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Red Sprites over Northwest Poland and the Southern Baltic Coast Observed from Świder Geophysical Observatory

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Abstract

In 2012–2015, during the peak of thunderstorm season (June–August), night-time optical observations of lightning discharges above storm clouds, called sprites, were conducted from the Geophysical Observatory of the Institute of Geophysics of the Polish Academy of Sciences in Świder (52.115°N, 21.238°E). Dozens of phenomena were recorded above mesoscale convective storm systems located in western and northern Poland, the Baltic Sea, Russia, and Lithuania. Details of the observed events are presented, along with the correlation of optical data with cloud-to-ground and in-cloud lightning recorded by the IMWM-NRI PERUN lightning detection and location system. The analysis concludes with statistics of the observed sprite forms in relation to the associated parent lightning.

Keywords: TLEs, sprites, lightning, PERUN, lightning detection.

1. INTRODUCTION

The phenomena called “red sprites” or in short “sprites” belong to the family of Transient Luminous Events (TLEs) or upper atmosphere lightning. Optically they are short-lived emissions (microseconds to milliseconds) observed during night time. Sprites are mainly produced above stratiform parts of Mesoscale Convective Systems during the mature and decay phase of storm development (e.g., Lyons 2006). Individual events are triggered by the quasi-static electric fields produced in the mesosphere following positive cloud-to-ground (+CG) lightning discharges, sometimes preceded or accompanied by in-cloud (IC) lightning. Extensive or particular IC activity accompanying sprite production has been detected and investigated by, e.g., Lyons (1996), Pineda et al. (2008), Van der Velde et al. (2010, and references therein). The duration, amplitude and waveform of the current of sprite parent lightning play an essential role in the formation of the favourable conditions of sprite onset and development of its streamers through the atmosphere. Different shapes of sprites, such as column or carrot, may be formed (e.g., Stenbaek-Nielsen et al. 2010), with the most simple columnar sprites usually associated with a return stroke current of a +CG, while the more delayed, long-lived, and complex carrot sprites could be related to +CGs with long continuing currents of +CGs (Cummer and Füllekrug 2001; Williams and Yair 2006; Rycroft and Odzimek 2010).

In Europe, first 40 sprites have been scientifically observed in 2000 in the region of the Mediterranean Sea (Neubert et al. 2001). More such observations have been confirmed in the decade from Israel (Ganot et al. 2007), the south of France (e.g., Neubert et al. 2008), at middle latitudes in Central Europe, and as far as from Finland (e.g., Bór et al. 2009; Iwański et al. 2009; Mäkelä et al. 2010). Observations and climatology of the TLEs in Western and Central Europe in 2011–2013 have been recently reviewed by Arnone et al. (2020).

Here we summarise the results of sprite observations from the Geophysical Observatory of the Institute of Geophysics, Polish Academy of Sciences, in Świder, Poland (51.1155°N, 21.2377°E). The most useful directions of optical observations of such phenomena at Świder span from the West to East, giving the possibility of observations of sprite activity of distant (~500 km) storms over western and northern Poland, southern Baltic Sea, and to a lesser extent other Baltic states or Belarus. The main aim of this work is to present details on the collection of the observed events, classify them, identify possible parent lightning and to provide links to where the data will be available for further analysis. Our focus is also on using PERUN, a LF/VHF[1] lightning detection system operated by the Institute of Meteorology and Water Management – National Research Institute (Bodzak 2004; Konarski 2014), and its capabilities in providing lightning data for research investigations of sprites.

2. OPTICAL SPRITE OBSERVATIONS FROM ŚWIDER

The Stanisław Kalinowski Geophysical Observatory of the Institute of Geophysics, Polish Academy of Sciences, is located in Otwock-Świder, about 25 km SE of Warsaw. The observatory was used as a TLE observation site during the thunderstorm seasons of 2012–2015. The view from the main observatory building allowed observations at azimuth range from approximately 270 (West) to 45 (N-East). The mature pine trees surrounding the observatory as well as some observatory instruments are the main obstacles in the field of view. The system was manually switched on and operated when it was technically possible at times when thunderstorms in relevant regions of Poland were occurring and the viewing conditions were favourable.

The observational set-up was similar to those used previously at other locations, as described in, e.g., Odzimek et al. (2008) using a low-light CCD[2] television camera Watec 902H2 Ultimate ½” model, CBC Computar lens H1214FICS model (12 mm, F1/4, ~30° horizontal FOV[3]), except for the latest observations in 2015 when the Computar H0512 model (5 mm, F1/2, ~65° horizontal FOV) was also used. From 2013 onwards a time video overlay unit GPSBOXSPRITE2, equipped with a GPS receiver from The BlackBoxCamera Co Ltd[4] was used for the timing of video fields. The camera was installed on a tripod on the roof of the main

[1] Low Frequency/Very High Frequency

[2] Charge-Coupled Device

[3] Field of view (in degrees)

[4] Online at http://www.blackboxcamera.com/pic-osd/pic-osd.htm

observatory building, and it was pointed manually using supporting information on the location of storms from satellite imagery of thunderstorms. For the initial calculation of the azimuth, we have often used the "PanTiltCalc" software created by Lasse Clausen for the observational campaign at Śnieżka Mount (Odzimek et al. 2008), although the azimuth and especially the tilt of the camera had sometimes to be modified because of the obstacles in the field of view. At a change of the position of the camera, the new azimuth has been noted in an auxiliary text file, referred to here as the "camera log". The video signal was analysed by the UFOCapture V2 software from SonotaCo.com[5]. Recommended settings of the UFOCapture programme for the detection of TLEs have been used. The programme recorded detected objects as "peak hold" .jpg images (Fig. 1), video files in .avi format, and other auxiliary files for the use with the UFOAnalysis programme, including selected settings in .xml format. The UFOAnalysis software allows estimation of viewing azimuth from the recorded star field, although such analyses have not been yet completed. TLE detections were approved by visual inspection of peak hold images and movies using the observers' experience. A list of the observed events has been added to the record of observations in an online database at http://private.igf.edu.pl/~aodzimek/tles/database.html.

The events analysed here were observed in the thunderstorm seasons of 2012 to 2015 over June-August. Taking into account information from the observational logs there have been 22 nights of active observations, i.e., not cancelled because of bad weather conditions or other technical obstacles: 7 nights in 2012, 11 nights in 2013, 3 nights in 2014, and 1 night in 2015. Only sprite events have been observed. The results of observations have been summarised in Tables 1 and 2. Table 1 lists the dates of successful observations, viewing directions, time period of sprite occurrence and a number of recorded phenomena counted as the number of events captured (detailed in Table 2). In 29 video recordings 36 events have been recorded. Each event

