BOREAL ENVIRONMENT RESEARCH 22: 415–430
ISSN 1797-2469 (online)

Helsinki 31 October 2017

Long-term changes in the frequency and intensity of thunderstorms in Latvia

Zanita Avotniece[1)]*, Svetlana Aniskevich[2)], Agrita Briede[1)] and Maris Klavins[1)]

[1)] *Faculty of Geography and Earth Sciences, University of Latvia, Jelgavas 1, LV-1004 Riga, Latvia (*corresponding author's email: zanita.avotniece@gmail.com)*

[2)] *Department of Forecasting and Climate, Latvian Environment, Geology and Meteorology Centre, Maskavas 165, LV-1019 Riga, Latvia*

Received 26 Apr. 2017, final version received 8 Oct. 2017, accepted 18 Oct. 2017

Avotniece Z., Aniskevich S., Briede A. & Klavins M. 2017: Long-term changes in the frequency and intensity of thunderstorms in Latvia. *Boreal Env. Res.* 22: 415–430.

Thunderstorms are the most hazardous meteorological phenomena in the summer season in Latvia. However, so far not much has been known about the climatic characteristics of thunderstorm distribution and intensity in the country, and how these have changed with changing climate. Therefore, the aim of this study was to analyse the spatial and temporal distribution of thunderstorms in Latvia during the period 1960–2015 by using surface observation data from 14 major weather stations. To assess the severity of thunderstorms and suitability of the existing warning system, the frequency and distribution of thunderstorm intensities according to the national warning and hazard criteria was analysed. The results of our analysis show significant decrease in thunderstorm frequency in Latvia since 1960, however indicators of an increase in thunderstorm severity were also found, which reveals and emphasizes the complex nature of convective atmospheric phenomena also on climatic scales.

Introduction

Severe weather associated with thunderstorms poses a significant threat to life, property and economy. Hence, detailed knowledge of the occurrence of thunderstorms and their characteristics is important (Doswell *et al*. 1990, Parsons 2015, Wapler and James 2015). Severe thunderstorms have been observed in every country in Europe, and their better documentation in recent years has improved the awareness of the threats associated with severe thunderstorm events. However, the number of studies on severe thunderstorm behaviour in changing climate is limited. Current predictions 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 (Brooks 2013, Collins *et al*. 2013). Even though these predictions are supported by a majority of climate model simulations, there are objections to using the recent climate variations as a base for modelling future changes associated with the effect of atmospheric greenhouse gases (Price 2009, Zwiers *et al*. 2013).

The effects of severe thunderstorms on society can be mitigated by developing warning systems based on assessments of the dependence of risks associated with severe thunderstorms on the climatological probability of the event to occur and

Editor in charge of this article: Antti Arola

also on how well the society is prepared to handle the event once it occurs (Rauhala and Schultz 2009). Numerous hazards that lead to fatalities, injuries, property damage, economic disruptions and environmental degradation are associated with convection. Such hazards belonging to a group called small-scale severe weather phenomena include hail, lightning, straight-line winds, tornadoes and heavy rainfall (Doswell *et al.* 1990, Dotzek *et al.* 2009, Zwiers *et al.* 2013, Parsons 2015, Czernecki *et al.* 2016). They occur widely, but are often short-lived and local in extent, so it is difficult to study them and establish their climate patterns. It is also very difficult to determine how many are missed and not recorded within meteorological observation networks, particularly in less populated areas (Burroughs 2003). In addition, accurate prediction of convective weather and hazards associated with it includes some very specific challenges: small-scale spatial distribution and short life span are limiting factors in predicting individual convective cells with numerical models, meaning that in practice those hazards are often nowcast using observations (Parsons 2015). Thus, the importance of convection in predicting weather events and the climate system, together with impacts of convective events on society, have resulted in an extensive scientific literature on convection and convective processes (Zwiers *et al.* 2013, Parsons 2015, Felgitsch and Grothe 2015, and references therein).

An opportunity to advance research on convective processes and develop effective national warning systems is the existence of easily accessible archives that contain multi-year data that allow for statistical analyses of convective systems (Parsons 2015). In recent years, the number of reported severe convection events has risen largely because of the increased ability to detect them using radar and satellites, as well as thanks to volunteer observers. Increased ability to observe these short-lived, small-scale phenomena is contributing to the compilation of stable, credible climatologies that in future years should give rise to better warning systems (Burroughs 2003). However, at the moment the body of knowledge that is available globally on changes in severe thunderstorm frequency and intensity remains limited, which is in part due to the available data being inhomogeneous in time because of changes in reporting practices and effectiveness of detection, as well as changes in population and public awareness (Zwiers *et al.* 2013). Observations of thunderstorms by humans are the oldest available records of convective activities, and therefore for the last two decades, the main climatological research on thunderstorm spatial and temporal distributions and variability was based on visual observations performed at the meteorological observation stations (Bielec-Bakowska 2003, 2013, Enno *et al.* 2013). During the past decade, rapid advances in technology allowed for remote sensing observations — such as lightning location data (Novak and Kyznarova 2011, Mäkelä *et al.* 2014, Czernecki *et al.* 2016), Doppler radar measurements (Kaltenboeck and Steinheimer 2015) and meteorological satellite observations (Dotzek and Forster 2011) — to be used in studies. These sources of information undoubtedly give a more detailed insight in the atmospheric conditions favourable for the development of thunderstorms and also the common features associated with thunderstorm events of different severity. However, as those measurement methods have been used for a relatively short time, data series are too short to be used in analysis of thunderstorm climatology and thunderstorm behaviour in changing climate.

Thunderstorms are the most hazardous meteorological phenomena in Latvia in the summer season, and the assessment of their climatic characteristic is essential for the development of an effective national climate and weather prediction service. Recent study of thunderstorm climatology in the Baltic countries (Enno *et al.* 2013) demonstrated the characteristics of the spatial distribution of thunderstorms in Latvia, their duration and time of occurrence, while another study (Enno *et al.* 2014) focused on assessing the long-term trends in thunderstorm frequency and atmospheric circulation patterns associated with thunderstorm occurrence. So far, however, not much is known about the climatic characteristics of thunderstorm intensity in Latvia, and how it has changed since the end 19th century, and particularly during the years studied here, as a result of changing climate. The National Meteorological Service (NMS) of Latvia is managed by the Latvian Environment, Geology and Meteorology Centre (LEGMC), which is responsible for monitoring of and warning against severe weather events, including thunderstorms. The thunderstorm warning criteria used by LEGMC in the past and now are based on intensity of wind gusts, amount of accumulated precipitation and intensity of hail.

The aim of this study was (1) to analyse spatial and temporal distributions of thunderstorm frequency and intensity in Latvia during the period 1960–2015 by using surface observation data from 14 major weather stations; and (2) to assess the severity and possible effects of thunderstorms by studying frequency and distribution of thunderstorm intensities according to the national warning and hazard criteria. The results of the current study highlight the areas prone to severe thunderstorms and assess the climatological representability of the currently used thunderstorm warning criteria in Latvia.

Data

Analysis of thunderstorm occurrence and hazardous weather phenomena associated with thunderstorms was performed by analysing the long-term data obtained from 14 major meteorological observation stations run by LEGMC. The data included daily observations of thunderstorm and hail events, daily amount of precipitation, daily mean wind speed and daily maximum wind gusts for the period 1960–2015 (1966–2015 for wind parameters). Majority of the observational data were obtained from the electronic meteorological data observation database maintained and managed by LEGMC, while observational data on atmospheric phenomena up to the year 1987 were obtained from the data archive where they were stored in form of printed monthly bulletins. The selection of meteorological observation stations used in the study was made based on two main criteria: (1) availability and completeness of observational data, and (2) quality of the data, i.e., were the measurements supervised throughout the whole period diminishing possible inhomogeneities in the data records due to changes in observation methodologies. After selecting the observation stations to be included in the study, the obtained data series underwent a quality control, such as looking for outliers of more than 4 standard deviations from the mean. As a result, corrupt or questionable data were excluded from the analysis. Data homogeneity assessment was also carried out by applying expert evaluation approach and spatial inter-comparison of parameter values and their dynamics. Similarly to the results of homogeneity testing performed by Enno *et al*. (2013), we concluded that the identified inhomogeneities were associated with natural factors rather than methodology. For instance, in 2010, one of the highest annual numbers of thunderstorms were observed in the country, resulting in the occurrence of outlier values and shifts in the statistical distribution of the time series.

