Publications of the Institute of Geophysics, Polish Academy of Sciences
Geophysical Data Bases, Processing and Instrumentation
vol. 442 (D-77), 2022, pp. 41-54
DOI: 10.25171/InstGeoph_PAS_Publs-2022-024

Red Sprites over Thunderstorms in Czech Republic, Germany and Poland Observed from Gliwice in 2011–2013

Anna ODZIMEK[1,✉], Magdalena MIELNICZEK[2], Monika PAJEK[3], and Petr NOVÁK[4]

[1]Institute of Geophysics, Polish Academy of Sciences, Warszawa, Poland
[2]Gliwice, Poland
[3]Institute of Meteorology and Water Management – National Research Institute, Kraków, Poland
[4]Czech Hydrometeorological Institute, Prague, Czech Republic

✉ aodzimek@igf.edu.pl

Abstract

Nigh-time observations of red sprites phenomena over thunderstorm seasons of 2011–2013 from Gliwice (52.116°N, 21.238°E) resulted in 45 events observed above convective storm system in the Czech Republic, Germany, and south-western Poland. This paper gives details of the observed events along with the correlation of optical data with cloud-to-ground and in-cloud lightning recorded by the CELDN lightning detection system. We also analyse the time sequence and locations of parent lightning in dancing sprites events produced at various stages of the thundercloud development and sprite production using visualisation of their locations mapped onto the "overshooting-tops" satellite images derived from Meteosat SEVIRI instrument data.

Keywords: TLEs, lightning, sprites, CELDN, OST, satellite imagery, dancing sprites.

1. INTRODUCTION

The red, milliseconds-long optical emissions observed high above thunderstorm systems usually come from upper-atmosphere lightning, or Transient Luminous Events, called "red sprites", in short "sprites". Early observations established that sprites are associated with positive cloud-to-ground (+CG) lightning discharges, accompanied by in-cloud (IC) lightning, and are able to discharge a substantial portion of positive charge accumulated in thunderclouds which can result in the dielectric breakdown in the stressed atmosphere above (e.g., Lyons 2006).

Sprites have been observed in Central Europe since at least 2003 (Bór et al. 2009; Bór 2013; Iwański et al. 2009; Arnone et al. 2020). In this work we summarise the results of observations of sprites from Gliwice, Poland, where the possible directions of optical observations of sprites span from the South to North-West, giving the possibility of observations of sprite activity of distant (~500 km) thunderstorms over the Czech Republic, Austria, southern Germany, and south-western Poland. The first part of the paper is aimed at providing detailed information on the number and types of observed sprites as well as providing corrected times of the events. In the second part we analyse positions of sprite parent lightning, selected from detections by the CELDN system, overlaid on satellite imagery-based mappings processed from the EUMETSAT Meteosat data and displaying the "overshooting tops" (OST) cloud features. Our focus is especially directed toward dancing sprites, i.e., the sprite formations being a series of sprites occurring one after another and in some spatial distance from the previous (Lyons 1994).

2. OPTICAL OBSERVATIONS OF SPRITES FROM GLIWICE

Observations have been run from a private flat in the Sikornik area of Gliwice (52.116°N, 21.238°E). The view from the western side allowed successful observations at azimuth range from approximately 180 (South) to 280 (West-N-West). The observational set-up consisted of a monochrome Watec 902H2 Supreme 1/2" low-light TV camera of the frame rate of 50 frames per second, CBC Computar lens (16 mm, F1/4 or 6 mm, F1/2), a time overlay – on-screen display (OSD) unit called KIWI-OSD[1] equipped with a Garmin GPS[2] antenna. The TV signal was analysed by the UFOCapture V2 programme from SonotaCo.com[3] installed on a personal computer. The software saved the video signal of detected objects in .avi and .jpg (such as in Fig. 1b) formats. Observational settings followed the UFOCapture programme settings recommended for the detection of TLEs. The camera was pointed manually using supporting information on the location of storm and lightning activity from meteorological radar maps and satellite

a) b)

