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Remote Sensing Observations of Thunderstorm Features in Latvia

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***Abstract* – Thunderstorms are the most hazardous meteorological phenomena in Latvia in the summer season, and the assessment of their characteristics is essential for the development of an effective national climate and weather prediction service. However, the complex nature of convective processes sets specific limitations to their observation, analysis and forecasting. Therefore, the aim of this study is to analyse thunderstorm features associated with severe thunderstorms observed in weather radar and satellite data in Latvia over the period 2006–2015. The obtained results confirm the applicability of the selected thunderstorm features for thunderstorm nowcasting and analysis in Latvia. The most frequent features observed on days with thunderstorm were maximum radar reflectivities exceeding 50 dBZ and the occurrence of overshooting tops and tilted updrafts, while the occurrence of gravity waves, V-shaped storm structures and small ice particles have been found to be useful indicators of increased thunderstorm severity potential.**

***Keywords* – Lightning detection; meteorological satellite; remote sensing; thunderstorms; weather radar**

1. INTRODUCTION

Thunderstorm events are associated with numerous small-scale severe weather phenomena that can lead to fatalities, injuries, property damage, economic disruptions and environmental degradation. These small-scale weather phenomena include hail, lightning, damaging straight-line winds, tornadoes and heavy rainfall leading to flooding [1]–[5]. Severe weather associated with thunderstorms has been observed in every country in Europe and poses a significant threat to life, property and economy. Therefore, it is important to be aware of the mechanisms of thunderstorm occurrence and to increase the ability of forecasting and warning for severe events [1], [4], [6], [7].

In recent years, the increased number of thunderstorm documentation has improved the awareness of the threats associated with severe events [7]–[9]. However, the accurate prediction of convection and associated hazards has some very specific challenges: the small-scale spatial distribution and short life span of thunderstorms impose limitations for the prediction of individual convective cells in numerical weather prediction (hereafter NWP) models, meaning that in practice these hazards are often nowcast using observations rather than model forecasts [4]. The complexity of convective phenomena leads to specific challenges in not only their forecasting, but also the detection and analysis of such events. The convective clouds of individual thunderstorms (*cumulonimbus* clouds) are comparatively small but can still extend over tens of kilometres horizontally and up to the tropopause. The formation and evolution of these clouds

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depend on a wide range of factors including meteorological conditions such as temperature and humidity as well as the atmospheric instability [10]. A convective cell typically goes through three stages during its lifetime of ~45 minutes: the cumulus stage, the mature stage, and the dissipating stage. During these lifetime stages, a convective cell develops an updraft core, a precipitation core, and circulations [11]. While thunderstorm observations from the surface meteorological observation stations only describe the occurrence of thunderstorms along with the small-scale weather phenomena associated with them, observations obtained from a variety of remote sensing detectors can significantly contribute to an increased understanding of the mechanisms and dynamics of thunderstorm development. Even though it is quite difficult to determine how many thunderstorm events are missed and not recorded within the national surface meteorological observation networks [12], recently the number of reported severe convection events has risen because of the increased ability of detection via remote sensing and volunteer observer activities. The increased ability to observe these short-lived, small-scale phenomena is contributing to the compilation of stable, credible climatologies and analyses that should give rise to better warning systems [12], [13].

Due to rapid advances in technology during the past couple of decades, a great proportion of the carried out research has focused on the use of archived remote sensing observations – such as lightning detector data [5], [14]–[16], Doppler radar measurements [17] and meteorological satellite observations [18] – for the analysis of convective phenomena. Several studies have looked at lightning characteristics during particular thunderstorm events [19], suggesting that lightning intensity can be used as a tool for the assessment of thunderstorm severity [20]. Studies have also revealed associations between weather radar reflectivity parameters, thunderstorm intensity and the occurrence of hail [21], [22]. In addition, a great proportion of scientific research studies has focused on the benefits of using algorithms and products obtained from meteorological satellite data. For instance, algorithms for the detection of rapidly developing thunderstorms [23], characteristics of the observed cloud top temperatures (hereafter CTT) [20], [24], [25] and visual cloud top features [26], [27] have been found to be good indicators for thunderstorm severity and could be used as practical tools for the analysis and nowcasting of thunderstorm events.

Increased awareness and knowledge of thunderstorm characteristics in the geographical area of interest form the basis for the development of algorithms for automated detection and warning systems. Initiatives for the development of such tools have recently been topical in many countries around the world. For instance, an automated radar-based hail detection algorithm has been established in Finland [28], whereas in Slovenia an automatic satellite-based severe thunderstorm detection mechanism has been developed [27]. Several applications have been developed for the mountainous terrain of the Alpine region, including a nowcasting algorithm and an automatic alert system. The thunderstorm nowcasting algorithm uses inputs from weather radar, satellite, NWP, climatology and digital terrain [24], while the automated alert system includes a radar-based thunderstorm severity-ranking product, which classifies each cell in four categories of severity [29]. A similar approach of using storm classification systems and decision trees based on weather radar data is used also within the Warning Decision Support System operated in the United States [30]. Besides the development of nowcasting tools, several approaches for the assimilation of remote sensing observations in NWP have been studied in order to increase their convection forecast accuracy [31].

In Latvia, the analysis of thunderstorm occurrence and intensity has so far been limited to the exploration of long-term data series obtained from the surface meteorological observation stations. Recent study of thunderstorm climatology in the Baltic countries [32] has demonstrated the characteristics of the spatial distribution of thunderstorm days in Latvia, their duration and time of occurrence, while another study [33] has focused on assessing the long-term trends of changes in thunderstorm frequency and atmospheric circulation patterns associated with thunderstorm occurrence. According to these studies, the annual mean number of days with thunderstorms in Latvia has been estimated to be 14–24 days over the period 1951 to 2000, with a distinct gradient in thunderstorm day frequency from the coastal areas towards inland. In most of the meteorological observation stations thunderstorms have been most frequent in July. Another historical analysis of tornados in Europe [7] stated that 15 tornado cases have been officially registered in Latvia over the period 1795–1986. However, it is important to note the absence of a consistent tornado database in Latvia, which has led to a possible underestimation of tornado frequency in the country. In addition, a couple of case studies focusing on severe thunderstorm cases in Latvia have been carried out recently [34], [35] outlining the complexity of convective events in the region.

