002; Takahashi et al., 2003], elve [Fukunishi et al., 1996; Mende et al., 2005; Frey et al., 2005], blue jet [Wescott et al., 1995], halo [Barrington-Leigh et al., 2001; Moudry et al., 2003; Miyasato et al., 2002], and gigantic jet [Pasko et al., 2002; Su et al., 2003; van der Velde et al., 2007] (see Figure 1). A sprite consists of one or several vertical columns of light and spans the region between 40 and 90 km altitudes. A halo is a featureless luminous disk at 75–85 km altitudes, which may precede sprites but often also occurs alone. Both sprites and halos are associated with optical emissions caused by quasi-static electric fields produced by cloud-to-ground (CG) lightning [Pasko et al., 1997], whereas elves are donut-shaped optical emissions in the ionosphere (altitude ~90 km) caused by the electromagnetic pulse (EMP) emitted by lightning strokes [Inan et al., 1991; Fukunishi et al., 1996]. Blue jets and gigantic jets are associated with upward electrical discharges from cloud tops. While the occurrence rate and global distribution of CG lightning in the troposphere has been extensively documented [Christian et al., 2003; Füllekrug and Constable, 2000], those for TLEs are not well assessed because of limitations in previous space or ground observations. For example, Sato and Fukunishi [2003] deduced a global occurrence rate of 0.5 sprites/min (720 events per day) based on 216 days of ELF data containing ~715,500 transient Schumann resonance events. Blanc et al. [2004] inferred a global occurrence rate of 1.33 sprites/min from 3.5 hours of ISS observations. Yair et al. [2004] estimated the occurrence rate of 0.13 event/min for sprites using 13 orbits of video data of the STS-107 space shuttle mission (~51 minutes of
2. Instrumentation and Observations

Ignacllo et al. [2006] proposed a formula to give an estimated global sprite occurrence rate of 2.8 events/min based on optical observation data of less than 4 hours as well as 27 days of radio measurements. Here we report the global occurrence rates and distribution for the major types of TLEs based on three-year survey data from the ISUAL experiment. The instruments and observations are discussed in section 2, while the method of data analysis and statistical results are shown in section 3. In addition, we explore the dependence between the sea surface temperature and the occurrence rate of elves in section 5. Corrections to the observed occurrence rate and the global impact of elves are discussed in sections 6 and 7. Conclusions are presented in section 8.

2. Instrumentation and Observations

[3] The Imager of Sprites and Upper Atmospheric Lightning (ISUAL) [Chen et al., 2003], the scientific payload onboard the FORMOSAT-2 satellite, is dedicated to a long-term and global survey of TLEs. ISUAL contains three bore-sighted sensors: an intensified CCD Imager, a six-channel spectrophotometer (SP) measuring photon fluxes at 6 pre-selected bands, and a 16-anode array photometer (AP) providing light variation at different vertical heights. The relevant specifications of these sensors are listed in Table 1. The FORMOSAT-2 spacecraft moves along a sun-synchronized orbit at 890 km altitude and ISUAL is configured with an eastward view observing TLEs over a region which is at a distance of 2,300 to 4,000 km away and close to local midnight. An ISUAL event was registered when the SP was triggered by either lightning or TLEs. The trigger levels associated time, instrument pointing, and position and attitude data of the FORMOSAT-2 spacecraft.

[4] The geolocation uncertainty of a TLE event, using the prescribed method, depends sensitively on the event distance and, on average, is better than 50 km/pixel along the line of sight. However, for events located above the Earth limb (distance to the spacecraft ~3,200 km), it can be as high as 220 km/pixel. Validations using the city light from major metropolitan areas show that our geolocating accuracy is better than 0.5° for objects within 2,800 km to the spacecraft [Chen et al., 2004]. Fortunately, this geolocational error will not affect the assessment of the global TLE distribution.

4. Results

[5] From July 2004 to June 2007, more than 6,000 TLEs were recorded by ISUAL. The TLE event tally are listed in...
Table 2, which shows the numbers of elves, sprites, halos, and gigantic jets observed as well as the percentage of each type occurring over the ocean, coast and land regions. Events containing more than one TLE type were tallied separately. The Earth surface is divided into $2.5^\circ \times 2.5^\circ$ grids as was done by Christian et al. [2003]. We define the ocean and land grids as the earth surface regions that contain only ocean or land while the coast grids are those with a mixture of land and ocean areas. In the ISUAL survey region, 61% of total area is classified as ocean, 16% as coast, and 23% as land.

