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CHARACTERISTICS OF LIGHTNING ACTIVITY IN DEEP CONVECTIVE CLOUDS WITH THE OVERSHOOTING TOPS

Karakteristike grmljavinske aktivnosti u konvektivnim oblacima čiji vrhovi nadvisuju tropopauzu

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Abstract: In this study characteristics of lightning activity, such as type and amplitude of lightning strokes in convective clouds with overshooting tops (OT), are analyzed. OTs are specific cloud-top signatures representing a strong updraft, which in some cases can penetrate through the tropopause region into the lower stratosphere. The focus was on the warm part of the year (May-September) during 2009. The study area covers a region from approximately 41°N 8°E to 49.5°N 24°E. Deep convective clouds with OTs were detected from the Meteosat 9 data, using a so called COMB method based on the infrared window (IRW, 10.8 μm) channel and the absorption channels of water vapor (WV, 6.2 μm) and ozone (O_3, 9.7 μm) in form of brightness temperature differences (BTD). Locations and times of the detected OTs were compared to the distribution and types of the lightning strokes, provided by the Lightning Location System, a part of the International Lightning Detection Network in Europe (LINET). For each satellite pixel meeting the OT criteria, occurrence of lightning discharge was searched 5 min before and after the time of the scan, within the range of 0.05° from the pixel position. The results present the characteristics of lightning in the vicinity of the OTs which might give an idea about the connection between the occurrence of the strongest updraft, represented with the OT in the cloud and the change in the lightning activity.

Key words: overshooting top, lightning, Meteosat 9 data, LINET data

Sažetak: Analizirane su karakteristike atmosferskih električnih pražnjenja, kao što su tip i amplituda izboja, u području konvektivnog oblaka s karakterističnim vrhom koji je posljedica vrlo jake uzlazne struje, te u većini slučajeva nadvisuje područje tropopauze (OT od engl. Overshooting Top). Analiza je provedena tijekom tople sezone, od svibnja do rujna 2009, za područje od 41°N 8°E do 49°N 24°E. Područje OT-a detektirano je iz podataka s meteorološkog satelita Meteosat 9, korištenjem tzv. COMB metode koja se temelji na podacima infracrvenog kanala (IRW, 10.8 μm), te podacima apsorpcijskih kanala u spektru vodene pare (WV, 6.2 μm) i ozona (O_3, 9.7 μm). Pomoću navedenih podataka računate su razlike temperature (BTD od eng. Brightness Temperature Differences) između pojedinih kanala, tj. WV – IRW i O_3 – IRW, čije vrijednosti upućuju na postojanje OT unutar konvektivnog oblaka. Položaji i vremena detektiranih OT-a uspoređeni su s razdiobom i tipom grmljavinskih izboja detektiranih pomoću internacionalnog sustava za lociranje munja LINET (International Lightning Detection Network in Europe). Pojava munja analizirana je za područja u radijusu od 0.05° oko svakog satelitskog piksela koji zadovoljava uvjete za postajanje OT-a, u vremenu od 5 minuta prije do 5 minuta poslije termina skeniranja satelita. Rezultati analize objedinjuju karakteristike grmljavinske aktivnosti u blizini detektiranih OT-a, pokušavajući uspostaviti vezu između vrlo jakih uzlaznih struja u konvektivnom oblaku i promjena u karakteristikama grmljavinske aktivnosti.

Ključne riječi: overshooting top, munje, Metosat 9, LINET

1. INTRODUCTION

Comparison of the location of the OT, a manifestation of very strong updraft within the convective cloud, and the type of lightning occurring in its vicinity might give an idea about the connection between the occurrence of the strongest updraft in the cloud and the change in the lightning activity.

Some theoretical considerations suggest that the updraft area within the thunderstorm is linked to the electrical activity of the storm (Boccippio, 2002). Updraft surges appear to coincide with an increase in flash rate (e.g. Wiens et al. 2005) and have been closely linked to severe weather (Williams et al. 1999). An indicator of a very strong updraft in the Cb cloud is the presence of an overshooting cloud top (OT) on top of the convective storm.Therefore in this work the relation between the occurrence of the OTs and the distribution and characteristics of lightning discharges in their vicinity will be studied.

Rapid-scan satellite data, available in the last decade, revealed the fact that an OT can exist for less than 15, even less then 5 minutes and has a maximum diameter of ~15 km. Cloud top features such as OT could be detected using multispectral satellite analysis. Different objective satellite-based OT detection methods using multispectral satellite data are presented in several studies, such as Schmetz et al. (1997), Setvák et al. (2007), Berendes et al. (2008), Lindsey and Grasso (2008) and Rosenfeld et al. (2008). Satellite-based methods that use combinations of solar satellite channels perform well only during the day time (e.g., Berendes et al., 2008; Lindsey and Grasso, 2008; Rosenfeld et al., 2008), while infra-red window (IRW) measurements are available during both day and night (Fritz and Laszlo, 1993; Ackerman, 1996; Schmetz et al., 1997, Bedka et al., 2010; Mikuš and Strelec Mahović, 2012). Brightness temperature difference (BTD) techniques such as WV-IRW, CO_2 – IRW, and O_3 – IRW could indicate the location of the OTs within convective clouds (Mikuš and Strelec Mahović, 2012). The most frequently used OT detection method is WV-IRW. This method suffers from a significant number of false alarms caused by water vapor anomalies, as described by Setvák et al. (2008a). However, WV – IRW BTD could be used as a proxy for deep convection. Machado et al. (2009) show that probability of lightning occurrences increase as the WV – IRW BTD increase.