Thunderstorms are the most hazardous meteorological phenomena in Latvia in the summer season, and the assessment of their characteristics is essential for the development of an effective national climate and weather prediction service. Nevertheless, the existing body of research on thunderstorms in Latvia has been insufficient for the development of effective nowcasting applications or warning tools, which efficiently exploit the benefits provided by remote sensing observation data. So far, the use of remote sensing data for the analysis and nowcasting of thunderstorm events in Latvia has still been based on theoretical approaches and assumptions, rather than scientific evaluations and studies. Therefore, the presented here study aims at providing an initial basis for the assessment of the performance of different theoretical remote sensing indicators of thunderstorm severity in Latvia. The results of this study will form a basis for the improvement of thunderstorm nowcasting system at the National Meteorological Service of Latvia provided by the Latvian Environment, Geology and Meteorology Centre (hereafter LEGMC), which is responsible for both monitoring and warning for severe weather events, including thunderstorms of different levels of severity.

2. MATERIALS AND METHODS

2.1. Data Used

The presented here study contains the analysis of thunderstorm events in Latvia over a 10-year period from 2006 to 2015, by using a synergy of surface in-situ and remote sensing observation data. Over the period of study, all detected thunderstorm days have been assessed by using the following approach.

For the identification of days with thunderstorms, lightning observation data from the Nordic Lightning Information System (NORDLIS) was used. NORDLIS is a joined lightning location network between Norway, Sweden, Finland, and Estonia, and the Finnish Meteorological Institute provided the data for this study. Even though the quality of the lightning location data is not homogenous in space and time over the whole network area [15], [36], the provided data present a sufficiently wider spatial coverage of detections than the surface thunderstorm observations and therefore are beneficial for the identification of local thunderstorms. For the aim of this study calendar days with at least one lighting flash detected within the territory of Latvia were used for the preliminary analysis and identification of thunderstorm days. However, for the characterisation of high impact thunderstorm events days with more than 10 lightning flashes detected were chosen for further analysis along with complimentary data. In this study, our data set consists of lightning flashes – although the basic unit of detection is a stroke, we use only the first located stroke in case of a multi-stroke flash. Lightning parameters describing the total daily number of lightning flashes, time of their occurrence (time period between the first and the last flash observed on a particular calendar day, UTC) and the daily lightning peak current (kA) were derived from the NORDLIS dataset. Days with more than 10 lightning flashes were subjected to further analysis by using additional observation data as described below. A script for the extraction of data from the lightning data archive was developed in software environment for statistical computing and graphics R.

Meteorological satellite observations were used for the characterisation of thunderstorm cloud features on days with more than 10 lightning flashes. For effective identification and analysis of the short-lived thunderstorm cloud features, data from geostationary *Meteosat* satellite operated by European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) were used. The main instrument of the payload of the *Meteosat* satellite is a passive radiometer referred to as the Spinning Enhanced Visible and Infrared Imager (SEVIRI), which has 12 spectral bands [37]. In order to describe thunderstorm cloud features identifiable from different parts of the electromagnetic spectrum, information from a long-wavelength infrared channel IR 10.8 μm (hereafter IR 10.8), medium-wavelength infrared channel IR 3.9 μm (hereafter IR 3.9) and broadband high-resolution visible channel HRV 0.4–1.1 μm (hereafter HRV) was obtained. The observation data were available with a 15-minute time step at a spatial resolution of ~3 km at the satellite subpoint for the IR channels and ~1 km for the high-resolution channel of the visible part of the spectrum. Observations from IR 10.8 were available daily, but the microphysical information provided by the IR 3.9 channel and visible features could only be analysed under the conditions of sufficient daylight. Data were obtained from the Data Centre that contains the long-term archive of satellite data operated by EUMETSAT and analysed by using an open source data analysis software tool *McIDAS-V* [38].

Thunderstorm cloud dynamics on days with more than 10 lightning flashes was assessed by using observations from the Doppler Weather Radar METEOR 500C [39] located near the Riga Airport. This particular radar operates within the C-band with a wavelength of 5.4 cm and a temporal resolution of 10 minutes. The weather radar has been operational since November 2006, therefore only data beginning from 2007 have been available for the study. However, due to local problems with the maintenance of the radar data archive at LEGMC, there were gaps in the data series (Table 1). In addition, only two radar products were available for the analysis – the Maximum Display MAX product and the Echo Height ETH product. For the characterisation of individual thunderstorm events, the maximum value of radar reflectivity, visual features in the reflectivity field and the height of the echo top (hereafter also ETH) and echo base (hereafter also EBH) as well as the echo thickness (hereafter also ET) were obtained. Radar observations were analysed by using the Display, Analysis and Research Tool (RainDART) which is a part of the Doppler Weather Radar System METEOR 500C [39].

TABLE 1. IN-SITU AND REMOTE SENSING DATA AVAILABILITY ON DAYS WITH LIGHTNING DETECTED IN LATVIA OVER THE PERIOD 2006–2015

Year	Total number of days with lightning detected		Number of days with >10 lightning flashes detected			
	Lightning detections	Thunderstorms observed at surface stations	Lightning detections	Thunderstorms observed at surface stations	Radar data available	Satellite data available
2006	104	71	55	54	–	55
2007	116	85	64	62	33	64
2008	111	59	52	48	38	52
2009	105	69	58	55	58	56
2010	106	90	75	75	75	75
2011	100	74	69	64	69	69
2012	109	78	61	59	60	61
2013	101	83	71	69	47	67
2014	108	78	82	73	42	81
2015	71	46	46	39	43	46
Total	1031	733	633	598	465	626
% of the total		71 %	61 %			
% of days with >10 lightning flashes				95 %	73 %	99 %

In order to assess the possible impacts of thunderstorm events in Latvia, in-situ observations from the surface meteorological observation stations were used. The analysis links observations of surface and remote sensing sources qualitatively, not spatially; therefore, information from all meteorological observation stations operating over the period of interest was used. The parameters used for the description of thunderstorm severity were the daily maximum amount of precipitation (mm), daily maximum wind gusts (m/s) and the occurrence of thunderstorms, hail and snow pellets. Data were obtained from the electronic observation database CLIDATA maintained by LEGMC.

