UNIVERSITY OF LATVIA
FACULTY OF GEOGRAPHY AND EARTH SCIENCES

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CHARACTERISTICS AND LONG-TERM CHANGES OF EXTREME CLIMATE EVENTS AND HAZARDOUS HYDROMETEOROLOGICAL PHENOMENA IN LATVIA

DOCTORAL THESIS
based on a thematically united collection of publications

Submitted for the Degree of Doctor of Geography in Environmental Science
Subfield of Nature Protection

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The dissertation is available at the Scientific Library of the University of Latvia, 4 Kalpaka blvd. and Academic Library of the University of Latvia, 24 Lielvardes Street, Riga.

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ANOTĀCIJA

Klimata pārmaiņas tiek uzskatītas par vienu no galvenajiem izaicinājumiem, kas 21. gadsimtā skars cilvēci un dabas sistēmas, turklāt ekstremālu un bīstamu parādību izmaiņas ir saistītas ar ievērojami lielākiem riskiem, nekā klimata pārmaiņas kopumā. Līdz šim ekstremālās klimatiskās parādības un bīstamās hidrometeoroloģiskās parādības Latvijā ir maz pētītas. Līdz ar to šī promocijas darba mērķis ir ar aptverošas analīzes un mūsdienīgas metodikas palīdzību apzināt ekstremālu klimatisko parādību un tādu bīstamu hidrometeoroloģisko parādību kā jūras ledus, migla un pērkona negaiss klimatiskās izplatības raksturu un ilggadīgās izmaiņas Latvijā.

Pētījuma rezultāti ilustrē būtiskas izmaiņas ekstremālo klimatisko parādību un bīstamo hidrometeoroloģisko parādību raksturā līdzšinējo klimata pārmaiņu ietekmē. Kopš pagājušā gadsimta vidus Latvijā novērota būtiska ekstremāli aukstu dienu un ziemas sezonai raksturīgo hidrometeoroloģisko parādību skaita samazināšanās, kamēr ekstremāli karstas dienas un dienas ar stipriem nokrišņiem ir kļuvušas biežākas. Konstatēto izmaiņu telpiskās atšķirības ir saistāmas ar pētījumā izmantoto hidrometeoroloģisko novērojumu staciju ģeogrāfiskās atrašanās vietas raksturu, kā arī valdošajiem atmosfēras cirkulācijas apstākļiem. Pētījuma rezultāti ilustrē attālināto novērojumu nozīmi bīstamu hidrometeoroloģisko parādību novērošanā Latvijā, kā arī iezīmē darba gaitā radīto datu kopu un zināšanu pārnesi izmantošanai turpmāku pētījumu, kā arī hidrometeoroloģisko un klimata pakalpojumu izstrādē.

Šis promocijas darbs ir tematiski vienota astoņu publikāciju kopa. Piecas no šīm publikācijām iekļautas SCOPUS datubāzē un piecas — ISI Web of Science datubāzē. Promocijas darbs izstrādāts laika periodā no 2012. līdz 2017. gadam.

Atslēgvārdi: *klimata pārmaiņas, ekstremālas klimatiskās parādības, bīstamas hidrometeoroloģiskās parādības, migla, pērkona negaiss, jūras ledus.*

ABSTRACT

Climate change has been recognized as a major challenge to human beings and natural ecosystems, and has been associated with changes in extreme and hazardous climate and weather events that pose much more significant threats than climate change itself. So far, little knowledge exists on extreme climate events and hazardous hydrometeorological phenomena in Latvia. Therefore this thesis aims at the provision of a comprehensive analysis of the climatic characteristics, favourable atmospheric conditions and long-term changes in the frequency and intensity of extreme climate events and such hazardous hydrometeorological phenomena as the occurrence of sea ice, thunderstorms and fog in Latvia.

During the analysis carried out in the study, significant changes in extreme climate events and hazardous hydrometeorological phenomena in Latvia have been found under the conditions of recent climate change. Since the middle of the past century, there has been a significant decrease in the number of extremely cold days and hazardous hydrometeorological events characteristic for the winter season, but the number of extremely hot days as well as the frequency and intensity of extreme precipitation has increased. The spatial differences in the distribution of such events are associated with the geographical location of the meteorological observation stations used in the analysis and the differences in the atmospheric conditions favourable for the occurrence of extreme and hazardous meteorological events. The obtained results highlight the importance of the applications of remote sensing observations for the monitoring and analysis of hazardous hydrometeorological phenomena in Latvia, as well as the applicability of the produced datasets and body of research for further investigations and development of hydrometeorological and climate services in Latvia.

This Doctoral thesis is based on thematically unified set of eight scientific papers published in various scientific periodicals. Five publications are presented in SCOPUS database and five are available in the ISI Web of Science database. The thesis was carried out over the period from 2012 to 2017.

Keywords: *climate change, extreme climate events, hazardous hydrometeorological phenomena, fog, thunderstorms, sea ice.*

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INTRODUCTION

Climate change has been recognized as a major challenge to human beings and natural ecosystems. A significant worldwide increase in the mean temperature near the surface of the Earth has been reported, indicating that the climate is changing. Climate change affects all elements of the climate system: air and water temperature, precipitation, river runoff, ice, snow cover, hazardous hydrometeorological phenomena and others. Thus, climate change is not only characterized by changes in the mean values, but also by changes in the variability of climate indicators and extreme and hazardous events, such as, for instance: extreme heat events and heat waves, extreme precipitation, floods and changes in the behaviour of hazardous hydrometeorological phenomena. In respect to the damage to the society and natural ecosystems, changes in extreme climate events and hazardous hydrometeorological phenomena may pose much more significant threats than climate change itself. Nevertheless, compared with existing knowledge on the long-term changes in mean climate indicators, much less is known about the changes in extremes. Therefore, analysis of national climate and weather characteristics is essential for building of a deeper understanding of the climatic processes taking place on a regional and global scale.

