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Observations of Transient Luminous Events from Greece †

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Abstract: Transient Luminous Events (TLEs) are rare electrical discharges occurring in the middle and upper atmosphere above thunderstorms. The results of systematic observations of TLEs in a region that includes Greece and its surrounding area during a 2-year period (September 2020–September 2022) are presented. This study provides a first insight about the frequency, the spatiotemporal distribution, and the variety of these events in that region. In total, 1632 TLEs were observed during these 2 years. Of these, 95.5% were red sprites. Most events occurred over the Ionian Sea, the southern Adriatic Sea, and western Greece. The most favorable period for TLEs in Greece and its surrounding area is from October to February. Noteworthy were two prolific nights, 15–16 October 2020 and 4–5 December 2021, over mesoscale convective systems at the Ionian Sea and the southeastern Aegean Sea, respectively, when hundreds of these events were observed. Observations of this kind are of great significance, not only because they are the first-ever conducted in the aforementioned region but also due to the fact that these events seem to exhibit a relatively high frequency of appearance there.

Keywords: transient luminous events; atmospheric electricity; red sprites

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1. Introduction

Transient Luminous Events (TLEs) constitute a "family" of electrical discharges, taking place above thunderstorms under specific conditions. There are two distinct categories in this "family". The first includes TLEs occurring in the middle and upper atmosphere (altitude range 40–100 km) as a result of the electromagnetic pulse (EMP) and the temporary electric field enhancement, sufficient for dielectric breakdown in the mesosphere, triggered by Cloud-to-Ground (CG) lightning. Emission of light and very low frequency perturbations due to electromagnetic pulse sources (ELVES), halos, green emissions from excited oxygen in sprite tops (GhOSTs), and red sprites belong to this category [1–3]. The second category includes TLEs stemming from convective thundercloud tops. Blue jets, blue starters, and gigantic jets (altitude range 15–90 km) fall into this category [4,5].

Red sprites are faint red streamer discharges in the middle and upper atmosphere (40–90 km), with a lifetime of up to tens of ms. They appear some ms after an intense positive polarity CG, which results in electric field enhancement between the thundercloud and the ionosphere. Electron acceleration in this field leads to collisions and subsequent excitations or ionizations of atmospheric molecules. De-excitation of the latter, mostly on the red and IR part of the electromagnetic spectrum, results in the manifestation of red sprites [6,7]. Sprites due to a negative polarity CG, termed "negative sprites", are an extremely rare event [8]. Halos occur due to the same mechanism responsible for sprites, appear higher than them, at 70–85 km, last for some ms, and look like faint red disks with a typical diameter of less than 100 km [3,9]. ELVES occur due to the EMP of CGs of either polarity, and they appear higher from all TLEs, at the lower ionosphere (80–100 km). They last less than 1 ms and look like very faint red "rings" with a diameter of more than

200 km [2]. GhOSTs were first observed in 2019, in a video of an intense red sprite event as a faint green afterglow on its top, persisting for about 1 s. These green emissions at 557.7 nm are possibly related to excited atomic oxygen due to electrons thermalized by the enhanced electric field, which caused the preceding sprite [10].

In this study, the results of systematic observations of TLEs for a 2-year period, from 23 September 2020 to 17 September 2022, from Greek-based observers are presented. This is the first time ever that such observations were conducted in a region that includes Greece and its surrounding area. The combination of the warm Mediterranean Sea with several frontal systems passing through the aforementioned region, especially in autumn and winter, is promising for observing a plethora of these events. Also, taking into consideration satellite data from previous missions, e.g., FORMOSAT-2 [11], the assumption that the number of events in this region is expected to be among the highest, if not the highest, in Europe and among the ten highest on the planet seems reasonable, thus underlining the significance of determining the frequency, the spatiotemporal distribution, and the variety of TLEs in the region of interest. In this case, the central and eastern Mediterranean Sea can become a European "laboratory" of research on these events in order to fully comprehend them.

2. Materials and Methods

Several night sessions for observations of TLEs took place, from different locations in Greece, over thunderstorms at an average distance of 300 km away from the observation point in straight line. For the purpose of creating a simple database with the time, place, and species of the observed TLEs, the region of interest was divided into 4 specific areas (Figure 1): the "WEST" including the southern Adriatic Sea, the Ionian Sea, and western Greece (west of Pindus Mountains), the "EAST" including all of the eastern and southeastern Aegean Sea together with western Turkey, and the "CONTINENTAL" including central and northern continental areas of Greece and the Balkans. The "REST" in Figure 1, refers to areas very close to the standard observation spots (green squares in Figure 1, namely Attica and Viotia) and most of southern Aegean Sea and Crete, between the lower white lines. Observations in the "REST" area are intermittent because of frequent cloud obstruction either due to the proximity of the storm at the standard observation spots or because of the location of the storm.