Table 1 shows the overall data availability over the study period. In the period from 2006–2015 there were altogether 1031 days with lightning detected within the territory of Latvia, of which 61 % or 633 days with more than 10 lightning flashes observed. Data from the surface meteorological observation stations confirmed the occurrence of thunderstorms on 71 % of the total lightning cases and 95 % of cases with >10 lightning flashes detected. The overall availability of satellite data for the analysis has been high (99 % of days with >10 lightning flashes detected), while weather radar data contained gaps in the time-series leading to the availability in 73 % of the cases with >10 lightning flashes detected.

2.2. Thunderstorm Features

In order to assess the applicability of remote sensing observations for the identification of severe thunderstorms, several theory-based features were identified and analysed within this study. The correct and quick interpretation of available observation data is essential for the assessment of thunderstorm severity during weather surveillance. However, as each data source provides only a partial picture of the storm, the combination of the available remote sensing data enhance their usefulness [21]. Thus, based on theoretical approaches, several measures and features suggested as indicators of thunderstorm severity were identified from the remote sensing observation data on days with more than 10 lightning flashes observed.

Data obtained from the weather radar measurements provide both qualitative and quantitative estimates beneficial for thunderstorm severity assessment. As for the quantitative indicators the height of the ETH, EBH and the ET were obtained in order to describe the vertical extent of the convective clouds, while reflectivity parameters – namely, the maximum reflectivity (hereafter also Z) – was used for the identification of the presence of characteristic visual features. Previous research studies suggest the presence of a tilted updraft, weak echo region (hereafter also WER) and hook echo amongst the visual indicators of thunderstorm severity, which can also be addressed to as signatures of a supercell thunderstorm [11], [21], [29], [40]–[41].

Meteorological satellite observations provide information on the cloud top features characteristic for severe thunderstorms. Some of such features can be observed in the infrared channels, while valuable information can also be obtained from the visible part of the spectrum. Features identified at the infrared part of the spectrum (channel IR 10.8) contain the minimum value of CTT and visual features identifiable in the CTT field – such as cold-ring structure or a U/V-shaped storm structure. These features in the CTT field are common with strong convective storms as their highest tops penetrate the tropopause and reach into the warmer lower stratosphere [26]–[27], [42]. Associated to the vertical extent of convective clouds up to the lower stratosphere is the occurrence of overshooting tops and gravity waves that can be identified from satellite measurements in the visible part of the spectrum. While overshooting tops occur because of cloud top penetration through the tropopause, gravity waves form and propagate outward when the cloud top oscillates vertically about the level of neutral buoyancy [25]–[27]. Another indicator used for severe thunderstorm detection was a value exceeding 45 obtained from the brightness temperature difference (hereafter BTD) of the channels IR 3.9 and IR 10.8. Both of these channels are considered window channels with very little absorption of atmospheric gases and water vapour, while by daytime the channel IR 3.9 contains information on the effective radius of cloud top particles. Smaller ice particle size corresponds to higher cloud top reflectivity in the channel IR 3.9. Thus, reflectivity information retrieved from the channel IR 3.9 by calculating the BTD can be used as a measure of the cloud-top particle size, with higher reflectivity values for smaller cloud-top particles. When small particles are present at the top of very cold cumulonimbus clouds, it can be assumed that these particles did not have substantial time to grow in size – smaller particles at very low temperatures are an indication of strong thunderstorm updrafts [43]–[45].