The basic vertical electrical structure of mature convective updraft is composed of four charge regions (e.g. Stolzenburg et al., 1998). Above the lower, relatively weak positive charge, the main dipole of the cloud is situated, composed of main negative and upper positive charge regions.
Uppermost region has a relatively shallow layer of negative charge. The charge structures in the non-updraft regions of convective storms are more complex and variable. According to previous investigations, the increasing in lightning production rate could be due to very rapid vertical storm growth. Large updraft magnitudes bring midlevel negative charge close to midlevel positive charge, what increases electric field magnitude in the convective cloud (e.g. Emersic et al., 2011). Close proximity of oppositely charged regions caused by strong updraft are more favorable for intracloud (IC) flashes. In such a configuration of cloud charge, conditions for development of cloud-to-ground channel are less favorable. Consequently, cloud-to-ground (CG) lightning production is decreased in the region of strong updraft. CG flashes require a configuration of cloud charge that would cause a channel to propagate to ground, and a degree of electrification strong enough to initiate flashes (e.g. MacGorman et al., 2007).

2. DATA AND METHODS

The study was focused on the warm part of the year (May-September) during 2009, over the study area covering a region from approximately 41.5°N 8.5°E to 49.5°N 20.5°E (Figure 1).

COMB BTD (brightness temperature difference) method

Deep convective clouds with OTs were detected from the Meteosat 9 data, using a so-called COMB BTD method (Mikuš and Strelec Mahović, 2012), which combines the criteria for the IRW brightness temperature and the criteria for two BTDs, WV-IRW (6.2 – 10.8 μm) and O_3-IRW (9.7 – 10.8 μm). All pixels with O_3-IRW BTD larger than 13 K in the region where IRW brightness temperature is lower than 215 K and WV-IRW BTD larger than 4

K are characterized as OTs. This method is used in order to avoid a significant number of false alarms produced by WV-IRW BTD method (e.g. Setvák et al., 2007; Setvák et al., 2008b; Putsay et al., 2011), but also to overcome the seasonal variation of the O_3-IRW BTD, caused by the seasonal variation of the ozone concentration above the midlatitudes. Mikuš and Strelec Mahović (2012) show that COMB BTD method have the smallest number of false alarms compared with other BTD methods such as WV – IRW, CO_2 – IRW and O_3 – IRW and therefore is the most appropriate BTD method for detecting the overshootings. It must be noted that OT detection is strongly dependent upon the spatial and temporal resolution of the satellite instruments, which implies that some of the OTs cannot be detected using COMB BTD method based on SEVIRI imagery with spatial resolution of 3 km/pixel and 15 minutes temporal resolution.

Lightning data

Lightning data were provided by the Lightning Location System, a part of the International Lightning Detection Network LINET (e.g., Betz et al., 2009b; Höller et al., 2009). The mentioned system covers an area from approximately 30°N 10°W to 65°N 35°E and has more than 100 sensors in 24 countries all over the Europe (Figure 1). The LINET system detects total lightning discharge, but it also separately differs cloud-to-ground (CG) from intra-cloud and cloud-to-cloud (IC) discharges.