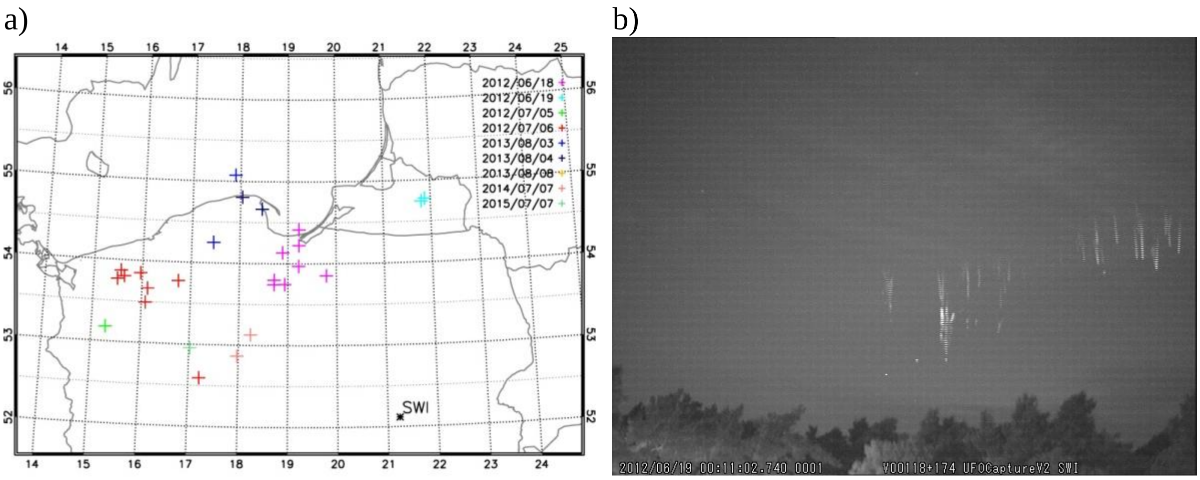

Fig. 1: a) Map of locations of assigned CG parent lightning of sprite events observed on subsequent dates (Table 2); b) example of recorded sprite clusters in Świder on 19 June 2012, ~00:11:03 UTC (peak-hold image). They (Nos. 11–12 in Table 2) consist of two events: one in the centre of the image and one on the right side. The groups are displaced both in space and in time. The sprite group to the right which happened ~300 ms earlier is a cluster of column sprites arranged in what resembles a circle. The event in the middle consists of multiple column sprites and one outstanding carrot or tree sprite.

[5] Online at http://sonotaco.com/e_index.html

Table 1

Summary of sprite-lightning observations from Świder over 2012–2015

No.	Date	Main direction of camera view from Świder	Time UTC (sprites observed)	Total event number	Storm location regions	GPS stamp	Time correction [s]
1	2012/06/18-19	NW-N	22:20–00:35	14	Pomerania/Żuławy/ Baltic Sea/Russia	No	+1.00
2	2012/07/05-06	NW	23:25–01:10	11	Pomerania/ Greater Poland	No	–12.60
3	2013/08/03-04	NW-N	23:10–00:30	7	Pomerania/Żuławy/ Baltic Sea	Yes	0
4	2013/08/08	NNE	21:35	1	Lithuania	Yes	0
5	2014/07/07	NWW-W	23:20–23:30	2	Greater Poland	Yes	0
6	2015/07/07	W	22:00	1	Greater Poland	Yes	0

is composed of up to three sprite subevents[6] – single sprites or sprite clusters separated in time or spatially, and within a continuous sequence of frames. In a video recording, a new sequence of sprites, separated from the previous by at least one field, sets a new event.

Most of the sprites have been captured in July, although a relatively small number of events and irregularity of observations prevent us from formulating any firm conclusions on the seasonal occurrence of sprites over the area. The most successful nights of observations were 18–19 June 2012, 4–5 July 2012, and 3–4 August 2013, each characterised by a long-lived MCS in the north or north-west of Poland moving approximately north-east. In order to present the spatial coverage of observations we mapped locations of parent lightning assigned to the observed sprites (see details in next section) in Fig. 1. There were no simultaneous observations of TLEs allowing any triangulation, at least when comparing with observations from the European database (Arnone et al. 2020).

At Świder, sprites could best be observed over regions such as northern Wielkopolska (Greater Poland), Pomorze (Pomerania), Żuławy (Vistula delta), the Bay of Gdańsk, and as far as the Kaliningrad Oblast in the Russian Federation, and parts of Lithuania. The west-northern and northern part of Poland where the sprite-lightning producing storms were located is characterised by a relatively low number of „thunderstorm days" but long-living thunderstorms, such as Mesoscale Convective Systems, occur there resulting in higher thunderstorm activity quantified by, e.g., their duration (Odzimek 2019). In Fig. 2 we show selected satellite observation-based images called „overshooting tops" which map the location of such storms, colour-coded by the brightness temperature differences as measured by the SEVIRI infrared spectral channels at 6.2 μm (water-vapour) and 10.8 μm. These values relatively reflect the vertical development of thunderstorm clouds and such maps have been used in support of sprite observations from Poland (Iwański et al. 2009; Pajek et al. 2008; Odzimek et al. 2014). Sprites are very often observed when the actual overshooting tops diminish or disappear, the storm is mature, or begins to decay. This is reflected in the satellite products when the green and yellow regions of the imaged storm increase their surface area compared with the red and orange regions (Odzimek and Pajek 2016).

[6] The subevent sprites can sometimes be of different types, which slightly differs from the definition of sprite entities in Bór (2013).