Table 1. Relevant Specifications of the ISUAL Sensors

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Imager</th>
<th>SP</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>intensified CCD with $524 \times 128$ pixels</td>
<td>six photomultiplier tubes</td>
<td>dual 16-anode arrays</td>
</tr>
<tr>
<td>Field of view</td>
<td>$20^\circ \times 5^\circ$</td>
<td>$20^\circ \times 5^\circ$</td>
<td>$20^\circ \times 3.6^\circ$</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>$0.04^\circ$/pixel</td>
<td>$20^\circ \times 5^\circ$</td>
<td>$0.23^\circ$ per channel</td>
</tr>
<tr>
<td>Time resolution for the survey</td>
<td>programmable, 30 ms in this survey</td>
<td>0.1 ms</td>
<td>0.5 or 0.05 ms</td>
</tr>
<tr>
<td>Band passes</td>
<td>N$_2$1PG</td>
<td>three broadbands and three narrow bands</td>
<td>blue and red bands</td>
</tr>
</tbody>
</table>

Figure 2. Accumulative observation time of ISUAL experiment between July 2004 and June 2007. (a) Northern summer (23 March – 21 September). (b) Northern winter (22 September – 22 March). Only the grid cells with sufficient accumulative observation time (higher than 30.7 minutes or 0.51 hours, see section 4) are denoted.
The occurrence density of each cell for a given type of TLE is defined as the cell accumulative event number (the sum of the spatial distributions) divided by the cell area and accumulative observation time. The ISUAL observed occurrence density distributions of sprites, elves and halos are shown in Figure 3 in the units of event/year/km². Figure 3d exhibits the distribution of mean sea surface temperature in the years 2004–2005 [Vazquez et al., 1998] and it shows a tight correlation with the TLE occurrence density, which will be discussed later. The ISUAL observed TLE rate (rISUAL) is defined as the sum of TLE rates for the grid cells with a sufficient observation time, to avoid biased contributions from cells with a very low observation time. In this study, we choose 2.5% of the mean observation time of all observed grids during the three-year survey as the threshold for computing the occurrence rate, since the derived rates stabilize after the threshold for the observation time exceeds this value. Under this criterion, we considered only cells that were observed for at least 30.7 minutes in 3 years and the resulting cell area covered 81.02% of the Earth surface (Figure 2, shade-coded area). The rISUAL of elves, sprite, halo, and gigantic jet are derived to be 3.23, 0.50, 0.39, and 0.01 events per minute. Because of FOR-MOSAT-2’s sun-synchronized orbit, the ISUAL derived occurrence rates are for the Earth at local time around midnight. Füllekrug [2004] reported that the hourly average occurrence of intense lightning at this local time is comparable to the diurnal mean. Therefore, the rates obtained by the ISUAL experiment likely are not biased by local time. Possible corrections to these values are discussed in section 6.

During the northern hemisphere summer, the ISUAL payload has to be turned off before exiting the Earth’s umbra around 25°N to protect the sensitive instruments from direct sunlight. Thus, the known TLE hot zones, like the U.S. High Plains [Lyons et al., 1996; Gerken et al., 2000] and the East China Sea [Su et al., 2002], are not in the survey region, and vice versa for the south hemisphere during the northern winter.

Gigantic jets were observed from space for the first time by ISUAL. During the 3-year survey, 13 gigantic jets