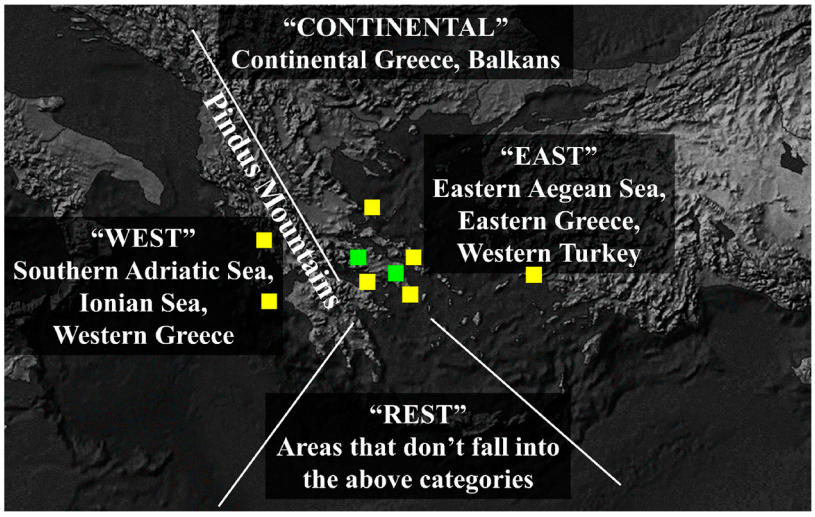

Figure 1. Standard (green squares) and non-standard (yellow squares) observation spots for TLEs, as well as a definition of the names of the specific areas used in this study.

The equipment used was commercial DSLR and low-light sensitive mirrorless cameras with "fast" lenses of aperture f/n, where $0.95 < n < 2.8$ at photo or video mode, pointing over the stratiform cloud layer of the distant thunderstorm. IR modified cameras were also used. The occurrence of one species of the TLEs "family" within a temporal range of 1 s

was considered as one event. If there were several groups of sprites within 1 s, over the same stratiform cloud (usually termed "dancing sprites"), they constituted one event. If there was more than one species (e.g., ELVES and sprites) at the same time, then they were counted as separate events.

3. Results

The first TLEs ever observed and captured in Greece were three red sprites by Dimitris Sagiakos over a thunderstorm at western Greece on 20 September 2015. Since then and up to 17 September 2022, 1656 TLEs were observed with the vast majority of them (1632) after the upgrade of the equipment used, with 23 September 2020 marking the beginning of the present 2-year study. There were 816 TLEs/year for these 2 years. Events other than red sprites were also observed (Figures 2–4 and associated Videos S1–S3).

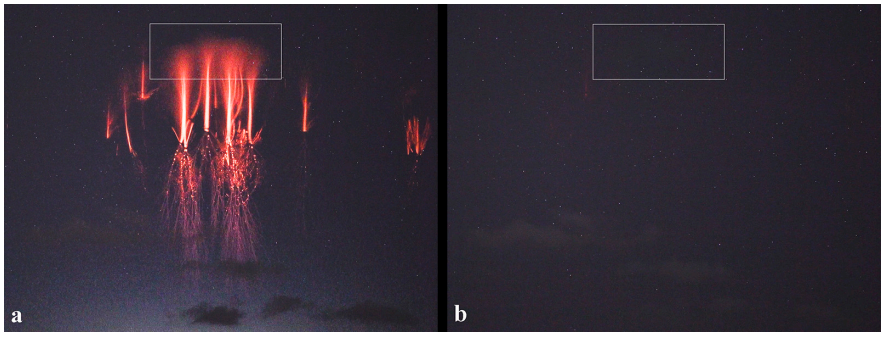

Figure 2. Intense red sprite event (**a**) on 04 December 2021, 23:29 UTC, over an MCS at the southeastern Aegean Sea, Greece, followed by a GhOST event (faint green hue inside the rectangle in (**b**)). The temporal separation between the two frames is in the order of tens of milliseconds. The observer was at eastern Attica, ~400 km from the storm. See also video S1.

Figure 3. ELVES event captured from 3 different cameras, using a 20 mm lens (**a**), a 50 mm lens (**b**), and an 85 mm lens (**c**), on 11 October 2021, 20:01 UTC, over a continental thunderstorm near the Greek–Bulgarian borders. Observers were on Mt. Kitheron, Attica, ~380 km away from that storm. See also Video S2.