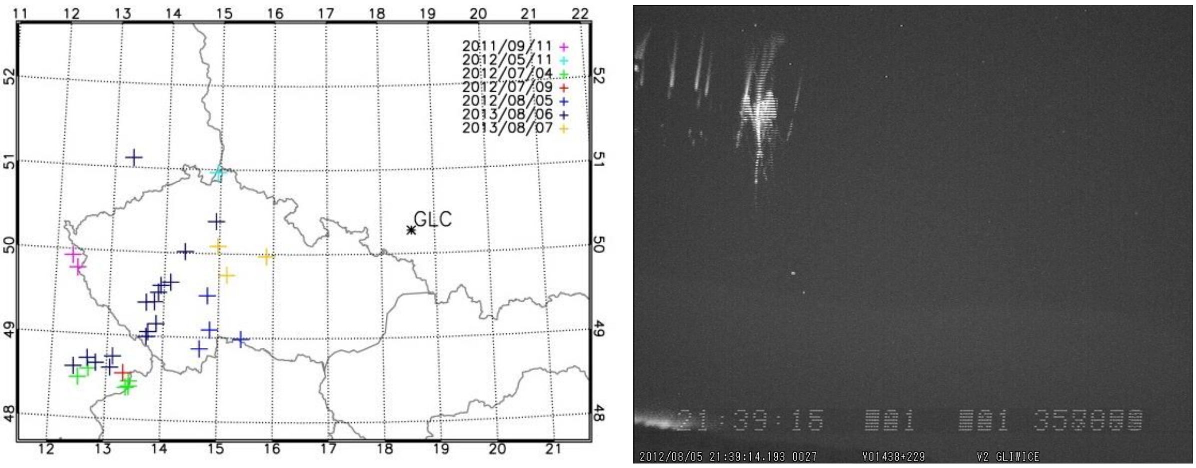

Fig. 1: a) Map of locations of assigned CG parent lightning of sprite events observed on subsequent dates of observations (see Tables 1 and 2); b) example of multiple-sprite event recorded from Gliwice on 5 August 2012, ~21:39:15 UTC (peak-hold image). The event (No. 19 in Table 2) consists of two sprite clusters visible on the left side of the image. They are displaced in space but happening partly simultaneously. One is a cluster of column sprites possibly arranged in a ring. The other is a lone angel or developing carrot sprite. Cloud lightning is visible left at the bottom of the image.

[1] Online at http://sites.google.com/site/kiwiosd
[2] Global Positioning System, https://www.gps.gov
[3] Online at http://sonotaco.com/e_index.html

imagery and maps of lightning detection available online. Initial azimuth has been usually calculated using PanTiltCalc software written by Lasse Clausen (Odzimek et al. 2008). The system was manually switched on and operated in favourable viewing conditions. The usage of lens with ~60° in the horizontal field of view (FOV) in 2013, compared with ~20° FOV in previous years has limited correct identification of the sprite species and, on the other hand, enabled capturing sprites over a wider area, including several dancing sprites events.

Sprites analysed here were observed over May–September in 2011–2013 with the majority of events observed in July and August. Observational logs indicate there were at least 27 nights of observations in total: 11 in 2011, 14 in 2012, and 2 in 2013 – one of the last two, on 6–7 August 2013, was one of the most successful nights of observations in terms of sprite production, in addition to 4 July 2012 and 5 August 2012. In 29 video recordings, 48 events have been recorded, including 7 cases of dancing sprites on the night of 6–7 August 2013, at ~21:27:53 UTC, ~21:33:27 UTC, ~21:45:27 UTC, ~22:38:31 UTC, ~22:42:27 UTC, ~22:59:38 UTC, and ~00:19:49 UTC. In the selection of these events we relied on the visual effect received from the video rather than by measurements of the time separation between sprites and locations. Other interesting events observed at Gliwice include column sprites that proceeded one after another in the same location, in cases considered as rebrightening (e.g., Bór et al. 2018). These are cases of 11 May 2012 at ~21:48:08 UTC and 7 August 2013 at ~23:02:22 UTC. The first sprite observed on 9 September 2011 was preceded by a sprite halo. The two events of 9 September 2011 have been subjected by Odzimek et al. (2013) to detailed analysis of their total, i.e., IC+CG, parent lightning, and the sprites' locations obtained from the triangulation of observations of these events from Gliwice and from Sopron in Hungary

Tables 1 and 2 provide details of the observed events. Table 1 gives information on the dates, and whether the recordings were time-stamped with the GPS, commonly used for precise positioning in time and space. In case the GPS times are absent, constant corrections to PC time are given rounded to the nearest multiple of 50 ms, valid for the whole time of observations or a limited period. These time shifts have been determined by comparison of a series of times of the observed sprites and a series of lightning detections from lightning detection systems over the area. The methodology of calculation of the time shifts as well as of the final estimate of the event times and their errors are described in Odzimek and Mielniczek (2022). Times listed in Table 2 are already given with the time corrections applied. Table 2 provides information on the number of events and subevents captured in each video recording, listed chrono-

Table 1

Summary of sprite observations from Gliwice over 2011–2013

No. nights	Dates	Direction from Gliwice	Time UTC (sprites observed)	Event count	GPS stamp	Time shift (intervals) [s]
1	2011/09/11	NW	20:18–20:23	2	No	+22.85
2	2012/05/11	W	21:48	2	No	–1.35
3	2012/07/04	SW	21:54–22:40	5	No	+0.50
4	2012/07/09	SW	00:44	1	Yes	0
5	2012/08/05	SW	20:47–21:53	8	Yes	0
6	2013/06/08-07	WSW	20:06–00:19	13	GPS missing from 20:30 UTC	+0.35 (21:30–22:05) +0.55 (22:35–23:00) +0.70 (23:55–00:20)
7	2013/08/07	W	23:02	1	Yes	0