### Table 2. Statistics of ISUAL TLE Survey for the Period from July 2004 to June 2007

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Land (%)</th>
<th>Coast (%)</th>
<th>Ocean (%)</th>
<th>L:C:O (L&amp;C:O) ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elf</td>
<td>5434 (80.7%)</td>
<td>9%</td>
<td>32%</td>
<td>59%</td>
<td>0.4:2.1:1 (1.1:1)</td>
</tr>
<tr>
<td>Sprite</td>
<td>633 (9.4%)</td>
<td>49%</td>
<td>23%</td>
<td>28%</td>
<td>4.7:3.2:1 (4.1:1)</td>
</tr>
<tr>
<td>Halo</td>
<td>657 (9.8%)</td>
<td>21%</td>
<td>40%</td>
<td>39%</td>
<td>1.4:3.9:1 (2.4:1)</td>
</tr>
<tr>
<td>Gigantic jet</td>
<td>13 (0.2%)</td>
<td>15%</td>
<td>15%</td>
<td>69%</td>
<td>0.6:0.8:1 (0.7:1)</td>
</tr>
</tbody>
</table>

*aThe numbers of elves, sprites, halos and gigantic jets as well as the percentage of each type observed over ocean, coast, and land are tabulated. The last column is the ratio of occurrence per unit area over ocean (O), coast (C), and land (L).
were recorded. Even though gigantic jets are observed rarely, the occurrence ratio between sprite and gigantic jet was found to be around 60. This ratio is comparable to the result from ground campaigns in the vicinity of Taiwan of \( \frac{24}{80} \) (648 sprites and 8 gigantic jets in 6 years). These recorded gigantic jets were all located in the tropics, within 20° latitude of the equator.

[10] The land/coast-to-ocean ratio of CG lightning was reported to be 10:1 [Christian et al., 2003], while the mean annual land (and coast)-to-ocean ratios for elf, sprite, and halo as shown in the last column (L&C:O) of Table 2 are 1.1:1, 4.1:1, and 2.4:1, respectively, after normalizing for the area. Obviously, elves concentrated over water with a significant percentage of 59% over the ocean but only 32% of elves over the coastal regions. Since elves are induced by the EMP from lightning strokes, the observed ratio is clearly discordant with that of the land-concentrated lightning flashes. On the other hand, sprites mainly congregate over land and coasts and have a comparable land (and coast)-to-ocean ratio as lightning. The land (and coast)-to-ocean ratio of halos fell between those of elves and sprites. It appears that the oceanic lightning strokes are much more effective in producing elves than their land counterpart. In the ISUAL surveyed area, the sprite hot zones are identified as Central Africa (Congo Basin), Japan Sea, and West Atlantic Ocean. In contrast, elves are found to be concentrated over Caribbean Sea, South China Sea, East Indian Ocean, Central Pacific Ocean, West Atlantic Ocean, and Southwest Pacific Ocean. For halos, the hot zones are similar to those for sprites, but with a lower land/coast-to-ocean ratio. No TLEs were found over desert areas (e.g., Sahara, Mongolia, and Central Australia deserts), and only a few were observed over the Northeast Pacific and Southeast Pacific Oceans.

5. Sea Surface Temperature and the TLE Occurrence Rates

[11] Since the tropical ocean is a good heat/energy reservoir in assisting vertical convection, we examine the relation between the elf occurrence rate and sea surface temperature (SST) as obtained from NODC/RSMAS AVHRR Oceans Pathfinder SST data [Vazquez et al., 1998]. Figure 4 shows that the elf production rate depends strongly on SST. The elf occurrence rate increases rapidly when the SST exceeds 26 degrees Celsius. The threshold temperature of 26 degrees Celsius is also commonly accepted as a necessary condition for the development of a tropical storm, typhoon or hurricane [Williams and Renno, 1993]. A detailed examination of Figure 3 shows that the average surface temperature of some ocean areas with extremely low elf occurrence rates is lower than those in their vicinities. This finding provides direct evidence that the warm sea surface supplies the heat to produce the intense oceanic lightning responsible for elves. Turman [1977] showed that 11 of 17 recorded superbolts with optical power greater than \( 3 \times 10^{12} \) watts were found over coast or ocean and concluded that oceanic lightning was more likely to produce superbolts. Füllekrug et al. [2002] compared the charge moment of CGs derived by ELF observations and arrived to a similar conclusion.

