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TOTAL LIGHTNING IN A TLE-BEARING WINTER THUNDERSTORM OVER THE WESTERN MEDITERRANEAN

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1. INTRODUCTION

Until recently, transient luminous events (TLEs) above winter thunderstorms had been observed exclusively in the Sea of Japan. Now, Ganot et al. (2007) and Greenberg et al. (2007) have reported TLE events in winter thunderstorms on the eastern Mediterranean near the coast of Israel. The Mediterranean Sea is one of the few regions in the Northern Hemisphere where winter thunderstorms are rather frequent. Space-borne observations of lightning (Christian et al., 2003) have shown that Mediterranean Sea exhibits lightning activity in most of the winter months.

In this paper we present the analysis of one specific thunderstorm, which occurred during the night of 17th to 18th December 2007 in the western Mediterranean Sea, in the coastal area of Catalonia (NE Spain) (Fig.1).

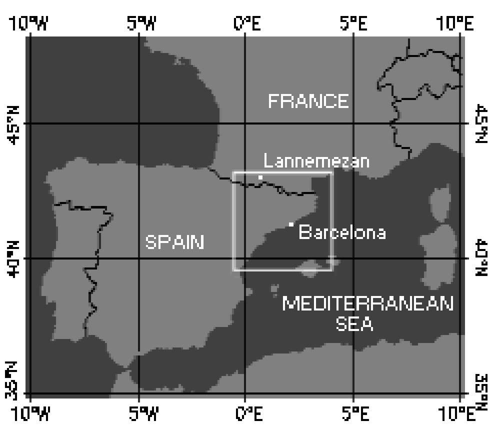


Figure 1. Region of interest in NE Spain. Lannemezan (South of France) is from where the TLE observations were recorded.

The analysis is focused on total lightning activity and its relation to the TLE events observed above this winter thunderstorm.

2. DATA

2.1. Data from the SMC

The Meteorological Service of Catalonia (SMC) operates a Vaisala Thunderstorm Information System (TIS) since 2003. In 2007 the system was upgraded with a CP8000 processor. Moreover, a new LS8000 station was installed in 2007. Currently, the SMC-TIS, hereafter XDDE, has 4 operational stations, two LS8000 and two SAFIR 3000 (Fig.2).

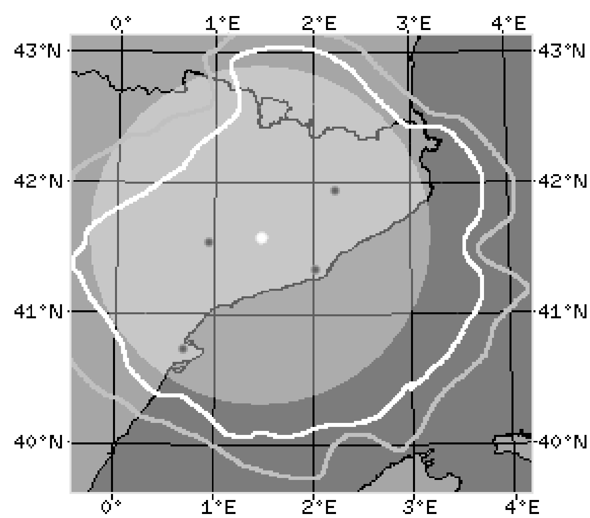


Figure 2. Area of study. Location of the CDV weather radar (white dot), and its area of coverage (lighter circle). XDDE sensors (black dots) and the limits of the <1km (white line) and <2km (grey line) location accuracy.

The total lightning locations of CP8000 combine both LF and VHF data to develop lightning location information from preliminary breakdown to ground strokes. The addition of the higher-frequency components of the lightning discharge (VHF) makes it possible to reconstruct the path (map) of the cloud discharge (VAISALA, 2004).

The SMC also operates a three C-band weather radar network. These radars generate volumes of data every 6 minutes, with one scan at 0.6º at a long range (240 km) and a series of 14 scans with elevations sweeping of 0.6º at a short range (150 km). More details of the radar network are given in the study of Bech et al. (2004). In this study, data from the "Creu del Vent" radar (41.60ºN,1.40ºE, 825m ASL) (hereafter CDV) have been used (Fig.2).