Table 2

Details of sprite cases observed from Gliwice in 2011–2013

Count	No. date	No. video	No. event	Sub-event count	Estimated time	Error[4] [ms]	Event description	CELDN parent lightning stroke type and time	CELDN parent CG RS current [kA]
1	#1	#1	#1	2	2011/09/11 20:18:27.404-584 20:18:27.585-645	50	Cluster of columns preceded by a halo Cluster of carrots	+CG 20:18:27.396 20:18:27.399	+5 +11
2		#2	#1	1	2011/09/11 20:22:16.435-475 20:22:16.603-663	50	Multiple columns	IC+CG 20:22:16.499	+6
3	#2	#1	#1	1	2012/05/11 21:48:07.899-959	26	Single column	IC+CG 21:48:07.945	+151
4			#2	1	2012/05/11 21:48:08.019-039	26	Single column repeated in same place as #1	IC+CG 21:48:08.024	+21
5	#3	#1	#1	1	2012/07/04 21:54:08.172-212	21	Cluster of columns	IC+CG 21:54:08.023	+57
6		#2	#1	1	2012/07/04 22:12:33.091-131	21	Cluster of wishbones with dots	IC+CG 22:12:33.097 22:12:33.147 22:12:33.197	+10 +89 +8
7		#3	#1	1	2012/07/04 22:18:17.672-712	21	Cluster of wishbones with an angel	IC+CG 22:18:17.742 22:18:17.742	+96 +17
8		#4	#1	1	2012/07/04 22:21:26.938-978	29	Cluster of carrots	IC+CG 22:21:26.954	+6
9		#5	#1	1	2012/07/04 22:39:43.017-077	24	Cluster of carrots with an angel	IC+CG 22:39:43.006	+188
10	#4	#1	#1	1	2012/07/09 00:44:25.328-368	19	Cluster of carrots	IC+CG 00:44:25.300	+39
11	#5	#1	#1	1	2012/08/05 20:47:18.395-555	0	Cluster of columns with dots	IC, no CG	
12			#2	1	2012/08/05 20:47:18.495-575	0	Cluster of columns with a carrot	IC, no CG	
13		#2	#1	1	2012/08/05 20:51:36.481-581	0	Cluster of columns	IC, no CG	
14		#3	#1	1	2012/08/05 20:54:08.926-09.046	0	Cluster of trees and angels with dots and tendrils	+CG 20:54:08.917	+41

to be continued

[4] This is inividual error due to time corrections within the recording. Additional 50 ms are to be added in case timing of whole series of events has been corrected with a constant calculated translation in time as detailed in the last column of Table 1.

Table 2 (continuation)

Details of sprite cases observed from Gliwice in 2011–2013

15			#2	1	2012/08/05 20:54:09.066-146	0	Cluster of columns with dots and tendrils		IC+CG 20:54:09.079	+26
16		#4	#1	1	2012/08/05 20:58:07.433-453	0	Cluster of columns with dots and tendrils jellyfish		no IC or CG	
17		#5	#1	1	2012/08/05 20:59:55.856-896	0	Cluster of wish-bones with dots		no IC or CG	
18		#6	#1	1	2012/08/05 21:06:00.106-126	0	Cluster of carrots		no IC or CG	
19		#7	#1	2	2012/08/05 21:39:15.881-961 21:39:15.921-16.001	0	Cluster of columns with dots Single angel with dots and tendrils		IC+CG 21:39:15.846 21:39:15.860 21:39:15.866	+99 +8 +11
21		#8	#1	1	2012/08/05 21:52:51.404-484	37	Multiple columns with dots		IC+CG 21:52:50.353	+46
22	#6	#1	#1	1	2013/08/06 20:06:58.705-725	0	Cluster of columns		no IC or CG*	
23		#2	#1	1	2013/08/06 20:24:14.276-296	0	Single carrot		IC+CG 20:24:14.279	+78
24		#3	#1	1	2013/08/06 21:27:52.932-952	29	Double carrot		no IC or CG	
25			#2	1	2013/08/06 21:27:53.112-152	29	Cluster of carrots	dancing	IC+CG 21:27:53.111	+95
26			#3	1	2013/08/06 21:27:53.332-352	29	Double carrot		IC+CG 21:27:53.208	+42
27			#4	1	2013/08/06 21:27:53.492-512	29	Cluster of columns		no IC or CG	
28		#4	#1	1	2013/08/06 21:33:21.777-797	20	Cluster of columns with tendrils jellyfish		+CG 21:24:14.607	+186
28		#5	#1	1	2013/08/06 21:36:49.001-021	18	Cluster of carrots		+CG 21:36:48.832	+127
29		#6	#1	1	2013/08/06 21:45:27.964-28.004	18	Cluster of unrecognised sprites		IC+CG 21:45:27.941	+53
30			#2	1	2013/08/06 21:45:28.144-164	18	Single carrot	dancing	IC+CG 21:45:28.080 21:45:28.094 21:45:28.171 21:45:28.171	+19 +10 +73 +167
31			#3	2	2013/08/06 21:45:28.164-204 21:45:28.184-204	18	Double carrots Cluster of carrots		+CG 21:45:28.094 21:45:28.171 21:45:28.171	+10 +73 +167

to be continued

Table 2 (continuation)