The aim of this thesis is to assess the climatic characteristics, favourable atmospheric conditions and long-term changes in extreme climate events and hazardous hydrometeorological phenomena (Table 1) in Latvia by using comprehensive analysis and advanced methodology.

Table 1

Overview of the scientific papers arising from this thesis

<table>
<tr><th>Effects of studied phenomena</th><th>Studied domain</th><th>Studied parameters</th><th colspan="2">Title of the scientific paper</th></tr>
<tr><td rowspan="8">Adverse effects on natural environment and society</td><td rowspan="2">Extreme climate events</td><td rowspan="2">Air temperature and precipitation</td><td>Paper 1</td><td>Trends in the frequency of extreme climate events in Latvia</td></tr>
<tr><td>Paper 2</td><td>Changes of extreme climate events in Latvia</td></tr>
<tr><td rowspan="6">Hazardous hydro-meteoro-logical phenomena</td><td>Sea ice</td><td>Paper 3</td><td>Dynamics and impacting factors of ice regimes in Latvia inland and coastal waters.</td></tr>
<tr><td rowspan="2">Fog</td><td>Paper 4</td><td>Fog climatology in Latvia</td></tr>
<tr><td>Paper 5</td><td>Temporal and spatial variation of fog in Latvia</td></tr>
<tr><td rowspan="3">Thunder-storms</td><td>Paper 6</td><td>Long-term changes in the frequency and intensity of thunderstorms in Latvia</td></tr>
<tr><td>Paper 7</td><td>The forecasting of tornado events: the synoptic background of two different tornado case-studies</td></tr>
<tr><td>Paper 8</td><td>Remote sensing observations of thunderstorm features in Latvia</td></tr>
</table>

The proposed **hypothesis** of this thesis is that there have been significant changes in the frequency and intensity of extreme climate events and hazardous hydrometeorological phenomena in Latvia since the middle of the past century. Therefore the following **scientific questions** are set to be addressed within this thesis:

1. What are the climatic characteristics and long-term trends of changes in the frequency of extreme climate events and such hazardous meteorological phenomena as fog and thunderstorms in Latvia?
2. What are the climatic characteristics and long-term changes in the occurrence and persistence of sea ice as a hazardous hydrometeorological phenomenon in the Latvian coastal areas of the Baltic Sea and the Gulf of Rīga?
3. How are remote-sensing observations applicable for the observations and analysis of hazardous hydrometeorological phenomena in Latvia?
4. What are the atmospheric conditions favourable for the occurrence of extreme climate events and hazardous hydrometeorological phenomena in Latvia?

Novelty of the research

The study presented within this thesis provides the results of investigations, which for the very first time provide comprehensive characteristics and complex analysis of extreme climate events and hazardous hydrometeorological phenomena in Latvia. Thus, the results of this thesis comprise the following **novelties** (Table 2):

- climatic and spatial distribution as well as long-term changes in the frequency and intensity of extreme climate events and hazardous hydrometeorological phenomena in Latvia have been determined, characterized and assessed;
- atmospheric conditions associated with the occurrence of extreme climate events and hazardous hydrometeorological phenomena have been identified and characterized;
- applicability of remote sensing observations for the observation and analysis of hazardous hydrometeorological phenomena in Latvia has been assessed and identifiers of increased thunderstorm severity obtained from remote sensing observations have been determined;
- representivity of the existing thunderstorm warning criteria in Latvia has been assessed by analysing the long-term observation time-series of thunderstorm frequency and intensity.

Table 2

Methodological components of the scientific papers arising from this thesis

Applied methodologies	Number of the scientific paper							
	1	2	3	4	5	6	7	8
Analysis of climatic and spatial distribution	✓	✓	✓	✓	✓	✓		✓
Trend analysis	✓	✓	✓	✓	✓	✓		
Analysis of atmospheric conditions of occurrence	✓		✓	✓	✓		✓	
Application of remote-sensing observations			✓	✓	✓		✓	✓
Assessment of national warning criteria						✓		

Practical applicability and significance of the research

The results obtained within this thesis can be used both for the development and improvement of the national hydrometeorological and climate service provided by the Latvian Environment, Geology and Meteorology Centre, as well as for the development of national policy initiatives and actions for climate change adaptation and mitigation. The obtained results can be used as a supplement to the existing national climatologies, as well as for the development of improved forecasting, nowcasting and warning techniques, thus contributing to an increased adaptation and resilience capacity. The developed databases and datasets can be used for further studies contributing to the increase in knowledge and capacity regarding the investigations of extreme climate events and hazardous hydrometeorological phenomena in Latvia.

Approbation of the results

The results of the study have resulted in eight scientific publications and presentations in 16 international and eight local conferences.

Scientific papers on the topic of the thesis

Paper 1. **Avotniece, Z.,** Rodinov, V., Lizuma, L., Briede, A., Kļaviņš, M. (2010). Trends in the frequency of extreme climate events in Latvia. *Baltica*, **23** (2), 135–148. (Scopus and ISI Web of Science)

Paper 2. **Avotniece, Z.,** Kļaviņš, M., Rodinovs, V. (2012). Changes of Extreme Climate Events in Latvia. *Environmental and Climate Technologies*, **9** (1), 4–11. (Scopus)

Paper 3. Kļaviņš, M., **Avotniece, Z.,** Rodinovs, V. (2016). Dynamics and Impacting Factors of Ice Regimes in Latvia Inland and Coastal Waters. *Proceedings of the Latvian Academy of Sciences, Section B: Natural, Exact, and Applied Sciences,* **70** (6), 400–408. (Scopus)

Paper 4. **Avotniece**, **Z.,** Klavins, M., Lizuma, L. (2014). Fog Climatology in Latvia. *Theoretical and Applied Climatology*, **122** (1–2), 97–109. (Scopus and ISI Web of Science)

Paper 5. **Avotniece, Z.,** Klavins, M. (2013). Temporal and Spatial Variation of Fog in Latvia. *Environmental and Climate Technologies*, **3**, 5–10.

