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Doktorska dizertacija-sažetak
D.Sc. Thesis-Summary

SATELITSKE KARAKTERISTIKE I GRMLJAVINSKA AKTIVNOST INTENZIVNIH KONVEKTIVNIH OLUJA

Satellite signatures and lightning characteristics of severe convective storms

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Sažetak: Intenzivne konvektivne oluje često predstavljaju potencijalnu opasnost za ljudski život i materijalna dobra, dok je vrijeme i mjesto nastanka te intenzitet istih još uvijek teško predvidiv i predstavlja jedan od najvećih izazova u prognozi vremena. Izuzetnu važnost u prognozi konvekcije imaju satelitski podaci i podaci o munjama, a njihovo karakteristično ponašanje prije i tijekom grmljavinskih oluja može uvelike poboljšati prognozu neposrednog razvoja vremena (eng. nowcasting). U ovom radu korišteni su podaci s geostacionarnih satelita druge generacije Meteosat-9 i Meteosat-10 te podaci o munjama iz međunarodnog LINET (od eng. LIghnting NETwork) sustava. Uspoređene su četiri objektivne satelitske metode koje se temelje na kombinaciji satelitskih kanala u infracrvenom dijelu spektra i služe za detekciju premašujućeg vrha (OT, od eng. Overshooting Top) iznad nakovnja kumulonimbusa (Cb), koji je posljedica jake uzlazne struje unutar konvektivne ćelije. Utvrđeno je da najmanji broj pogrešnih detekcija ima nova jednostavna objektivna satelitska metoda, nazvana COMB (od eng. COMBination). Većina pogrešno detektiranih OT-ova koristeći spomenutu metodu nalazila se u području specifičnih termičkih oblika na vrhovima konvektivnih oblaka (hladnog prstena ili hladnog U/V) koji su također karakteristični za intenzivnu konvektivnu aktivnost. U blizini detektiranih OT-ova najčešće dolazi do olujnih udara vjetra koji su često praćeni intenzivnim pljuskom, dok je u značajnom broju slučajeva zabilježen i izražen pad temperature. Analizom grmljavinske aktivnosti nad promatranim područjem utvrđeno je da su grmljavinski najaktivnija pred-alpska područja, a u Hrvatskoj Istra u ljeto i južni Jadran tijekom jesenskih mjeseci. Neposredno prije ili za vrijeme OT-a te prije pojave tuče pri tlu opažen je nagli porast broja ukupnih električnih izboja, izmjerene su najviše amplitude struje i opažen porast srednje visine munja između i unutar oblaka.

Summary:

Introduction

Development and forecasting of convective storms are still one of the biggest challenges in the operational meteorology. Although in global and mesoscale numerical modeling continuous improvement is observed, time and location of development, as well as intensity of convective storms are very difficult to forecast due to their relatively short duration and small spatial dimensions. Thus, using of remote sensing data in the convection forecasting is very important. Characteristics and typical behavior of those data before and during the convective storms could serve as parameters for estimation of storm intensity and their potential for causing severe weather conditions on the ground. Thunderstorms often produce hazardous weather conditions, such as large hail, damaging wind, heavy rainfall, tornadoes (e.g. Bedka, 2011; Setvák et al., 2010; Dworak et al., 2012), strong horizontal and vertical wind shear and frequent lightning (Wiens et al., 2005; Machado et al., 2009; Meyer et al., 2013) posing significant risks for human lives and properties. The updraft area of a severe thunderstorm is frequently manifested by the appearance of the overshooting tops (OTs). The OT is dome-like structure above the cumulonimbus (Cb) anvil, which protrudes through the equilibrium level (in the convective storms very close to the tropopause level). Generally, the largest OTs, with diameters of up to 15 km and lifetimes of several hours, are usually detected within the strongest storms. Thunderstorms with the characteristic thermal features on the top of the convective clouds, such as cold ring or cold U/V are a consequence of very strong convective activity characterized with the OT development (Setvák et al., 2008b). 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, 2013; Mikuš and Strelec Mahović, 2012). Because of significant correlation between the occurrence of an OT and severe weather conditions on the ground (Bedka, 2011; Mikuš and Strelec Mahović, 2012; Dworak et al., 2012), OT detection has become more important in operational nowcasting.