Details of sprite cases observed from Gliwice in 2011–2013

32		#7	#1	1	2013/08/06 22:01:45.025-065	29	Cluster of carrots in circle		IC+CG 22:01:45.120	+37
33			#2	1	2013/08/06 22:01:45.582-602	29	Cluster of columns with tendrils		IC+CG 22:01:45.641	+156
34		#8	#1	1	2013/08/06 22:38:31.740-780	18	Multiple columns with tendrils, jellyfish	dancing	IC+CG 22:38:31.717 22:38:31.718	+18 +184
35			#2	1	2013/08/06 22:38:31.560-680	18	Multiple carrots		IC+CG 22:38:31.846 22:38:31.846	+65 +89
36		#9	#1	1	2013/08/06 22:42:27.580-640	21	Cluster of unknown	dancing	IC+CG 22:42:27.559 22:42:27.644	+77 +15
37			#2	1	2013/08/06 22:42:27.620-660	21	Cluster of unknown		IC+CG 22:42:27.559 22:42:27.644	+77 +15
38			#3	1	2013/08/06 22:42:27.660-740	21	Multiple unknown		+CG 22:42:27.559 22:42:27.644 22:42:27.806	+77 +15 +146
39			#4	1	2013/08/06 22:42:27.820-840	21	Cluster of columns with tendrils, jellyfish		+CG 22:42:27.806 22:42:27.899	+146 +12
40		#10	#1	1	2013/08/06 22:52:17.167-187	17	Cluster of columns with tendrils, jellyfish		IC+CG 22:52:17.099 22:52:17.153	+21 +165
41		#11	#1	1	2013/08/06 22:59:38.969-39.009	17	Cluster of carrots	dancing	+CG 22:59:38.962	+106
42			#2	1	2013/08/06 22:59:38.089-129	17	Double carrots		+CG 22:59:39.135	+125
43			#3	1	2013/08/06 22:59:39.149-169	17	Cluster of columns and wishbones		+CG 22:59:39.135	+125
44		#12	#1	1	2013/08/06 23:58:40.883-923	17	Cluster of carrots or trees	dancing	+CG 23:58:40.797	+53
45			#2	1	2013/08/06 23:58:41.243-283	17	Cluster of columns with tendrils		+CG 23:58:41.102 23:58:41.221 23:58:41.221	+11 +26 +61

to be continued

Table 2 (continuation)
Details of sprite cases observed from Gliwice in 2011–2013

46	#7	#1	#1	1	2013/08/07 00:19:49.861-921	17	Cluster of columns and wishbones	dancing	+CG 00:19:49.868	+35
47			#2	1	2013/08/07 00:19:50.201-241	17	Cluster of carrots in circle		IC+CG 00:19:50.096 00:19:50.230	+19 +53
48		#2	#1	2	2013/08/07 23:02:22.448-488 23:02:22.488-548	0	Single column Single column repeated		+CG 23:02:22.457 23:02:22.491	+158 +51
Total				52						

*Indications of parent lightning confirmed in lightning dataset used for Eurosprite campaigns (e.g., Arnone et al. 2020).

logically, and calculated time errors resulting for the corrections of the timing within video recordings. An additional 50 ms error is to be applied for events with the time correction performed on series of events without GPS timing (see Table 1). The total number of subevents, i.e., sprites which may be of different types or be spatially displaced but captured in the same video field sequence (starting in intervals not exceeding one frame lasting 40 ms) amounts to 52.

3. SUPPORTING OST SATELLITE PRODUCTS

A thundercloud's overshooting top (Glickman 2000), the cloud's part protruding high beyond the troposphere, indicates a high degree of its vertical development and activity which may be associated with severe weather phenomena. The need for detecting such features with remote sensing methods resulted in the development of OST nowcasting products (e.g., Pajek et al. 2008, Bedka et al. 2010). An OST product is generally based on the difference of brightness temperatures in two infrared spectral channels, and the highest differences of these temperatures are related to the occurrence of the overshooting tops.

In the case of sprite observations, we rather look for periods when the activity decreases (Odzimek and Pajek 2016), and the OST maps help to identify locations of the stratiform precipitation area (characterised by lower brightness temperature gradients) over which the most intense sprite production may occur. For confirmation we have also checked the Czech meteorological radar data published at the Czech Hydrometeorological Institute website[5]. The observations have been supported by the display OST images in near-real-time at 15-min frequency (Odzimek et al. 2014). These OST products were processed from the EUMETSAT Meteosat imagery data of the SEVIRI instrument channels at 6.2 μm and 10.8 μm, at the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI) in Kraków. The images have been prepared in two formats: one covering whole Europe and another focused on the locations of observations sites in Poland and the neighbourhood. Examples of such OST images from the four most active nights of observations are shown in Fig. 2.