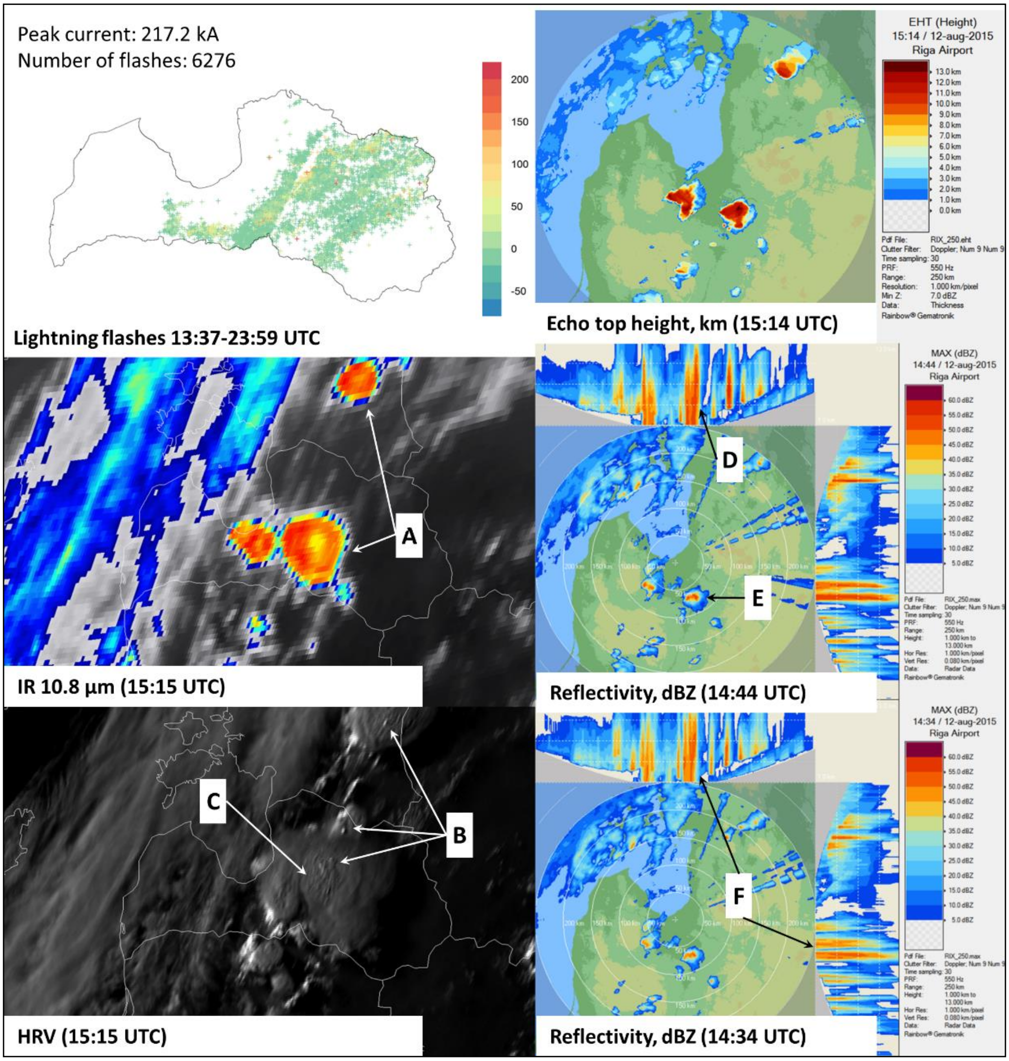

Fig. 1. Example of the thunderstorm features identified for a severe convective storm observed in Latvia on the 12th August 2015. The identified features are marked with letters A–F as follows: A – cold-ring structures; B – overshooting tops; C – gravity waves; D – tilted updraft; E – hook echo; F – weak echo region.

Fig. 1 illustrates an example of the features obtained for the characterization of a thunderstorm event observed on 12th August 2015. During this particular event, most of the characteristic features of severe thunderstorms could be depicted from the remote sensing data. However, it was not the case for the majority of the days under study as quite few storms develop clearly pronounced features. In addition, the analysis and visual inspection of remote sensing data depends on a variety of factors, including specifics of the detectors, synoptic situation, solar illumination and even the human factor of the observer. Therefore, the presented here analysis contains quantified information regarding the occurrence of the selected thunderstorm features based on a subjective or manual approach towards their identification, which is in accordance to the operational environment and decision-making during weather surveillance.

3. RESULTS AND DISCUSSION

Over the period of 10 years analysed within this study (2006–2015), there were in total 1031 days with lightning observed in the territory of Latvia, of which 633 days or 61 % had more than 10 lightning flashes detected (see Table 1). The year with the overall lowest thunderstorm activity in Latvia as depicted by lightning detections has been the year 2015 with in total 71 day with lightning flashes detected, of which only 46 days had more than 10 lighting flashes. The year with the maximum total lightning activity has been the year 2007 (116 days with lightning flashes), while the highest number of days with more than 10 lightning flashes (82 days) detected has been the year 2014. The total number of days with lightning detected has been by 16–52 days larger than the number of thunderstorm days registered by the surface meteorological observation stations, while for days with at least 10 lightning flashes detected this difference has been substantially lower (0–9 days). It is important to note that the presented here analysis is not directly comparable to the results obtained by Enno et al. [32], since the particular study has looked at thunderstorm occurrence at particular observation sites, while this analysis considers the occurrence of thunder within the whole territory of the country.

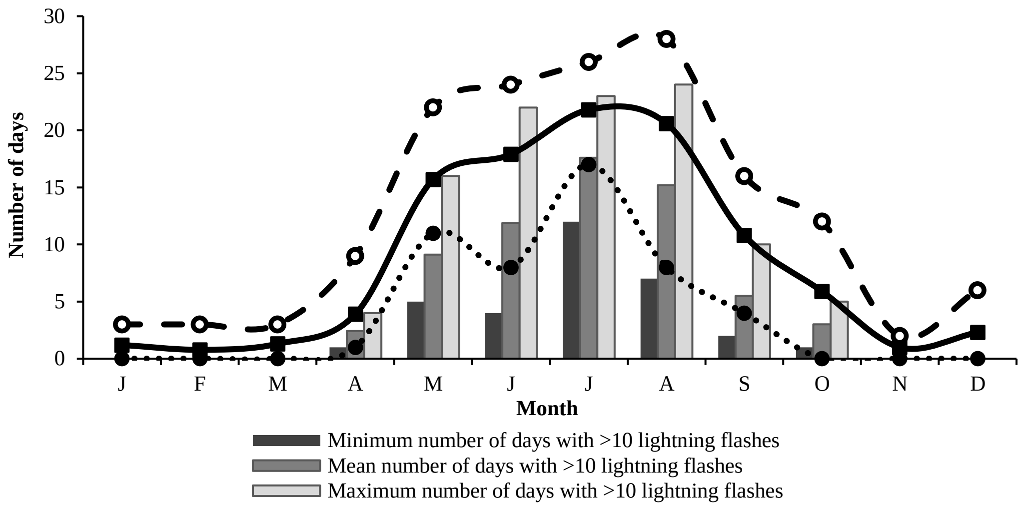

Fig. 2. The seasonal course of the frequency of days with lightning flashes presented as the multi-year mean, minimum and maximum number of days with at least 1 lightning flash and more than 10 lightning flashes detected in Latvia over the period 2006–2015.

The monthly distribution of the total number of days with lightning flashes and days with more than 10 lightning flashes observed (Fig. 2) reveals a maximum of lightning activity in the summer season. In general, lightning flashes have been detected in Latvia throughout the year, however on particular years there were no lightning flashes observed during the period between October and March. The time period between May and September can be considered as the period of increased convective activity in Latvia, since the average number of days with lightning detected varies between 11 and 22, with the maximum observed in the summer months (18, 22, 21 days on June, July and August accordingly). At the same time, days with more than 10 lightning flashes have been observed within the period between April and October, with a maximum of on average 18 days detected in July. During years with low convective activity over the country, the number of days with more than 10 lightning flashes detected has not exceeded 12 days per month, while on some years there were 22–24 days with more than 10 lightning flashes observed – for instance, June 2014, July 2011 and August 2010.