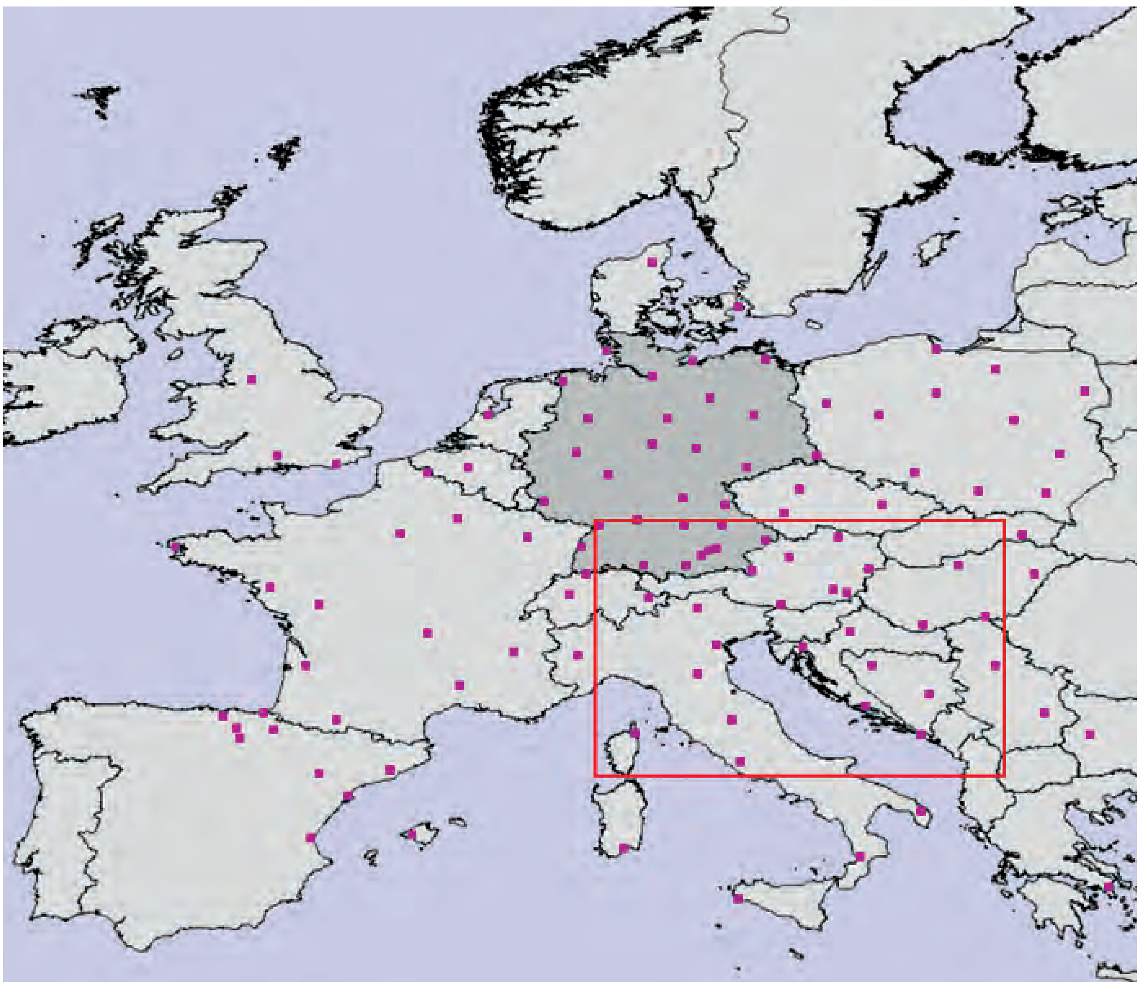


Figure 1: Map of LINET sensors (magenta) (source: *https://www.nowcast.de/en/produkte-und-vorteile/linet-data.html*). Study area is outlined with the red box.

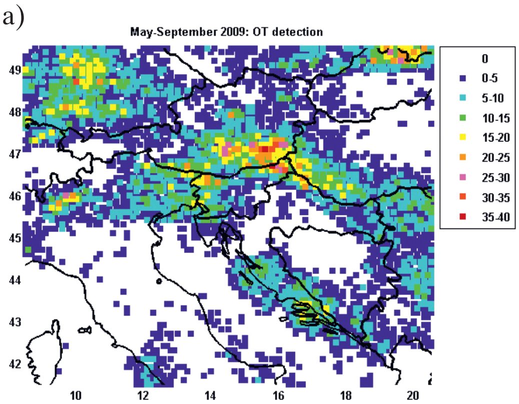
Slika 1: Mapa LINET senzora (purpurno crvena) (source: *https://www.nowcast.de/en/produkte-und-vorteile/linet-data.html*). Proučavano područje omeđeno je crvenim okvirom.

The successful detection of lightning depends on various parameters, such as sensor baseline and sensitivity, noise handling, network geometry, response time and processing of the signal (Betz et al., 2009b). In a radial distance of 100 km, the minimum detectable signal is in the range of 1-2 kA, IC and CG discharges locations are detected with an accuracy of ± 100 m. With the increasing distance of a lightning strike position from the sensor the minimum detectable signal decreases gradually, with a threshold of 10 kA in a radial distance of 300 km (Höller et al., 2009).

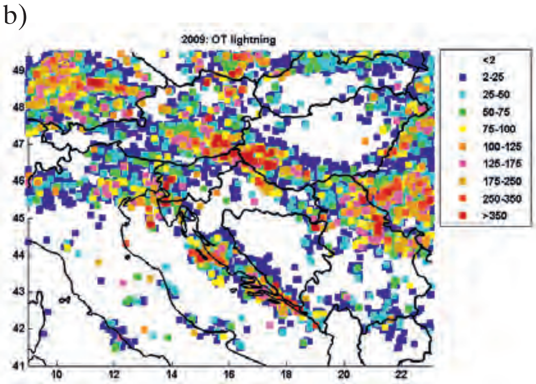
LINET data provide an information about date and time, location (coordinates) and current (kA) of lightning strokes, as well as stroke type (IC or CG), height of lightning (km) and 2D-error of stroke location (km). The discimination between IC and CG discharges is helpful for the recognition of severe weather conditions, which are characterized by an increase of IC rates and altitudes (Carey and Rutledge 1998; Shafer et al. 2000; Emersic et al., 2011). LINET measures only low-frequency range (VLF/LF) signals, what is suitable for detection of CG lightning. However, comparison between VHF (high-frequency range) source points from the high-quality 4DLSS network operated by NASA and VLF/LF cloud strokes measured by LINET showed very good agreeement in time and location of detected IC lightning, pointing out detection efficiency and the ability of LINET system to detect IC lightning (Betz, 2010).