OT are most easily observed in high resolution visible (HRV) images that give an information about the 3D structure of the storm tops, but are limited to daytime hours. The OT detection using HRV satellite image depends on the sun angle, OT heights and shadow lengths, time period of the OT observation, and experience of the forecasters. In color enhanced infrared 10.8 μm (IR10.8) 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, recent studies have shown that OTs are not always 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 (e.g. Stástka and Setvák, 2008). In that kind of situations, OT temperature is similar to the temperature of cold ring features, and sometimes could even be situated in the warm area of the cold ring. 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 recognition and detection of OT using objective satellite based methods (Rosenfeld et al., 2008; Bedka et al., 2010; Mikuš and Strelec Mahović, 2012) are strongly dependent on the spatial and temporal resolution of the satellite data, 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). In several studies (Elliot et al., 2012) specific behavior of lightning activity was found during thunderstorms with OT, what can possibly improve the objective detection of the OT. Potential for the lightning production, as well as lightning distribution are different for the different type (single cell, multicell, supercell, mesoscale convective system) of convective storms. Nonetheless, some typical behavior of lightning characteristics could be observed during severe thunderstorms. A rapidly growing flash rate (Williams et al., 1999) and/or significant increase in the number of positive strokes have been related to an increase in the potential for severe weather, yet do not guarantee that severe weather will occur. In strong and severe convective storms cloud to ground (CG) lightning production usually decreases, whereas a significant increase in the number of intra-cloud (IC) flashes is detected (Buechler et al., 2000; Lang et al., 2000; Lang and Rutledge, 2002; Emersic et al., 2011). Furthermore, the total flash rate rapidly increases before severe weather occurrence (Schultz et al., 2009, 2011; Darden et al., 2010; Gatlin and Goodman, 2010). Therefore, total lightning (TL) information is considered to be one of the best early indicators of a strengthening updraft within a thunderstorm (Schultz et al., 2011).

Intensity of a convective storm's updraft and its potential to produce severe weather conditions can be estimated using satellite-retrieved vertical profiles of cloud top temperature vs. cloud particle effective radii (TĐr profiles) (Lensky and Rosenfeld, 2008; Rosenfeld et al., 2008). Deep convective clouds composed of small particles at the cloud top (r 's of 15Đ20 μm) have stronger updrafts and consequently are associated with greater updraft velocities and very cold supercooled drops (< 30 °C). Analyzing a large number of severe hailstorms, Rosenfeld et al. (2008) showed that strong to severe updrafts are characterized by delayed growth of r to greater heights and lower temperatures.

Data and methods

In this study the characteristics of convective cloud tops were analyzed and objective satellite based OT detection methods tested using Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) data (Schmetz et al., 2002). Tested OT detection methods are calculated from Meteosat 9 15-min data and defined as brightness temperature differences (BTD) between following channels: WVÐIRW, which is the difference of BTs in channels 6.2 and 10.8 μm; CO ÐIRW, which is the BTD of channels 13.4 and 10.8 μm and O ÐIRW, which is the BTD of channels 9.7 and 10.8 μm. Beside mentioned BTD methods, the ability of a new simple method, called COMB has also been tested. COMB method is combination of two BTD methods, WV Ð IRW and O Ð IRW, and is composed to avoid significant number of false alarms which are produced using just WV Ð IRW method.

The ability of each BTD method to detect OTs was tested during July 2009, between 15 and 16 UTC (five SEVIRI scans) using Meteosat 9 HRV images. Locations of the OTs detected by the mentioned BTD methods are compared with subjectively visually observed OTs on HRV images. Color-enhanced IR10.8 satellite images have also been analyzed to determine infrared (IR) BT and specific thermal signatures of convective clouds in cases with OTs. Every mentioned BTD method includes criteria for the 10.8 μm BT and for certain BTD (COMB method for two BTDs). The criteria for IR BT were chosen based on previous investigations by Bedka (2011) and Martin et al. (2008) who used IR10.8 BT Ê 215 K as a threshold for very cold pixels within convective clouds. Setvák et al. (2007), using 1 km MODIS data, determined a WV 6.2ÐIRW BTD in the range of 4 to 7 K in the overshootings above the coldest cloud tops. The thresholds for CO ÐIRW and O ÐIRW were adapted from those mentioned by Kwon et al. (2009) and Kwon et al. (2010) for the tropics, based on the empirical results over Europe. Using the COMB method only the O ÐIR BTD values >13 K in the region where the IR10.8 BT is 215 K and WVÐIR BTD > 4 K are detected as OT pixels.