[5] Online at https://www.chmi.cz/

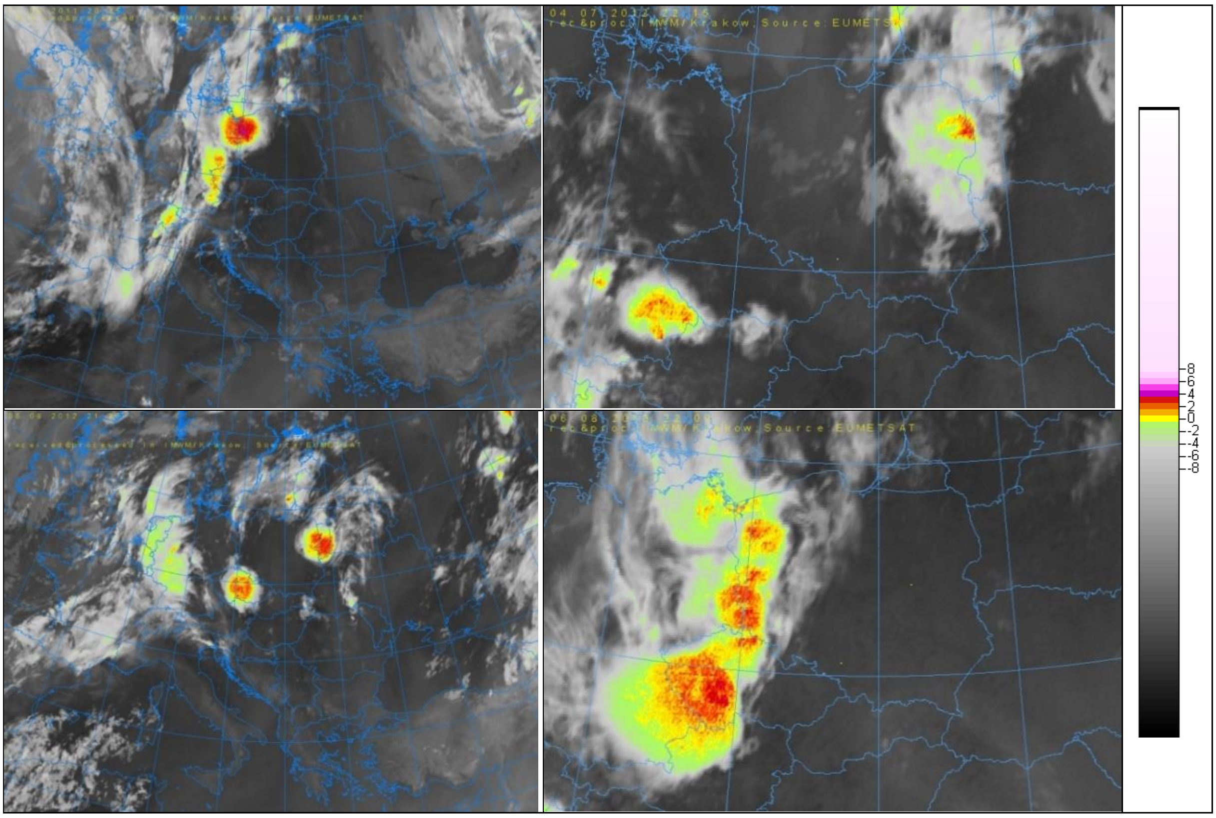

Fig. 2. The “overshooting tops” images of the sprite-producing thunderstorms in Central Europe, processed at IMWM-NRI in Kraków from Meteosat SEVIRI imagery. Top left: 11 September 2011, 20:15 UTC; top right: 4 July 2012, 22:15 UTC; bottom left: 5 August 2012, 21:30 UTC; bottom right: 6 August 2013, 22:00 UTC. The selected moment is approximately in the middle of the sprite production period by a storm. Rightmost: the scale for the OST brightness temperature gradient.

4. PARENT THUNDERSTORMS AND PARENT LIGHTNING OF SPRITES

Table 2 includes also information on parent lightning identified in the detections of cloud-to-ground and in-cloud lightning by the CELDN (Central European Lightning Detection Network) system used in the Czech Republic (e.g., Novák and Kyznarová 2011). CELDN differentiates between cloud-to-ground and in-cloud lightning and provides the location and polarity of both types of lightning. In many sprite cases, positive CG parent lightning, SP+CG, have been identified among CELDN detections. Also, many positive ICs (not listed) have been associated as parent. The positive in-cloud lightning strokes prevail as associated parent lightning approximately at the ratio 2:1 with respect to negative IC lightning. Association as a parent lightning was considered positive in case the lightning occurred in the vicinity of aimed location and within the time range of 100 ms from the start of the first video field till the ending of last field containing the event, including errors. In cases when the time shift was applied, the duration of the range was prolonged by 50 ms from both ends.

4.1 Post-analysis of combined OST and CELDN lightning data

In this section we use information resulting from combining OST and lightning data in regard to parent lightning of sprite events. By mapping the lightning positions onto the OST products we obtain the relative position of lightning in the convective or stratiform area of the parent

