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Lightning, overshooting top and hail characteristics for strong convective storms in Central Europe

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ABSTRACT

Lightning activity in storms with overshooting tops and hail-producing storms over Central Europe is studied, in order to find typical lightning characteristics that can be useful in nowcasting of the severity of the storm and its ability to produce hail. The first part of the study gives the analysis of lightning activity in thunderstorms with overshooting tops (OT) for the warm part of the year (May–September) from 2009 to 2010 over central and southeastern Europe. Deep convective clouds with OT were detected in Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) data, using methods based on the infrared window (IRW, 10.8 μm) channel and absorption channels of water vapor (WV, 6.2 μm) and ozone (O_3, 9.7 μm) in the form of brightness temperature differences. The locations and times of the detected OT were compared to the distribution and types of lightning strokes, which were provided by the LINET Lightning Location System. The results show that the spatial distribution of lightning generally coincides with the spatial distribution of the detected OT. The largest numbers of lightning strokes and OT were found in western Hungary, southeastern Austria, northeastern Slovenia and the northern Adriatic. The largest number of OT occurred between 1600 and 1800 UTC, whereas from 0600 to 1000 UTC OT detections were rather rare. Lightning activity showed a similar temporal distribution, with an increase in lightning activity evident at or close to the time of the OT detections. At the time of and close to the location of the OT, the lightning was found to occur well above the tropopause and was clearly related to the OT of cumulonimbus clouds.

In the second part of the study, lightning characteristics are studied for 35 events of hail-producing thunderstorms over Croatia in the summer months (May to September), from 2008 to 2012. The lightning distribution, also registered by LINET, was compared to hail parameters based on measurements at the hailpad polygon. A polygon with dimensions of 30 km × 20 km was located in the area of highest average number of days with hail occurrence in the continental part of Croatia. In a majority of the studied cases, the number of total lightning strokes sharply increased slightly before the beginning of hailfall. At the time the hailfall started there is a brief decrease in the number of lightning strokes, followed by a sharp increase shortly after. Additionally, larger hailstones with higher kinetic energy values appeared at the beginning of the hailshower. Microphysical properties of the cloud tops, investigated using MSG SEVIRI 3.9 μm reflectivity, i.e. profiles of the effective radii of cloud particles vs. temperature, clearly verify the presence of strong updrafts associated with hail-producing clouds.

1. Introduction and background

The updraft area of a severe thunderstorm is frequently manifested by the appearance of the overshooting tops (OTs). Generally, the largest OTs, with diameters of up to 15 km and lifetimes of several hours, are usually detected within the strongest storms. These storms often produce hazardous weather conditions, such as large hail, damaging wind, heavy rainfall and tornados with significant consequences on the Earth's surface (Bedka, 2010; Setvak et al., 2010; Dworak et al., 2012). In addition to the hazardous weather conditions on the ground, storms with OTs have also been associated with strong horizontal and vertical wind shear and frequent lightning (Wiens et al., 2005; Machado et al., 2009; Meyer et al., 2013) and generate significant near-storm turbulence, which is a consequence of gravity wave generation at storm top (Wang et al., 2010) and subsequently represent a serious risk for aircraft. The OT and cold ring features can be indicators of severe thunderstorms that usually produce large hail, severe wind and possibly tornadoes (Iršič Žibert and Žibert, 2012; Mikuš and Strelec Mahović, 2012b). Because of the significant correlation between the occurrence of an OT and severe weather conditions on the ground (Bedka, 2010; Mikuš and Strelec Mahović, 2012b; Dworak et al., 2012), as well as aircraft accidents caused by convectively induced turbulence (Cornman and Carmichael, 1993), OT detection has become more important in operational nowcasting. OT are most easily observed in high resolution visible (HRV) images that are limited to daytime

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hours and depend on the sun angle, OT heights and shadow lengths, time period of the OT observation, and experience of the forecasters. In color enhanced infrared (IRW, 10.8 μm) satellite images, OTs are usually represented with a relatively small group of pixels colder than the surrounding pixels of the convective cloud anvil (Bedka et al., 2010). However, sometimes OTs are not represented with a brightness temperature (BT) minimum, especially in storms with specific thermal features at the cloud top, such as cold ring or cold U/V (Stastka and Setvak, 2008). Because of these visual detection limitations, objective satellite-based OT detection methods have been developed that represent helpful nowcasting tools, especially for regions that lack radar coverage. The objective OT detection methods are usually satellite based (Rosenfeld et al., 2008; Bedka et al., 2010; Mikuš and Strelec Mahović, 2012b), but the recognition and detection of OT in satellite imagery are strongly dependent on the spatial and temporal resolution of the satellite instruments, and for those methods that rely on visible satellite imagery possible only during daytime.

OTs are linked to the electrical activity of the storm, since updraft surges coincide with an increase in total flash rate (Wiens et al., 2005). The specific behavior of lightning discharges during thunderstorms with OT was found in several investigations (Elliot et al., 2012) and suggested that the amount of lightning within a convective cloud can improve the detection of the OT. In order to include lightning data in an objective detection method over central Europe, an analysis of lightning activity in convective clouds with OT is required, aiming to define the important criteria and thresholds. In Section 3.1 the total number of lightning strokes along with their spatial and temporal distributions (in general and separately in penetrative convective clouds) is analyzed over central and southeastern Europe. The number, type and peak currents of lightning strokes in convective clouds with OT are then shown for several cases.