The meteorological stations used in this study are evenly distributed throughout the country (Fig. 1 and Table 1) thus providing the opportunity to study the characteristics of the spatial distribution of thunderstorm events. However, specific areas, such as the southeastern regions of Latvia, are poorly covered by the surface observation network and therefore for the assessment of local features in the distribution of thunderstorms, data interpolation on a 1 × 1 km grid was performed.

Methods

Thunderstorm frequency and intensity

To study thunderstorm climatology in Latvia thunderstorm days were defined as calendar days with at least one thunderstorm event observed at any meteorological station. To evaluate thunderstorm severity, occurrence and intensity of additional meteorological parameters on the identified thunderstorm days was used. As mentioned before, the national thunderstorm warning scale (green, yellow, orange and red) is based on such parameters as hail intensity, wind gusts and precipitation amount, and is in line with the Meteoalarm warning levels (*see* http://www.meteoalarm.eu/?lang=en_UK and also http://www.meteo.lv/en/bridinajumi/?nid=679). Due to peculiarities in the available long-term archived data on atmospheric phenomena in Latvia, such as the temporal resolution of archived data and approach to data archiving, for the climato-

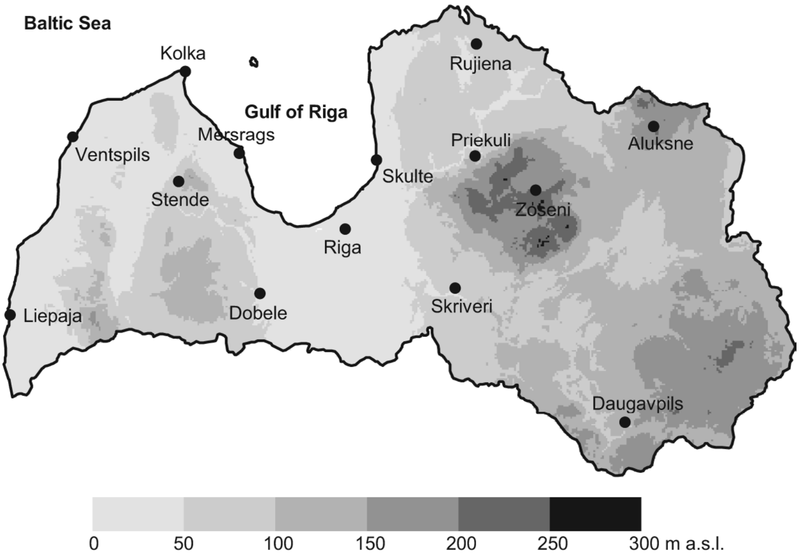

Fig. 1. Location of the 14 meteorological stations in Latvia.

logical analysis of thunderstorm day severity a slightly different approach regarding severity criteria was used (Table 2). To assess hazardous weather phenomena observed on thunderstorm days, the daily accumulated precipitation amount and maximum wind gusts were used as criteria. Due to a relatively small number of hail events found in the historical data, all recorded hail events were attributed to the yellow, orange or red severity level regardless of the hail diameter.

In both approaches, severity levels were applied only to cases in which precipitation and/or hail and/or wind gusts were observed at the same meteorological observation station as the thunderstorm itself. Taken into account the spatial extent of a thunderstorm cloud system, this approach might lead to underestimated thunderstorm intensity, since the observer might register a thunderstorm that is not located directly above the station, and thus the associated hazardous

Table 1. Characteristics of the meteorological stations and coverage of the available observation data used in the study.

Meteorological station		Data coverage			
Name (abbreviation)	Elevation (m a.s.l.)	Thunderstorms	Hail	Precipitation	Wind gusts
Aluksne (Al)	196.67	1960–2015	1960–2015	1960–2015	1966–2015
Daugavpils (Da)	129.90	1960–2015	1960–2015	1960–2015	1966–2015
Dobele (Do)	42.00	1960–2015	1960–2015	1960–2015	1966–2015
Kolka (Ko)	4.10	1960–2015	1960–2015	1960–2015	1966–2015
Liepaja (Li)	3.54	1960–2015	1960–2015	1960–2015	1966–2015
Mersrags (Me)	4.60	1960–2011	1960–2011	1960–2011	1966–2011
Priekuli (Pr)	121.90	1960–2011	1960–2011	1960–2011	1966–2011
Riga (Ri)	6.00	1960–2015	1960–2015	1960–2015	1966–2015
Rujiena (Ru)	67.55	1960–2011	1960–2011	1960–2011	1966–2011
Skriveri (Si)	79.45	1960–2015	1960–2015	1960–2015	1966–2015
Skulte (Sk)	7.50	1960–2011	1960–2011	1960–2011	1966–2011
Stende (St)	79.80	1960–2011	1960–2011	1960–2011	1966–2011
Venstpils (Ve)	1.69	1960–2015	1960–2015	1960–2015	1966–2015
Zoseni (Zo)	187.54	1960–2015	1960–2015	1960–2015	1966–2015
Mean for Latvia (LV)		1960–2015	1960–2015	1960–2015	1966–2015

phenomena might also take place outside the observation site and vice versa. Another aspect to be considered was the temporal resolution of the historical data used: namely, daily values of parameters and their combinations might not directly represent individual thunderstorm events, resulting in overestimated thunderstorm day severity levels during particular events.

By applying the described criteria, we developed and analysed a thunderstorm day severity database, presenting both the spatial distribution and frequency of thunderstorm days of different severity levels in the country.

Trend analysis

For the identification and assessment of long-term trends in the data series the non-parametric Mann-Kendall test (Libiseller and Grimvall 2002, Salmi *et al*. 2002, Mondal *et al*. 2012, Gonzales-Inca *et al*. 2016) was applied. This test is widely used to detect trends in environmental data: since it is based on ranks rather than the values, it is also less sensitive to extreme values and not affected by the data distribution (Smith 2000, Mondal *et al*. 2012, Blain 2015, Gonzales-Inca *et al*. 2016). The test assumes a monotonic trend and depends on the length of the analysed time-series (Yu *et al*. 1993). To identify trends in thunderstorm variables and their spatial distribution in Latvia, we applied the Mann-Kendall test separately to each variable at each site. The trend was considered statistically significant if the test statistic was greater than 1.96 or smaller than –1.96.

Gust factor indicator

To assess gustiness of convection-related wind events, the gust factor G was calculated from the daily mean wind speed U and the maximum wind gust U_g as $G = U_g/U$ (Choi and Hidayat 2002, Jungo *et al*. 2002). The gust factor was calculated for the three following periods: (1) whole year, (2) days with no thunderstorms between April and October, and (3) days with thunderstorm between April and October. The results obtained this way highlight both the seasonal and spatial distribution of thunderstorm-related gustiness in the prevailing wind field.

Spatial interpolation

We also studied spatial distribution of thunderstorm days in the country to identify local features and risk-prone areas. To this end, the data obtained from the stations were subjected

Table 2. National thunderstorm warning levels and thunderstorm severity levels used in this study.

	Hail diameter	Precipitation accumulation (mm) during 12 h	Maximum wind gusts (m s^{-1})
Thunderstorm warning level			
Green	No hail	< 15	< 15
Yellow	No hail or hail with diameter ≤ 5 mm	< 15	15–19
Orange	Hail diameter 6–19 mm	15–49	20–24
Red	Hail diameter ≥ 20 mm	≥ 50	≥ 25
	Hail	**Precipitation accumulation (mm) during 24 h**	**Maximum wind gusts**
Thunderstorm severity level			
Green	No hail	< 15	< 15
Yellow	Hail of any diameter	< 15	15–19
Orange	Hail of any diameter	15–49	20–24
Red	Hail of any diameter	≥ 50	≥ 25

to spatial interpolation on a 1 × 1-km grid. Kriging with external drift interpolation routine (Hengl 2009) was applied to the data series. This routine, which is a very common interpolation method for various applications in meteorology, uses a regression model as part of the Kriging process to model the mean value expressed as a linear trend. For the interpolation of observation data the R package *gstat* was used (https://cran.r-project.org/web/packages/gstat/gstat.pdf).