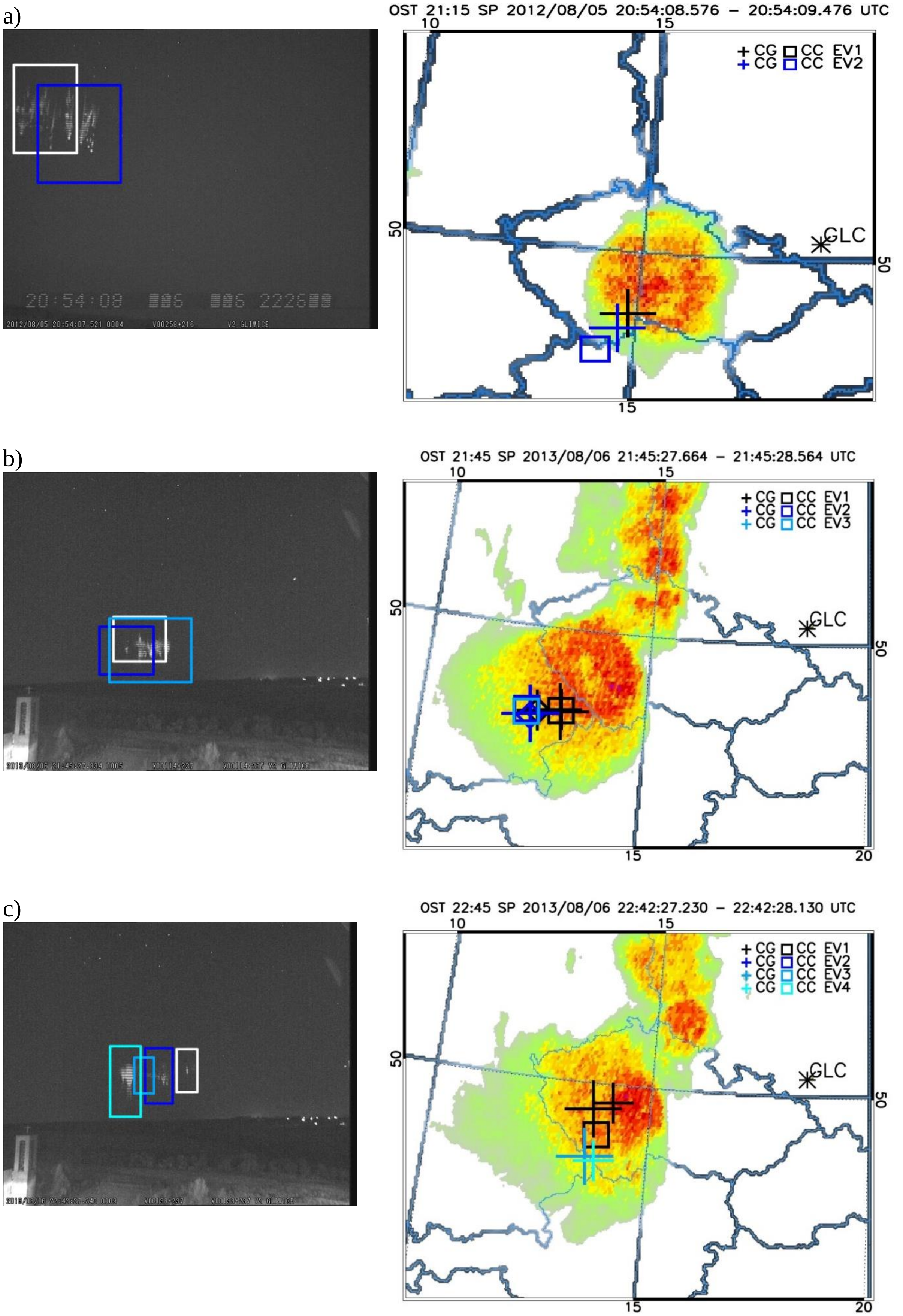

Fig. 3. Continuation on the next page.

d)

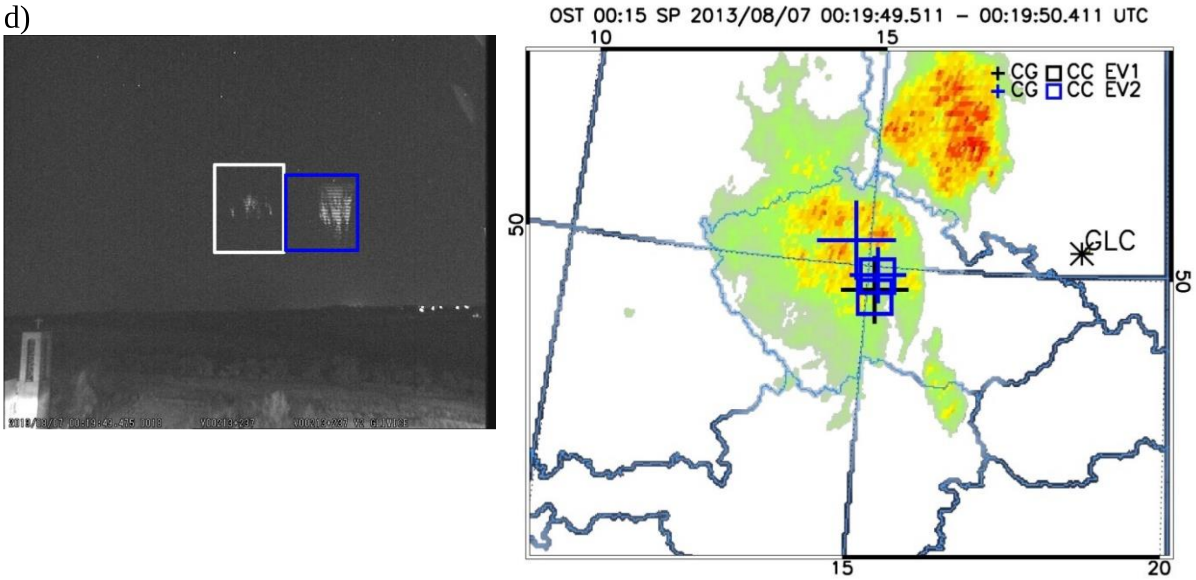

Fig. 3. Peak-hold images (left) of sprites and the map of parent lightning (right) of subsequent events (EV) coloured black (or white), blue, light blue, turquoise from oldest to latest in cases of: a) 5 August 2012, 20:54:08 UTC, events 14–15; b) 6 August 2013, 21:45:27 UTC, events 29–31; c) 6 August 2013, 22:42:27 UTC, events 36–39; d) 7 August 2013, 00:19:49 UTC, events 46–47. Legend: crosses mark locations of +CGs, squares mark locations of +CCs, diamonds mark locations of –CCs.

storm, and, in the case of multiple-sprite events, the position of subsequent parent strokes. Results of such analysis are presented in Fig. 3. In four multiple-sprite events, we show the position and sequence of parent lightning associated with a consecutive event mapped on the OST image reflecting also the stage of the thundercloud development. The grey "background" around the active clouds, visible in examples in Fig. 2, has been erased to white in order to make the images more clear.

The first example in Fig. 3a is a two-event case of 5 August 2012 starting at ~20:54:08 UTC when a cluster of tree and angel sprites with tendrils was followed by a cluster of column sprites. In Fig. 3b-d similar mappings are presented for the three cases of dancing sprites on 6–7 August 2013, at ~21:45:27 UTC, ~22:42:27 UTC, and ~00:19:49 UTC. Each example is represented in Fig. 3 by a peak-hold image of an event (panels on the left) and an OST map (panels on the right). The locations of parent lightning associated with subsequent events are mapped on the OST image and coloured differently, depending on which subsequent event it was associated with. Locations of the subsequent events are also marked by colour frames in the peak-hold images (black is replaced by white).