6. Corrected Global Occurrence Rate

[12] The brightness of elves is closely related to the power of the EMP emitted by the lightning return strokes, which in turn is linked to peak current. Figure 5 shows the model-computed correlation between the integrated photon flux of elves and the peak current of the return stroke (solid line). The theoretical elf photon flux is calculated using an EMP model [Kuo et al., 2007] and the method is similar to the work of Barrington-Leigh and Inan [1999]. The detection limit of ISUAL is determined by the background fluctuation of the recorded images and typically is \( 1.5 \times 10^3 \) photons/cm\(^2\) (dotted line), which corresponds to an elf flux induced by a CG peak current of \( \sim 80 \) kA. The annual occurrence rate of negative CG lightning discharges recorded over North America by the National Lightning Detection Network (NLDN) from 1989 to 1995 [Wacker and Orville, 1999] is also plotted as a function of peak current. It can be seen that only \( \sim 0.82\% \) of continental lightning events (red filled area) are able to trigger elves that are detectable by ISUAL. Barrington-Leigh and Inan reported that 52% of the NLDN flashes with peak current over 38 kA exhibited the telltale signature of elves, and above \( \sim 60 \) kA of peak current essentially all of the flashes had accompanying elves. About 6.3% of the NLDN flashes have a peak current greater than 60 kA (green- plus red-filled area), while lightning with peak current greater than 80 kA (red-filled area only) is almost eight times less likely. This implies that \( \sim 90\% \) of elves are initiated by lightning with a peak current greater than 60 kA, but those from parent CG lightning with peak current of less than 80 kA could have been missed by ISUAL. Therefore the true global elf occurrence rate could be 10 times larger than that directly calculated from the ISUAL data and an estimated global occurrence rate of 35 elves per minute is derived.

[13] Close inspection of the SP light curves of the ISUAL registered columniform sprites shows that instrument recordings of these dimmer sprites were triggered by their parent lightning, not by the columniform sprites themselves. It is possible that some columniform sprites with their...
parent lightning outside the FOV, for example, behind the limb, might have been missed by ISUAL under the current trigger threshold. Also, note that known regions of high sprite occurrence, such as the U.S. High Plains in northern summer and parts of Brazil and Argentina in southern summer [Thomas et al., 2007] are not viewed. It is difficult to estimate precisely how these two factors contribute to the underestimation of the global sprite occurrence rate. A factor of two higher is conjectured and it yields \( \mu/C_{24} \) events/min for both sprites and halos. Thus, the global occurrence rate of all TLEs is \( \mu/C_{24} \) events per minute, or 57,000 TLE events per day.

### 7. Global Impact of Elves

[14] In this paper, elves are identified as the dominant type of TLEs in the upper atmosphere. Mende et al. [2005], Kuo et al. [2007], and Cheng et al. [2007] demonstrated that elves manifest themselves not only in optical and UV emissions, but also in the increase of free electrons in the luminous region. With the global occurrence rate of elves obtained in the previous section, their contribution to the electron content of the ionospheric D-region can be assessed.

[15] The fractional global increase in total number of free electrons due to elves at the height of 80–90 km can be expressed as:

\[
\mu = \frac{\Delta N_e}{N_e} = \frac{V_{\text{elve}} \cdot \Delta n_e \cdot r \cdot l}{V_0 \cdot n_e},
\]

where \( N_e \) and \( \Delta N_e \) are the total number of ambient electrons and the change in the region of an elve. \( V_{\text{elve}}, V_0, r, l \) are the volume of an elve, volume of the spherical shell between 80 and 90 km height, the global occurrence rate of elves and the lifetime of the free electrons at this height, respectively.

\[\alpha \equiv \frac{\Delta n_e}{n_e}\]  

[16] Therefore, equation (1) can be rewritten as below:

\[
\mu = \frac{V_{\text{elve}} \cdot \alpha \cdot r \cdot l}{V_0}
\]