Based on the climatic, geographic and orographic characteristics of the country and trials of different interpolation approaches, the grid mean elevation of a 5 × 5 km moving window, geographic coordinates, distance from the Gulf of Riga and the Baltic Sea and Gams' continentality index were chosen as the explanatory variables for the interpolation of multi-year values of thunderstorm-related parameters (Fig. 2). The continentality index was calculated by using meteorological observations from 77 meteorological stations in Latvia from the period 1971–2000 and clculated with the R package *ClimClass* (https://cran.r-project.org/web/packages/ClimClass/ClimClass.pdf). Such combination of explanatory variables showed the highest accuracy of the interpolation routine: the maximum obtained errors for the minimum, mean and maximum values of thunderstorm day frequencies was between 0.1 and 0.4, while the RMSE (root mean squared error) did not exceed 0.04 to 0.13.

Thus, given the accuracy of the interpolation routine and increased precision of the obtained spatial maps, we found the produced results reliable and useful for a meaningful spatial analysis of thunderstorm events in the country. However, as only data obtained from the Latvian observation network were used in this study, the results for the country border areas, especially along the eastern border, might be biased.

Results and discussion

Thunderstorm day frequency

In Latvia thunderstorms can occur at any time of the year, however the majority takes place between May and September (*see* Fig. 3). During the period of increased thunderstorm activity there are on average three to five thunderstorm days in the country, but during favourable years thunderstorm frequency can increase up to 5–6 days. The two months with the highest annual thunderstorm day frequency are July (2.9 to 6.6 days) and August (3.5 to 4.8 days). In August, thunderstorm days tend to be most frequent also in years with relatively low annual number of thunderstorms. These results are in line with the findings of Enno *et al*. (2013): at most of the weather stations thunderstorm days have been most frequent in July. However, at the stations closest to the Baltic Sea, the maximum thunderstorm day occurrence shifted to August, while in Daugavpils and the eastern parts of Lithuania a local maximum in June can be observed. Such distribution might in part be explained by the atmospheric circulation conditions favourable for the occurrence of thunderstorms as in the Baltic states they are most common during E, SE, S, SW and cyclonic flows (Enno *et al*. 2014).

The annual number of thunderstorm days in the country varied from 14.5–16.4 in the coastal areas to 23 on in the highland areas of the eastern part of the country (Fig. 4). Very similar values were obtained by Enno *et al*. (2013): 14–24 thunderstorm days in the period 1951–2000 by using monthly thunderstorm observation data. A distinct increase in the thunderstorm day frequency from the coastal areas toward inland was identified also in Poland, where, however, the annual number of thunderstorm days is on average higher than in Latvia and can exceed 30 days per year in the southern part of the country and the Tatra Mountains (Bielec-Bakowska 2003, 2013). In Latvia, during the years with increased occurrence of thunderstorms, the maximum thunderstorm day frequency per year exceeded the long-term mean values reaching 26–46 days. Years with an increased thunderstorm activity were found mainly during the first part of the studied period: 21 (Liepaja) and 46 (Priekuli) thunderstorm days in 1961, 19 (Skulte) and 41 (Rujiena) days in 1963; and 17 (Ventspils) and 37 (Priekuli and Riga) days in 1972. However, also during the recent decades there were years when thunderstorm days were considerably more numerous than the long-term mean: for instance in 2010 there were 21 to 39 thunderstorm days

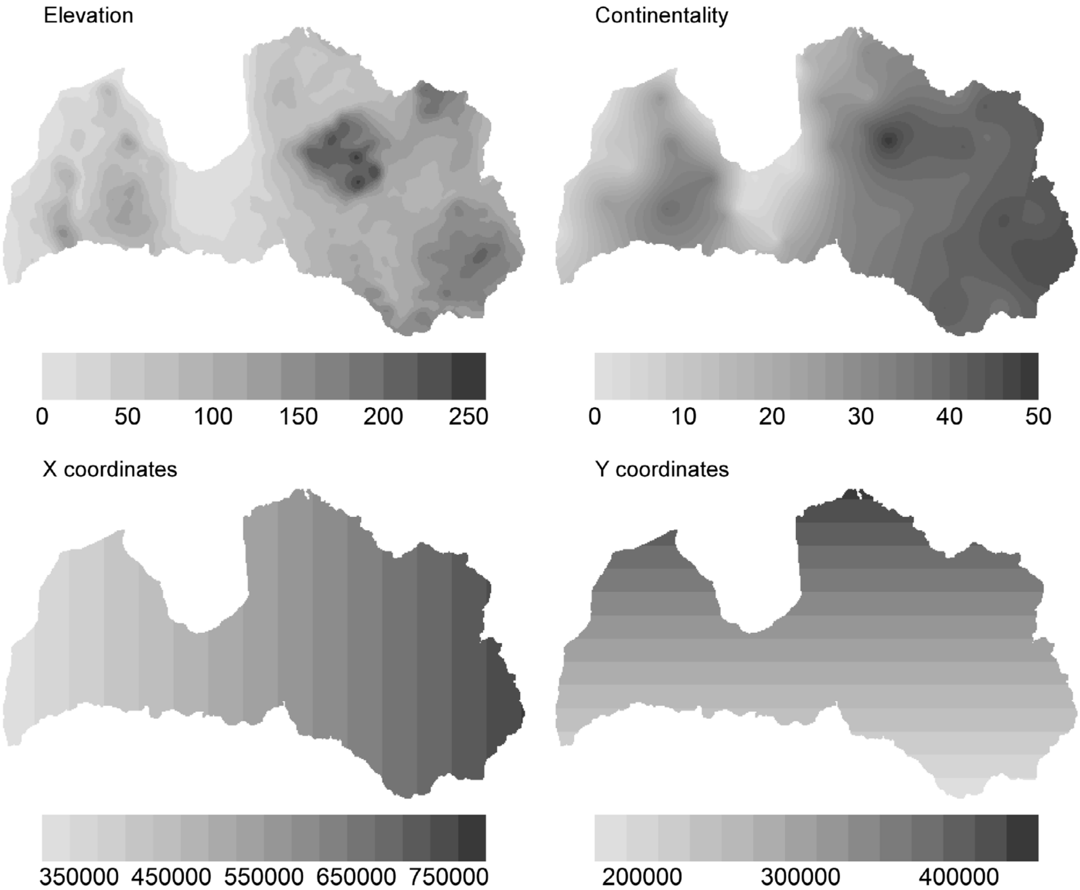

Fig. 2. Explanatory variables used in the interpolation routine: mean elevation (m a.s.l.) of 5 km^2 moving window and Gams' continentality index; X and Y coordinates in LKS-92 TM.

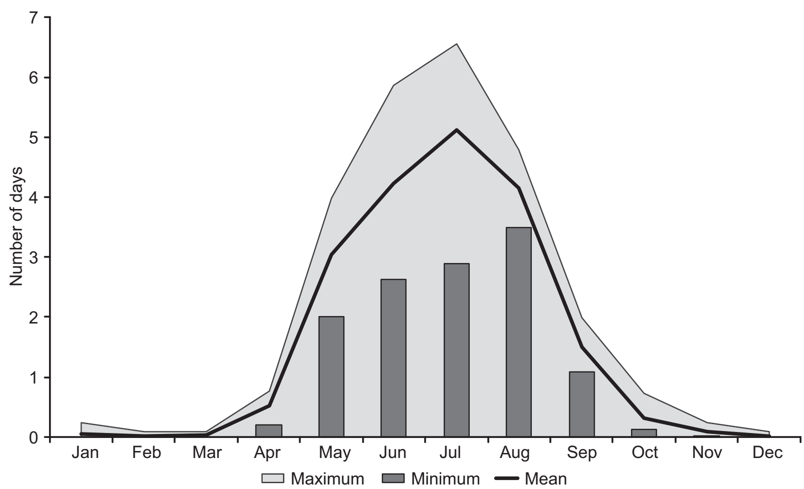

Fig. 3. Frequency of thunderstorm days in Latvia during 1960–2015.