Finally, the SMC radiosonde records of the Barcelona station (41.62ºN, 2.20ºE, 98 m ASL) have been used to infer the isotherms heights and to calculate instability indexes during the analyzed period.

Besides SMC data, Cloud-to-ground lightning data was taken from EUCLID (http://www.euclid.org/), as the SMC CP8000 LF processing was not fine tuned at that time, due to its recent installation.

2.2. TLE observations

Several sensitive video cameras were available during EuroSprite 2007 campaign (http://www.eurosprite.net/). The images of sprites and elves analyzed in this paper were obtained from Lannemezan, in the south of France (Fig.1). The camera is a Watec 902H, with a sensitivity of 0.0003 lux at f/1.4 (Fig.3). The pan-tilt unit and the camera were remotely controlled by using a VNC software. The system performed real-time automatic event detection for reduction of the data volume. The video images have a 20 ms frame time duration.

During the night of 17th to 18th 2007, images of 17 sprites and 8 elves were obtained over the western Mediterranean and the Catalan coast (Fig. 4 shows one example). From these events, 5 sprites and 2 elves were located in the area of the study, delimited by the XDDE and the CDV radar coverage area (Fig.2). The TLE events analyzed are presented in Table 1.

Figure 3. The Watec 902H camera with the pan/tilt uni, located in Lannemezan.

Table 1. TLE observations from Lannemezan

TLE Observation				
nº	DATE	hh:mm:ss	ms	type
S7	18/12/2007	0:05:35	161-181	Sprite
S9	18/12/2007	0:35:23	626-646	Sprite
S10	18/12/2007	0:56:05	306-326	Sprite
S11	18/12/2007	1:06:03	895-915	Sprite
S12	18/12/2007	1:43:59	658-678	Sprite
E3	18/12/2007	1:58:56	171-191	Elve or halo
E7	18/12/2007	4:12:16	556-576	Elve

Figure 4. Sprite image from the Lannemezan camera. Sprite at 0:05:35 UTC.

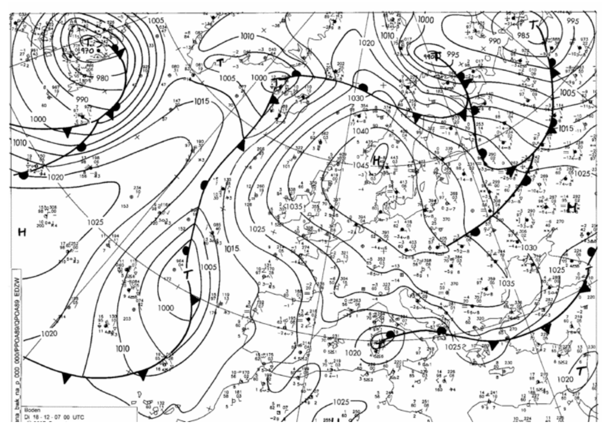
3. ANALYSIS

3.1. Synoptic analysis

A weak low (1015 hPa) was originated in the days before the studied episode, in the north of the western Mediterranean, between Balearic Islands and the gulf of Genova. The low moved to west, and on December 18th 00:00 UTC it was situated between Corsica and Cerdegna (Fig.5). Such situation has lead to an advection from the east to the Catalan coastal area, generating wind gusts up to 40 km/h At 500 hPa, during December 17th, an upper-level trough has developed on the eastern Mediterranean, with cold air with temperatures of –38ºC. The trough moved to the western Mediterranean, and on December 18th 00:00 UTC it was situated in the vertical above Catalonia, with temperatures around -33ºC.This combination of maritime winds at low levels with the upper-level trough has generated the analyzed thunderstorm.