Paper 6. **Avotniece, Z.,** Aniskevich, S., Briede, A., Klavins, M. (2017). Long-term changes in the frequency and intensity of thunderstorms in Latvia. *Boreal Environment Research,* **22**, 415–430. (Scopus and ISI Web of Science)

Paper 7. Wrona, B., **Avotniece, Z.** (2015). The Forecasting of Tornado Events: the Synoptic Background of Two Different Tornado Case-studies. *Meteorology Hydrology and Water Management*, **3** (1), 51–58. (ISI Web of Science)

Paper 8. **Avotniece, Z.**, Klavins, M., Briede, A., Aniskevich, S. (2017). Remote Sensing Observations of Thunderstorm Features in Latvia. *Environmental and Climate Technologies*, **21**, 28–46. (ISI Web of Science)

Other scientific papers

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Avotniece, Z., Dimants, M. (2018). The use of Satellite Scatterometry and Altimetry Data for Wind and Wave Monitoring in the Central part of the Baltic Sea and the Gulf of Riga. *Journal of Maritime Transport and Engineering* [In Press].

Other publications

Kļaviņš, M., **Avotniece, Z.**, Rodinovs, V. (2012). Heat Waves in Latvia: Occurrence, Impacts and Consequences In: Kļaviņš, M., Briede, A. (eds.), *Climate Change in Latvia and Adaptation to it* (pp. 62–78). Riga: University of Latvia Press.

Avotniece, Z., Aņiskeviča, S., Maļinovskis, E. (2017). *Klimata pārmaiņu scenāriji Latvijai* [Climate Change Scenarios for Latvia] (in Latvian with summary in English). Available: http://www2.meteo.lv/klimatariks/ [Accessed 19.03.2018]

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Avotniece, **Z.**, Higgins, M., Roebeling, R. The experience and instructions for creating a satellite-based climate atlas for Europe and Latvia. In: *The Climate Symposium 2014, 13–17.10.2014 Darmstadt, Germany.*

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Lizuma, L., Briede, A., **Avotniece**, **Z.** Augsnes temperatūras ilgtermiņa izmaiņas Latvijā [Long-term Changes in Soil Temperature in Latvia] (in Latvian). In: *72nd Scientific Conference of the University of Latvia, 30.01.2014. Riga, Latvia.*

Avotniece, **Z.**, Higgins, M., Roebeling, R. Uz satelītu novērojumiem balstīta atlanta izveide Latvijai un Eiropai [Satellite-based Climate Atlas for Latvia and Europe] (in Latvian). In: *73rd Scientific Conference of the University of Latvia, 04.02.2015. Riga, Latvia.*

Avotniece, **Z.**, Briede, A., Koreļska, L. Ekstremālo klimatisko parādību mainības izmaiņas Latvijā 1923.–2010. gadā [Changes in the variability of extreme climate events in Latvia over the period 1923–2010] (in Latvian). In: *73rd Scientific Conference of the University of Latvia, 04.02.2015. Riga, Latvia.*

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Avotniece, Z., Aņiskeviča, S., Briede, A., Kļaviņš, M. Pērkona negaisu biežums un intensitāte Latvijā [Frequency and Intensity of Thunderstorms in Latvia] (in Latvian). In: *75th Scientific Conference of the University of Latvia, 30.01.2017. Riga, Latvia.*

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Avotniece, Z., Briede, A., Kļaviņš, M., Aņiskeviča, S. Pērkona negaisiem raksturīgās attālinātajos novērojumos Latvijā [Features in Remote Sensing Observations Characteristic for Thunderstorms in Latvia] (in Latvian). In: *76th Scientific Conference of the University of Latvia, 31.01.2018. Riga, Latvia*.

Author's contribution

The author has had principal responsibility for the creation of databases and datasets used as the primary source of information for the studies presented within these scientific papers and other publications. The author has had a significant contribution in the development of the methodology, data analysis and writing of the scientific papers resulting from this thesis. Author's contribution within the creation of the scientific papers on the topic of the thesis has been as follows:

Paper 1. Database 80%; Methodology 50%; Data analysis 80%; Writing 50%.
Paper 2. Database 80%; Methodology 50%; Data analysis 80%; Writing 50%.
Paper 3. Database 50%; Methodology 40%; Data analysis 50%; Writing 20%.
Paper 4. Database 80%; Methodology 60%; Data analysis 80%; Writing 60%.
Paper 5. Database 80%; Methodology 60%; Data analysis 80%; Writing 60%.
Paper 6. Database 80%; Methodology 60%; Data analysis 70%; Writing 70%.
Paper 7. Database 20%; Methodology 20%; Data analysis 20%; Writing 30%.
Paper 8. Database 90%; Methodology 70%; Data analysis 90%; Writing 70%.

Structure of the thesis

This thesis consists of a thematically united collection of publications. The main results of the study on four topics are presented in 8 scientific papers. The thesis also contains a section of literature review.

1. LITERATURE REVIEW

1.1. Extreme climate events and hazardous hydrometeorological phenomena

In order to develop effective climate change adaptation and mitigation strategies and activities, it is essential to obtain comprehensive knowledge and understanding of the behaviour of extreme climate events and hazardous hydrometeorological phenomena under the conditions of recent climate change. However, while a large body of research has recently focused on the analysis of the climatic means, certain limitations in the available concepts and data have resulted in several problems for observing, analysing and building credible climatologies of extreme and hazardous events (Klein Tank, 2004). Amongst these limitations first of all is the complex nature of extreme and hazardous phenomena: high-impact events are usually local and they can also be short-lived, thus they might not be observed and correctly represented by the surface observation networks (Burroughs, 2003).