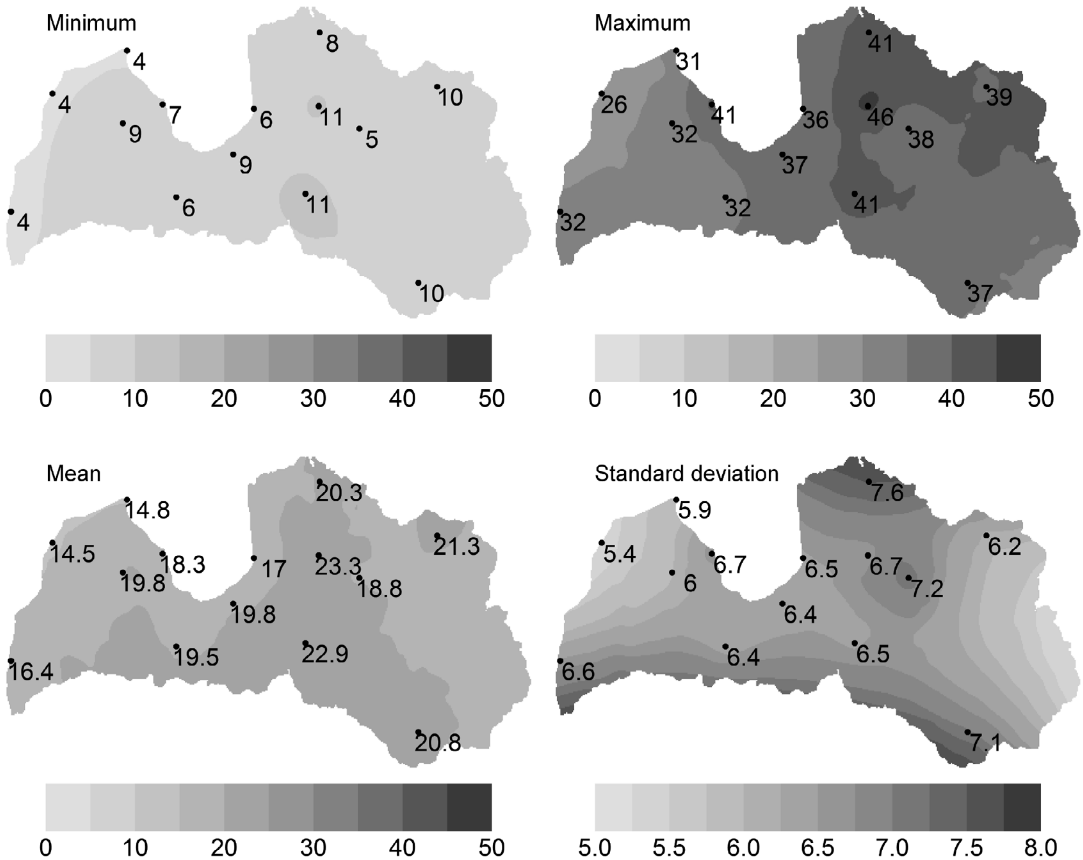

Fig. 4. Thunderstorm day frequency and variability in Latvia during 1960–2015. Top panels: minimum and maximum annual number of thunderstorm days; bottom panels: mean annual number of thunderstorm days and variability in annual thunderstorm day frequency expressed as standard deviation.

in Riga and Aluksne, respectively (Fig. 5). The spatial distribution of maximum thunderstorm day frequencies reveals similar characteristics to that of the long-term means, pointing out the eastern highland areas as places where thunderstorms may appear more often. During 1960–2015, there were also periods with relatively low thunderstorm activity such as 1990–1994 with as little as 4–16 thunderstorm days in 1994 recorded in the country.

Thunderstorm day frequencies varied greatly among the 14 weather stations included in our study (*see* Figs. 4 and 6). and some data were initially classified as outliers. During the quality control however, these values were reassessed and identified as correct, which indicates that exceptional values characterising rare and extreme events should be retained in the analysis to account for considerable temporal and spatial variability in the distribution of thunderstorm days. Also, skewness of the data from nine weather stations was positive, indicating a shift towards greater values.

Hazardous meteorological phenomena observed on thunderstorm days

Hail is frequently associated with thunderstorm events, however, due to its local nature, it is poorly represented in the long-term data of the traditional meteorological stations. Therefore, according to the long-term data records in Latvia, hail was observed at the official observation sites on only 0.3–1.1 thunderstorm days per year (Fig. 7). The majority of the observed

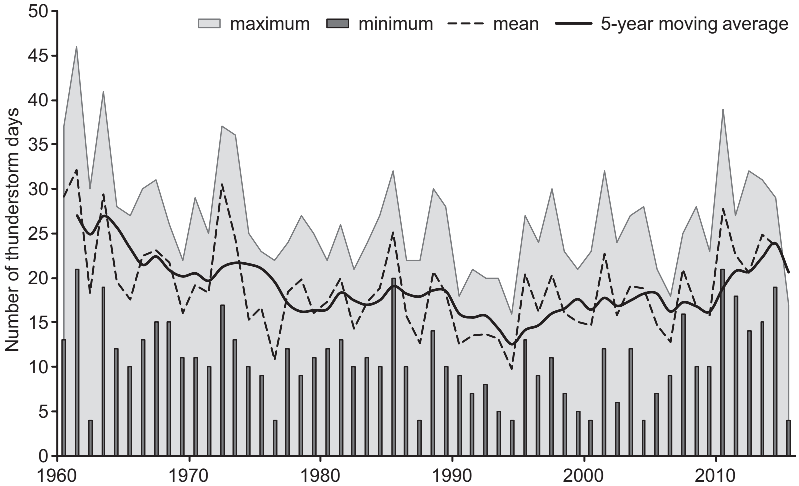

Fig. 5. Number of thunderstorm days in Latvia (data from 14 weather stations; *see* Fig. 1 and Table 1).

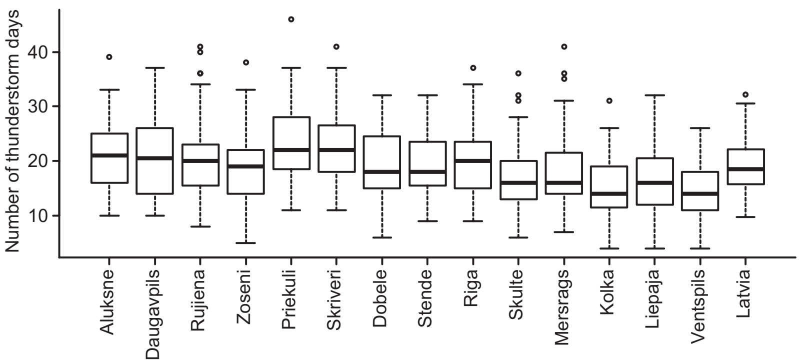

Fig. 6. Number of thunderstorm days in Latvia during 1960–2015. Thick line inside the box = median, top and bottom of the box = upper and lower quartiles, respectively, whiskers = minimum and maximum (excluding outliers), circles = outliers (more than 1.5 times greater than the quartiles).

hail events on thunderstorm days occurred in the central part of the country, where they might be associated with the lake-effect phenomenon in early autumn (cold advection over the warm water surface of the Gulf of Riga is a frequent trigger of precipitation showers and thunderstorms in the downwind coastal areas). Also, the maximum annual number of hail events during thunderstorm days was observed in the coastal areas of the Gulf of Riga (nine cases observed at the Mersrags weather station in 2004).