The three selected dancing events occurred at various stages of the thundercloud development. The first one (Fig. 3b) belongs to a still active phase, although some signs of decay of the vertical size can also be noticed. The second one (Fig. 3c) happens in the continuing decay phase, and the third (Fig. 3d) in the latest stages of this thunderstorm and production of sprites.

5. DISCUSSION

Among sprites recorded from Gliwice there are events recognised as column, carrot, wishbone, tree, and angel sprites. Sprite types in four events were not recognised. Compared with sprites observed from Świder (SWI) in the north (Odzimek et al. 2022, this issue), carrot sprites are more numerous (44% at GLC vs. 23% at SWI) and column sprites are less prevalent, although still most common (46% at GLC vs. 72% at SWI). Jellyfish formations, familiar from other

Central European sprite observational campaigns (e.g., Bór 2013) are on a comparable level (11% at GLC vs. 13% at SWI). In addition, compared with one dancing event observed in 2012 from Świder here we have recordings of 7 dancing sprites events; albeit they have been products of rather exceptional situation on the night of 6–7 August 2013 (Fig. 2d) when several long-lived mesoscale thunderstorms developed west of the Germany-Czech Republic and Germany-Poland border, at times merging their cells into one system. Approximately 20% of the 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 such as that in Fig. 1b. The longest sprite sequences comprising up to 2 sprite subevents have been captured in a sequence of video frames lasting up to 6 video fields equivalent to 120 ms. A dancing event is composed of a series of single or mixed-sprite events, and its duration may be several hundred milliseconds.

Bór et al. (2018) have analysed the location of the sequence of lightning in five dancing events of 6/7 August 2013 in detail, including events at ~21:45:27 UTC and ~22:42:27 UTC analysed here. They also determined triangulated positions of events observed simultaneously from two observational stations, and studied their relation to the parent of next sprite events in the dancing sequence. Similarly to previous observations (e.g., Lang et al. 2010; Soula et al. 2017; Tomicic et al. 2021, and references therein) it emerged that the sequence was such that the next sprite and its parent lightning SP+CG occurred each time farther away from the convective core of the thunderstorm, and closer to the rear of the thunderstorm and its stratiform part. This is in agreement with general positive lightning activity in an active MCS system (e.g., Carey et al. 2005). The maps in Fig. 3a-c support such a scenario, as also does the sequence of parent lightning in the dancing events at ~22:01:44 UTC and ~22:59:38 UTC (not shown). In a smaller thunderstorm system, like the one of 5 August 2012, the edge-of-core-to-rear progression of SP+CG seems also valid, as the first example at ~20:54:08 UTC shows. The events in Fig. 3d at ~00:19:49 UTC on 7 August 2013 show the opposite behaviour. They happened in the latest stages of this thunderstorm system and the OST map from 00:15 UTC reflects the already devolved structure of the thunderstorm. The division into leading convective and trailing part is no longer so clear – the whole structure collapses, and perhaps therefore the path of consecutive lightning produced by the decaying thunderstorm is different. This event would also support the postulate that the distribution of positive charge producing different potential difference received by the negative leader of propagating lightning helps to maintain or stop the development of this lightning.

It has been also previously hypothesised that in the case of dancing sprites the series of +CG parent lightning together with in-cloud lightning are part of one complex lightning discharge, recently called a megaflash (Lyons et al. 2020). The second dancing event at ~22:42:37 UTC (and a very similar at ~22:38:31 UTC, not shown), may potentially be the product of a parent megaflash – an extended lightning that produces a series of positive CGs and sprites along – resulting in such multi-event dancing sprites. The thunderstorm system of 6/7 August 2013 had sufficiently large surface area (covering more than half of the Czech Republic) with an extensive stratiform part where such lightning could develop, discharging the vast reservoir of positive charge along and producing dancing sprites. Looking at the maps displaying the types and locations of lightning by CELDN we find intra-cloud detections along SP+CG but the interpretation of the total lightning path is not possible. On the other hand, parent lightning of the dancing sprites at ~21:27:53 UTC occurred no later than the end of the first event, so the other events might have been rather associated with resurges in the +CG continuing currents – such occurrences were reported by Lu et al. (2013). In the two-sprite event shown in Fig. 3a no in-cloud lightning has been detected but each sprite has its probable parent +CG.

6. SUMMARY

The total of 52 TLEs of the red sprite type TLE events have been recorded optically between September 2011 and August 2015 from Gliwice. The ratio of column and carrot sprites, observed over the area of the Czech Republic and parts of Germany and Poland, is higher than that based on observations in the north of Poland. Some long-lived storms, such as those on the nights of 11 September 2011, 4 July 2012, 5 August 2013, and 6–7 August 2013, have been prolific in the production of sprite-lightning, especially the last one which produced several dancing sprite events. There were also observed two events of column sprite rebrightening. We have utilised Meteosat satellite imagery used for detection of thunderclouds' overshooting tops (OST) for analysing the sequence of the sprites' parent lightning locations in some multiple-sprite events, on the background of the thunderclouds structure as denoted by the OST. The products provide another valuable opportunity for the investigation of the relationships between parent lightning and dancing sprite events. The observed rule that subsequent SP+CGs proceed away from the verge of convective parts towards the stratiform rear holds in the active phase of the parent thunderstorm system but in the latest stage of decay the progression may become disorganised.