Another limitation is the inequality of the concepts associated with extreme climate events and hazardous hydrometeorological phenomena. As countries around the world and in Europe have different climatic conditions and weather-related challenges, it is common for every National Hydrometeorological Service to identify and define the hydrometeorological phenomena and their intensity associated with hazardous impacts in the particular country. Thus even neighbouring countries have differences in the attribution of hazardous hydrometeorological phenomena (Meteoalarm, 2017), which leads to specific problems for the comparability of research results on a regional and global scale. In Latvia, the National Hydrometeorological Service is provided by the Latvian Environment, Geology and Meteorology Centre (hereafter — LEGMC), which in cooperation with the State Fire and Rescue Service of Latvia has defined the following hydrometeorological phenomena as hazardous:

- severe heat and cold;
- heavy rain and snow;
- strong wind gusts;
- high water level in the coastal areas of the Baltic Sea and the Gulf of Rīga and in the largest rivers of Latvia;
- high risk of forest fires;
- poor visibility during fog or heavy precipitation;
- icing;
- continuous blizzard;
- severe thunderstorm (LEGMC, 2017).

These hydrometeorological phenomena are associated with the issuance of warnings and awareness materials for the general public and state institutions. However, additional hydrometeorological phenomena exist for which the monitoring, reporting and warning routine is carried out for specific sectors. Amongst these are the hazardous phenomena that affect air and marine traffic (such as the occurrence of turbulence and in-cloud icing, significant wave height and formation of sea ice), agriculture and forestry (such as frosts and drought) and other sectors. All of these hazardous hydrometeorological phenomena are characteristic for the climatic conditions of the country and therefore occur relatively frequently.

In order to define a hydrometeorological phenomenon an extreme event, several approaches can be applied depending on the underlying aim. Classical approach for the identification of extreme climate events is the compliance with several criteria: the phenomenon has to be of a high intensity and with a relatively rare occurrence characterised by low repeatability. Thus extreme climate events are commonly associated with significant deviations from the long-term mean values and climate normals. However, not all of the intense phenomena are rare and thus comply with both of these criteria. The third criterion for the distinction of extreme climate events is the impact and socioeconomical loss associated with the occurrence of the event (Beniston *et al.*, 2007). Under the framework of climate change analysis and impact assessment, extreme climate events have been defined by using a different approach: extreme climate events are characterized as hazardous hydrometeorological phenomena leading to extensive negative impacts to ecosystems and social sectors such as security and health, water management, agriculture, energy, insurance, tourism and transportation. The examples of such events are the natural catastrophes that can be short-lived (for instance, severe cyclonic storms) or persistent and last for several days, months or even years (for example, drought). Often, extreme climate events have been identified using internationally agreed, predefined indices such as number of days exceeding a fixed threshold, percentile threshold, extreme event duration, etc. (Easterling *et al.*, 2000). Hazardous hydrometeorological phenomena associated with negative impacts are not always associated with significant deviations from the climatic normal, and their adverse impacts are to a large extent associated with the conditions and state of the system under effect, such as the adaptation state and capacity. Thus, for instance the hydrology of a particular area determines whether it can survive torrential rainfall without getting flooded. Even though extreme climate events do not always become catastrophic, it is very likely that systematic changes in extreme values of climatic variables will result in systematic changes in their impacts (Klein Tank, 2004).

This study contains the analysis of extreme climate events and hazardous hydrometeorological phenomena. In order to describe the behaviour of extreme climate events under the conditions of recent climate change, extreme climate indices defined by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ECA&D, 2017) were used. These indices were developed with a primary aim of monitoring climate change and assess its possible impacts on different social and economic processes. In order to increase the applicability of the indices, they were built to characterize both the mean and extreme values of climatic variables and to represent events with return periods of weeks rather than unique and rare climate events (Klein Tank, 2004; Klein Tank and Zwiers, 2009). Even though these indices do not describe extreme events in classical terms (rare, intense and with high impact), they are essential for the analysis of the long-term behaviour of climate variable values near the tails of distribution. However, in order to describe events with a high impact to several sectors, the climatic characteristics and long-term trends of changes in the occurrence and intensity of fog, thunderstorms and sea ice was analysed. These particular phenomena have been selected due to their occurrence in different times of the year and also due to their impact on different sectors, and threats associated with climate change.

1.2. Effects of extreme climate events and hazardous hydrometeorological phenomena

The changes in climate occurring worldwide, have led to changes in the frequency, timing, duration, spatial extent and intensity of weather and climate extremes (Seneviratne *et al.*, 2012). While extreme events pose the greatest threat to the society and individuals, extreme weather-related impacts can also occur from events that may not be considered as extreme. Research shows that economic losses from weather and climate-related disasters have increased, with the economic disaster losses associated with weather, climate and geophysical events being higher in the developed countries. It has been estimated, that the economic sectors most exposed and vulnerable to weather and climate extremes are transportation, infrastructure, agriculture, water management and tourism. Continued changes in climate will lead to an even increased magnitude of impacts on these sectors (Handmer *et al.*, 2012). Estimation of the impacts of the recent and future climate change has led to the conclusion that in Europe, changing climate will affect all of the sectors — energy, transport, settlements, tourism, human health, environmental quality, social and cultural environment — by 2050. Furthermore, extreme events can affect multiple sectors and may have the potential to cause systemic impacts from secondary effects (Kovats *et al.*, 2014). As has been stated in several studies, an increase in the frequency of extreme climate events can increase the threat to society and individuals (Alexander *et al.*, 2007; Beniston, 2007; Kysely *et al.*, 2010; Unkaševica and Tošic, 2009; Jungerius, 2008). The following paragraphs of this section give an insight in the effects of the extreme climate events and hazardous hydrometeorological phenomena assessed in this thesis.