3.2. Instability Indexes

The CAPE (Convective Available Potential Energy) calculated from the Barcelona radiosonde (aprox. 100 km from the sprite observations), on December 17th 2007 12:00 UTC had a value of 108 J Kg^{-1}. Such value is lower than the CAPE values of the winter thunderstorms in the Eastern Mediterranean analyzed by Ganot et al 2007, which were between 200 and 400 J Kg^{-1}. Rigo (2004) has analyzed the CAPE in the region of study in rainy days (1996-2000), and has obtained a mean value for the winter months of 130 J Kg^{-1}. Thus the CAPE of the present episode does not seem to be higher than the usual value in rainy episodes in the winter season in the region. While CAPE values are small in winter thunderstorm situations, the warm sea water relative to the cold air mass keeps replenishing the boundary layer with heat and moisture (Van der Velde, 2008). Moreover, it must be taken into account that usually, CAPE values in the region are lower than those found in the Great Plains of the U.S. (Romero et al., 2007). This appears to result in a smaller average size and shorter duration of storm systems (Van der Velde, 2008).



Synoptical analysis 2007-12-18 00:00

Figure 5. Surface synoptic analysis from December 18th at 00:00 UTC.

Table 2. Cloud top temperature from Meteosat imagery and heights from the Barcelona radiosonde (18/12/2007 00:00 UTC), and radar maximum reflectivity (Zmax) and Echotop-12dBZ product heights in the vicinity of the TLE parent +CGs (P+CG)

TLE #	Meteosat time UTC	Cloud Top Max ºC	Cloud Top Max Alt(m)	Cloud top P+CG ºC	Cloud top P+CG Alt(m)	RADAR time UTC	TLE dist.(km)	Zmax dBZ	Echotop-12 (km)
S7	0:00	-49	7550	-45	7100	0:06	106	17.5	4
S9	0:30	-51	7990	-47	7290	0:36	96	13.0	3.4
S10	1:00	-47	7290	-37	6140	0:54	80	17.0	3.3
S11	1:00	-47	7290	-38	6260	1:06	61	22.5	3.6
S12	1:45	-47	7290	-39	6370	1:42	104	21.5	4.6
E3	2:00	-47	7290	-41	6630	2:00	90	22.0	4.2
E7	4:15	-44	6950	-33	5660	4:18	110	15.0	3.3

3.3. Meteosat imagery

The results of the analysis done on the Meteosat-9 (MSG-2) imagery (example in Fig.6), is summarized in Table 2. We have found that the coldest thundercloud tops at the moment of the analyzed TLEs were around -50ºC, while the cloud top temperature above the TLE parent +CG location (hereafter P+CG) was warmer by 3-11 degrees. This result is similar to the ones found in van der Velde et al. (2006).

According to the Barcelona radiosonde on December 18th at 00:00 UTC, the tropopause was around -51ºC, which corresponds to an altitude of 8010 meters. Maximum cloud tops observed are close to the tropopause, while the cloud top temperature above the P+CG location were 500 to 2000 meters below.

It can be seen in Table 2 that cloud tops above TLE P+CGs have heights between 5.5 and 7.3 km approximately, and temperatures between -33ºC and -47ºC. Takahashi et al., (2003), in their study of sprites in winter thunderstorms over the Sea of Japan, have found lower heights (between 4.2 and 6.6 km) and warmer cloud top temperatures (ranging from about –25º to –10ºC). On the other hand, Ganot et al. (2007) reported more similar thunderstorm cloud conditions in their observations of sprites in winter thunderstorms in the eastern Mediterranean, with cloud top temperatures around –40ºC and higher cloud tops (7 to 9 km).

The total shield of cloud tops colder than -30ºC reached an area of almost 70,000 km^2, while the area colder than -50ºC reached its maximum around 01:00 UTC with 216 km^2 (table 3). According to Mohr and Zipser (1996) such dimensions and temperatures are indicative of a Mesoscale Convective System (MCS).