Distribution of lightning strokes was studied in order to compare the regions of the highest lightning density with the regions where OTs occur more frequently. Additionally, for each satellite pixel meeting the criteria for the OT, occurrence of lightning discharge was searched 5 min before and after the time of the scan within the range of 0.05° from the pixel position, giving the information on the changes in lightning activity in the vicinity of the OT.

a)



b)



c)

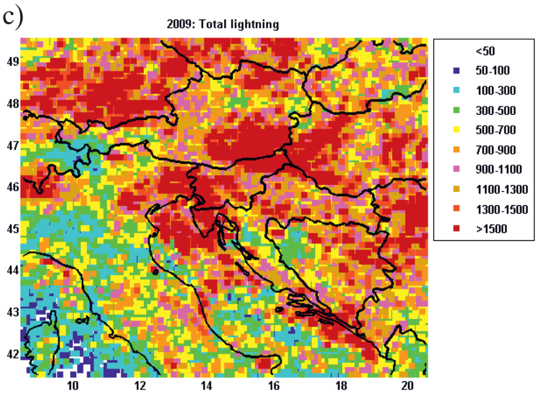


Figure 2: a) Number of OT detections using COMB method computed over 0.1° x 0.1° grid boxes from May to September 2009. b) Number of lightning strokes 5 min before and after the time of the scan within the range of 0.05° from the OT position. c) Number of lightning strokes computed over 0.1° x 0.1° grid boxes from May to September 2009.

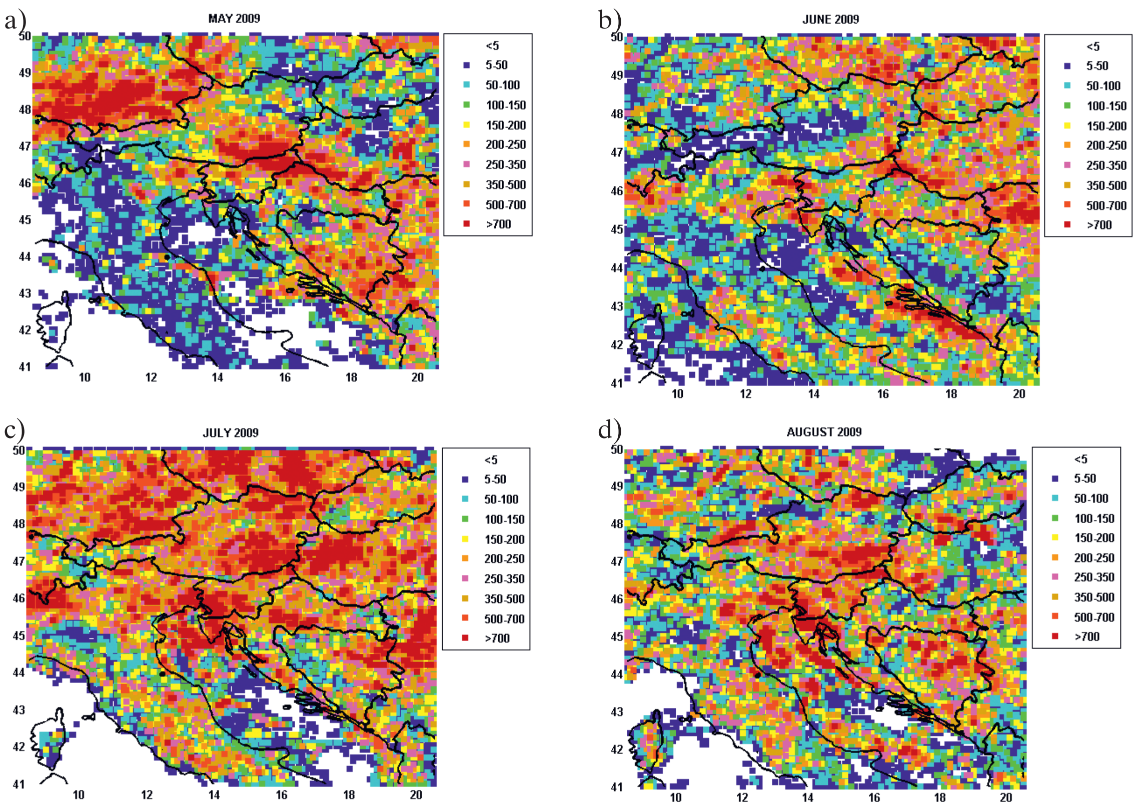
Slika 2: a) Broj OT-a detektiranih pomoću COMB metode na prostornoj rezoluciji 0.1° x 0.1° za razdoblje od svibnja do rujna 2009. b) Broj munja u vremenu od 5 minuta prije do 5 minuta poslije termina skeniranja satelita u radijusu od 0.05° oko svakog satelitskog piksela koji zadovoljava uvjete za postajanje OT-a. c) Broj munja na prostornoj rezoluciji 0.1° x 0.1° za razdoblje od svibnja do rujna 2009.

3. RESULTS

For the warm season, from May to September 2009, a total of 10947 OTs were detected (Table 1) over the analyzed region, on average app. 72 OT detections per day. Convective activity is significantly lower in the cold season, due to unfavorable weather conditions (e.g. Rivas Soriano et al., 2005), therefore occurrence of the OTs and related lightning activity during winter months was not analyzed in this study. The maximum number of OTs using COMB BTD satellite-based detection method is found at the slopes of the Alps, in the southeastern Austria and Germany, as well in the northern Italy (Figure 2a).