[17] We assume elve has a cylindrical shape with a diameter \( D_{\text{elve}} \) of 165 km and vertically spans the height \( H \) between 80 km and 90 km, hence \( V_{\text{elve}} = \pi(D_{\text{elve}}/2)^2 \times H \) [Mende et al., 2005]. Here we adapt \( r \) as 35 events per minute as just discussed in the previous section. Mika et al. [2006] and Cheng et al. [2007] showed that the free electron clouds at the elve altitude can sustain for 2 minutes or more. Therefore, \( l \) is chosen as 2 minutes. Rodger et al. [2001] also noted that a strong lightning-EMP can lead to \( \sim100\% \) or even greater increase in the electron density at the lower ionosphere, hence \( \alpha \geq 1 \). Mende et al. [2005] demonstrated that an elve can produce an electron cloud with an average electron density of \( 210 \text{ cm}^{-3} \) over a large circular region. On the basis of the IRI model [Bilitza, 2001], the mean nighttime ambient electron density at 80–90 km is \( \sim90 \text{ cm}^{-3} \) and this leads to \( \alpha \approx 1.3 \). Hence we can safely take \( \alpha \) to be unity. Plugging all of these values into equation (3), the average fraction of global electrons in the 80–90 km range produced by elves is \( \mu \sim 1\% \).

[18] However, elves could exert a greater influence on the local electron density and chemical composition over the elve hot zones, since \( \mu \) is proportional to the occurrence rate.
r as shown in equation (3) and r has a geographical variation as large as an order of magnitude (see Figure 3b). We can rewrite equation (3) as below to emphasize the fractional local electron density change owing to elves:

$$\mu_{\text{local}} = \frac{V_{\text{local}} \cdot \alpha \cdot r_{\text{local}} \cdot I}{V_{\text{local}}} \quad (4)$$

[19] Here $V_{\text{local}}$ and $r_{\text{local}}$ are the local volume of the spherical shell between 80 and 90 km height and the corresponding local occurrence rate of elves (after correction taken as described in the previous section). To demonstrate the local effect, we carry out the calculation for the Caribbean Sea hot zone (75–85°W and 5–15°N) using equation (4) and obtain $\mu_{\text{local}} \approx 5\%$ with $r_{\text{local}} \sim 1.5$ events/min. The 5% increase in the local electron density could have a significant impact on the local chemical equilibrium at the lower ionosphere. Hence, to model the atmospheric chemical reactions over the elves hot zones, a proper inclusion of the effect from elves may be required. Detailed assessment of the TLE contribution to the upper atmospheric energy budget and chemical composition will be presented in a separate paper.

8. Conclusions

[20] On the basis of a 3-year survey data from the ISUAL/FORMOSAT-2 experiment, 80% of recorded TLEs are elves, 20% are sprites or halos. The survey also yields the occurrence ratio between sprites and gigantic jets as ~60. Sprites mainly occur over land as lightning does, whereas elves occur mostly over oceans and coasts. The land/coast-to-ocean ratio of halos is between those of elves and sprites. A theoretical calculation based on a lightning peak current statistics indicates that only a very small fraction, less than 1%, of continental CG lightning are able to generate ISUAL detectable elves. We find, however, that the relative frequency of elves, and thus also of greater than 80 kA peak current lightning, is 10 times higher over ocean than over land. The strong dependence of elf occurrence over the sea surface temperature indicates that the warm tropical oceans provide the heat source to drive vertical convection and produce intense oceanic lightning, which in turn induce a large fraction of ISUAL recorded elves. This is a manifestation of ocean-atmosphere-ionosphere coupling. The increase of free electrons in the lower ionosphere from elves at global and local levels was also evaluated. Our results indicate that the global free electron contribution from elves is 1% approximately; however, the free electron content above elf hot zones could be elevated by more than 5%.

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References


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Y.-S. Chang and T.-Y. Liu, National Space Organization, 8F, 9 Prosperity 1st Road, HsinChu City, Hsinchu 30078, Taiwan.

A. B. Chen, R.-R. Hsu, C.-L. Kuo, Y.-J. Lee, and H.-T. Su, Department of Physics, National Cheng Kung University, 1 University Road, Tainan City, Tainan 70101, Taiwan. (htsu@phys.ncku.edu.tw)

J.-L. Chern, Department of Photonics, National Chiao Tung University, 1001 University Road, Hsinchu City, Hsinchu 30010, Taiwan.

H. U. Frey and S. B. Mende, Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720-7450, USA.

H. Fukunishi and Y. Takahashi, Department of Geophysics, Tohoku University, Aramaki, Aoba-ku, Miyagi 980-8578, Sendai, Japan.

L.-C. Lee, Institute of Space Science, National Central University, 300 Jhongda Road, Jhongli City, Taoyuan 32001, Taiwan.