Table 3. Cloud Area colder than -30ºC and -50ºC in km^2

Time (UTC)	0:00	0:30	1:00	2:00	4:15
T < -30ºC	63800	66000	68200	63000	6000
T < -50ºC	0	90	216	0	0

Takahashi et al. (2003), have observed sprites above the highest cloud tops of the storm system, thus near the most active vertical motion is occurring. These observations differ from summer thunderstorms observations, where the majority of sprites are observed above large stratiform regions and not near the convective core (Lyons, 1996). In the TLEs analyzed here, two different patterns were observed. Sprites S7 (0:06 UTC) and S9 (0:35 UTC) are located in the SW cell, above the Ebro river delta, while the rest of events are located in the NW cell, which appeared later on, and was located over sea in front of the Catalan coast (Fig.6). According to the Meteosat images, the P+CG of sprites S7 and S9 occurred near the coldest cloud tops in the SW cell, during the growing period of this cell, which reached its maximum cloud cold area around 01:00 UTC.

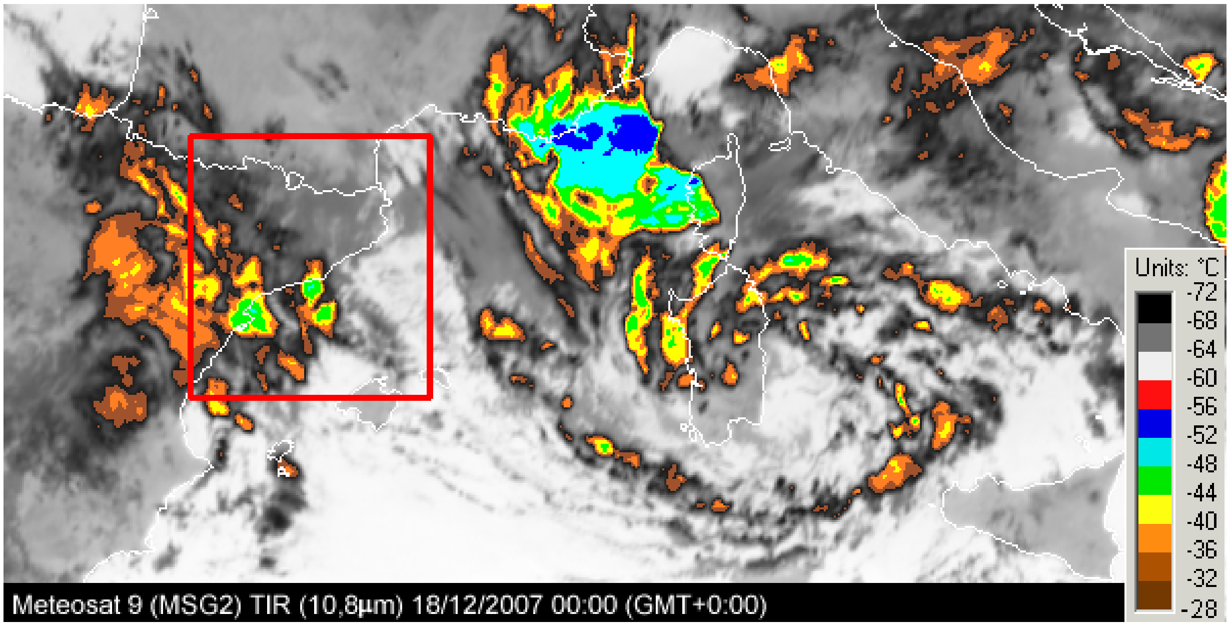


Figure 6. Thermal infrared image from Meteosat-9 of the Western Mediterranean area. The red square indicates the region where the TLE events were observed.

In the NE cell, P+CG of sprites S10 (0:56 UTC), S11 (1:06 UTC) and S12 (1:43 UTC) were located above warmer cloud tops (see Table 2), with heights lower in almost 1 km compared to sprites S7 and S9. Elves E3 and E7 came after the Sprites. Elve E3 (1:58 UTC) was seen just after both cells have merged in one, and its P+CG is located above the tail zone of the merged cell. Finally, E7 occurred two hours later (4:12 UTC) in a large but thin stratiform band, in the decaying stage of the thunderstorm, when lightning flashes were rare.