Precipitation is the most frequent atmospheric phenomenon associated with thunderstorms, with on average 4.3–9.3 mm per thunderstorm day. The annual maximum precipitation per thunderstorm day in Latvia was between 25 and 29 mm (Fig. 8), with higher precipitation intensities related to orography and proximity to the Baltic Sea. So far, the highest daily precipitation amount associated with a thunderstorm event (160 mm in Ventspils) was measured in 1973, and this record still holds. Also in 2014 there were exceptionally intense rainfalls (123 mm in 24 hours) at the Sigulda weather

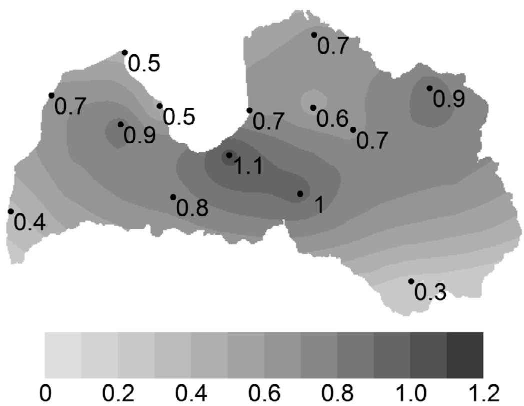

Fig. 7. Mean number of hail events on thunderstorm days in Latvia during 1960–2015.

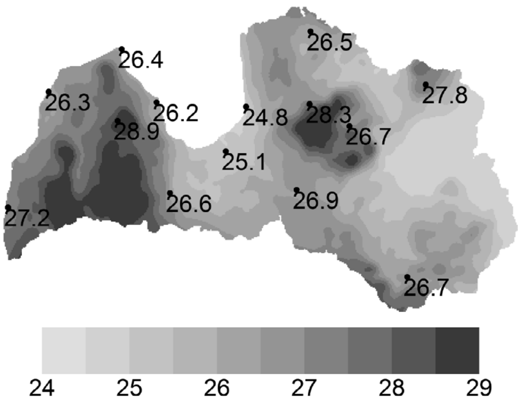

Fig. 8. Maximum precipitation amount (mm) per thunderstorm day in Latvia during 1960–2015.

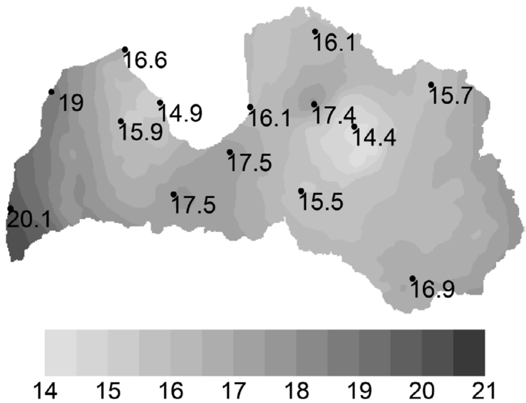

Fig. 9. Annual maximum wind gusts (m s^{-1}) during a thunderstorm day in Latvia during 1966–2015.

station located in the highland areas of the eastern part of the country which however were not included in this study.

The most hazardous effects of thunderstorms in the country are associated with severe straight-line and tornadic convective wind gusts reaching 14–20 m s^{-1} during thunderstorms (Fig. 9). The strongest wind gusts during the studied period were measured in the coastal areas of the Baltic Sea where severe cyclonic storms (48 m s^{-1} in Liepaja in 1967 and 34 m s^{-1} in Skulte late 1969) were associated with thunderstorms. During summertime thunderstorm events, the strongest wind gusts were measured in the central regions of the country (33 m s^{-1} in the summer of 2002 at the Dobele station). On average, thunderstorm gustiness expressed as the gust factor was higher at the inland meteorological stations (Fig. 10). As the gust factor is the relation between the mean wind speed and the maximum wind gust, its smaller values on thunderstorm days at the coastal stations can be explained by higher mean wind speed on the Baltic Sea coast. Therefore, even though stronger wind gusts on thunderstorm days were measured in the coastal areas, the long-term data reveal an increased gustiness on thunderstorm days in the inland areas.

Assessment of thunderstorm severity

Thunderstorm severity in Latvia has been classified for warning purposes according to the intensity of hazardous weather phenomena associated with thunderstorm events. In order to assess the long-term changes in thunderstorm intensity and suitability of the warning criteria, a similar approach was used to our thunderstorm day analysis on the climatic time scale. Namely, all thunderstorm days in the period 1966–2015 were divided into 4 groups according to the intensity of precipitation, wind gusts and occurrence of hail (*see* Table 2). Majority of the thunderstorm events observed in Latvia since 1966 were not associated with any hazardous weather (no hail, wind gusts less than 15 m s^{-1}, daily precipitation amount < 15 mm), and therefore 71%–85% (11–20 days on average) of observed thunderstorm events were classified as level green (Fig. 11). The proportion of green-level thunderstorm days in a year varied from only 28.6% in Ventspils (2005) to 100% at altogether 11 meteorological stations (except Liepaja, Riga and Priekuli). While the spatial distribution of non-severe thunderstorm days followed the pattern of the thunderstorm day frequency distribution (*see* Fig. 4), the overall variability in the fraction of green-level thunderstorm days was the greatest in the coastal regions.

Thunderstorm days of the yellow severity level are associated with wind gusts exceeding 15 m s^{-1}, and therefore there was a greater proportion of such events in the coastal areas of the Baltic Sea (10%–13% or 1.5–2.2 days on average). In the remaining parts of the country the fraction of such days varied between 4.6% and 9.3% (or 0.7 and 1.8 days). Within the studied period, the years when no yellow severity

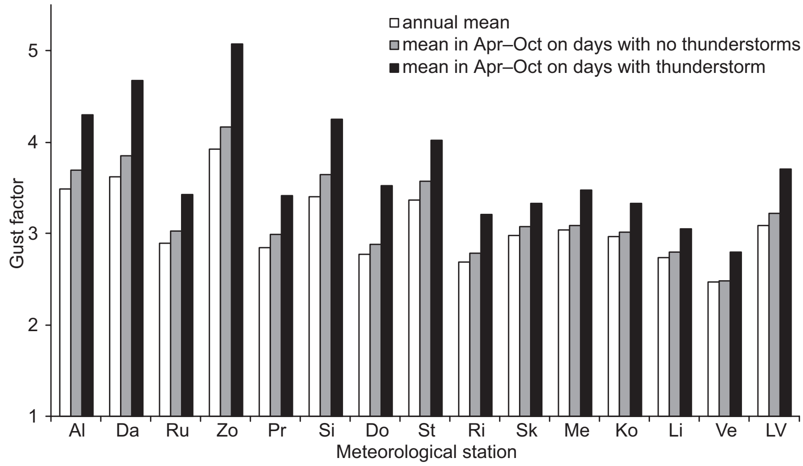

Fig. 10. Mean gust factor in Latvia during 1966–2015.