Significant number of lightning strokes in the vicinity of the OTs is registered in western Hungary and southern Adriatic coastal region at the slopes of the Dinaric Alps (Figure 2b). These regions are the regions with maximum lightning activity during 2009 (Figure 2c), while the maximum number of about 6414 lightning strokes was detected in western Hungary.

Comparison of the figures 2a and 2c shows that the locations of detected OTs coincide well with the regions of maximum lightning activity. Over the sea, OTs often appear close to the coastline (Figure 2c) what is in agree-



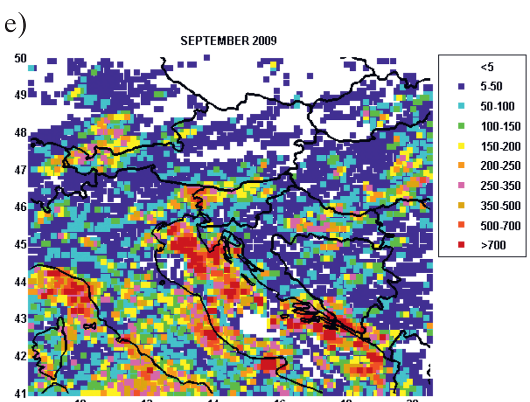


Figure 3: Monthly distribution of lightning activity. Number of lightning strokes in 0.1°x0.1°boxes for: a) May, b) June, c) July, d) August and e) September 2009.

Slika 3: Mjesečna razdioba grmljavinske aktivnosti. Broj munja na prostornoj rezoluciji 0.1° x 0.1° za: a) svibanj, b) lipanj, c) srpanj, d) kolovoz i e) rujan 2009.

MONTH	NUMBER OF OT
MAY	5255
JUNE	3994
JULY	1320
AUGUST	191
SEPTEMBER	187
TOTAL	**10947**

Table 1: Number of OT detection using COMB method from May to September 2009.

Tablica 1: Broj OT-a detektiranih pomoću COMB metode za razdoblje od svibnja do rujna 2009.

ment with lightning occurrences, which are more often identified along the coast than over the sea (Mikuš et al., 2012; Seity et al., 2001).

Figure 3 displays the total monthly distribution of lightning activity for the warm season of 2009. It is evident that the months in which the distribution reaches its maximum are different depending on the region. The highest lightning occurrence over the continental part of the studied region is recorded during July 2009 (Figure 3c), while convective activity over the sea is more pronounced in the autumn (Figure 3e). This is in agreement with the results in e.g. Mikuš et al. (2012) and Christian et al. (2003). Table 1 displays the total monthly number of OT detections for the 2009 from May to September (Mikuš and Strelec Mahović, 2012). Frequency of OT occurrences shows monthly variations, with maximum number in June. During September, the number of OTs detected in the studied area is the smallest. Due to unfavorable weather conditions for the occurrence of convection such as cooling of the land mass and the increasing sun angle (Morel and Sensi, 2002), convective activity sharply decreases in September over the continental part of the observed area, and greatly increases over the Mediterranean Sea (Tudori and Ramis, 1997), as well as over the Adriatic Sea (Figure 3).

In general, the largest number of OTs occurs during the afternoon and early evening, with a well pronounced peak around 16:00 UTC (Figure 4a). Relative frequency of detected OTs within given hour is well correlated with temporal analysis of the occurrence of lightning activity (Figure 4b). Between 06:00 and 10:00 UTC, OT detections as well as lightning discharges are rather rare.

In order to present the characteristics of lightning activity in the vicinity of detected OTs, an example of a convective storm on 23 August 2010 is taken. OTs were detected using COMB BTD method (locations of the OTs detected by the COMB method are marked with black dots in Figure 5). OTs are well pronounced on the HRV images (Figure 5) as the lumpy textured appearance with characteristic shadowing within the convective cloud in the mature stage. Cold ring structure was visible

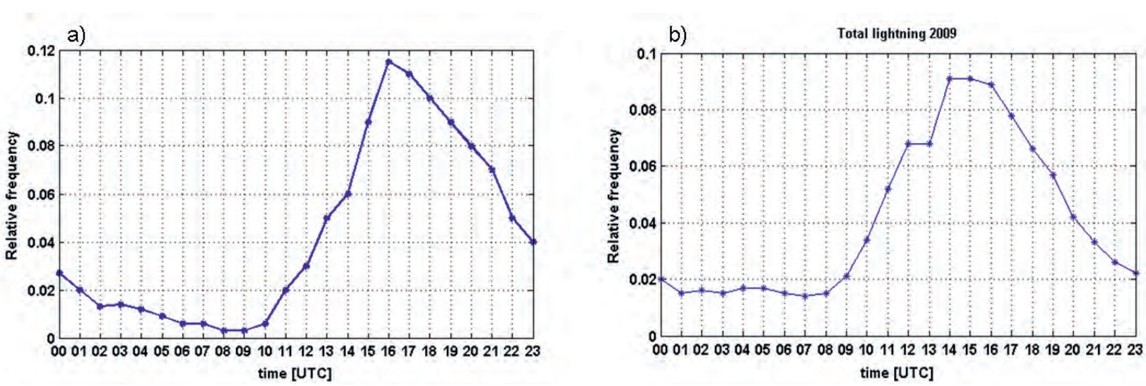


Figure 4: Relative frequency of a) OTs, detected using COMB method and b) lightning discharges, within given hour.