Figure 4. Halo with small sprites captured from 2 different cameras, using an 85 mm lens (**a**) and a 50 mm lens (**b**) both located at Sounion, Attica, ~300 km away from the storms. This double event took place on 28 October 2021, 23:39 UTC, over a cluster of storms near southwestern Crete. See also Video S3.

The most active period for TLEs in Greece and the surrounding areas appears to be from October to February (Figure 5), which is expected since most thunderstorms in general

and most TLE-active storms in particular, e.g., Mesoscale Convective Systems (MCS), occur in this period of the year.

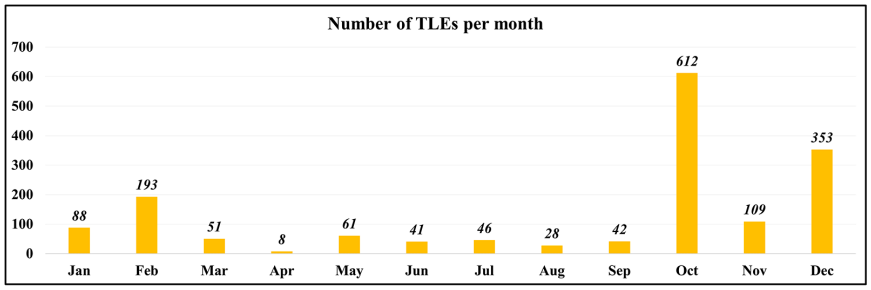

Figure 5. Total number of TLEs per month from 23 September 2020 to 17 September 2022.

A total of 1559 out of the 1632 captured TLEs were red sprites, corresponding to 95.5%. The rest of them were halos (29) and ELVES (44), as there have been no jets captured yet (Figure 6).

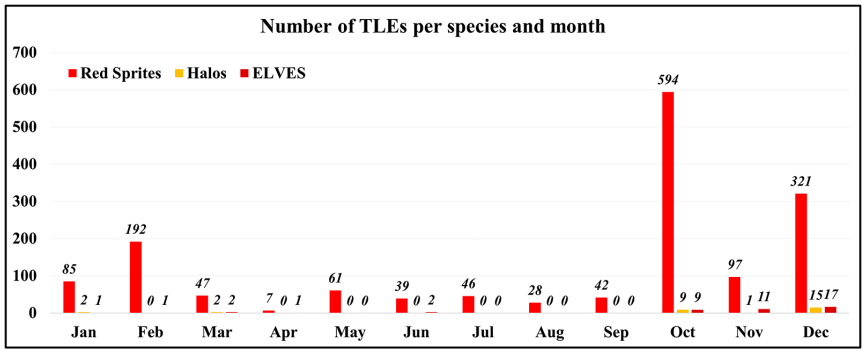

Figure 6. Number of TLEs per species and month from 23 September 2020 to 17 September 2022.

According to this 2-year study, the "WEST" area was the most active concerning TLEs. The activity peaked in autumn there. Then, the "EAST" area was mostly active during the cold winter months. Finally, the "CONTINENTAL" area produced most of its TLEs during the warm summer months. This was expected since thunderstorms are more frequent over continental areas in the summer and over/near the sea in the late autumn and winter (Figure 7).

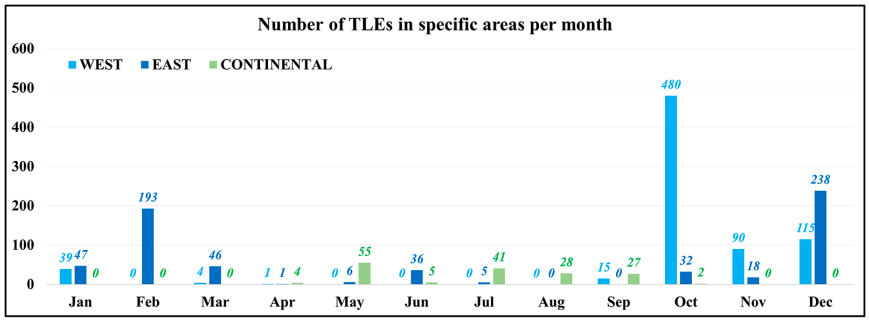

Figure 7. Number of TLEs in specific areas per month from 23 September 2020 to 17 September 2022.

Finally, there are two nights that can be considered as "case studies". On 15–16 October 2020 and on 4–5 December 2021, hundreds of TLEs were observed and/or captured over MCSs at the Ionian Sea (Figure 8a) and the southeastern Aegean Sea–southwestern Turkey (Figure 8b and Spreadsheet S4), respectively.