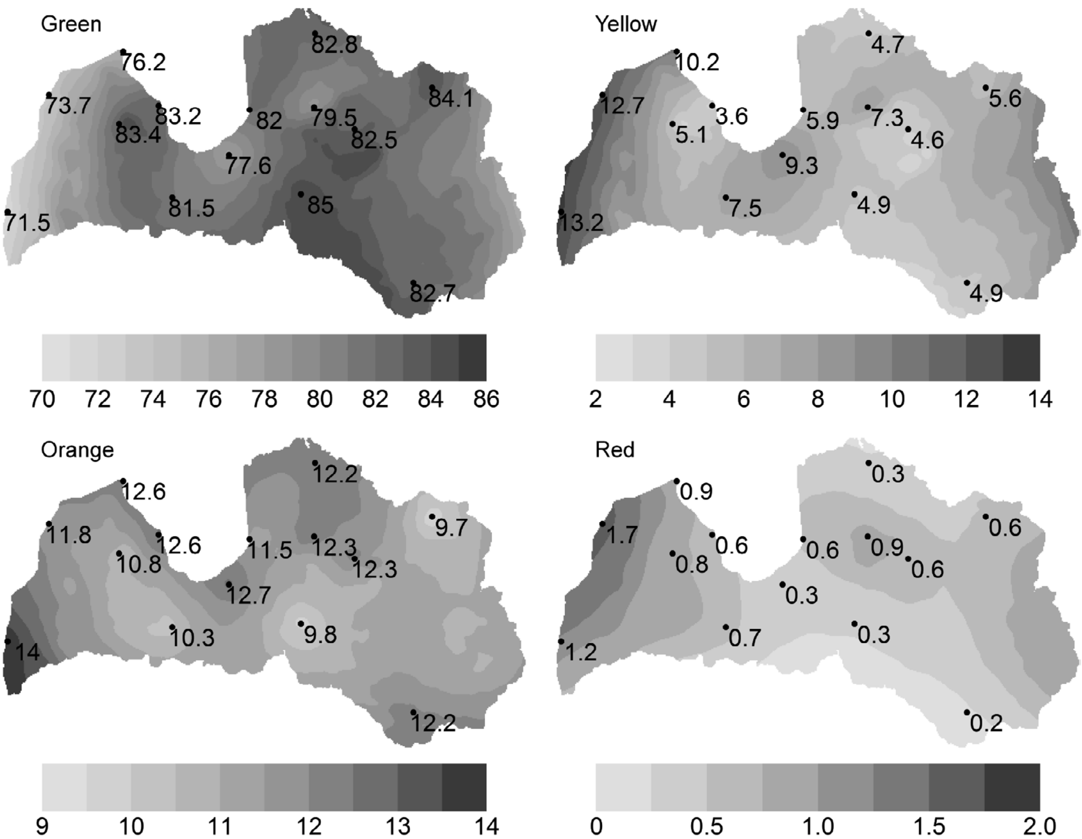

Fig. 11. Mean proportions (%) of thunderstorm days of four severity levels in Latvia in 1966–2015.

level thunderstorm events were observed at any particular station were common (minimum 4 stations to maximum 13 stations in 2009–2012). The proportion of thunderstorm events classified to the yellow severity level varied from 18.8% at Skriveri (1991) to 50% at Kolka (2000).

The orange thunderstorm severity level is associated with a further increase in wind speed (wind gusts exceeding 20 m s^{-1}) and the occurrence of heavy precipitation (≥ 15 mm in 24 hours). Such events were more frequent than the less severe yellow level thunderstorm days, reaching 9.7%–14% (1.7–2.9 days) of all the thunderstorm events during the studied period. This increase on one hand might be associated with an increased frequency of thunderstorm days associated with heavy rain events or could be a result of the original severity level classification that had used 15 mm precipitation within 12 hours as a threshold. Variation in the orange severity level thunderstorm days was considerable: in 2002 such events were recorded at only 7 weather stations, whereas there were also 9 years within the studied period when orange level thunderstorm days were registered at all observation stations included in this study. The maximum proportions of thunderstorm days classified to the orange severity level varied from 22.7% in Skriveri (2007) to 50% in Kolka (1994). The locations, where orange severity level thunderstorm days may occur are the coastal areas of the Baltic Sea and the Gulf of Riga, and the northernmost and southernmost regions of the eastern part of the country.

Red severity level thunderstorm days are defined as extreme events accompanied by wind gusts exceeding 25 m s^{-1} and very heavy rainfall of more than 50 mm during 24 hours. Such events were rare: only 0.2%–1.7% (0.1–0.2 days on average) of the events analysed. Even though the frequency of this level thunderstorm events in particular location may be low (from 5.3% at Aluksne in 2009 to 18.2% at Zoseni in 1983), such thunderstorm days were observed in some areas on most years. There have only been 12 years with no thunderstorm days of red severity level anywhere in Latvia, while in 4 years (1981, 1985, 2005, 2011) such severe conditions were observed at 4 stations included in this study.

Changes in thunderstorm frequency and intensity

The climatic behaviour of thunderstorm events in Latvia was altered as a result of changing climate (Avotniece *et al.* 2010). In comparison with the reference period 1961–1990, during the recent 30-year (1981–2010) normal period the number of thunderstorm events per year decreased by about 2 (Table 3), with the smallest and greatest changes taking place in the western part and the eastern parts of the country, respectively. However, the intensities of hazardous weather phenomena associated with thunderstorms did not change much, except for wind parameters.

The results of the trend analysis (Table 4) confirm an overall decrease in thunderstorm day frequency, significant at 8 of 14 weather stations included in the study. Similar was identified for Lithuania and Estonia (Enno *et al.* 2014), but not for Finland (Tuomi and Mäkelä 2008). In a recent study carried out in Poland, Bielec-Bakowska (2013) also found no trend in thunderstorm day frequency, but revealed a spatially inconsistent pattern of changes: thunderstorms were becoming more frequent in the southeastern part of the country and less frequent in the northwestern part of the country. Thus, the aforementioned results emphasize spatial variability in the annual thunderstorm frequency in the region. However, it was also noted previous that the changes in thunderstorm frequency might have a cyclic nature on a longer time scale (Tuomi and Mäkelä 2008). Changes in the frequency of thunderstorm days in the Baltic countries might be associated with changes in the general atmospheric circulation patterns: it has been found that the decrease in the thunderstorm frequency was accompanied by an increase in the frequency of circulation patterns unfavourable for the occurrence of thunderstorms, namely: northerly and anticyclonic flows (Enno *et al.* 2014).

The changes in frequency and intensity of heavy precipitation and hail events during thunderstorms was spatially inconsistent due to the local distribution of these hazardous phenomena. However, the positive trend in the mean precipitation amount and the frequency of cases of precipitation exceeding 50 mm during thunderstorm days was mainly limited to the coastal areas of the Gulf of Riga, thus emphasizing the impact of the Gulf on the distribution of summertime precipitation in the country. The most evident changes in the long-term data series were found for wind parameters on thunderstorm days, with a significant increase in either the absolute

Table 3. Changes (differences in absolute values between the periods 1961–1990 and 1981–2010) in the number of thunderstorm days, proportion of thunderstorms of different severity levels (%), number of hail events, mean and maximum precipitation (mm) and wind gusts (m s^{-1}) and number of cases exceeding the given precipitation and wind gust intensity thresholds during thunderstorm days as at the meteorological stations.