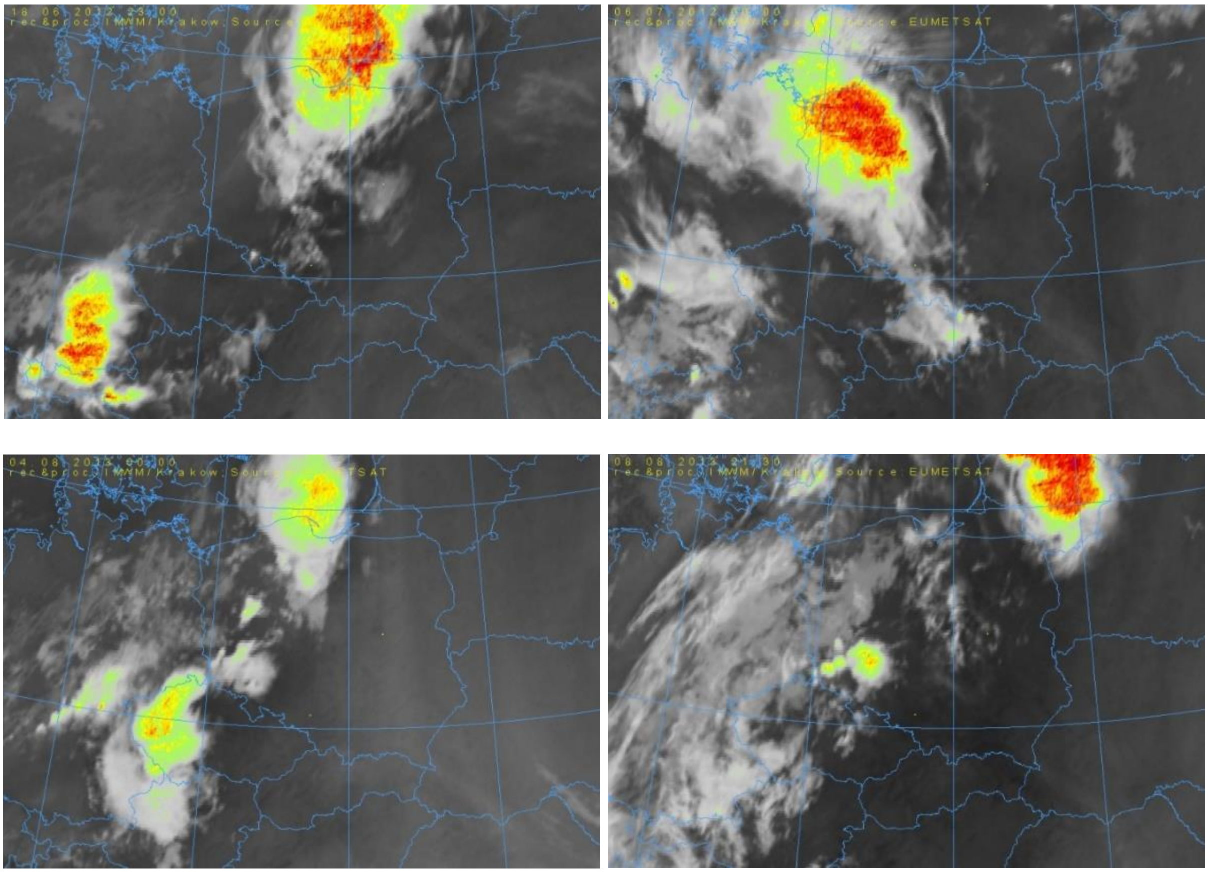

Fig. 2. The "overshooting tops" images of the sprite-producing thunderstorms in northern Poland and Baltic Sea region. Top left: 18 June 2012, 23:00 UTC; top right: 5 July 2012, 00:00 UTC; bottom left: 4 August 2013, 00:00 UTC; bottom right: 8 August 2013, 22:00 UTC (if many sprites observed this is approximately in the middle of the sprite production period by the storm).

Table 2 shows the details of the observed sprites such as time, duration, and the sprite type, as well as assigned parent lightning from detections by the Polish national lightning detection system PERUN. The timing and necessary time corrections have been determined according to the rules described in Odzimek and Mielniczek (2022, this issue). In the case of the recordings from two nights (18–19 June 2012 and 5–6 July 2012), when GPS timing was not available, a time correction has been found, based on PERUN data, in cases supported by detections from the Eurosprite lightning database (courtesy of Torsten Neubert). The correction values rounded to 0.05 s are indicated in the last column of Table 1.

Lightning occurrences have been studied compared to the corrected times of sprite events. In many cases, the occurrence of parent positive +CG lightning has been confirmed, and in many more cases the events were preceded by a more complex lightning sequence, including IC lightning. For any event, a parent lightning has been assigned from those detected in the time range of 100 ms before the first field of the event till the end of last field of the event plus the error of the time of the first (last) field resulting from the timing calculations, individual for an event, ranging between 7 and 50 ms (see Table 2). In case when the timing did not come from GPS and a calculated time shift was applied, additional ±50 ms of uncertainty is added to this range from both ends. Especially in cases when the location of thunderstorms where the probability of detection is decreased near the borders of Poland, PERUN used to miss some detections of CG lightning (e.g., Iwański et al. 2009). Therefore, we have also checked CG lightning detections provided by the Météorage/Euclid to support the Eurosprite campaigns (Neubert et

Table 2
Listing of observed sprite events from Świder and their parent lightning recorded by PERUN system (IMWM-NRI)

No.	No. date	No. video	No. event	Sprite sub-event count	Estimated time	Error[7] [ms]	Event description	PERUN Parent IC+CG Information with +CG RS time	PERUN Parent +CG RS current [kA]
1	#1	#1	#1	3	2012/06/18 22:22:32.077-217	50	Cluster of columns Cluster of carrots Cluster of columns in circle	IC, no +CG*	
2		#2	#1	2	2012/06/18 22:24:43.772-872	50	Cluster of columns Single carrot	IC, no CG*	
3			#2	2	2012/06/18 22:24:43.972-44.072	50	Cluster of columns with tendrils Cluster of wishbones with tendrils and spots, jellyfish	IC+CG 22:24:43.937	+92
4		#3	#1	1	2012/06/18 22:26:30.382-422	8	Cluster of columns with tendrils and spots, jellyfish	IC+CG 22:26:30.307	+74
5		#4	#1	1	2012/06/18 22:37:48.916-996	8	Single carrot Cluster of columns	IC+CG 22:37:48.812 22:37:49.001	+9 +12
6		#5	#1	3	2012/06/18 22:53:53.742-842	8	Multiple columns with spots Multiple columns with spots Cluster of columns	no IC or CG*	
7		#6	#1	1	2012/06/18 23:03:12.063-123	8	Multiple columns	IC+CG 23:03:12.132	+125
8			#2	1	2012/06/18 23:03:12.223-263	8	Multiple columns with unrecognized sprite type	+CG 23:03:12.132 23:03:12.289	+125 +92
9		#7	#1	1	2012/06/18 23:13:51.134-154	8	Multiple columns with tendrils	IC, no +CG*	
10	#2	#1	#1	1	2012/06/19 00:05:44.809-869	11	Cluster of carrots in circle	no IC or CG**	

to be continued

[7] This is individual error due to time corrections within a recording. Additional 50 ms is to be added in case timing of whole series of events was corrected as detailed in Table 1.

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Table 2 (continuation)
Listing of observed sprite events from Świder and their parent lightning recorded by PERUN system (IMWM-NRI)

<table>
<tr><td>11</td><td></td><td>#2</td><td>#1</td><td>1</td><td>2012/06/19
00:11:03.318-378</td><td>8</td><td colspan="2">Cluster of columns in circle</td><td>no IC or CG*,**</td><td></td></tr>
<tr><td>12</td><td></td><td></td><td>#2</td><td>2</td><td>2012/06/19
00:11:03.678-698</td><td>8</td><td colspan="2">Multiple columns with tendrils and spots
Single tree</td><td>no IC or CG*,**</td><td></td></tr>
<tr><td>13</td><td></td><td>#3</td><td>#1</td><td>1</td><td>2012/06/19
00:31:15.368-408</td><td>8</td><td colspan="2">Cluster of wishbones with tendrils and spots, jellyfish</td><td>no IC or CG*</td><td></td></tr>
<tr><td>14</td><td></td><td>#4</td><td>#1</td><td>1</td><td>2012/06/19
00:37:24.129-169</td><td>8</td><td colspan="2">Cluster of carrots in circle</td><td>IC, no CG*</td><td></td></tr>
<tr><td>15</td><td>#3</td><td>#1</td><td>#1</td><td>2</td><td>2012/07/05
23:27:39.653-733</td><td>8</td><td colspan="2">Cluster of columns
Wishbone sprite with a cluster of columns in circle</td><td>IC, no CG*</td><td></td></tr>
<tr><td>16</td><td>#4</td><td>#1</td><td>#1</td><td>1</td><td>2012/07/06
00:20:27.533-593</td><td>8</td><td colspan="2">Cluster of columns
and wishbones with tendrils and spots in circle</td><td>IC and CG
00:20:27.528</td><td>+114</td></tr>
<tr><td>17</td><td></td><td>#2</td><td>#1</td><td>1</td><td>2012/07/06
00:29:11.622-662</td><td>7</td><td colspan="2">Cluster of columns with tendrils</td><td>IC, no CG</td><td></td></tr>
<tr><td>18</td><td></td><td>#3</td><td>#1</td><td>1</td><td>2012/07/06
00:32:41.347-387</td><td>8</td><td colspan="2">Cluster of columns with tendrils and spots, jellyfish</td><td>IC and CG
00:20:27.528</td><td>+169</td></tr>
<tr><td>19</td><td></td><td></td><td>#2</td><td>1</td><td>2012/07/06
00:32:41.467-507</td><td>8</td><td colspan="2">Cluster of sprites of unrecognised type</td><td>IC and CG
00:20:27.528</td><td>+169</td></tr>
<tr><td>20</td><td></td><td>#4</td><td>#1</td><td>1</td><td>2012/07/06
00:39:38.994-034</td><td>7</td><td colspan="2">Multiple columns with tendrils and spots</td><td>IC, no CG*</td><td></td></tr>
<tr><td>21</td><td></td><td></td><td>#2</td><td>1</td><td>2012/07/06
00:39:38.114-134</td><td>7</td><td colspan="2">Cluster of columns</td><td>IC, no CG*</td><td></td></tr>
<tr><td>22</td><td></td><td>#5</td><td>#1</td><td>1</td><td>2012/07/06
00:48:49.488-508</td><td>8</td><td>Single carrot</td><td rowspan="2">dancing</td><td>no IC, CG*
00:48:49.606</td><td>+37</td></tr>
<tr><td>23</td><td></td><td></td><td>#2</td><td>2</td><td>2012/07/06
00:48:49.608-668</td><td>8</td><td>Cluster of carrots
Cluster of columns</td><td>no IC, CG*
00:48:49.785</td><td>+18</td></tr>
<tr><td>24</td><td></td><td>#6</td><td>#1</td><td>1</td><td>2012/07/06
00:58:27.905-925</td><td>8</td><td colspan="2">Multiple columns with spots</td><td>no IC or CG</td><td></td></tr>
</table>