3.4. Sea Surface Temperature

The Sea surface temperature of the Mediterranean Sea in the area of study was between 16 and 17ºC, as calculated with NOAA AVHRR imagery (Chic and Font, 2004). Such temperatures are similar those found by Ganot et al (2007) in their sprite's study in eastern Mediterranean (SST 17ºC) and warmer than the temperatures in TLE bearing winter thunderstorms in the sea of Japan for the case study of Suzuki et al 2006, (14ºC).

3.5. Weather radar analysis

The first sprites (S7 and S9 in Table 2) were associated to a relatively small linear convective structure approximately 35 km long considering 10 dBZ contours in the 3-D radar MAX product (this structure was named SW cell in the satellite analysis). Maximum intensities were about 20 to 35 dBZ. From 00:00 UTC to 1:00 this system grew in size, enlarging the linear convective area (with values above 30 dBZ) suggesting Quasi Linear Convective System characteristics.

A larger precipitation structure mainly made up of scattered stratiform radar echoes (>10 dBZ), was located north east from the first one. This system, considering 10 dBZ contours, exceeded 100 km in size, thus verifying the spatial requirement for a Mesoscale Convective System (MCS) according to Houze (1993). This precipitation area (named NE cell in the satellite analysis) was associated to sprites S10, S11 and S12 (see Table 1). It was mainly stratiform with embedded convection, with a few precipitation cores exceeding 30 dBZ. At 1:00 UTC it was approximately elliptical with semi-axes of 120 km and 60 km.

According to the radar analysis, both SW and NE cells have merged around 1:54 UTC, the new cell having a size about 150 x 100 km, but most cores had decreased in intensity. Elve E3 (1:58 UTC) occurred soon after this merging, while elve E7 (4:12 UTC) was observed in the splitting and dissipating stage of the thunderstorm.

Table 2 shows also the mean value of Maximum reflectivity (Zmax) and the Echotops (at 12 dBZ) in a 5 x 5 pixel box (aprox. 25 km^2) around the TLE parent +CGs. Zmax values are between 13 and 22.5 dBZ, while Echotops are between 3.3 and 4.6 km. Analyzing the radar images, we have seen that the majority of the events are located near a core reflectivity area. Figure 7 shows an example of the analyzed cross sections.

3.6. Total lightning analysis

The XDDE has recorded from December 17th 20:00 UTC to December 18th 07:00 UTC 200 cloud-to-ground (CG) flashes, 322 CG strokes, 318 intracloud (IC) flashes and 110 IC isolated VHF sources. The CG multiplicity is therefore 1.6 while the annual 2007 mean in the region is generally 2.1. 69% of the CG flash first strokes were of negative polarity, and therefore 31% of positive polarity. The maximum flash rates reached 4 IC flashes min^{-1} and 2.3 CG flashes min^{-1}, around 01:00 UTC for both cells joined together. Lyons (1996) has pointed out that the sprite production is not correlated with the total CG flash activity. In the present episode, we have observed sprites during different CG flash rates. In the case of the two observed elves, both occurred when the CG flash rate was very low.

Altaratz et al. (2001) has characterized winter thunderstorms in the eastern Mediterranean, defining the following conditions for lightning activity: 1) Top of clouds higher than 6.5 km at temperatures colder than -30ºC; 2) Maximum radar reflectivity higher than 45 dBZ; 3) Intensity of reflectivity exceeding 35 dBZ at the -10ºC level, and 4) Radar-derived rain intensity higher than 26 mm h^{-1}. In the analyzed case, all conditions were accomplished.

Moreover, Altaratz et al. (2001) defined some thresholds to be exceeded before the beginning of the lightning activity, which are: 1) A period between the first radar echo and the first CG of 10-15 min; 2) The 40 dBZ echo top should be above the -8ºC level; 3) The 30 dBZ echo top should be above the -12ºC level and 4) The radar reflectivity at the -10ºC level should be larger than 32 dBZ at the time of the first CG. In the analyzed episode, it was hard to determine condition 1). Conditions 3) and 4) were reached before the first CG stroke, while condition 2) was reached only at the moment of the maximum CG flash rate and not at the beginning of the activity.