Over the last decades, there has been a growing interest in the connection between climate and health, largely due to the potential impacts of climate variability and change on human health (Epstein, 2002; Haines and Patz, 2004; Patz and Kovats, 2002). Studies have shown that increase in the frequency and length of the periods of prolonged heat can have a significant negative effect on human morbidity and mortality (Diaz *et al.*, 2006; Beniston, 2007; Unkaševica and Tošic, 2009). Another important area of climate-related impacts is associated with changes in the precipitation pattern — while some regions, for instance the Southern Europe, have experienced a decrease in precipitation frequency and intensity, in the Northern Europe precipitation intensity and frequency is increasing (Beniston *et al.*, 2007; Kjellström and Ruosteenoja, 2007). Extreme precipitation events can have an extensive negative effect to the society and infrastructures and therefore it is essential to study the long-term pattern of changes in the precipitation regimes along with the development of effective adaptation mechanisms (Mason *et al.*, 2004).

Amongst the hazardous hydrometeorological phenomena which vary both by the season of occurrence and the sectors affected, each phenomenon is associated with a different set of impacts. For instance, the formation of sea ice in the coastal areas of the Baltic Sea and the Gulf of Rīga has been common for winter seasons in the past century, while recent climate change has led to an increase in winter temperatures and thus deteriorated the formation of sea ice. However, the observed changes have not been linear, and due to variability, cold and icy winters have also been observed in the beginning of the 21st century resulting in difficulties for the navigation of ships. Another hazardous phenomenon affecting transportation is the occurrence of fog. Fog is a hazardous weather phenomenon worldwide, which can cause accidents and affect urban air quality, especially in combination with impacts of air pollutants (Lange *et al.*, 2003; Singh and Dey, 2012). Traffic obstacles such as flight delays, automobile and marine accidents due to poor visibility can be considered as the most common negative effects of fog (Cermak and Bendix, 2008; Heo *et al.*, 2010). At the same time, fog can be associated with critical conditions of air pollution, because air pollutants can be trapped in the fog droplets and can reach high concentrations, causing the formation of smog or in some cases acid fog (Bendix, 2002; Witiw and LaDochy, 2008). On the other hand, fog as a source of humidity is also very important to the health of ecosystems and humans, and as fog has an important influence on the radiation balance, the long-term changes in their frequency can play an important role in the accuracy of the climate model predictions (Sachweh and Koepke, 1997). The occurrence of fog is related to the atmospheric circulation and local geographical features of a site and thus fog climatology studies are of especial importance for airports, where local meteorological conditions (lowland and flatland territories) may support increased occurrence of fog, but the impacts might have serious consequences.

The most hazardous weather phenomenon observed in Latvia in the summer season is the occurrence of thunderstorms. Numerous hazards that lead to fatalities, injuries, property damage, economic disruptions and environmental degradation are associated with convection. Such hazards belonging to a group defined as small-scale severe weather phenomena include hail, lightning, damaging straight-line winds, tornadoes and heavy rainfall leading to flooding (Parsons, 2015; Zwiers *et al.*, 2013; Czernecki *et al.*, 2016; Dotzek *et al.*, 2009; Doswell *et al.*, 1990). Severe weather associated with thunderstorms has been observed in every country in Europe and poses a significant threat to life, property and economy. Severe thunderstorms 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, particularly in less populated areas (Burroughs, 2003).

1.3. Changes in extreme climate events and hazardous hydrometeorological phenomena under the conditions of recent and future climate change

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that the observed warming of 0.5–1.3 °C in the values of the global mean surface temperature over the period 1951–2010 has been mainly associated with anthropogenic effects, namely the increase in concentrations of the greenhouse gases in the atmosphere (IPCC, 2014). Tendencies of increasing temperatures have also been evident in the Baltic Sea region: the annual mean temperatures in the region have increased by 0.08 to 0.11 °C per decade over the period 1871 to 2011, with the most prominent changes evident in spring and winter seasons (BACC II Author Team, 2015). The conclusions arising from the IPCC Fifth Assessment Report claim that the observed warming has led to changes also in other climatic variables, such as for instance changes in global precipitation amount (IPCC, 2014).

1.3.1. Changes in extreme climate events

Climate change is characterized not only by changes in the mean values of climatic variables, but also by changes in the variability of climate indicators, extremes and weather hazards for example, extreme heat events and heat waves, extreme precipitation, floods (Karl and Trenberth, 2003). The conclusions arising from the IPCC Fifth Assessment Report claim that there have also been changes in the occurrence of extreme climate events. Research studies have confirmed a long-term increase in the frequency of occurrence of extremely warm days and nights, while extremely cold days and nights have become more seldom (IPCC, 2014). This has led to a growing interest in extreme climate events (Easterling *et al.*, 2000; Alexander *et al.*, 2006; Beniston, 2007; Fischer and Schär, 2009; Beniston *et al.*, 2007) and trends of their changes, which may be the effect of changes in the mean values, the variance effect or structural changes in the shape of the distribution of climatic variables (Heino *et al.,* 2008). Therefore the determination of changes in extreme events has been the topic of several international projects, for instance, ECA&D (Klein Tank *et al.*, 2002; Klein Tank and Könen, 2003), EMULATE (Moberg *et al.,* 2006) and STARDEX (Haylock and Goodess, 2004).

In several studies in Europe, significant increasing trends have been found in a variety of extreme indices over the latter part of the 20th century (Heino *et al.,* 1999; Wibing and Glowicki 2002; Klein Tank and Können, 2003). A study based on the analysis of temperature extremes (Klein Tank and Können, 2003) has reported an increase in the frequency of high temperature extremes and a decrease of the low temperature extremes in Europe. In summer, the increase concerns both daily maximum and daily minimum air temperatures while in winter — mostly daily minimum air temperatures (Moberg *et al.*, 2006; Fischer and Schär, 2009). The countries around the Baltic Sea have also experienced an increase in the number of warm nights and a decrease in the number of cold nights and days in the latter part of the 20th century as well as a slightly increased number of summer days with daily maximum temperatures of above +25 °C (Moberg and Jones, 2005; Kažys *et al.*, 2011). The observed increase in the frequency of extremely hot days and nights as well as heat waves has been to a large extent associate with anthropogenic effects, and forecasts of regional and global climate models suggest the persistence and amplification of the observed trends also throughout the 21st century (Fischer and Schär, 2009; IPCC, 2014).