to be continued

Table 2 (continuation)
Listing of observed sprite events from Świder and their parent lightning recorded by PERUN system (IMWM-NRI

25		#7	#1	1	2012/07/06 01:10:16.435-475	7	Cluster of columns	IC+CGs 01:10:16.423 00:10:16.455	+12 +111
26	#5	#1	#1	1	2013/08/03 23:13:55.843-863	0	Cluster of columns and wishbone	no IC, +CG 23:13:55.837	+36
27		#2	#1	1	2013/08/03 23:25:14.157-197	0	Cluster of wish-bone and columns	no IC or CG*	
28		#3	#1	1	2013/08/03 23:52:18.242-262	0	Cluster of wish-bone and columns	IC, no CG*	
29	#6	#1	#1	1	2013/08/04 00:19:25.707-767	0	Double carrots	IC+CG* 00:19:25.719	+27
30		#2	#1	1	2013/08/04 00:24:18.305-325	0	Multiple columns with spots	IC, no CG*	
31		#3	#1	1	2013/08/04 00:30:38.361-401	0	Double unrecog-nised types	IC, no CG	
32			#2	1	2013/08/04 00:30:38.441-501	0	Single unrecognised type	IC, no CG	
33	#7	#1	#1	1	2013/08/08 21:38:34.991-35.031	0	Single carrot	no IC or CG**	
34	#8	#1	#1	1	2014/07/07 23:25:23.503-543	0	Cluster of col-umns with tendrils	IC, no CG*	
35		#2	#1	1	2014/07/07 23:34:29.297-337	0	Cluster of col-umns with tendrils jellyfish	IC, no CG*	
36	#9	#1	#1	1	2015/07/07 22:01:33.445-465	0	Cluster of col-umns with tendrils	IC+CG 22:01:33.455	+137
Total				45					

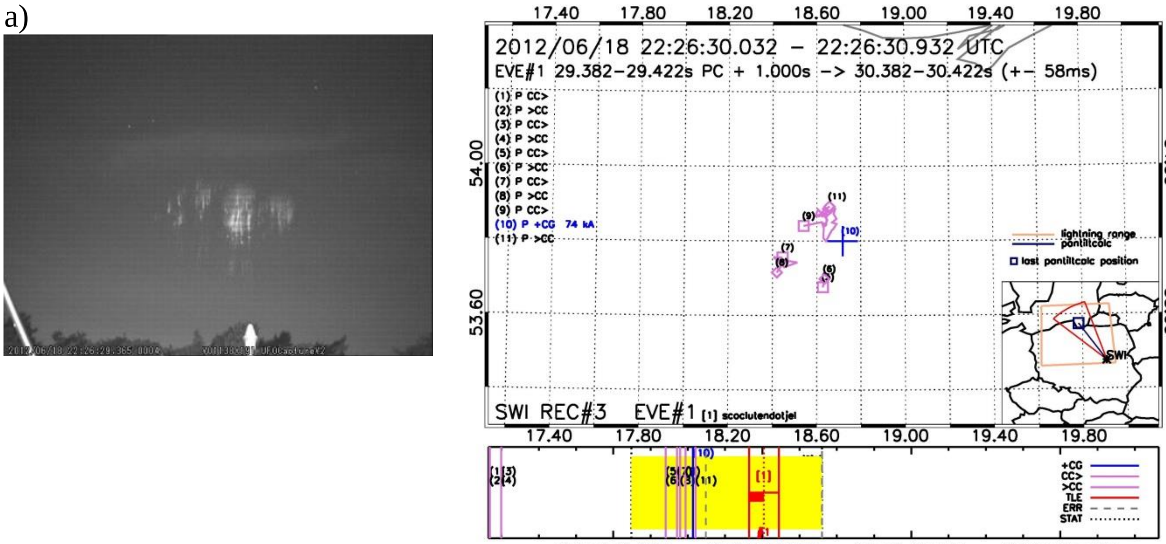
*CG lightning was detected; **Most probably out of the PERUN range.

al. 2008; Arnone et al. 2020). If a +CG was missed by PERUN, but the other was detected, this is indicated by a star note (*). The last column shows amplitudes of the return stroke current of the detected positive CGs. Negative CGs have been excluded from the procedure as being not efficient in sprite lightning production – see, e.g., Lyons (1996), Pineda et al. (2008), Rycroft et al. (2007).

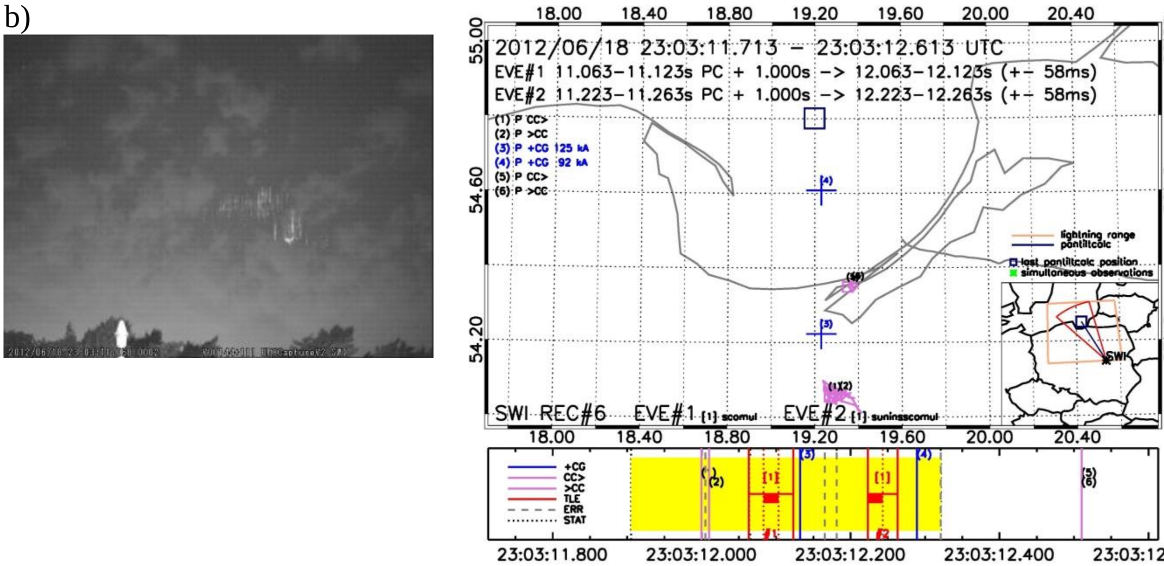
3. PARENT LIGHTNING OF OBSERVED SPRITE EVENTS INCLUDING PERUN INCLOUD DETECTIONS

Since the PERUN system has the ability of detecting the cloud-to-cloud lightning, we have focused our analysis on the properties of the total lightning activity associated with sprite events.