For the analysis of thunderstorm features identified in remote sensing observations, days with more than 10 lightning flashes detected in Latvia were studied. During these days, surface in-situ meteorological observations display signs of potentially hazardous weather associated with thunderstorm activity (Table 2). One of the most frequent weather hazards associated with summertime thunderstorms is high precipitation with a potential for causing local flash floods. Over the 10 years of study, precipitation has been observed in 99 % of days with >10 lightning flashes, with the multi-year mean of the maximum amount of daily precipitation reaching 18.3 mm/24h. However, on all of the years the maximum precipitation amount registered at a particular observation site has reached 35.7–87.6 mm/24h. Maximum wind gusts on average reach 14.4 m/s on days with >10 lightning flashes, while the maximum registered at a particular meteorological observation stations reaches 20–29 m/s. However, it is important to note that during recent years volunteer observers have reported many severe thunderstorm cases associated with high wind damage, while no significant daily fluctuations in the time series from the observation stations could be detected. Hail and snow pellets are hazardous phenomena associated with severe thunderstorms, however due to their local occurrence rarely observed at the official measuring sites. Therefore, in the period of interest there have been 111 days with hail and 12 days with snow pellets detected within the surface observation network of Latvia on days with >10 lightning flashes. Typically, hail is a summertime weather phenomenon, while snow pellets are associated with thunderstorms in the cold part of the year – thus the identified thunderstorm cases with snow pellets observed were detected mainly during October thru December (7 cases) and April (3 cases).

TABLE 2. OCCURRENCE AND INTENSITY OF METEOROLOGICAL PHENOMENA OBSERVED AT SURFACE METEOROLOGICAL OBSERVATION STATIONS ON DAYS WITH >10 LIGHTNING FLASHES

Year	Occurrence and intensity of precipitation			Daily maximum wind gusts		Occurrence of hail and snow pellets	
	Occurrence of precipitation, days	Mean of the maximum precipitation, mm/24h	Maximum precipitation, mm/24h	Mean of the maximum wind gusts, m/s	Maximum wind gusts, m/s	Hail, days	Snow pellets, days
2006	54	19.4	67.7	14.2	29	7	0
2007	62	21.5	76.0	14.7	24	21	1
2008	52	19.7	87.6	14.1	22	8	0
2009	57	19.2	70.7	15.1	27	14	1
2010	74	21.8	82.0	14.7	27	14	1
2011	67	19.1	73.0	15.0	26	11	4
2012	59	17.9	67.7	15.3	27	12	2
2013	71	16.3	58.0	13.6	23	13	1
2014	82	14.9	74.3	13.5	25	9	0
2015	46	13.0	35.7	13.3	20	2	2
Mean intensity		18.3	69.3	14.4	25		
% of the cases	99 %					18 %	2 %

For the identification of features characteristic for severe thunderstorm events in Latvia, daily weather radar and satellite observations were analysed on days with >10 lightning flashes detected. Due to peculiarities in data archiving and maintenance, it was only possible to obtain two reflectivity-based products from the weather radar data archive. While radial wind products have also been found beneficial for severe thunderstorm analysis and detection [41], information on the maximum radar reflectivity and height of the echo can also be efficiently used for both analysis and nowcasting [21], [22], [40]. The analysis of the three components of the Echo height ETH product – ETH, EBH and ET – reveal valuable information regarding the vertical extent of convective clouds in Latvia (Fig. 3). Over the period 2007–2015, the majority of clouds have had EBH of ~1–2 km above ground level, with nearly 80 of the cases EBH estimated to be lower than 1 km above ground level. At the same time the majority of convective cloud tops have extended at the height of 6–11 km, while a significant fraction of cases have seen ETH reaching 14 km above ground level. Thus, the thickness of the convective cloud echoes mainly range between 5–7 km, but on particular occasions can extend to 11–13 km. While interpreting these results, it is important to take into account the specifics of radar observations: the location and measurement technique of the weather radar can lead to overestimation in the echo height measurements at areas located at the furthest edges of the radar scan area. Thus, during the analysis it has been identified that in cases with thunderstorm clouds emerging far from the radar (for instance, in the easternmost regions of the country), due to the curvature of the Earth's surface and the radar beam configuration, the radar is not able to detect the lowest part of the convective cloud, leading to an overestimated EBH. Therefore, ETH can be considered as the most accurate measure for the vertical extent of thunderstorm clouds.

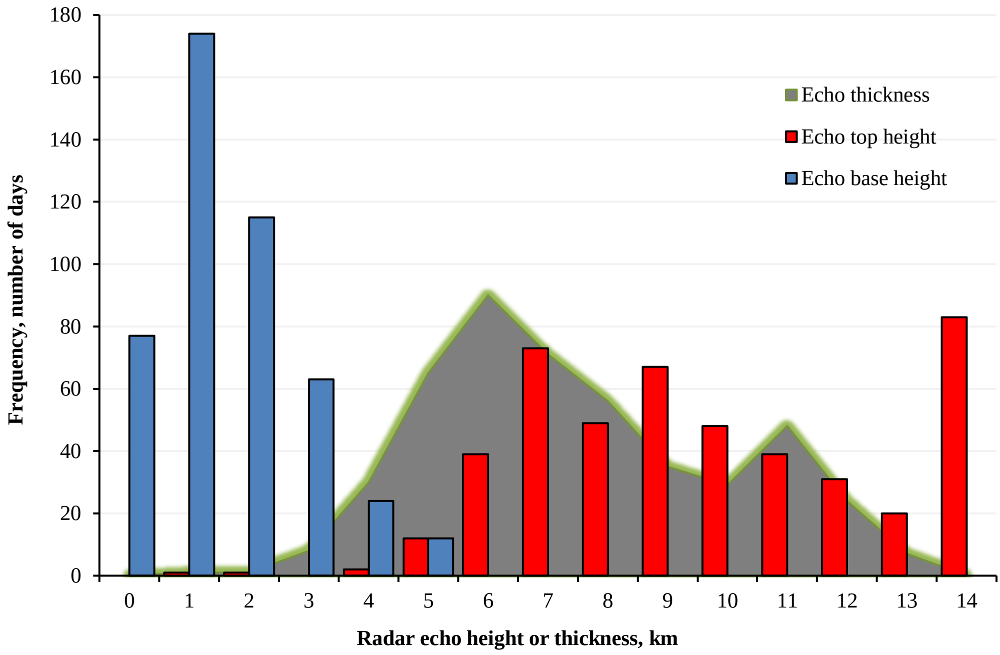

Fig. 3. The frequency distribution of weather radar Echo height EHT product parameters on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015.