For OTs detected from the satellite data by the COMB method spatial, temporal and seasonal analysis over central Europe were performed in order to determine spatial and temporal distribution of intensive convective activity over the analyzed region. Furthermore, the appearances of the OTs were compared with the weather conditions over central Europe (Croatia, Slovenia, Hungary, Austria, Slovakia) recorded by the automatic weather stations. Analysis of the correlation between the appearance of the OTs and the occurrence of the wind gusts, temperature drops, relative humidity increases and precipitation has been performed for the periods of May-September 2009 and 2010, which is the warm part of the year when the convective activity is the most dominant (e.g., Mikuš et al., 2012; Morel and Sensi, 2002).

When comparing satellite data with the data from the ground stations, the parallax shift of the cloud pixels, whose values are significant for deep convective clouds, has to be taken into account. For calculation of parallax shift the height of cloud top have to be estimated. Because the OTs are considered to have a height similar to the height of the tropopause, the mean tropopause height was derived from the radio-sounding data representative for the studied regions. Parallax correction was then estimated using the tables from http://convection-wg.org/parallax.php, taking the mean tropopause height as the OT cloud-top height. To avoid shifting each cloud pixel, the locations of the automatic stations were shifted north-eastwards for the amount of the parallax correction in the given region.

Coordinates of each pixel meeting the criteria for the BT and BTD have been compared to the parallax corrected coordinates of the automatic stations. If a parallax corrected location of an automatic station falls within the range of 0.1° (approx. 10 km) from the OT detection, the data of that automatic station are used for the analysis. Because the nominal time of the MSG satellite images is the time when the scan starts at the South Pole and the region of Central Europe is scanned app. 10 min after, it is considered that the data have a time stamp of the nominal satellite time +10 min. For that time stamp, automatic station data in the period ±15 min were analyzed. Hail occurrences observed at nearly 500 locations over the continental part of Croatia were also compared to the detected OTs within the range of 0.2° from the parallax-corrected hailpad location.

Over the central European domain, an analysis of lightning activity was performed using the lightning data provided by the low-frequency (VLF/LF) international lightning detection network (LINET). Analysis is done on high resolution grid with spatial resolution of 0.1° (app. 10 km), which gives more detailed information about the lightning ''hot spots''.

Spatial and temporal distributions of lightning activity, but also seasonal and monthly variations of lightning density over the studied region have been analyzed. Detailed analysis of lightning activity was done for selected convective episodes when the OTs were detected at the tops of the thunderstorms, and also for the hail-producing storms. 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 TL, but it also separately detects CG strokes and IC discharges (Betz et al., 2009; Mikuš et al., 2012). LINET IC detections will be termed “IC-strokes” according to the terminology given by Betz et al. (2008). This technical term is used to emphasize thedistinction from IC radio sources detected with very high frequency (VHF) sensors and should not be confused with CG return strokes.

Sensitivity of LINET sensors is very high, enabling detection of strokes with current amplitudes 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., 2008). For the reliable determination of the IC strokes height, at least 4 sensors are needed, located within 150Đ 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.

Lastly, for the hail-producing storms registered by the hailpads, the cloud-top microphysical properties were analyzed using MSG SEVIRI 3.9 μm reflectivity data in form of TĐr profiles. Based on the properties of the 3.9 μm channel, the vertical evolution of the cloud top particle size can be retrieved using the methodology of Rosenfeld and Lensky (1998). The maximum detectable r is 35 mm because the signal saturates at higher values. The methodology of Lensky and Rosenfeld (2008) assumes that the TĐr relations obtained from a scene of clouds at various stages of their development equals the TĐr evolution of the top of a single cloud as it grows vertically. The limitation of the method is the availability of the 3.9 μm reflectivity only during the day time.