Slika 4: Relativne satne čestine a) OT-a detektiranih pomoću COMB metode i b) atmosferskog pražnjenja.

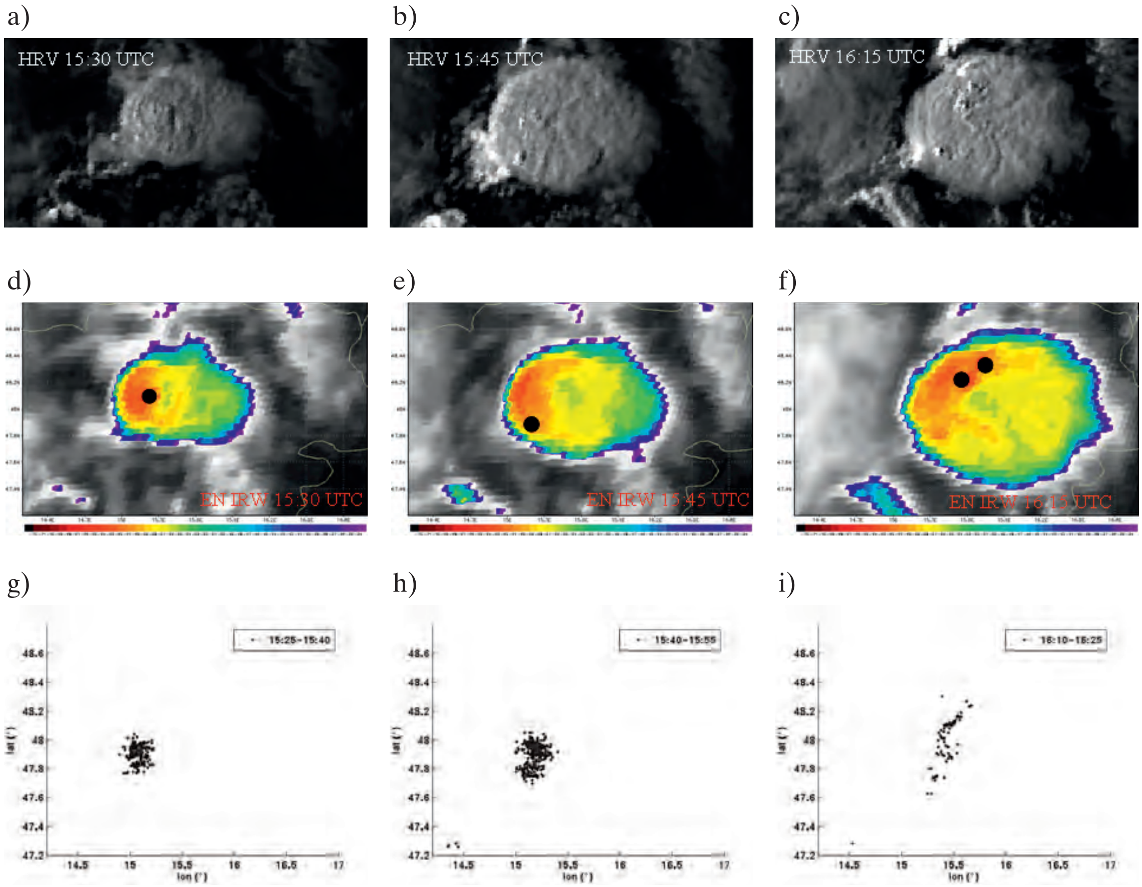


Figure 5: Meteosat 9 HRV channel imagery on 23 August 2010 at a) 1530, b) 1545, c) 1615 UTC, and color–enhanced (EN) Meteosat 9 10.8 (IRW) µm imagery at d) 1530, e) 1545, f) 1615 UTC. Locations of the OTs detected by the COMB method are marked with black dots. Map of total lightning activity (IC + CG) above 12 km on 23 August 2010 g) 1525 – 1540 h) 1540 – 1555 and i) 1610 – 1625 UTC for the analyzed convective storm region.

Slika 5: Meteosat 9 slika u vidljivom dijelu spektra, horizontalne razlučivosti 1 km za 23. kolovoza 2010. u a) 1530, b) 1545, c) 1615 UTC, te Meteosat 9 slika u infracrvenom dijelu spektra (10.8 µm) u d) 1530, e) 1545, f) 1615 UTC. Boje označavaju temperaturne intervale. Skala temperature: od -33 (ljubičasto) do -72°C (tamno crveno). Položaji OT-a detektiranih COMB metodom označeni su crnim točkama. Ukupna grmljavinska aktivnost detektirana iznad 12 km visine u vremenskim intervalima g) 1525 – 1540 h) 1540 – 1555 i i) 1610 – 1625 UTC za analizirano područje konvektivne aktivnosti.

on top of the cloud in the color-enhanced IRW satellite imagery, suggesting the severity of the storm (e.g. Iršić Žibert and Žibert, 2012). In the period between 15:15 UTC and 16:15 UTC the largest number of total lightning was recorded, with a peak around 15:45 UTC (Figure 6a). Larger values of the electric current (Figure 6b) are evident at the time of OT detections, while the maximum values of current correspond well with the maximum number of lightning discharges.