In order to assess the intensity and structure of the convective clouds, the radar reflectivity measures can be used. In this study, we looked at the values, vertical and horizontal extent and structure of the maximum radar reflectivity (dBZ) obtained from the Maximum Display MAX product. It was estimated that the majority of thunderstorm clouds have a maximum reflectivity value exceeding 50 dBZ (Fig. 4). According to the theoretical relation between radar reflectivity and observed rain rate at the surface, 50 dBZ corresponds to intense rainfall of 48.7 mm/h, while 60 dBZ is an indicator of large hail or torrential rainfall of 205 mm/h [39]. However, over the period of the analysis, there have been thunderstorm cases with the maximum reflectivity falling well below the 40 dBZ threshold. Besides the absolute values of radar reflectivity, the extent and structure of the maximum reflectivity areas was assessed in order to identify some theoretical severe thunderstorm identificators, such as tilted updraft, WER and hook echo (see Fig. 1).

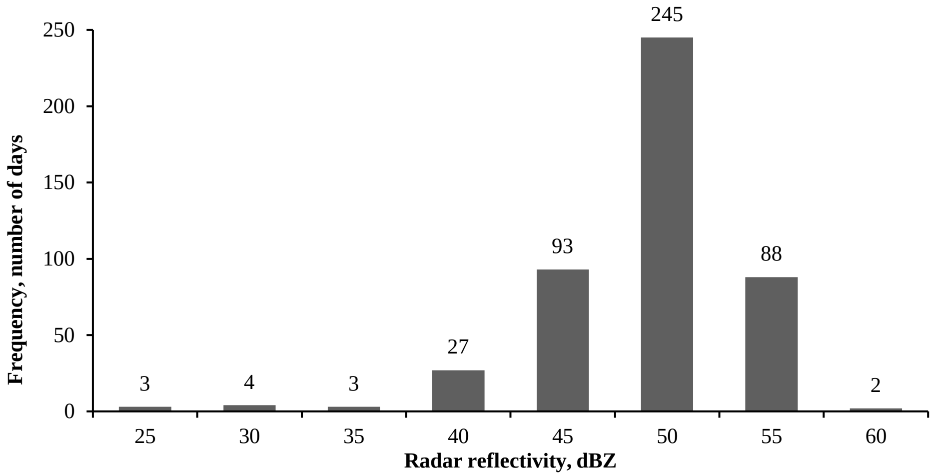

Fig. 4. The frequency distribution of reflectivity values (dBZ) obtained from the weather radar Maximum Display MAX product on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015.

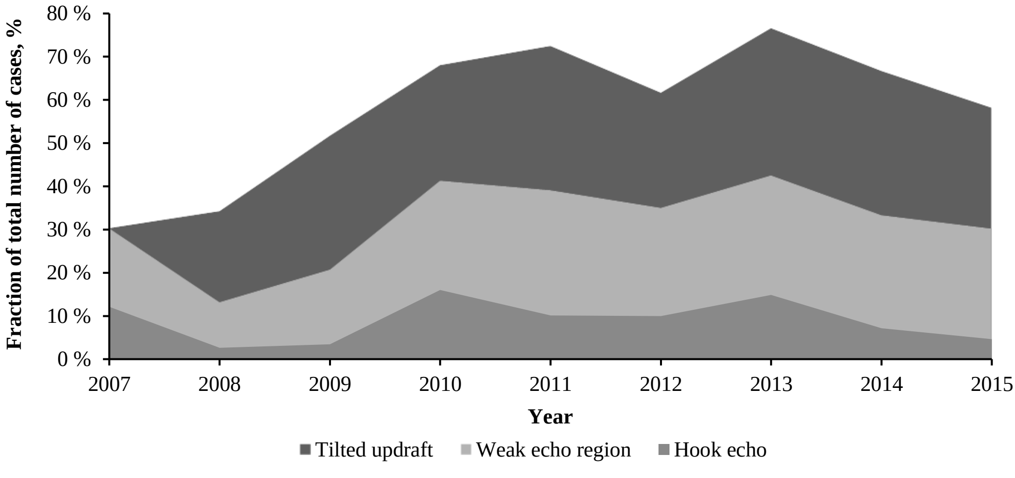

Fig. 5. The fraction of cases (%) with characteristic thunderstorm features identified from weather radar observations on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015.

The analysis revealed that the occurrence of a tilted updraft, identified by a vertically tilted reflectivity area in the radar images, is a frequently observed convective storm feature in Latvia (Fig. 5). The occurrence of WER feature has been rarer, identifiable on 13–43 % of the analysed cases. However, the most seldom severe thunderstorm feature observed in Latvia is the occurrence of a hook echo in the horizontal field of radar reflectivity. This feature, which is often associated with the rotation of the mesocyclone associated with a supercell storm, has only been identified in 2–16 % of thunderstorm cases. The majority of the detections of a hook echo falls in the year 2010, when there were 12 days with such a feature identifiable from the weather radar images. In the timely distribution of the occurrence of features associated with severe thunderstorms, two maxima can be identified in the year 2010 and 2013, followed by a decrease in 2015. While weather radar observations bring an opportunity of a deeper understanding of the convective processes, the limitations for a comprehensive analysis comprise difficulties in identification of storms with tilted updrafts and rotation [30]. Identification of such features in the radar imagery comprises uncertainties related both to the degree at which such features are pronounced during a particular event as well as the subjective views and approach of the analyst.

The observations of geostationary weather satellites serve as an essential tool for the observation and nowcasting of convective phenomena, however in order to exploit the data efficiently, it is essential to be aware of the limitations in detection and representation of the provided information. The main problem associated with operational use of satellite imagery available in the visible to infrared part of the spectrum, is the fact that the observations only describe the surfaces seen from the satellite. Therefore, in order to utilize the provided information, one must be aware of and understand the processes taking place at the top of the convective clouds. One of the indicators of a potentially severe thunderstorm is its vertical extent indirectly inferred from the satellite observations of temperature. Thus for the aim of this study we looked at CTT depicted by the IR 10.8 channel (Fig. 6). The analysis reveals that the majority of thunderstorm cases observed in Latvia have had CTT reaching 210–230 K (–63 °C to –43 °C). While there have been cases with thunderstorms occurring in relatively warm clouds (256 K or –17 °C), a significant fraction of the cases has seen CTT falling below 215 K (–58 °C), considered as a threshold for very cold pixels [46], and even 204 K (–69 °C).