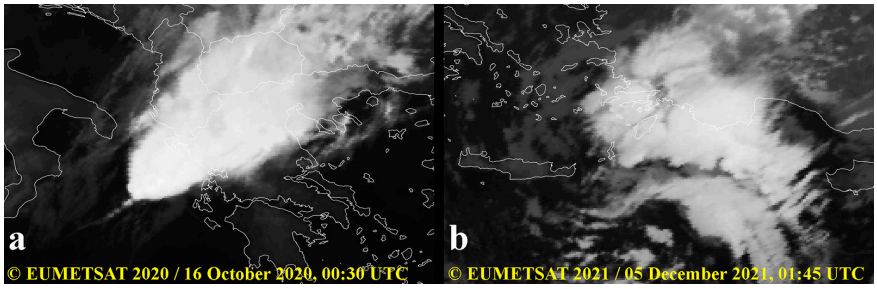

Figure 8. IR satellite images from the 2 MCSs, which produced hundreds of TLEs. IR satellite image of the MCS over the Ionian Sea on 16 October 2020 (**a**) and of the MCS over the Aegean Sea on 5 December 2021 (**b**). © EUMETSAT.

4. Discussion

The first-ever systematic observations for TLEs from Greek-based observers within a 2-year period in a region including Greece and its surrounding area, resulted in numerous recordings, thus providing evidence that this region might be among the most TLE-active of the planet. The autumn and winter months appear to be the most active, which is expected since several weather systems pass over the relatively warm seas of this region. In total, summer continental storms appear to produce fewer TLEs than their marine counterparts in autumn and winter. The latter can produce up to more than 200 events/night, something that occurred twice in this 2-year period, indicating that such prolific nights might be a yearly standard.

The results presented here point out the need for thorough research on TLEs in this region. The maximum distance from which an observer, at sea level, can observe TLEs occurring in the mesosphere is approximately 800 km. This limit includes observations in a much greater region (red circle in Figure 9b) compared to the one in this study (green circle in Figure 9b). With the addition of cameras able to record continuously on the VIS and IR spectrum, at strategic locations (e.g., Gavdos isl. or southern Crete and Rhodes, or Kastellorizo isl., Samos isl., Corfu isl., Evros, etc.), combined with data from professional lightning detector networks, a full and detailed mapping of these events can be achieved for this largely TLE-unexplored region. Finally, the quest for very rare species like negative sprites, blue, and gigantic jets can also be a strong motive.

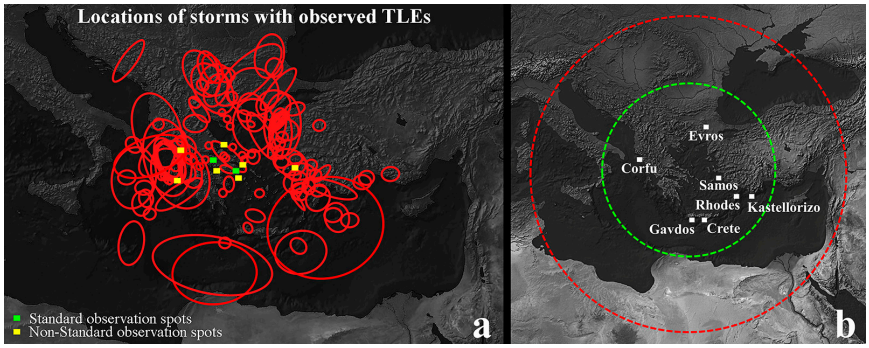

Figure 9. Almost all the TLE-producing storms observed in this 2-year period, shown in (**a**), are inside the green circle in (**b**), but the future addition of standard observation spots like the ones proposed in (**b**) can extend the maximum observational limit for Greek-based observers up to the red circle in (**b**). The mapping of the locations of the TLE-active storms in (**a**) was made by combining data from publicly available IR satellite imagery and lightning detectors as well as visual contact with the storm whenever the latter was possible.

Supplementary Materials: Video S1: Ghost event after intense red sprite, which can be downloaded at: https://doi.org/10.6084/m9.figshare.22297018 (accessed on 1 June 2023). Video S2: ELVES event,

which can be downloaded at: https://doi.org/10.6084/m9.figshare.22297045 (accessed on 1 June 2023). Video S3: Halo event, which can be downloaded at: https://doi.org/10.6084/m9.figshare.22297051 (accessed on 1 June 2023). Spreadsheet S4: TLEs Case Study 4–5 December 2021, which can be downloaded at: https://doi.org/10.6084/m9.figshare.22300807 (accessed on 1 June 2023).

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Conflicts of Interest: The authors declare no conflict of interest.

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