According to studies carried out in Europe, there are significant spatial differences in the trends of changes for extreme precipitation events (Klein Tank, 2004; Beniston *et al.*, 2007), though the most significant increasing tendency has been observed in the Baltic Sea region (Bhend and Storch, 2007; Kjellström and Ruosteenoja, 2007). Recent studies reveal an increase in the frequency of events associated with heavy precipitation in many parts of the world during the 20th century, with most prominent changes occurring in the countries where at the same time an increase in the total precipitation amount has been reported (Easterling *et al.*, 2000). However, changes in precipitation have been subject to regional variations (Alexander *et al.*, 2007): in Europe an increase in the frequency of heavy precipitation events has been observed in regions with increasing total annual precipitation amounts, while regions with decreasing total precipitation amounts have also seen a decrease in the number of heavy precipitation events. Thus the spatial inconsistency of heavy precipitation events has been much more prominent than for extreme temperature events, and statistically significant positive and negative tendencies in the frequency and intensity of heavy precipitation can be observed even in meteorological observation stations located relatively nearby (Klein Tank, 2004). In general, the occurrence of heavy precipitation events in the winter season has increased in Central and Northern Europe, while an increase in summertime heavy precipitation events has been characteristic for the northeastern regions of Europe. At the same time both wintertime and summertime cases of heavy precipitation have become more seldom in the Southern part of Europe (Beniston *et al.*, 2007; Kjellström and Ruosteenoja, 2007). Studies claim that in the Baltic Sea basin the annual total precipitation amount has increased by 8.24 mm per decade (Bhend and Storch, 2007). The future climate change scenarios for Europe predict a further increase in the gradient of changes in precipitation between the Southern and Northern part of Europe (Rowell, 2005; IPCC, 2014).

1.3.2. Changes in hazardous hydrometeorological phenomena

Even though hazardous hydrometeorological phenomena cause extensive socio-economic damage and loss in Europe, their long-term trends of changes so far have been poorly represented by research studies. Recent studies on such phenomena have mainly focused on the investigation of atmospheric processes favourable for their occurrence (Witiw and LaDochi, 2008; Błas´ *et al.*, 2002; Roberts and Stewart, 2008; Simeonov and Georgiev, 2003), as well as the assessment of possibilities for their forecasting (Lopez *et al.*, 2007; Grimbacher and Schmid, 2005; Rigo and Llasat, 2007) and observation (Lange *et al.*, 2003; Bendix, 2002). Nevertheless, recent climate change has impacted all elements of the climate system. Global changes in land and ocean surface temperatures observed over the period 1880–2012 indicate an increase in water surface temperature by 0.85 °C. Such warming has been accompanied by a gradual decrease in the sea ice cover (IPCC, 2014b). However sea ice has an essential role in the formation of climate and global decrease in sea ice cover contributes to a decrease in the surface albedo of the Earth, thus amplifying the warming processes in the atmosphere (UNEP, 2007). Therefore records of the dates of ice freeze-up and break-up are good indicators to assess inter-annual and seasonal climate variability, especially in relation to long-term climate change (Beltaos and Burrell, 2003; Johannessen *et al.*, 2004; Saucier *et al.*, 2004; Laidre and Jorgensen, 2005; Granskog *et al.*, 2006; Sarauskiene and Jurgelenaite, 2008). The records on ice break-up dates on rivers in the Northern Hemisphere during the last two centuries provide consistent evidence of later freezing and earlier break-up (Magnuson *et al.*, 2000; Gebre *et al.*, 2014). In addition, the increase in the values of air temperature have also led to significant changes in ice conditions both at the Latvian coastline of the Baltic Sea and in the Gulf of Rīga (Jevrejeva, 2001).

The most intense fog events in both persistence and thickness were observed in many sites of the industrialized world in the 1940s and 1950s, when some famous low visibility episodes in combination with heavy air pollution such as the Great Smog of London in 1952 occurred (MetOffice, 2015). Since this time, owing to the introduction of clean air legislation and a decrease in total suspended particulates, fog climatology has changed considerably and many sites have experienced a decrease in fog frequency (Bendix, 2002; Witiw and LaDochy, 2008; Shi *et al.*, 2008). Due to the anthropogenic factors influencing the climate in urban areas, studies have demonstrated a decrease in the annual number of fog events in big agglomerations, which could be associated with the growth of cities and the resulting decrease in natural surfaces (Sachweh and Koepke, 1995; Shi *et al.*, 2008). However, in developing countries such as India, with rapidly growing industry and rising anthropogenic emissions, the frequency of fog events has increased and visibility has rapidly decreased over the past 30 years (Singh and Dey, 2012; Syed *et al.*, 2012).

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 and because of the volunteer observer activities established in many countries. At the same time studies carried out in Europe do not confirm an increase in thunderstorm frequency — a decrease in thunderstorm frequency has been identified for Lithuania and Estonia (Enno *et al.*, 2014), while no significant changes in thunderstorm frequency have been found in Finland (Tuomi and Mäkelä, 2008) and Poland (Bielec-Bakowska, 2003), thus emphasizing the pronounced spatial variability in the dynamics of annual thunderstorm frequency. It has also been identified that changes in the annual frequency of thunderstorm days in the Baltic countries have been associated with changes in the general atmospheric circulation patterns, with a decreased thunderstorm frequency accompanied by an increased frequency of circulation patterns unfavourable for the occurrence of thunderstorms, namely: northerly and anticyclonic flows (Enno *et al.*, 2014). The scientific community suggests a likely increase in thunderstorm frequency under the conditions of future climate change (Collins *et al.*, 2013), however 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 (Enno *et al.*, 2014). This conclusion has been stated also by other authors (Zwiers *et al.*, 2013), suggesting that on one hand, greenhouse gas induced warming may lead to greater atmospheric instability due to increases in temperature and moisture content, leading to a possible increase in severe weather, but on the other hand, vertical shear may decrease due to reduced pole-to-equator temperature gradients. The lack of firm conclusions regarding the past and future behaviour of thunderstorm environments is highly associated with their observational limitations, and therefore the development of effective national warning systems and mechanisms is essential for mitigation of adverse effects of any possible changes to come.