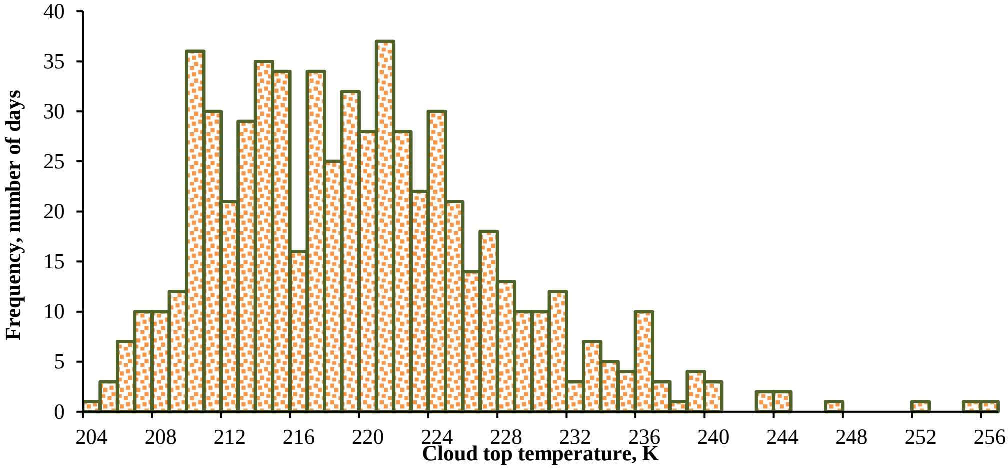

Fig. 6. The frequency distribution of CTT (K) identified from IR 10.8 spectral channel of the SEVIRI instrument aboard the *Meteosat* satellites on days with more than 10 lightning flashes detected in Latvia over the period 2006–2015.

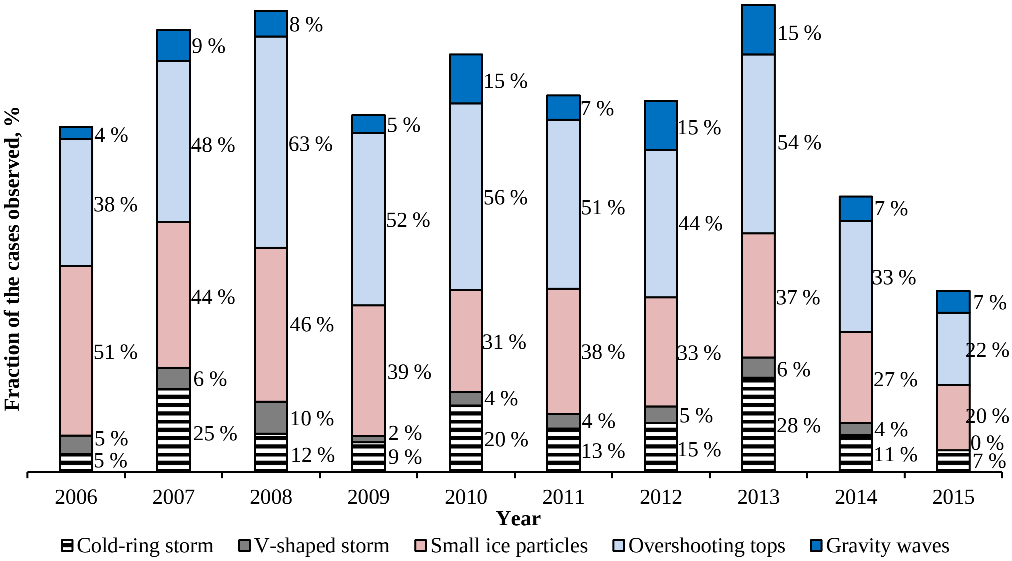

Fig. 7. The fraction of cases (%) with characteristic thunderstorm features identified from weather satellite observations on days with more than 10 lightning flashes detected in Latvia over the period 2006–2015.

Besides the values of thunderstorm CTT, it is also possible to obtain additional information from meteorological satellite observations. During this study, several features characteristic for severe thunderstorms were identified from satellite observations (Fig. 7). From the CTT field obtained from the IR 10.8 channel, the structures of cold-ring storms and V-shaped storms were identified, while exceedances of the threshold of 45 in the BTD of the channels IR 3.9 and IR 10.8 revealed the presence of small ice particles at the top of the cloud. Such features are commonly associated with severe thunderstorms [26], [42], [45]. It was estimated that the presence of small ice particles at the top of deep convective clouds was evident in 20–50 % of the cases analysed. Small ice particles are an indicator of intense updrafts and strong vertical motions within the thunderstorm cloud, which are conditions favourable for the occurrence and growth of hail [45], [47]. The cold-ring and V-shape structures were detected more seldom. Cold-ring storms occurred about 5–28 % of the cases, while the fraction of V-shaped storms did not exceed 10 % of the cases or five cases in the year 2008. Studies show that these types of structures visible in the field of CTT have been associated with the occurrence of hail, strong winds and precipitation [26]. Valuable information was obtained also from the visible part of the spectrum during daytime hours by analysing the reflectivity images obtained from the HRV channel. Two main features were identified from the reflectivity images – overshooting tops and gravity waves. Overshooting tops occur as the thunderstorm cloud top reaches the tropopause and penetrates into the stratosphere in a form of short-lived bubble-like structures. In previous studies, the presence of overshooting tops has been associated with the occurrence of hail and severe wind, but rarely with tornado events [48]. Over the 10 years of analysis, overshooting tops could be identified in 22–63 % of the cases. On relatively rare occasions the presence of gravity waves at the top of convective clouds could be identified – such features were evident 4–15 % of the thunderstorm days analysed.