Acknowledgments. This work is supported by subsidies from Poland's Ministry of Education and Science to the Institute of Geophysics, Polish Academy of Sciences (IG PAS).

The system for sprite observations at Gliwice has been provided from the private resources of authors A. Odzimek and M. Mielniczek.

We acknowledge that the Meteosat satellite images used during observations have been processed at IMWM-NRI in Kraków in agreement with the EUMETSAT licence IMWM/LIC/MSG/10/06 (50002869), and uploaded to a server at IG PAS. We thank Mariusz Neska of IG PAS for his support in organising this upload.

We thank Torsten Neubert and National Space Institute, Technical University of Denmark for the access to cloud-to-ground lightning data from the Eurosprite campaigns 2012–2014.

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.

Bedka, K., J. Brunner, R. Dworak, W. Feltz, J. Otkin, and T. Greenwald (2010), Objective satellite-based detection of overshooting tops using infrared window channel brightness temperature gradients, *J. Appl. Meteorol. Clim.* **49**, 2, 181–202, DOI: 10.1175/2009JAMC2286.1.

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.

Bór, J., Z. Zelkó, T. Hegedüs, Z. Jäger, J. Mlynarczyk, M. Popek, and H.D. Betz (2018), On the series of +CG lightning strokes in dancing sprite events, *J. Geophys. Res.: Atmos*. **123**, 19, 11030–11047, DOI: 10.1029/2017JD028251.

Carey, L.D., M.J. Murphy, T.L. McCormick, and N.W.S. Demetriades (2005), Lightning location relative to storm structure in a leading-line, trailing-stratiform mesoscale convective system, *J. Geophys. Res.: Atmos*. **110**, D3, D03105, DOI: 10.1029/2003JD004371.

Glickman, T. (2000), *Glossary of Meteorology*, 2nd ed., American Meteorological Society, Boston.

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.

Lang, T.J., W.A. Lyons, S.A. Rutledge, J.D. Meyer, D.R. MacGorman, and S.A. Cummer (2010), Transient luminous events above two mesoscale convective systems: Storm structure and evolution, *J. Geophys. Res.: Space Phys*. **115**, A5, A00E22, DOI: 10.1029/2009JA014500.

Lu, G., S.A. Cummer, J. Li, L. Zigoneanu, W.A. Lyons, M.A. Stanley, W. Rison, P.R. Krehbiel, H.E. Edens, R.J. Thomas, W.H. Beasley, S.A. Weiss, R.J. Blakeslee, E.C. Bruning, D.R. MacGorman, T.C. Meyer, K. Palivec, T. Ashcraft, and T. Samaras (2013), Coordinated observations of sprites and in-cloud lightning flash structure, *J. Geophys. Res.: Atmos*. **118**, 12, 6607–6632, DOI: 10.1002/jgrd.50459.

Lyons, W.A. (1994), Characteristics of luminous structures in the stratosphere above thunderstorms as imaged by low-light video, *Geophys. Res. Lett*. **21**, 10, 875–878, DOI: 10.1029/94GL00560.

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.

Lyons, W.A., E.C. Bruning, T.A. Warner, D.R. MacGorman, S. Edgington, C. Tillier, and J. Mlynarczyk (2020), Megaflashes: Just how long can a lightning discharge get?, *Bull. Am. Meteorol. Soc.* **101**, 1, E73-E86, DOI: 10.1175/BAMS-D-19-0033.1.

Novák, P., and H. Kyznarová (2011), Climatology of lightning in the Czech Republic, *Atmos. Res*. **100**, 4, 318–333, DOI: 10.1016/j.atmosres.2010.08.022.

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., J. Bór, M. Mielniczek, M. Pajek, P. Struzik, and P. Novak (2013), A case study of two sprite events recorded over western Europe. **In:** *EGU General Assembly 2013, 7-12 April 2013, Vienna, Austria*, Geophysical Research Abstracts, Vol. 15, EGU2013-8775-2.

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.

Odzimek, A., W. Gajda, M. Pajek, and M. Kubicki (2022), Red sprites over northwest Poland and the southern Baltic coast observed from Świder Geophysical Observatory, *Publs. Inst. Geoph. PAS* **D-77 (442)**, 55–70, DOI: 10.25171/InstGeoph_PAS_Publs-2022-025 (this issue).

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.

Soula, S., J. Mlynarczyk, M. Füllekrug, N. Pineda, J.-F. Georgis, O. van der Velde, J. Montanyá, and F. Fabró (2017), Dancing sprites: Detailed analysis of two case studies, *J. Geophys. Res.: Atmos*. **122**, 6, 3173–3192, DOI: 10.1002/2016JD025548.

Tomicic, M., S. Soula, E. Defer, S. Prieur, J. Mlynarczyk, T. Farges, O. Chanrion, C. Köhn, and T. Neubert (2021), Dancing sprites above a Lightning Mapping Array – An analysis of the storm and flash/sprite developments, *J. Geophys. Res.: Atmos*. **126**, 20, e2021JD035059, DOI: 10.1029/2021JD035059.

Received 16 September 2022
Received in revised form 30 December 2022
Accepted 31 December 2022