2. DATA AND METHODS

This section contains the description of the data and main methodology used for the identification, characteristic and assessment of extreme climate events and hazardous hydrometeorological phenomena in Latvia. Additional and more detailed information on the data and methodology can be obtained from the corresponding sections of the research papers supplemented to this thesis.

2.1. Data used for the analysis

2.1.1. Surface hydrometeorological observation data

The basis for the performed analysis lies on the investigation of surface hydrometeorological observation data obtained from the long-term data archive maintained and managed by LEGMC. The analysis of extreme climate events and hazardous hydrometeorological phenomena has been based on the information obtained from hydrometeorological stations of Latvia with uninterrupted long-term data records available for each of the hydrometeorological parameters analysed (Figure 1). The main body of research

Figure 1. **The location of hydrometeorological observation stations used in this thesis.**
Meteorological observation stations are presented in black print,
while hydrological observation stations — in blue print.

presented in this thesis relies on observations from 14 major meteorological observation stations (Daugavpils, Stende, Mērsrags, Kolka, Zosēni, Skrīveri, Alūksne, Skulte, Rīga-Universitāte (hereafter also Rīga), Rūjiena, Priekuļi, Dobele, Liepāja and Ventspils). However, for an in-depth investigation of particular events under study, data obtained from additional meteorological and hydrological observation stations have been analysed (Table 3). The surface observation data were obtained from the historical data archive as well as the electronic hydrometeorological observation database CLIDATA, while data on ice regime were extracted from bulletins of hydrological observations maintained by LEGMC.

Table 3

Hydrometeorological observation stations used in the scientific papers arising from this thesis

Meteorological observation stations	Number of the scientific paper								Hydrological observation stations	Number of the scientific paper	
	1	2	3	4	5	6	7	8		3	8
Ainaži		x					x	x	Carnikava		x
Alūksne	x	x		x	x	x	x	x	Dagda		x
Bauska		x					x	x	Griškāni		x
Daugavpils	x	x		x	x	x	x	x	Kalnciems		x
Dobele		x		x	x	x	x	x	Krāslava		x
Gulbene		x					x	x	Kuldīga	x	x
Jelgava		x					x	x	Lagaste		x
Kolka		x	x	x	x	x	x	x	Lielpeči		x
Liepāja	x	x	x	x	x	x	x	x	Limbaži		x
Mērsrags		x	x	x	x	x	x	x	Litene		x
Pāvilosta		x					x	x	Lubāna		x
Priekuļi		x		x	x	x	x	x	Mežotne		x
Rēzekne		x					x	x	Piedruja		x
Rīga-Universitāte*	x	x	x	x	x	x	x	x	Pļaviņas		x
Rucava		x					x	x	Salacgrīva	x	x
Rūjiena		x		x	x	x	x	x	Sigulda	x	x
Saldus	x	x					x	x	Sīļi		x
Skrīveri		x		x	x	x	x	x	Vaikuļāni		x
Skulte		x		x	x	x	x	x	Valmiera		x
Stende		x		x	x	x	x	x	Vārdava		x
Ventspils		x	x	x	x	x	x	x	Velēna		x
Zīlāni		x					x	x	Vendzava		x
Zosēni		x		x	x	x	x	x			

*– within papers 3 and 5 observations obtained from additional surface observation stations in the vicinity of the capital city have been used: Jūrmala hydrological station for the characterization of the sea ice conditions and Rīga Airport automated meteorological observation station for the characterisation of fog

As the thesis contains an investigation of a variety of hydrometeorological parameters, information obtained from the archived data of surface observations include the following parameters:

- daily mean, minimum and maximum air temperature;
- daily precipitation amount;
- daily mean wind speed and maximum wind gusts;
- daily mean water temperature and occurrence of sea ice;
- daily mean relative humidity;
- daily mean atmospheric pressure at the station level;
- daily observations of atmospheric phenomena — fog, thunderstorms, hail, snow pellets.

For the assessment of the climatic characteristics and trends of changes in extreme climate events and hazardous hydrometeorological phenomena in Latvia, data records of various periods have been used in this study as follows:

- **Paper 1:** 1924–2008, for the Rīga-Universitāte observation station — data records since 1852;
- **Paper 2:** 1950–2010, for the Rīga-Universitāte observation station — data records since 1852;
- **Paper 3:** 1925–2013;
- **Paper 4:** 1960–2012;
- **Paper 5:** 1960–2012, for the Rīga Airport observation station — data records over the period 2010–2012;
- **Paper 6:** 1960–2015;
- **Paper 7:** July 29, 2012 for the analysis of atmospheric conditions in Latvia and July 14, 2012 for the analysis of atmospheric conditions in Poland;
- **Paper 8:** 2006–2015.

The data have been subjected to basic quality control and homogeneity assessment, ensuring the use of reliable and representative information for the analysis.

2.1.2. Remote sensing observation data

In addition to surface meteorological station data, remote sensing observations were used for the analysis of hazardous hydrometeorological phenomena. These include information obtained from the lightning detector network, meteorological radar and weather satellites.