Analyzing the radar echo top of 20, 30 and 40 dBZ and the lightning activity (Fig 8), in our case study we have observed the following:

1) Lightning activity was present when the 20 dBZ echo top was above the -20ºC level.
2) Lightning activity was present when the 30 dBZ echo top was above the -10ºC level.
3) The maximum IC and CG flash rates were not related to the presence of reflectivity above 40 dBZ, and seemed more related to the evolution of the 30 dBZ echo top heights.

Diendorfer et al. (ILDC 2006) has observed the first flashes, at the Gainsberg tower (near Salzburg, Austria) in a winter thunderstorm, few minutes after the 20 dBZ reflectivity echo exceeded the -20ºC level, and in our case study, the same thresholds were reached before there was lightning activity.

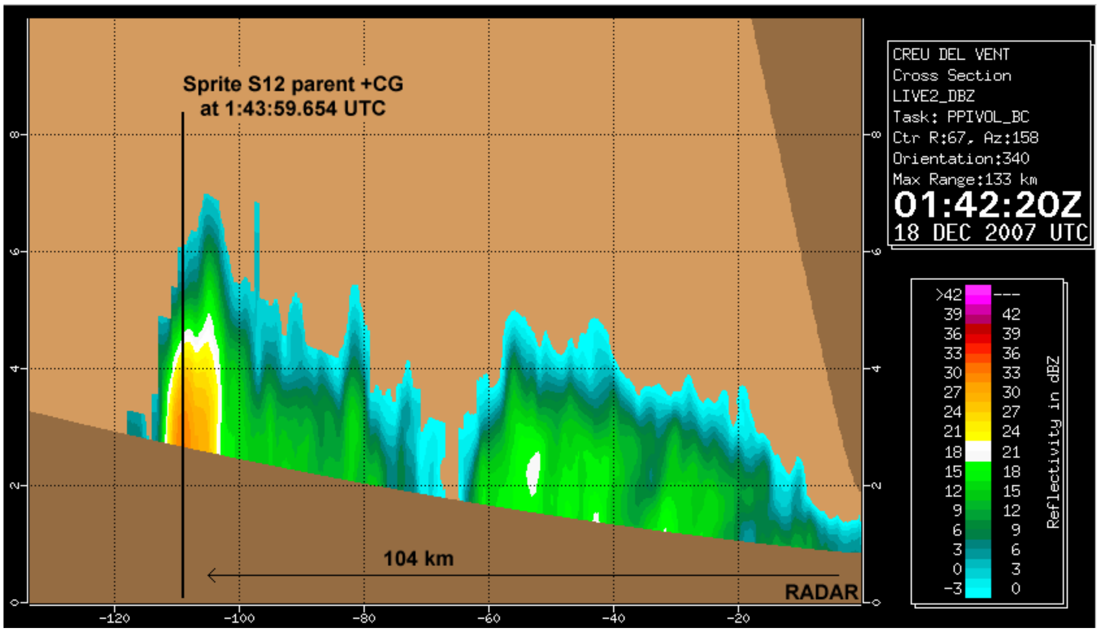


Figure 7. Radar cross section at 01:42:20 UTC on the direction of the sprite S12 parent +CG (01:43:59 UTC), which is printed on the cross section with a vertical line as its height is unknown.