Results and concluding remarks

From the three tested OT detection methods, the COMB BTD method was found to be the most appropriate BTD method for detecting the OTs over the studied region due to lowest number of false alarms. Eighty percent of the OT pixels detected using the COMB BTD method is associated with visually detected OTs in the HRV images. According to the comparison with HRV images supported by the analysis of cloud-top temperature based on color-enhanced IR10.8 images, all tested BTD methods detected regions of deep convective clouds. In some cases, detected OT pixels occupy an area too large to exclusively represent an OT. Most of the OT pixels referred to as a “false alarm” are located within the cold ring or cold U/V features observed in color-enhanced IR10.8 images. These thermal features represent very strong and intense convection (Setvák et al., 2010) and are often connected with severe weather conditions, such as large hail, strong winds and heavy rain (e.g. Iršič Žibert et al., 2010). A certain number of the OTs cannot be detected using IR channel-based methods, although they are visible in HRV images. This number includes OTs with an IR10.8 BT > 215 K, i.e., “warm thunderstorms,” which are not very frequent. Additionally, the OT detection is strongly dependent upon the spatial resolution of the satellite instruments. Consequently, some of the OTs can be recognized in the 1 km/pixel HRV imagery, but cannot be detected using BTD methods which are based on IR satellite data with spatial resolution of 3 km/pixel.

An analysis of the weather conditions related to the satellite-based detected OTs showed that the best correspondence is found for precipitation, but it is also significant for strong and gale wind gusts. Additionally, significant temperature drops and relative humidity increases are also frequently observed in the vicinity of detected OTs. A correlation between OTs detected using the COMB method and hail in the continental part of Croatia was found in 38 % of the cases. According to the results presented, in a significant number of cases, extreme weather conditions, such as gale wind gusts or significant 10-min precipitation amounts, are observed in the vicinity of the detected OTs. For that reason, it appears that the detected OT could be a very good indicator that some severe weather conditions could be expected. In such situation, a more detailed analysis and the attention of the forecasters for the particular convective storm with OT are required. Other indicators of severe weather, such as specific thermal features (observed in color-enhanced IR10.8 images), right-moving storms (observed on HRV or IR10.8 images), above anvil plumes (HRV images), which indicate the penetrations of the OT through the tropopause level, and many other indicators (Putsay et al., 2011a), should be analyzed to provide better information on the possibilities for severe weather conditions near the ground.

During the analyzed time period maximum number of lightning strokes is detected in northeastern Italy and western Slovenia, as well as in the pre-alpine region. On the territory of Croatia in the analyzed period, thunderstorm most active region is the Istrian peninsula during the summer months and southern Dalmatia in the autumn. Above the highest areas of the Alps, Apennines and Dinaric Alps lightning activity is rather low, but a weaker lightning activity is also detected over the sea. Over the mentioned regions the observed minimum of lightning activity is partly due to lack of the sensors above these areas.

During spring, lightning activity increases over the continental part of the study area, especially during the month of May. Summer months are most active, as expected, wherein intensive convective thunderstorms usually occur over the land with pronounced maximum in the pre-alpine area, especially in the region of Friuli-Venetia-Giulia. In autumn, intensity of lightning activity increases over the sea and along the coastline as a consequence of stronger temperature contrast between the colder air and warmer sea surface. Lightning activity is very weak and concentrated along the coastline during the winter months.

In average, about 70 % of all detected lightning strokes have negative polarity and approximately 30 % are positive lightning strokes. That is in accordance with the results from the relatively new study by Wapler (2013), while in numerous other studies the amount of positive lightning strokes is significantly lower (Finke and Hauf, 1996; Schulz et al., 2005), probably due to sensitivity of the sensors used. LINET sensors employed in this analysis can detect very weak lighting strokes (current amplitudes < 5 kA), what have a large impact on the results, because lightning strokes with the current amplitudes smaller than 10 kA are most numerous during the lifetime of the convective cells.