Figures 3a–d show the peak-hold image of selected events and the analysis of position and time sequence of their nominated parent lightning strokes, including CG and IC lightning (here a)



b)



c)

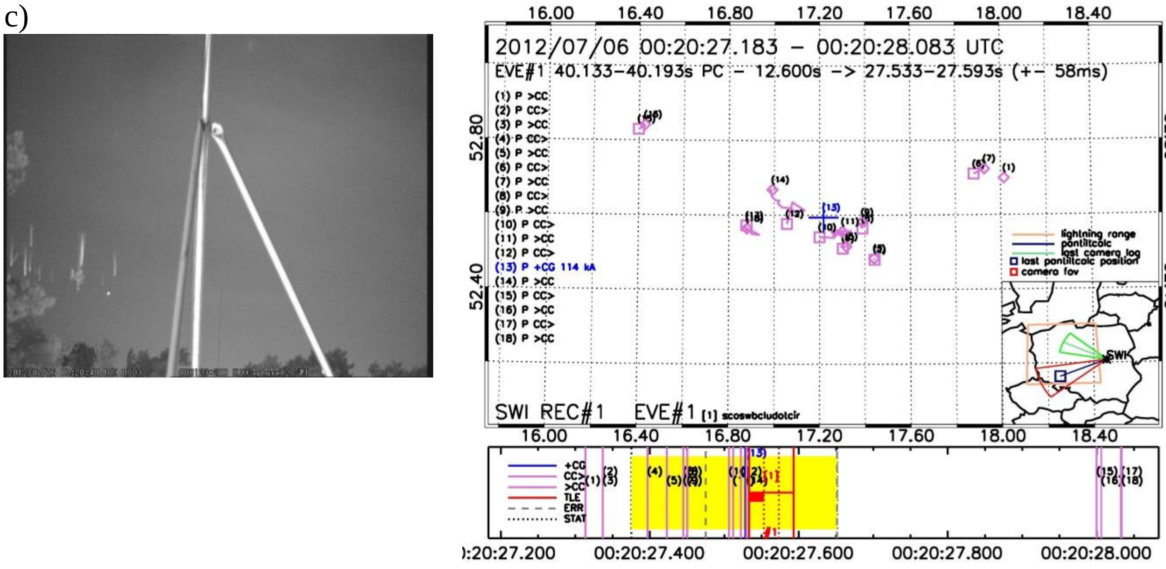


Fig. 3. Continuation on the next page.

d)

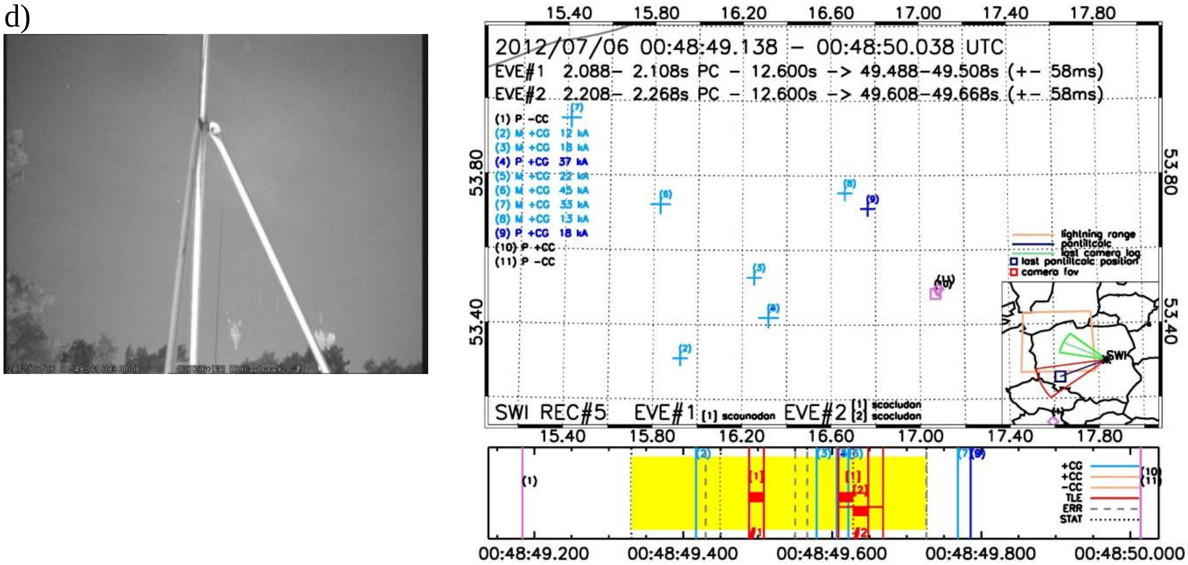


Fig. 3. Peak-hold images (left) of sprites and the mapping and time sequence of lightning (right) at the events: a) 18 June 2012, 22:26:30 UTC, event 4; b) 18 June 2012, 23:03:12 UTC, event 8; c) 6 July 2012, 00:20:27 UTC, event 16; d) 6 July 2012, 00:48:49 UTC, events 22–23. See description in the text.

also denoted by CC – cloud-to-cloud). Each "analysis" figure (panels on the right) consists of the upper and bottom panel. The larger, upper panel shows the map of lightning positions in geographical coordinates near the moment of a sprite capture. The lightning flashes are marked schematically according to their classification by the PERUN system, i.e.: "+" for positive CG lightning, "CC>" outgoing IC lightning, ">CC" incoming IC lightning. The lilac line connects the starting (CC>), intermediate (0CC, not explicitly shown), and final (>CC) points. Since geographical coordinates of all these points were available it was also possible to calculate the distance between the starting and final points of IC lightning along their path, i.e., by following consecutive "0CC" points from a starting point till the final point was encountered. There has been also a category of isolated points; however, these have not been analysed. A statistical count of displayed discharge types is shown in the legend. The detected lightning strokes are also listed chronologically (numbered) on the left side together with all positive CGs highlighted by blue colour (P denotes PERUN detection, M – detection provided by Météorage; CG detections by both systems at the same time (to 10 μs accuracy) are considered as one, and denoted by "<>").

The small map in the bottom right corner includes schematic countries borders, position of the camera (Świder – SWI), the latest used azimuth calculated with PanTiltCalc tool and the field of view of the camera (only the horizontal distance is correct). The last calculated or aimed position (although not always indicating the true direction – see remarks above) is marked by a navy square. This square is also plotted in the big map. A similar direction and "field of view" indication in green colour is the direction as noted in camera logs. The orange contour indicates the spatial cover range of the large map.

The bottom panel shows the time sequence of lightning mapped in the upper panel in the corresponding colour code. In red colour the time range of TV fields (each 20 ms-long) of the recorded sprite events (numbered by #) and their subevents (numbered in []) has been shown. Thick red stripe marks the field of maximum brightness (determined by eye) in the subevent. The dashed grey lines indicate the time error applied before the first field and after the last field, resulting from the inaccuracy of recorded timing. The dotted lines and yellow colour indicates the time interval in which any found lightning can be assigned as parent. The events are also described in the big map, including information on timing, number of recording, event and subevents count with a short description encoded by patchwork messages built from 3-letter codes describing types and features of sprites (explained in Appendix 1).