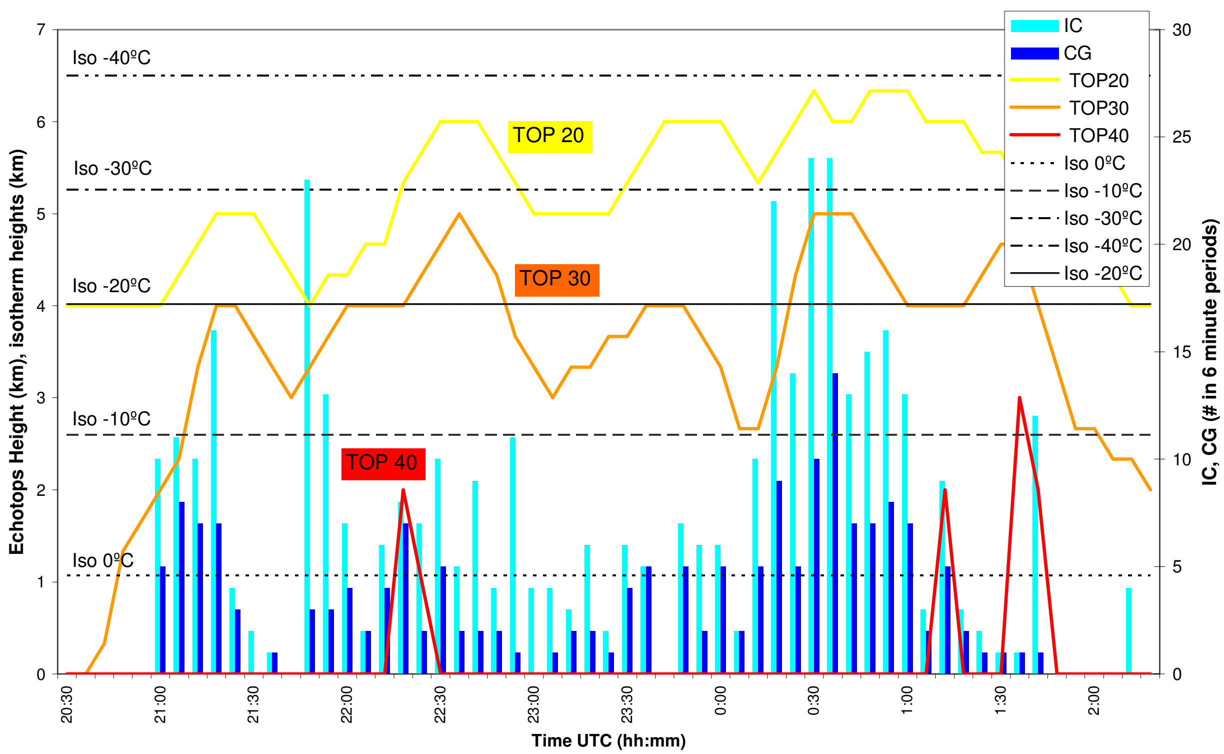


Figure 8. Radar echo top of 20 (TOP20), 30 (TOP30) and 40 (TOP40) dBZ and IC and CG flash evolution from 17/12/2007 at 20:30 UTC to 18/12/2008 at 03:00 UTC, period that corresponds to the main lightning activity during the thunderstorm lifetime. Isotherm heights are taken from the Barcelona radiosonde 18/12/2008 at 00:00 UTC.

Table 4. TLE events and their related IC flashes registered by the XDDE.

TLE Observation			Video		IC/CG	IC or			P+CG	TLE	
		time	frame		time	CG start	IC end	IC flash	P.Cur.	Delay (ms)	
nº	Type	(UTC)	(ms)		(UTC)	(ms)	(ms)	node	(kA)	Min.	Max.
S7	Sprite	0:05:35	161-181	IC	0:05:35	160.0	181.9	87		-21	21
				CG	0:05:35	154.8			4.8	6	26
S9	Sprite	0:35:23	626-646	IC	0:35:23	561.3	606.9	72		19	85
				CG	0:35:23	628.7			80.2	-3	17
S10	Sprite	0:56:05	306-326	IC	0:56:05	298.1	327.6	132		-22	28
				CG	0:56:05	300.6			40.7	5	25
S11	Sprite	1:06:03	895-915	IC	1:06:04	2.8	61.0	52		-166	-88
				CG	1:06:03	901.6			249.0	-7	13
S12	Sprite	1:43:59	658-678	IC	1:43:59	647.6	680.3	280		-22	30
				CG	1:43:59	654.2			117.5	4	24
E3	Elve or halo	1:58:56	171-191	IC	1:58:56	173.2	197.8	297		-27	18
				CG	1:58:56	174.3			189.4	-3	17
E7	Elve	4:12:16	556-576	IC	4:12:16	549.7	584.9	321		-29	26
				CG	4:12:16	570.8			186.8	-15	5