Parameter	Al	Da	Do	Ko	Li	Me	Pr	Ri	Ru	Si	Sk	St	Ve	Zo	LV
Thunderstorm days	–1.9	–3.7	–0.1	–2.2	–1.9	0.0	–2.0	–3.3	–4.4	–2.7	–4.3	–0.1	–0.6	–5.1	–2.3
Green severity level	–3.0	5.0	–3.5	–5.1	–0.2	–1.7	–4.8	–9.8	–3.0	–3.4	–2.8	3.2	–1.8	1.4	–2.1
Yellow severity level	3.0	–0.4	2.1	2.3	0.5	0.5	5.0	3.3	3.1	2.6	1.0	–1.5	1.9	0.4	1.7
Orange severity level	–0.2	–4.3	1.5	2.9	0.1	0.4	–0.1	6.5	–0.5	0.8	1.7	–1.1	0.1	–1.7	0.4
Red severity level	0.3	–0.3	–0.2	–0.2	–0.5	0.8	–0.2	0.0	0.4	0.0	0.2	–0.6	–0.2	–0.1	0.0
Hail events	0.6	–0.3	0.0	0.3	0.0	0.6	0.4	–0.6	0.4	–0.1	–0.1	0.0	0.2	–0.1	0.1
Mean precipitation	0.6	–0.5	0.3	1.7	–0.2	0.5	0.3	2.7	0.2	0.3	0.9	–0.1	–0.5	0.1	0.4
Maximum precipitation	3.8	–4.3	2.8	3.2	–2.8	4.7	0.3	5.4	0.9	–1.8	0.5	–1.1	–6.4	–1.3	0.3
Precipitation ≥ 15 mm	–0.2	–0.6	0.3	0.1	–0.3	0.6	–0.2	0.9	–0.3	0.1	0.0	0.0	0.0	–0.6	0.0
Precipitation ≥ 50 mm	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	–0.1	0.1	0.0	0.0	0.0	0.0
Mean wind gusts	2.2	–0.7	1.8	1.3	–0.2	1.2	1.9	2.1	1.7	1.9	0.8	0.6	0.8	1.4	1.2
Maximum wind gusts	1.5	–2.5	3.0	–0.3	–2.1	–0.4	1.3	1.1	0.4	1.2	–0.8	–1.4	–1.5	0.2	0.0
Wind gusts 15–19 m s^{-1}	0.5	–0.8	1.1	0.2	–0.7	0.0	1.0	1.3	0.3	0.5	–0.1	–0.2	–0.1	–0.2	0.2
Wind gusts 20–24 m s^{-1}	0.1	–0.4	0.3	–0.2	–0.1	–0.1	0.0	0.1	0.0	0.0	–0.1	–0.1	–0.3	–0.1	–0.1
Wind gusts ≥ 25 m s^{-1}	0.0	0.0	0.0	0.0	–0.1	0.0	–0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4. Trends in the number of thunderstorm days, proportion of thunderstorms of different severity levels (%), number of hail events, mean and maximum precipitation amount (mm) and wind gusts (m s^{-1}) and number of cases exceeding the given precipitation and wind gust intensity thresholds on thunderstorm days at the meteorological stations during 1960–2011 (1966–2011 for wind gust parameters and thunderstorm severity levels). Values in boldface indicate significant trends (Mann-Kendal test).

Parameter	Al	Da	Do	Ko	Li	Me	Pr	Ri	Ru	Si	Sk	St	Ve	Zo	LV
Thunderstorm days	**–2.26**	**–3.35**	–0.51	**–2.46**	–0.64	–0.74	–1.50	**–2.98**	**–2.48**	**–3.35**	**–3.38**	–0.71	–1.11	**–3.77**	**–2.74**
Green severity level	–1.62	1.94	**–2.84**	**–2.28**	–0.27	–1.04	**–3.21**	**–3.87**	–1.95	**–2.40**	–0.99	0.28	–1.60	–0.65	**–3.55**
Yellow severity level	**2.03**	0.50	**2.59**	1.60	0.50	0.42	**4.73**	**2.04**	**3.26**	**2.33**	0.20	–0.26	1.56	1.39	**3.55**
Orange severity level	0.72	**–2.67**	1.25	0.57	0.06	0.67	0.68	**3.27**	–0.40	0.63	1.06	0.31	0.94	0.16	1.62
Red severity level	1.23	–1.85	0.44	1.25	–0.75	**2.43**	–1.31	–0.81		0.02	–0.11	–1.93	1.37	–0.46	0.13
Hail events	**3.70**	**–2.24**	–0.73	0.75	–0.52	**2.95**	1.31	**–2.66**	1.58	–0.16	**–2.31**	–0.95	0.44	–0.42	–0.02
Mean precipitation	**2.06**	–1.44	1.39	**3.39**	0.19	**2.35**	1.12	**3.11**	1.46	1.31	**2.11**	1.71	0.66	1.37	**3.65**
Maximum precipitation	0.38	**–2.57**	1.46	1.68	–0.56	1.14	–0.25	0.48	0.57	–0.58	–0.52	1.05	–0.28	–1.18	0.71
Precipitation ≥ 15 mm	0.05	–1.71	1.53	1.24	0.25	1.31	–0.77	1.07	–0.72	–0.39	–0.11	0.57	1.03	–1.08	0.19
Precipitation ≥ 50 mm	1.03		–0.31	1.45	–0.32	**3.19**	–0.35	0.20	0.65	–1.61	**2.36**	–0.16	0.01	0.09	0.88
Mean wind gusts	**5.47**	0.02	**5.47**	**3.97**	–0.29	**5.23**	**4.71**	**6.49**	**4.67**	**4.41**	**3.45**	**3.37**	**3.94**	**3.68**	**6.45**
Maximum wind gusts	**2.27**	**–2.02**	**4.05**	0.41	–1.41	–0.03	1.21	**2.69**	1.45	1.83	0.44	–1.35	–0.98	1.36	1.29
Wind gusts 15–19 m s^{-1}	**2.03**	–1.40	**4.67**	1.71	–0.28	0.71	**4.12**	**4.61**	**2.42**	**2.37**	0.83	–0.99	0.86	0.95	**2.53**
Wind gusts 20–24 m s^{-1}	1.13	**–3.49**	**2.38**	0.27	–0.76		0.03	1.35	–0.02	0.62	–1.49	**–2.29**	–0.33	0.24	–1.13
Wind gusts ≥ 25 m s^{-1}	–0.59	–1.47	1.26	–0.74	–0.87		–1.05	–1.18		0.84			1.00		–0.49

values of wind speed or the frequency of high wind gusts observed during thunderstorm days at most of the weather stations. Due to increasing wind gusts on thunderstorm days, the fraction of yellow severity level thunderstorm days also increased significantly (0.16 days per decade). It is important to note that the increase in wind gusts on thunderstorm days in Latvia was evident even though Briede (2016) found a significant decrease in the mean wind speed during the period 1966–2011.

Even though thunderstorms in Latvia are not associated with such devastating damage as for instance in the United States or even the southern parts of Europe, almost every year intense thunderstorms cause considerable damage. Although the results of our study show indications of an overall decrease in thunderstorm day frequency, at the same time they point out a likely increase in thunderstorm intensity and associated wind-related damage.

Although long-term meteorological data records were used here in order to obtain representative climatology both spatially and phenomenologically, nevertheless it is important to note that the results presented here might be biased due to the small-scale spatial distribution and short life-span of convective events as even extremely severe ones might take place at locations not covered by the observation network (Doswell *et al*. 2005). In recent decades, the introduction of remote sensing helped to improve data coverage but it is still not sufficient for comprehensive climatological analyses. Also, the attempt to classify thunderstorms according to their intensities by using supplementary meteorological parameters might be biased due to the same reasons.

Our results revealed that, with an exception of orange severity level thunderstorms, the currently used national thunderstorm warning criteria serve the purpose well. As recent trends in European National Meteorological Services have been towards the introduction of impact-based meteorological warning systems (Rauhala and Schultz 2009), our results could be used as a starting point for modifications and improvement of the national warning system in Latvia.

Given the complex nature of thunderstorm events, the indications of changes in their intensity may increase the associated threat levels as these high-impact events include several hazardous meteorological phenomena. However, even though the scientific community suggests a likely increase in thunderstorm frequency with changing climate (Collins *et al*. 2013), these projections might not be unambiguous in the Baltic Sea area, as the recent changes in climate have led to a decrease in the frequency of thunderstorms in the region (Enno *et al*. 2014). Also Zwiers *et al*. (2013) pointed out that on one hand, greenhouse-gas induced warming may lead to greater atmospheric instability due to increasing temperature and moisture content leading to a possible increase in severe weather, but on the other hand, vertical shear may decrease due to a reduced pole-to-equator temperature gradient. The lack of firm conclusions regarding the past and future behaviour of thunderstorm events is highly associated with the aforementioned observational limitations, and therefore the development of effective national warning systems is essential for mitigation of adverse effects of any possible changes to come.

Conclusions

The climatic characteristics of thunderstorm frequency and intensity in Latvia and their changes over the period 1960–2015 have been analysed in the presented study. It was found, that the average thunderstorm day frequency in Latvia over the period of study has been between 14.5 days in the coastal areas of the Baltic Sea and 23 days in the upland areas of the eastern part of the country, highlighting the role of orography in the spatial distribution of convective phenomena in the country. At the same time the temporal distribution of thunderstorm days showed considerable intra-annual and inter-annual variations as well as a significant decrease in thunderstorm day frequency in Latvia since 1960.