Results combined from the analysis of each event such as that presented in Fig. 3 allowed to take a closer look at some individual events as well as to make statistics of the events' types and the sprites' most frequent features, dependent on characteristics of their parent lightning. The studied features are related to:

- multiplicity and organisation, e.g., single or dual, multiple, including more organised clusters, specific organised clusters such as in the circle formation (referred to as single, multi or circle in Fig. 4),
- complexity of sprite events defined by having tendrils or being most complex types such as carrot sprites (referred to as complex in Fig. 5).

These are studied against the following parent lightning characteristics:

- CG and IC count,
- mean amplitude of parent CG return strokes,
- the maximum amplitude of parent CG return strokes,
- IC lightning extent (span) measured by the radius of a circle inscribed in the rectangle determined by the most distant points of lightning path from the centre calculated as mean average of geographical coordinates of the lightning,
- IC lightning length measured as the sum of distances between points along a lightning path. If more IC lightning is detected, their lengths are summed up.

Events with no assigned parent lightning have been excluded from the analysis. Statistics of the considered sprite features against parent lightning characteristics are presented in Figs. 4

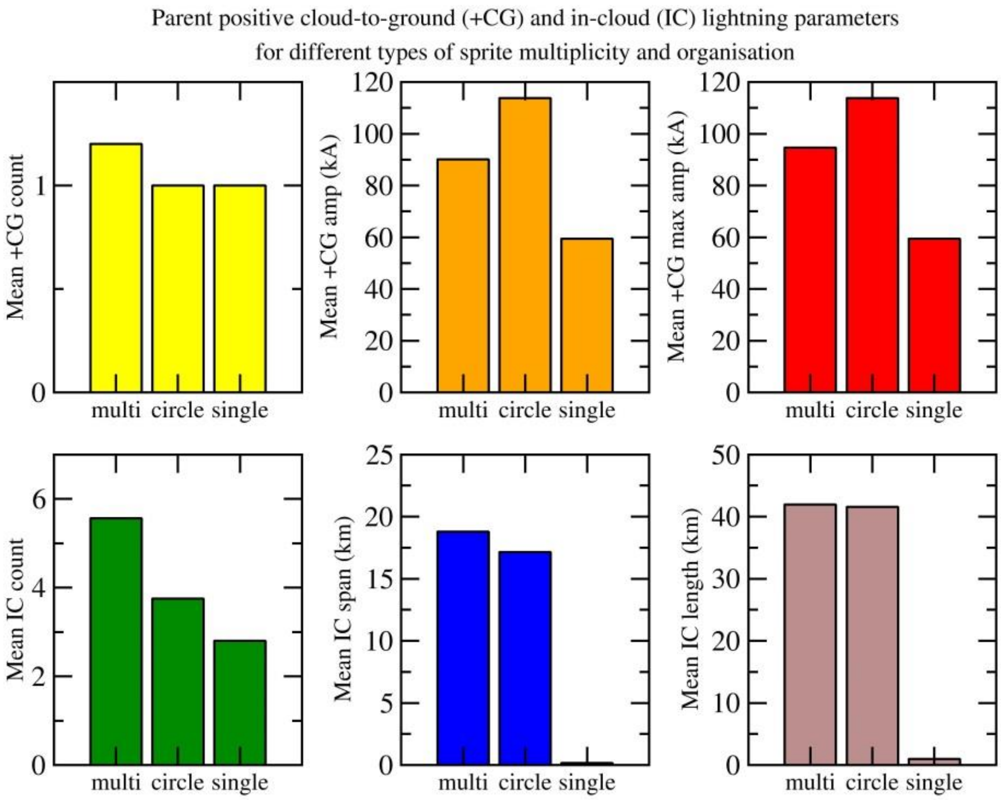


Fig. 4. Statistics of CG and IC parent lightning in relation to sprite multiplicity and organisation.

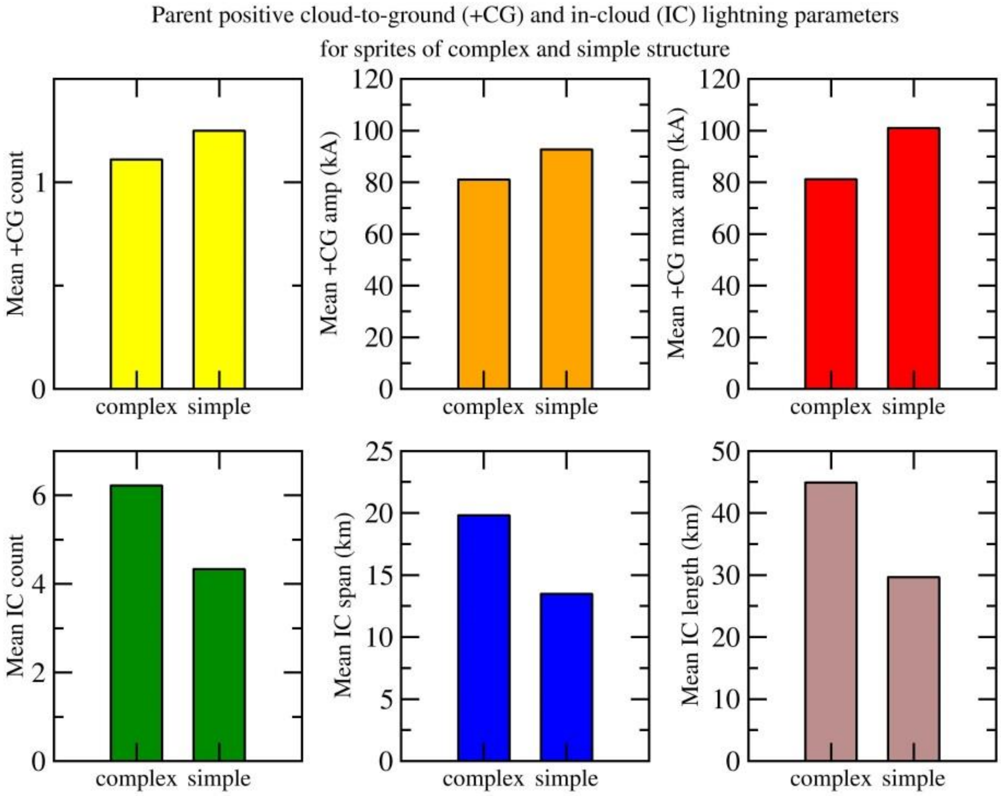


Fig. 5 Statistics of CG and CC parent lightning in relation to complexity of sprite morphology.

and 5, respectively. We do not show statistical errors but the standard deviations are high since the population of events is not very large. The CG statistics are based on PERUN detections only.

4. DISCUSSION

The majority of sprites observed from Świder in northern Poland and beyond over 2012–2015 are column sprites, also named columniform or c-sprites. There is also a significant number of carrot and wishbone sprites. In about 16% of events, sprites are assembled into jellyfish formations[8]. Bór (2013) indicated jellyfish as a common form of sprites over Central Europe as well. One case of dancing sprites event was recorded (6 July 2012, 00:49:02.088-268, Fig. 3d). Approximately 30% of events are mixed events comprising different types of sprites in different organisation, i.e., single sprites or groups of sprites in less or more organised groups and clusters (see Fig. 1). Cluster of different types of sprites may appear simultaneously in the time period equivalent to a single TV frame field, i.e., 20 ms. Multiple-sprite events comprising 2 to 3 sprite subevents can be captured in one sequence of video frames – up to 9 fields equivalent to 180 ms.