A rapidly growing flash rate has been related to an increase in the potential for severe weather (Williams et al., 1999), yet does not guarantee that severe weather will occur. During severe thunderstorms, cloud-to-ground (CG) lightning production appears to decrease, whereas a significant increase in the number of intra-cloud (IC) flashes is registered (MacGorman, 1993; Buechler et al., 1996; Lang et al., 2000 and Lang and Rutledge, 2002; Emersic et al., 2011). In hailstorms, regions with a reduced number of lightning strokes, called lightning holes, have been observed (Emersic et al., 2011). These regions are usually short lived and are related to wet hail growth that is not conducive to hydrometeor charging (Emersic et al., 2011; Lynn et al., 2012), or in the case of supercell storms, the consequence of a strong rotating updraft (MacGorman et al., 2008). Many previous studies of thunderstorms have shown that graupel and ice crystals are the species that are the most important in the electrification of storms and the occurrence of lightning (Black and Hallett, 1999; Bruning et al., 2007). Carey and Rutledge (1998) compared hail and CG lightning trends and showed that in certain cases, the maximum of CG lightning activity occurs after hail occurrence, while Soula et al., (2004) found very weak CG lightning activity during the severe hailstorms. The studied hail-producing storms in their mature phases sometimes produced more positive CG flashes, while production of negative CG flashes was very low (Soula et al., 2004; Montanya et al., 2007, 2009; Dimitrova et al., 2013). Furthermore, the total flash rate rapidly increases before severe weather occurrence, such as large hail, severe wind or tornadoes (Schultz et al., 2009, 2011; Darden et al., 2010; Gatlin and Goodman, 2010). Dimitrova et al., (2013) observed significant jump in total flash rate before the beginning of the hail fall. Previous studies also showed significant increase of IC lightning activity and IC/CG ratio before the occurrence of severe weather at the ground (Montanya et al., 2007, 2009). Therefore, total lightning information is considered to be one of the best early indicators of a strengthening updraft within a thunderstorm (Schultz et al., 2011).

Another measure of the intensity of a convective storm's updraft, and hence its ability to produce large hail, is the vertical evolution of cloud-top microphysical features (Lensky and Rosenfeld, 2006; Rosenfeld et al., 2008). A conceptual model is presented that assesses the intensity of severe convective storms by using satellite-retrieved vertical profiles of cloud top temperature vs. particle effective radii ($T–r_e$ profiles), whereas deep clouds composed of small particles at cloud top (r_e's of 15–20 μm) are associated with greater updraft velocities and very cold supercooled drops to below −30 °C. Rosenfeld et al. (2008) further analyzed a large number of severe hail-producing storms and showed that stronger updrafts are revealed by the delayed growth of particle r_e to greater heights and lower temperatures.

The present study is divided into two parts. The first part, given in Section 3.1 is dealing with distribution and general properties of lightning activity over Central Europe in correlation to OT occurrence. In the second part of the study (Section 3.2), spatial and temporal characteristics of lightning are studied for thunderstorms producing hail over a hailpad polygon located in the northwestern part of Croatia. Additionally, for the studied hailstorm cases, hail characteristics, such as the hailstone diameter and kinetic energy, as well as $T–r_e$ profiles were analyzed. Finally, the main findings and conclusions are summarized in Section 4.

2. Data and methods

Over the central European domain (Fig. 1a), an analysis of lightning activity in thunderstorms with OT was performed using the lightning data provided by the low-frequency (VLF/LF) International Lightning Detection Network (LINET). For general analysis of the spatial distribution, the number of detected lightning strokes was calculated over 0.2° × 0.2° grid boxes. Detailed analysis of lightning activity was done for selected convective episodes. The convective cells were tracked during their lifetime and only the lightning activity connected to the tracked cell was analyzed. LINET system covers a wide area from approximately 30°N 10°W to 65°N 35°E and detects the total lightning, but it also separately detects CG strokes and IC discharges (Betz et al., 2009; Mikuš et al., 2012). LINET intra-cloud detections will be termed “IC-strokes” according to the terminology given by Betz et al. (2004). This technical term is used to emphasize the distinction from IC radio sources detected with VHF sensors and should not be confused with CG return strokes. Detection efficiency of LINET sensors is very high, enabling detection of strokes with peak currents below 5 kA. Statistical average location accuracy is better than 150 m (Betz et al., 2009); however the sensitivity of the sensors decreases as the distances of the lightning strokes from the LINET sensors increase (Höller et al., 2009). The discrimination between IC and CG lightning strokes is possible by using the three dimensional time-of-arrival (TOA) analysis (Betz et al., 2004). For the reliable determination of the IC strokes height, at least 4 sensors are needed, located within 150–200 km of each other (Betz et al., 2009). In the central part of the network even very weak lightning events can be detected (<5 kA) and discrimination between CG and IC lightning is more successful than in the surrounding areas, where the sensors detect predominantly stronger events such as CG strokes (Dimitrova et al., 2013; Betz et al., 2009). Over the studied domain lightning is detected by approximately 40 sensor sites.

OTs of the deep convective clouds were detected from the Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) data with a sampling distance of 3 km per pixel (Schmetz et al., 2002) and 15 minute temporal resolution, using a ‘COMB’ method (Mikuš and Strelec Mahović, 2012b). The ‘COMB’ method is 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 the form of brightness temperature differences (BTD). It combines the criteria for the IRW brightness temperature (BT) and criteria for the two BTDs, WV-IRW and O_3-IRW. All pixels with O_3-IRW BTD larger than 13 K in the region where the IRW BT is lower than 215 K and WV-IRW BTD is larger than 4 K are characterized as OT. Additionally, the ‘COMB’ method is strongly dependent upon the spatial resolution of