On average 71%–85% of the thunderstorm day cases have been classified as non-severe, with annual variations in the fraction of such days being the highest in the coastal areas of the Baltic Sea. Thunderstorm days of yellow, orange and red severity level have been significantly less frequent, however severe thunderstorm days have been observed on each of the years within the study period. It was estimated that among hazardous meteorological phenomena associated with thunderstorm days, hail was rarely registered by the observation stations on thunderstorm days, while maximum precipitation amount on average varied between 25 and 29 mm and wind gusts reached 14 to 20 m s^{-1} on thunderstorm days.

Even though thunderstorm day frequency in Latvia has decreased significantly, indicators of increased thunderstorm intensity have been observed. Long-term trends in precipitation intensity and frequency of heavy precipitation cases on thunderstorm days show a significant increasing tendency in the coastal areas of the Gulf of Riga, while widespread increasing tendencies have been observed for wind parameters. The increase in wind parameters on thunderstorm days has occurred along with an overall decrease in the mean wind speed in the country.

The obtained results suggest that the currently used national thunderstorm warning criteria represent the climatic distribution of severe thunderstorm events, with an exception of orange severity level thunderstorms. Thus the findings presented here could be used as a starting point for the modifications and improvement of the national warning system in Latvia.

Acknowledgements: The presented here study has been carried out with a financial support from the Latvian Council of Science (grant No. 526/2016). Authors would also like to thank the Latvian Environment, Geology and Meteorology Centre for the provided meteorological observation data.

References

Avotniece Z., Rodinov V., Lizuma L. & Klavins M. 2010. Trends in the frequency of extreme climate events in Latvia. *Baltica* 23: 135–148.

Bielec-Bakowska Z. 2003. Long-term variability of thunderstorm occurrence in Poland in the 20th century. *Atmospheric Research* 67–68: 35–52.

Bielec-Bakowska Z. 2013. Thunderstorms and hails in Poland. *Prace Geograficzne* 132: 99–132. [In Polish with English summary].

Blain G.C. 2015. The influence of nonlinear trends on the power of the trend-free pre-whitening approach. *Acta Scientiarum Agronomy* 37: 21–28.

Briede A. 2016. The climate of Latvia and its variability. In: Klavins M. & Zaloksnis J. (eds.), *Climate and sustainable development*, University of Latvia Academic Press, Riga, Latvia, pp. 55–90. [In Latvian with English summary].

Brooks H.E. 2013. Severe thunderstorms and climate change. *Atmospheric Research*. 123: 129–138.

Burroughs W. (ed.) 2003. *Climate: into the 21st century*. Cambridge University Press for World Meteorological Organization, Cambridge.

Choi E.C.C. & Hidayat F.A. 2002. Gust factors for thunderstorm and non-thunderstorm winds. *Journal of Wind Engineering and Industrial Aerodynamics* 90: 1683–1696.

Collins M., Knutti R., Arblaster J., Dufresne J.L., Fichefet T., Friedlingstein P., Gao X., Gutowski W.J., Johns T., Krinner G., Shongwe M., Tebaldi C., Weaver A.J. & Wehner M. 2013: Long-term climate change: projections, commitments and irreversibility. In: Stocker T.F., Qin D., Plattner G.K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V. & Midgley P.M. (eds.), *Climate change 2013: the physical science basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp. 1029–1136.

Czernecki B., Taszarek M., Kolendowicz L. & Konarski J. 2016. Relationship between human observations of thunderstorms and the PERUN lightning detection network in Poland. *Atmospheric Research* 167: 118–128.

Doswell C.A., Brooks H.E. & Kay M.P. 2005. Climatological estimates of daily nontornadic severe thunderstorm probability for the United States. *Weather Forecasting* 20: 577–595.

Doswell C.A., Rasmussen E.N., Davies-Jones R. & Keller D.L. 1990. On summary measures of skill in rare event forecasting based on contingency tables. *Weather Forecasting* 5: 576–585.

Dotzek N. & Forster C. 2011. Quantitative comparison of METEOSAT thunderstorm detection and nowcasting with in situ reports in the European Severe Weather Database (ESWD). *Atmospheric Research* 100: 511–522.

Dotzek N., Groenemeijer P., Feuerstein B. & Holzer A.M. 2009. Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmospheric Research* 93: 575–586.

Enno S.E., Briede A. & Valiukas D. 2013. Climatology of thunderstorms in the Baltic countries, 1951–2000. *Theoretical and Applied Climatology* 111: 309–325.

Enno S.E., Post P., Briede A. & Stankunaite I. 2014. Long-term changes in the frequency of thunder days in the Baltic countries. *Boreal Environment Research* 19: 452–466.

Felgitsch L. & Grothe H. 2015. Up into the sky. In: Bloeschl G., Thybo H. & Savenije H. (eds.), *A voyage through scales*. Boesmueller, Stockerau. pp. 33–37.

Gonzales-Inca C.A., Lepistö A. & Huttula T. 2016. Trend detection in water-quality and load time-series from agricultural catchments of Yläneenjoki and Pyhäjoki, SW Finland. *Boreal Environment Research*. 21: 166–180.

Hengl T. 2009. *A Practical guide to geostatistical mapping*. University of Amsterdam, Amsterdam.

Jungo P., Goyette S. & Beniston M. 2002. Daily wind gust speed probabilities over Switzerland according to three types of synoptic circulation. *International Journal of Climatology*. 22: 485–499.

Kaltenboeck R. & Steinheimer M. 2015. Radar-based severe storm climatology for Austrian complex orography related to vertical wind shear and atmospheric instability. *Atmospheric Research*. 158–159: 216–230.

Libiseller C. & Grimvall A. 2002. Performance of partial Mann-Kendall test for trend detection in the presence of covariates. *Environmetrics* 13: 71–84.

Mäkelä A., Enno S.E. & Haapalainen J. 2014. Nordic Lightning Information System: Thunderstorm climate of northern Europe for the period 2002–2011. *Atmospheric Research* 139: 46–61.

Mondal A., Kundu S. & Mukhopadhyay A. 2012. Rainfall trend analysis by Mann-Kendall test: a case study of north-eastern part of Cuttack District, Orissa. *International Journal of Geology, Earth and Environmental Sciences* 2: 70–78.

Novak P. & Kyznarova H. 2011. Climatology of lightning in the Czech Republic. *Atmospheric Research* 100: 318–333.

Parsons D.B. 2015. Continental convective system. In: *Seamless prediction of the Earth system: from minutes to months*, World Meteorological Organization, Geneva, pp. 233–264.

Price C. 2009. Will a drier climate result in more lightning? *Atmospheric Research* 91: 479–484.

Rauhala J. & Schultz D.M. 2009. Severe thunderstorm and tornado warnings in Europe. *Atmospheric Research* 93: 369–380.

Salmi T., Määttä A., Anttila P., Ruoho-Airola T. & Amnell T. 2002. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates — the Excel template application MAKESENS. *Publications on Air Quality* 31: 1–35.

Smith L.C. 2000. Trends in Russian Arctic river-ice formation and breakup, 1917 to 1994. *Physical Geography* 21: 46–56.

Tuomi T.J. & Mäkelä A. 2008. Thunderstorm climate of Finland 1998–2007. *Geophysica* 44: 67–80.

Wapler K. & James P. 2015. Thunderstorm occurrence and characteristics in central Europe under different synoptic conditions. *Atmospheric Research* 158–159: 231–244.

Yu Y.S., Zou S. & Whittemore D. 1993. Nonparametric trend analysis of water quality data of rivers in Kansas. *Journal of Hydrology* 150: 61–80.

Zwiers F.W., Alexander L.V., Hegerl G.C., Knutson T.R., Kossin J.P., Naveau P., Nicholls N., Schär C., Seneviratne S.I. & Zhang X. 2013. Climate extremes: challenges in estimating and understanding recent changes in the frequency and intensity of extreme climate and weather events. In: Asrar G.R. & Hurrell J.W. (eds.), *Climate science for serving society: research, modeling and prediction priorities*. doi:10.1007/978-94-007-6692-1_13.