The height of the tropopause, estimated from the soundings of three closest radiosounding stations: Vienna, Budapest and Zagreb, was between 11 and 12 km (Figure 8). 4D view of the lightning distribution (Figure 7) reveals the presence of lightning discharges at heights above 12 km from 15:00 to 17:00 UTC, which corresponds to the time of the overshootings detected in the images. The spatial distribution of lightning discharges above 12 km (Figures 5g, 5h, 5i) shows very good correlation with locations of the OTs observed on HRV images. Most of lightning discharges at the altitudes higher than the estimated tropopause height are concentrated within and in the vicinity of OTs.

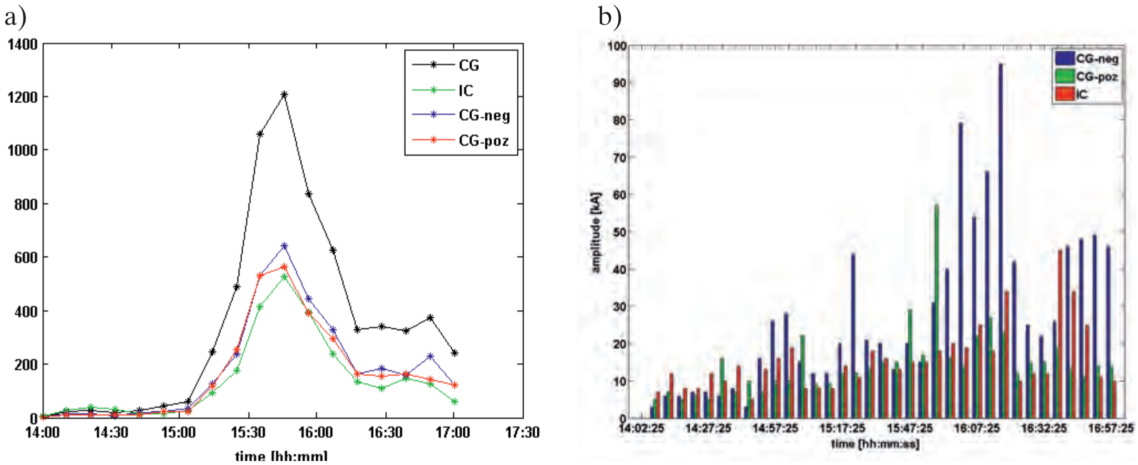


Figure 6: Temporal distribution of a) lightning discharges (cloud to ground (CG), intra cloud (IC), CG positive (CG-poz) and CG negative (CG-neg)) and b) maximum 5-min lightning current on 23 August 2010 from 1400 to 1700 UTC.

Slika 6: Vremenska razdioba a) grmljavinskih izboja (oblak-tlo, oblak-oblak, oblak-tlo pozitivni naboj, oblak-tlo negativni naboj), te b) maksimalna detektirana struja munje unutar 5-minutnih intervala za 23. kolovoza 2010. od 1400 do 1700 UTC.

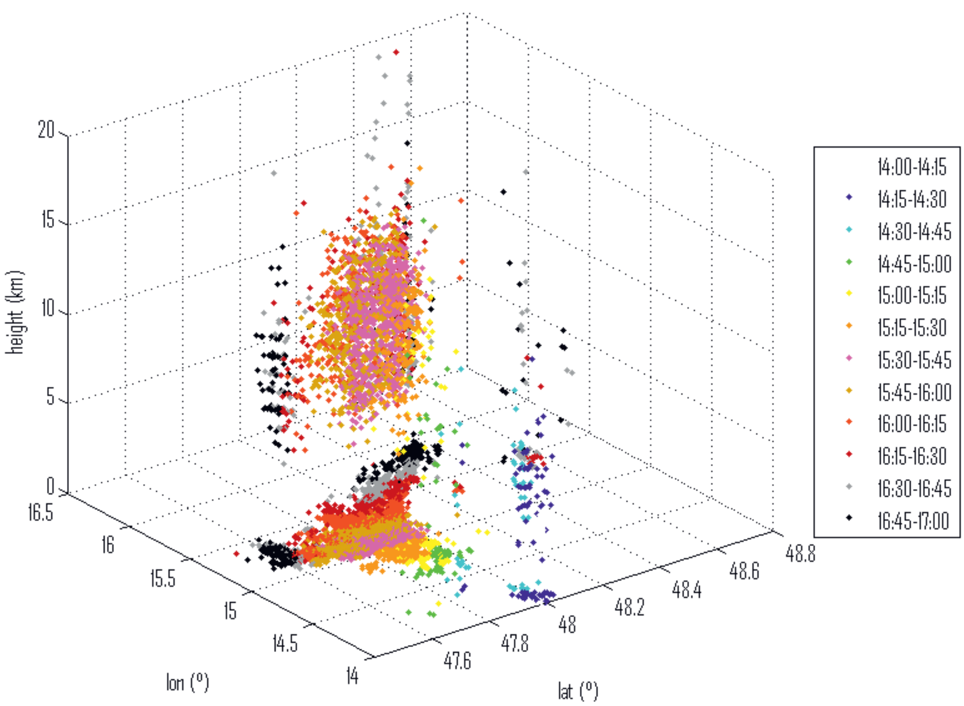
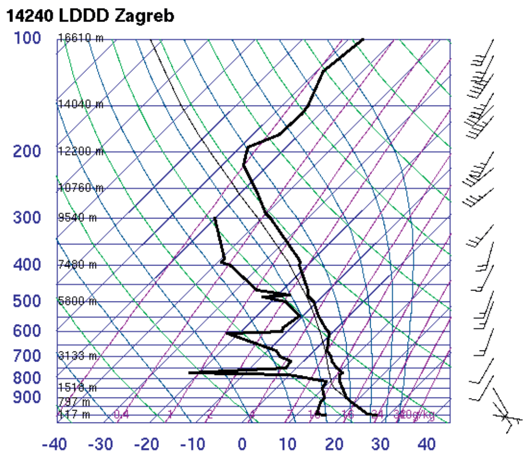
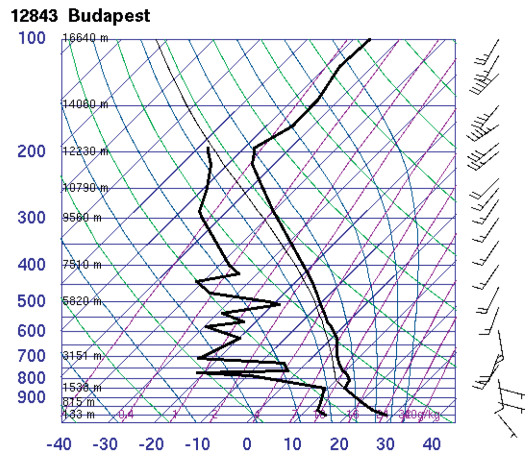