3.7. Analysis of the TLE and their parent +CG and IC flashes

Table 4 presents the IC and CG activity related to the TLE events according to the time of occurrence of each event. IC indicates VHF activity but it can be associated with the CG lightning process in a same flash event. The 2 last columns show the minimum and maximum delay between events. As the video frames have a 20 ms time duration and IC flashes have two times (start and end) the delays can not be established uniquely, and a minimum and maximum delays have been calculated.

For each TLE we compare the lightning activity detected by both systems. In the events S10, S12, E3 and E7, the CG stroke occurred between the first and last VHF sources. In the case S7 the +CG was detected 5 milliseconds before the first VHF source, and in the events S9 and S11, the CG occurred after the VHF sources. Only in case S11, the delay was large enough to doubt about the relation between VHF sources and the CG stroke. Spatially, all events matched except in the case S11, which confirms that the VHF sources and the CG stroke related to the event S11 were not linked between them. According to the delay observed this sprite was probably linked to the CG stroke.

Lyons (1996) has proposed that the sprite-generating +CG are associated with unusually large charge transfers and continuing currents associated with intra-cloud “spider” or “dendritic” lightning known to accompany many +CG events.

According to this proposal, when comparing the time of the IC activity and the TLE observations, it can be seen that in 5 of the 7 cases, the TLE could occur during the IC activity. In case S9 the sprite occurred after the IC activity and in case S11 the TLE occurred previous to the IC. This seems to confirm that such IC activity was not related to the TLE S11.

Moreover, ICs associated to the TLEs have a large number of nodes (ranging from 52 to 321) and quite important dimensions. Calculating the distance between the most far apart nodes, the extension of the IC flashes associated to the TLE observations were between 17 and 32 kilometers. Finally, it is interesting to note that IC flashes related to Elves have more nodes than IC flashes related to sprites.

Looking at the delays between the CG and the sprite event, they were always lower than values between 13 and 26 milliseconds. According to Van der Velde et al. (2006), these values should be typical of column sprites, and as a matter of fact, the sprites observed were all of this type, as illustrated in Figure 4. The elve events exhibited lower values (< 17ms) which is also generally observed.

Rivas Soriano and De Pablo (2002), have analyzed the lightning data of the Spanish Lightning Detection Network over the sea in the same region of study. They have found, in a three year period (1992-1994), a mean (median) annual value for positive CG flashes of 74.1 kA (47.7 kA).

The peak currents of the TLEs parent +CG analyzed here (Table 4) have, in 5 of the 7 cases, values above the annual mean, and in 4 cases values above 100 kA .

According to Huang et al. (1999), elves are associated with large peak current +CG (50-200 kA). Both elves analyzed in this study have peak currents above 180 kA.

4. SUMMARY

A case study of TLE observations in the Mediterranean and its meteorological analysis has been presented. While other studies have given evidence of the occurrence of TLEs in the winter thunderstorms in the eastern Mediterranean, this study has shown that TLEs occur in winter in other regions of the Mediterranean Sea. Wintertime thunderstorms develop over warm sea surfaces in other regions such as the Sea of Japan. These storms are usually smaller in both dynamical evolution and vertical extent compared to large MCSs bearing TLEs, and therefore are less common in generating TLEs.

The Meteosat and weather radar imagery analysis have shown similarities of the analyzed winter thunderstorm with those analyzed in the eastern Mediterranean by Altaratz et al. (2007) and Ganot el al. (2007)

The results found in this study supports the Lyons (1996) proposal that the sprite-generating +CG are associated with intra-cloud “dendritic” lightning. Results also support the Lyons (1996) proposal that sprites and elves appear to be uniquely related to +CG events, moreover TLE parent +CG usually have larger average peak currents than the remaining +CG population in the thunderstorm.

5. ACKNOWLEDGEMENTS

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