Some column sprite clusters seem to be arranged in a circle: about 13% of events. It has been anticipated that this happens around or close to the axis pointing at the parent return stroke position. Optical observations of sprites in Israel during the winters of 2006–2008 have brought a number of such events when the elements of columniform sprites were organised in spaced intervals on the circumference of a circle centred above, or in small offset to the vertical direc-

[8] An effect of jellyfish sprite is created by a large cluster of column or wishbone sprites with diffuse tops and long tendrils below.

tion from a positive parent lightning. Furthermore, the time and spatial range of conditions of such geometry, favourable for sprite initiation, has been shown to be possible using the observations and modelling of quasi-static fields following a positive return stroke (Vadislavsky et al. 2009). In our observations, such column sprites ensembles have been observed on 18 June 2012 and 5 July 2012 – events Nos. 1, 11, 16, and 18 (see also Fig. 1). It has to be noted that the circular symmetry of sprite clusters is also observed in case of other sprite type shapes, for example carrots, as in events Nos. 10 and 14. Approximately in 50% of events, sprites are more developed vertically and have tendrils – that includes all jellyfish formations and carrot sprites. Many sprites also produced spots – the bright points over their bodies.

In regard to the statistics made over the sprite morphology and multiplicity characteristics depending on parent lightning, although some parent strokes may have been missed, we note that PERUN provides an opportunity of comparing the sprite features with characteristics of total lightning. As far as sprite multiplicity is concerned, the results from Świder imply that groups or multiple sprites and sprite clusters require more extended IC lightning. In the cases of single sprites, the extent or length of ICs was not such a factor. In addition, for circle-arranged clusters, the large amplitude of the return stroke of parent CG may have been a significant factor. Even though the amplitude of the current flowing in the return stroke (RS max) is not linearly proportional to the total charge moment change, CMC (e.g., Nieckarz et al. 2011), the lightning parameter important for sprite generation (e.g., Huang et al. 1999), the strokes with high RS amplitude and not necessarily large CMC can produce strong quasi-static fields at high altitudes and initiate organised clusters of morphologically developed sprites. Such a dependence of sprites on RS amplitude was observed very early (Wescott et al. 1998). In regard to sprite morphological complexity, more spatially extended IC lightning was associated with more developed sprites such as carrot and jellyfish sprites which have tendrils. However, the appearance of tendrils and spots (analysis not shown), was also a matter of more powerful RSs of parent CG lightning. The results of these simple statistics are generally consistent with both previous observations (e.g., Wescott et al. 1998; Pineda et al. 2008; Van der Velde et al. 2010), and modelling results, including those by Rycroft and Odzimek (2009, 2010). Although column sprites have initially been not associated with large IC activity, in contrast to carrot sprites (Van der Velde et al. 2006), clusters and their jellyfish formations which involve more complicated morphologies may well be. We also note that some IC activity happens within the duration of sprites (i.e., the video fields); however, since many of our observation have no GPS stamps, we refrain from further kind of analyses on the time coincidence or delays between parent IC and CG lightning and sprites, although such analyses are potentially possible. A larger collection of observations with correctly timed events, preferably at higher time resolution, is required to perform more detailed analysis.

5. SUMMARY

The total of 36 TLEs of the “red sprite” type events have been recorded optically between 2012 and 2015 over north-western and northern Poland and the southern Baltic region, from Świder Geophysical Observatory, Poland. Some long-lived storms, such as that on the night of 18–19 June, 5–6 July 2012, and 4–5 July 2013, have been prolific in the production of sprite-lightning. The majority of sprites are of columniform type, with a smaller number of carrot and even fewer sprites of other types. Jellyfish sprite formations are not rare. At least one event of dancing sprites was recorded. PERUN, the Polish lightning detection system operated by IMWM-NRI, provides a valuable opportunity for the investigation of relationships between parent lightning and sprite events, including an analysis of total lightning.

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Appendix 1

ABBREVIATIONS OF SPRITE EVENT DESCRIPTIONS IN FIG. 3A–D

sco – column sprite	uno – single
sca – carrot sprite	cir – circle
swb – wishbone sprite	ins – inside or next to
sun – unrecognised sprite	ten – tendrils
mul – multiple	dot – spots
clu – cluster	dan – dancing

References

Arnone, E., J. Bór, O. Chanrion, V. Barta, S. Dietrich, C.-F. Enell, T. Farges, M. Füllekrug, A. Kero, R. Labanti, A. Mäkelä, K. Mezuman, A. Odzimek, M. Popek, M. Prevedelli, M. Ridolfi, S. Soula, D. Valeri, O. van der Velde, Y. Yair, F. Zanotti, P. Zoladek, and T. Neubert (2020), Climatology of Transient Luminous Events and lightning observed above Europe and the Mediterranean Sea, *Surv. Geophys*. **41**, 2, 167–199, DOI: 10.1007/s10712-019-09573-5.

Bodzak, P. (2004), System detekcji i lokalizacji wyładowań atmosferycznych, *Gazeta Obserwatora IMGW* **5**, 11–15.

Bór, J. (2013), Optically perceptible characteristics of sprites observed in Central Europe in 2007–2009, *J. Atmos. Sol.-Terr. Phys*. **92**, 151–177, DOI: 10.1016/j.jastp.2012.10.008.

Bór, J., G. Sátori, and H.D. Betz (2009), Observation of TLEs in Central Europe from Hungary supported by LINET, *AIP Conf. Proc.* **1118**, 1, 73–83, DOI: 10.1063/1.3137716.

[9] https://www.blitzortung.org/

Cummer, S.A., and M. Füllekrug (2001), Unusually intense continuing current in lightning produces delayed mesospheric breakdown, *Geophys. Res. Lett.* **28**, 3, 495–498, DOI: 10.1029/2000GL012214.

Ganot, M., Y. Yair, C. Price, B. Ziv, Y. Sherez, E. Greenberg, A. Devir, and R. Yaniv (2007), First detection of transient luminous events associated with winter thunderstorms in the eastern Mediterranean, *Geophys. Res. Lett*. **34**, 12, L12801, DOI: 10.1029/2007GL029258.

Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, and C. Wong (1999), Criteria for sprites and elves based on Schumann resonance observations, *J. Geophys. Res.: Atmos*. **104**, D14, 16943–16964, DOI: 10.1029/1999JD900139.

Iwański, R., A. Odzimek, L.B.N. Clausen, V. Kanawade, I. Cnossen, and N.J.T. Edberg (2009), Meteorological study of the first observation of red sprites from Poland, *Acta Geophys*. **57**, 3, 760–777, DOI: 10.2478/s11600-009-0008-7.

Konarski, J. (2014), Validation of cloud-to-ground (CG) lightning flash discriminations obtained from two different lightning data processing programs by the reference E-field recordings. **In:** *Proc. 15th International Conference on Atmospheric Electricity, 15–20 June 2014, Norman, Oklahoma, USA*, 11 pp.

Lyons, W.A. (1996), Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res.: Atmos*. **101**, D23, 29641–29652, DOI: 10.1029/96JD01866.