Figure 7: Temporal distribution of total lightning activity (IC + CG) on 23 August 2010 from 1400 to 1700 UTC for the analyzed convective storm region shown on figure 5. Colors represent the time of detected lightning strokes.

Slika 7: Vremenska razdioba ukupne grmljavinske aktivnosti (oblak-tlo + oblak-oblak) za 23. kolovoza 2010. od 1400 do 1700 UTC za analizirano područje konvektivne aktivnosti prikazano na slici 5. Boje označavaju vremena detektiranih grmljavinskih izboja.





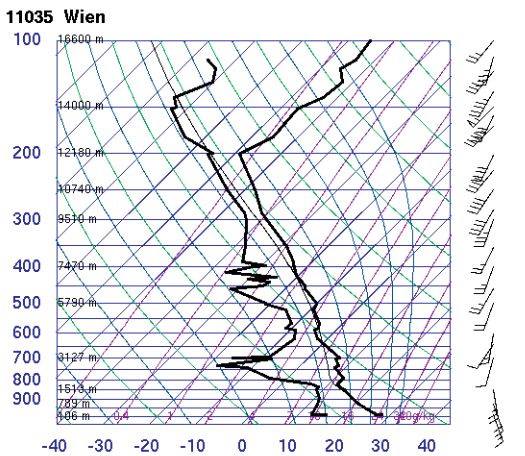


Figure 8: Skew-T log-P diagrams of radiosounding data from Zagreb, Budapest and Vienna on 23 August at 1200 UTC.

Slika 8: Radiosondažni podaci izmjereni na postajama Zagreb, Budimpešta i Beč 23. kolovoza 2010 u 1200 UTC.

4. CONCLUSION

Characteristics of lightning activity, detected using LINET network, were analyzed in the vicinity of the OTs during warm season of 2009 (May - September). OTs were detected using objective satellite-based detection method, so-called COMB BTD method. Spatial distribution of lightning activity coincides well with the spatial distribution of the detected OTs. The largest numbers of lightning strokes, as well as OTs were detected in the western Hungary, southeastern Germany, northern Adriatic and southern Adriatic coastal region at the slopes of the Dinaric Alps. Over the sea, OTs often appear close to the coastline, what is in agreement with the lightning occurrences.

In general, the largest number of OTs occur between 14:00 and 21:00 UTC, while from 06:00 to 10:00 UTC OT detections are rather rare. Lightning activity shows similar temporal distribution. Sharp increase of lightning activity and larger values of the electric current are evident at the time of the OT detections.
An example showed that lightning activity greatly enhances at the times of the overshootings. Lightnings occur well above the tropopause, therefore are clearly related to the OT parts of the Cb cloud.

5. Acknowledgments

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6. LIST OF ABBREVIATIONS

OT	Overshooting Top
BTD	Brightness Temperature Difference
WV	Water Vapor
IRW	Infrared Window
LINET	Lightning Detection Network in Europe
O_3	Ozone
IC	Intracloud
CG	Cloud to Ground
VLF/LF	Low Frequency Range
VHF	High Frequency Range
4DLSS	Four-Dimensional Lightning Surveillance System
NASA	National Aeronautics and Space Administration
UTC	Coordinated Universal Time
COMB BTD	Objective satellite-based method for detecting OTs.
HRV	High Resolution Visible

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