TABLE 3. NUMBER OF DAYS WITH THUNDERSTORM FEATURES OBSERVED IN WEATHER RADAR AND SATELLITE OBSERVATIONS AND THE OCCURRENCE AND INTENSITY OF METEOROLOGICAL PARAMETERS OBSERVED AT SURFACE METEOROLOGICAL OBSERVATION STATIONS

Thunderstorm features	EHT >10 km	ET >8 km	EBH <1 km	Max Z <50 dBZ	Max Z >50 dBZ	Tilted updraft	Weak echo region	Hook echo	CCT <215 K	Cold-ring storm	V-shaped storm	Small ice particles	Overshooting tops	Gravity waves
EHT ≥10 km	221													
ET ≥8 km	181	199												
EBH ≤1 km	71	89	251											
Max Z <50 dBZ	27	20	82	130										
Max Z ≥50 dBZ	194	179	169		335									
Tilted updraft	166	165	151	40	240	280								
Weak echo region	115	120	89	7	146	140	153							
Hook echo	41	42	19	0	44	42	41	44						
CCT ≤215 K	134	123	66	25	145	126	86	35	228					
Cold-ring storm	63	60	27	6	63	59	50	22	92	94				
V-shaped storm	14	16	10	4	17	14	7	3	27		29			
Small ice particles	85	82	76	33	115	98	62	20	125	65	17	227		
Overshooting tops	143	138	105	40	178	155	104	39	177	87	28	160	291	
Gravity waves	41	41	21	3	42	38	35	13	58	43	10	47	59	59
Mean intensity of precipitation (mm/24h) and wind gusts (m/s) on days with particular thunderstorm features observed														
Maximum precipitation	19	21	18	16	19	20	21	20	21	23	23	23	22	26
Maximum wind	14	14	15	15	14	15	15	15	15	15	14	15	15	16
Occurrence (number of days) of thunderstorms, hail and snow pellets at the surface meteorological observation stations on days with particular thunderstorm features observed														
Thunderstorm	214	196	239	114	327	271	151	44	219	93	28	221	287	59
Hail	32	36	39	17	56	48	27	10	43	21	8	45	64	21
Snow pellets	1	1	7	10	1	6	2	1	2	2	0	2	3	2

Convective storm observations, assessment and identification of their severity strongly depends on the possibility to obtain a complex image of the processes taking place within the convective cloud. Such approach can be applied by combining the available remote sensing, in-situ and NWP data during the observation and nowcasting, as well as the analysis of the convective storms. Table 3 contains a summary of the frequency of cases with two thunderstorm features observed at the same time. The most frequent features identified on days with >10 lightning flashes detected over the period 2006–2015 were maximum radar reflectivities exceeding 50 dBZ, the occurrence of overshooting tops and tilted updrafts, while the most seldom ones were V-shaped storm structures, hook echoes and gravity waves. Based on the analysis, it can be approximated that the maximum radar reflectivity exceeding 50 dBZ and the occurrence of overshooting tops are the two features most frequently associated with the occurrence of other features as well. Besides these parameters have most often been associated with the occurrence of thunderstorms and hail at the surface meteorological observation stations. Therefore, it can be assumed that these two are the main indicators useful for the identification of high impact thunderstorms. These features are also easily identifiable from the available radar and satellite observations, which increases their applicability in operational forecasting and nowcasting of thunderstorm events. On the other hand, it was found that the most intense precipitation occurred during events with gravity waves, V-shaped storm structures and small ice particles visible, while wind gusts were the strongest on days with gravity waves, small ice particles or radar reflectivity <50 dBZ observed. Thus, the occurrence of gravity waves, small ice particles and V-shaped storm structures can serve as an indicator of an increased thunderstorm severity potential. While high wind speeds and the occurrence of snow pellets have predominantly been associated with radar reflectivities below 50 dBZ, it can be assumed that these conditions are mainly associated with thunderstorms in the cold part of the year.

For a comprehensive attribution of severe weather associated with thunderstorm events, it is essential to extend the analysis by developing a classification of the synoptic conditions and environments as well as the storm structures. Previous studies claim that different types of linear convective systems on many occasions produce high winds, while air mass thunderstorms tend to have strong updrafts capable of producing hail or strong downbursts [30]. In addition, the awareness of changes in thunderstorm occurrence under the conditions of recent and future climate change is essential for further analysis as well as the applicability of the results obtained here. Current expectations of how environments will change as the planet warms are that increasing surface temperature and boundary layer moisture will result in increased atmospheric instability and decreased wind shears due to a decrease in the equator-to-pole temperature gradient [8], [9]. Even though these expectations are supported by a majority of climate model simulations, there are numerous objections for using the recent climate variations as an assumption of the behaviour of future changes associated with the effect of atmospheric greenhouse gases [3], [49]. Also the results of the trend analysis confirm an overall decreasing tendency in thunderstorm day frequency in the Baltic countries [33], while no significant changes in thunderstorm frequency have been found in Finland [50] and Poland [51], thus emphasizing the pronounced spatial variability in the dynamics of annual thunderstorm frequency. However, even though the scientific community suggests a likely increase in thunderstorm frequency under the conditions of future climate changes [9], these projections might be ambiguous in the Baltic Sea area, as the recent climate change has led to a decrease in the frequency of thunderstorms in the region [33].

4. Conclusions

The presented here study contains an investigation of thunderstorm features in Latvia detected from remote sensing observations over a 10-year period from 2006 to 2015. The results obtained within this and previous studies suggest that thoughtful exploitation of remote sensing data undoubtedly gives a more detailed insight in the atmospheric conditions favourable for the development of thunderstorms and the common features associated with severe thunderstorm events. The analysis shows that the majority of convective activity in Latvia takes place in the warm part of the year, when thunderstorms have been associated with frequent occurrence of precipitation and wind gusts of 14 m/s on average. During the analysis, it was found that the thunderstorm features under analysis contribute to the assessment of different thunderstorm severity levels as well as inference of the conditions for convective development. It was estimated that the occurrence of overshooting tops as well as maximum radar reflectivities exceeding 50 dBZ serve as good initial indicators for the identification of severe thunderstorms, while the presence of additional features such as gravity waves, small ice particles and V-shaped storm structures indicate an increased thunderstorm severity potential. These findings may contribute to the development and improvement of existing thunderstorm nowcasting and warning processes at the National Weather Service of Latvia through effective integration of remote sensing information in the daily nowcasting routines.

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