The largest number of lightning strokes was detected during the afternoon, with the maximum between 1500 and 1600 UTC, where the largest contribution comes from lightning detected during summer. In spring, maximum of lightning activity is reached earlier, between 1400 and 1500 UTC, while during autumn and winter months lightning activity does not have pronounced diurnal cycle.

An analysis of lightning activity in thunderstorms with OT showed that the spatial distribution of lightning activity generally coincides with the spatial distribution of the detected OT. The temporal distribution showed that within the studied area the largest number of OT with significant lightning activity was detected between 1630 and 1730 UTC, whereas from 0600 to 1000 UTC, both the lightning and OT were rare. In May, most of the intense lightning activity as well as the largest number of OT were detected over the continental part of the study area, whereas in autumn, lightning and convective activity were more pronounced along the coastline and over the sea in association with increased midlatitude cyclonic activity across this area.

In the convective storms with the OT, cold ring or cold U/V features detected using the satellite data, the number of TL strokes significantly increased at the time of the OTs. In order to compare the results with other studies (Montanya et al., 2007, 2009) we have filtered out the CG strokes with peak currents below 10 kA. Consequently, IC strokes dominated during the lifetime of the studied convective storms, leading to the conclusion that these storms produce a significant number of CG strokes with low peak currents. Because of that, the results are strongly dependent on the detection efficiency and sensitivity of used lightning sensors (Betz et al., 2008).

The temporal analysis of the mean current showed that the largest values appeared at the beginning of a storm's lifecycle, before the severe phase of the storm, but also in their dissipation stage. Previous studies have also found an increase in peak currents before severe weather at the ground (Dimitrova et al., 2013). Moreover, IC lightning strokes at the time of OT occurred well above the tropopause; therefore, they are clearly related to the OT parts of the Cb cloud. Usually, the mean height of IC strokes had largest values at the time of OT detections, which is associated with larger number of IC strokes above the height of the tropopause (Elliot et al., 2012).

For the thunderstorm which produced hail recorded by the hailpads at the hail polygon, the number of TL strokes showed an increase slightly before hail occurrence at the ground. At the time the hailfall started, the number of TL strokes briefly decreased, followed by a sharp increase shortly after. Significant increase in the number of TL was usually not observed in the cases with hailstone diameter lower than 1 cm and hail detected at very small area, with one or two hailpads. OTs were usually observed at the cloud tops of the hailstorms which produced hailstones larger than 2 cm. Also, in these hailstorms a significant number of CG lightning strokes with peak currents below 10 kA were produced. The largest values of mean current for CG+, CG and IC strokes were detected before the hailfall, while during the hailfall they were rather low compared to the values before and after hail falling. Also, the mean height of IC strokes showed an increase before hail was detected by hailpads and decrease during the hailfall. Additionally, larger hailstones with higher kinetic energy values appeared at the beginning of the hailshower.

Analyzed satellite-based T-r vertical profiles indicated that all studied hail-producing storms were storms with moderate to strong (even severe) updraft, indicative for hailstorms. The results clearly show that there is a strong connection between lightning characteristics and updraft strength, which is manifested in the appearance of the OT (in some cases cold ring and cold U/V) on the convective cloud tops, timing of the hailfall and properties of the hail stones and microphysical characteristics of the cloud tops observable in the satellite data.

In conclusion, satellite data show very good results in the analysis of severe storms despite their rather low spatial resolution. The presented results showed that using certain satellite images or objective methods strong vertical updrafts manifested as OTs or cold rings and U/Vs could be detected. Furthermore, the intensity of storm's updraft could be estimated using the properties of 3.9 μm channel data in form of vertical T-r vertical profiles. All mentioned indicators of strong vertical updraft were observed with significant lead times what makes these methods very useful in nowcasting, with an important role, especially in the areas lacking radar coverage. Lightning monitoring and detailed analysis of lightning data, combined with satellite-based methods during severe weather conditions, can improve the nowcasting of extreme convective weather events. Also, the observed lightning characteristics and satellite signatures during the severe convective storms can be used as important parameters in the complex forecasting tool for the objective estimation of potential for severe weather conditions on the ground.