Lyons, W.A. (2006), The meteorology of Transient Luminous Events – an introduction and overview. **In:** M. Füllekrug, E.A. Mareev, and M.J. Rycroft (eds.), *Sprites, Elves and Intense Lightning Discharges*, NATO Science Series II, Vol. 225, Springer, Dordrecht, 19–56.

Mäkelä, A., T. Kantola, Y. Yair, and T. Raita (2010), Observations of TLEs above the Baltic sea on Oct 9 2009, *Geophysica* **46**, 1–2, 79–90.

Neubert, T., M. Rycroft, T. Farges, E. Blanc, O. Chanrion, E. Arnone, A. Odzimek, N. Arnold, C.-F. Enell, E. Turunen, T. Bösinger, Á. Mika, C. Haldoupis, R.J. Steiner, O. van der Velde, S. Soula, P. Berg, F. Boberg, P. Thejll, B. Christiansen, M. Ignaccolo, M. Füllekrug, P.T. Verronen, J. Montanya, and N. Crosby (2008), Recent results from studies of electric discharges in the mesosphere, *Surv. Geophys*. **29**, 2, 71–137, DOI: 10.1007/s10712-008-9043-1.

Neubert, T., T.H. Allin, H. Stenbaek-Nielsen, and E. Blanc (2001), Sprites over Europe, *Geophys. Res. Lett*. **28**, 18, 3585–3588, DOI: 10.1029/2001GL013427.

Nieckarz, Z., A. Kulak, S. Zieba, and A. Odzimek (2011), Cloud-to-ground lightning dipole moment from simultaneous observations by ELF receiver and combined direction finding and time-of-arrival lightning detection system, *J. Geophys. Res.: Atmos*. **116**, D8, D08107, DOI: 10.1029/2010JD014736.

Odzimek, A. (2019), Spostrzeżenia z obserwacji i modelowania wyładowań elektrycznych nad chmurami burzowymi typu Red Sprite. **In:** J. Ćwiklak (ed.), *Wybrane Aspekty Zabezpieczenia Nawigacji Lotniczej*, Wydawnictwo Lotniczej Akademii Wojskowej (LAW), Dęblin, 49–60 (in Polish).

Odzimek, A., and M. Mielniczek (2022), Methodology of estimating time accuracy in TV recordings of sprite lightning observed from Gliwice and Świder 2011–2015, *Publs. Inst. Geoph. PAS* **D-77 (442)**, 71–83, DOI: 10.25171/InstGeoph_PAS_Publs-2022-026 (this issue).

Odzimek, A., and M. Pajek (2016), Support for sprite optical observations by near real-time analysis of thunderstorm development from satellite overshooting tops images. **In:** *Book of Abstracts: TEA-IS Conference Thunderstorm Effects on the Atmosphere-Ionosphere System, 27–29 June 2016, Copenhagen, Denmark*, Technical University of Denmark, p. 45.

Odzimek, A., L.B.N. Clausen, V. Kanawade, I. Cnossen, N. Edberg, F. Faedi, A. Del Moro, U. Ural, K. Byckling, P. Krzaczkowski, R. Iwanski, P. Struzik, M. Pajek, and W. Gajda (2008), SPARTAN Sprite-Watch Campaign 2007. **In:** V.Ya. Choliy, H. Ivashchenko, and V.N. Ivchenko (eds.), *Proceedings of Contributed Papers, 15th Young Scientists Conference on Astronomy and Space Physics*, Kyivskyi Universytet, Kyiv, 64–67.

Odzimek, A., M. Pajek, J. Bór, P. Struzik, P. Novak, M. Mielniczek, and M. Popek (2014), Optical observations of sprites supported by OST images. **In:** *Book of Abstracts, 22nd Cartographic School "Geoinformatics and Atmospheric Science", 6–9 May 2014, Wałbrzych-Książ, Poland,* University of Wroclaw, p. 47.

Pajek, M., R. Iwanski, M. König, and P. Struzik (2008), Extreme convective cases – the use of satellite products for storm nowcasting and monitoring. **In:** *Proc. 2008 EUMETSAT Meteorological Satellite Conference, Darmstadt, Germany,* 8 pp.

Pineda, N., J. Montanya, O. Van der Velde, and S. Soula (2008), Total lightning in a TLE-bearing winter thunderstorm over the western Mediterranean. **In:** *20th International Lightning Detection Conference, 21–23 April 2008, 2nd International Lightning Meteorology Conference, 24–25 April 2008, Tucson AZ, USA,* 10 pp.

Rycroft, M.J., A. Odzimek, N.F. Arnold, M. Füllekrug, A. Kułak, and T. Neubert (2007), New model simulations of the global atmospheric electric circuit driven by thunderstorms and electrified shower clouds: The roles of lightning and sprites, *J. Atmos. Sol.-Terr. Phys*. **69**, 17–18, 2485–2509, DOI: 10.1016/j.jastp.2007.09.004.

Rycroft, M.J., and A. Odzimek (2009), The impact of lightning flashes and sprites on the earth's global electric circuit: An overview of recent modeling results, *AIP Conf. Proc*. **1118**, 1, 124–135, DOI: 10.1063/1.3137704.

Rycroft, M.J., and A. Odzimek (2010), Effects of lightning and sprites on the ionospheric potential, and threshold effects on sprite initiation, obtained using an analog model of the global atmospheric electric circuit, *J. Geophys. Res.: Space Phys*. **115**, A6, A00E37, DOI: 10.1029/2009JA014758.

Stenbaek-Nielsen, H.C., R. Haaland, M.G. McHarg, B.A. Hensley, and T. Kanmae (2010), Sprite initiation altitude measured by triangulation, *J. Geophys. Res.: Space Phys*. **115**, A3, A00E12, DOI: 10.1029/2009JA014543.

Vadislavsky, E., Y. Yair, C. Erlick, C. Price, E. Greenberg, R. Yaniv, B. Ziv, N. Reicher, and A. Devir (2009), Indication for circular organization of column sprite elements associated with Eastern Mediterranean winter thunderstorms, *J. Atmos. Sol.-Terr. Phys*. **71**, 17–18, 1835–1839, DOI: 10.1016/j.jastp.2009.07.001.

Van der Velde, O.A., Á. Mika, S. Soula, C. Haldoupis, T. Neubert, and U.S. Inan (2006), Observations of the relationship between sprite morphology and in-cloud lightning processes, *J. Geophys. Res.: Atmos*. **111**, D15, D15203, DOI: 10.1029/2005JD006879.

Van der Velde, O.A., J. Montanyà, S. Soula, N. Pineda, and J. Bech (2010), Spatial and temporal evolution of horizontally extensive lightning discharges associated with sprite-producing positive cloud-to-ground flashes in northeastern Spain, *J. Geophys. Res.: Space Phys*. **115**, A9, A00E56, DOI: 10.1029/2009JA014773.

Wescott, E.M., D.D. Sentman, M.J. Heavner, D.L. Hampton, W.A. Lyons, and T. Nelson (1998), Observations of 'columniform' sprites, *J. Atmos. Sol.-Terr. Phys*. **60**, 7–9, 733–740, DOI: 10.1016/S1364-6826(98)00029-7

Williams, E., and Y. Yair (2006), The microphysical and electrical properties of sprite-producing thunderstorms. **In:** M. Füllekrug, E.A. Mareev, and M.J. Rycroft (eds.), *Sprites, Elves and Intense Lightning Discharges,* NATO Science Series II: Mathematics, Physics and Chemistry, Vol. 225, Springer, Dordrecht, 57–83, DOI: 10.1007/1-4020-4629-4_3.

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