The most extensive application of remote sensing observations for the analysis has been presented in **Paper 8**. For the identification of days with thunderstorms, lightning observation data from the Nordic Lightning Information System (NORDLIS) was used (Mäkelä *et al.*, 2010). For the aim of the particular 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. Lightning parameters describing the total daily number of lightning flashes, time period 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 (The R Foundation, 2017).

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. 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, medium-wavelength infrared channel IR 3.9 μm and broadband high-resolution visible channel HRV 0.4-1.1 μm was obtained. 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 (SSEC, 2017).

Thunderstorm cloud dynamics on days with more than 10 lightning flashes was assessed by using observations from the Doppler Weather Radar METEOR 500C (SELEX Sistemi Integrati GmbH, 2006) located near the Rīga 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. 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 and echo base as well as the echo thickness 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 (SELEX Sistemi Integrati GmbH, 2006).

Papers 4 and 5 contain an example of the possible applications of specific products and datasets derived from meteorological satellite data. Satellites are considered to be a powerful tool for the observation of fog, as satellite observations provide both wide spatial and temporal coverage, which is essential for the detection and characterisation of such a variable phenomenon. For the climatic characterization of fog occurrence data sets on low cloud cover obtained from the data archive maintained by the Satellite Application Facility on Climate Monitoring (CM SAF) were used. The data set (CM SAF, 2009) covers a period 2005-2011 and provides information on low cloud cover (%) obtained from Meteosat satellites at a 15x15 km spatial resolution. The information was extracted from the data set and calculated by applying routines within the Climate Data Operators (CDO) (Schulzweida, 2017) and R (The R Foundation, 2017).

In addition to the use of remote sensing observations for the purpose of analysis, they are also a good tool for the visualization and initial assessment of several hydrometeorological features. Thus, examples of the appearance of fog, sea ice and thunderstorms in Meteosat, Aqua and NOAA weather satellite and radar images have been presented in **Papers 3, 5, 7 and 8**.

2.2. Indices of extreme climate events

Ensemble climate change indices derived from daily temperature and precipitation data, describing changes in the mean indices or extremes of climate, were computed and analysed within **Papers 1 and 2**. The indices follow the definitions recommended by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ECA&D, 2017), with a primary focus on extreme events (Table 4).

Table 4

Extreme climate indices used in the thesis

Index abbreviation	Explanation	Unit
TX	Annual or monthly mean of daily maximum temperature	°C
TN	Annual or monthly mean of daily minimum temperature	°C
TG	Annual or monthly mean of daily mean temperature	°C
TNn	Annual or monthly minimum value of daily minimum temperature	°C
TNx	Annual or monthly maximum value of daily minimum temperature	°C
TXn	Annual or monthly minimum value of daily maximum temperature	°C
TXx	Annual or monthly maximum value of daily maximum temperature	°C
FD	Frost days (annual count when daily minimum temperature < 0 °C)	Days
ID	Ice days (annual count when daily maximum temperature < 0 °C)	Days
SU	Summer days (annual count when daily maximum temperature > 25 °C)	Days
TR	Tropical nights (annual count when daily minimum temperature > 20 °C)	Days
CSDI	Cold spell duration indicator (annual count of days with at least 6 consecutive days when minimum temperature < 10th percentile)	Days
WSDI	Warm spell duration indicator (annual count of days with at least 6 consecutive days when maximum temperature > 90th percentile)	Days
CFD	Maximum number of consecutive FD	Days
GSL	Growing season length (annual count of days between the first span of at least 6 days TG > 5 °C and first span in the second half of the year of at least 6 days TG < 5 °C)	Days
GD4	Growing degree days (sum of days with TG > 4 °C)	°C
Ptot	Annual total precipitation amount on wet days (precipitation amount ≥ 1mm)	mm
SDII	Simple daily intensity index (annual total precipitation divided by the number of wet days (precipitation amount ≥ 1mm) in the year)	mm/day
CDD	Consecutive dry days (annual maximum number of consecutive days with precipitation amount < 1mm)	Days
CWD	Consecutive wet days (annual maximum number of consecutive days with precipitation amount ≥ 1mm)	Days
R10	Annual number of heavy precipitation days (precipitation amount ≥10 mm)	Days
R20	Annual number of very heavy precipitation days (precipitation amount ≥ 20 mm)	Days
R95p	Very wet days (annual total precipitation when precipitation amount > 95th percentile)	mm
R99p	Extremely wet days (annual total precipitation when precipitation amount > 99th percentile)	mm
Rx1day	Max 1-day precipitation amount (annual or monthly maximum 1-day precipitation)	mm
Rx5day	Max 5-day precipitation amount (annual or monthly maximum consecutive 5-day precipitation)	mm

The climate indices were computed by using The RClimDex 1.0 developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of Meteorological Service of Canada. RClimDex 1.0 was designed to provide a user friendly interface to compute indices of climate extremes. RClimDex 1.0 runs in the R platform and besides the computation of indices it also includes a simple quality control of the data (Zhang and Yang, 2004).

2.3. Trend analysis

Trends in meteorological event time series were analysed by applying the Mann-Kendall test. For this purpose the MAKESENS tool was used, which was developed for detecting and estimating trends in the time series of annual data (Salmi *et al.*, 2002). The procedure is based on the nonparametric Mann-Kendall test (Richard, 1987) for the trend and the nonparametric Sen's method for the magnitude of the trend. The Mann-Kendall test is applicable to the detection of a monotonic trend of a time series with no seasonal or other cycle. This is a relatively robust method concerning missing data and has no strict requirements regarding data heteroscedasticity, and for these reasons it is a comparatively popular tool used for trend analysis for climate applications (Salmi *et al.*, 2002).

The Mann-Kendall test was applied separately to each variable at each site. Two approaches regarding the interpretation of the obtained results were used within the Papers presented in the thesis. First of them was a categorical distinction between statistically significant and insignificant trends of changes by applying the proxy of the test statistic value of ≥ 1.96 or ≤ -1.96 at $p \leq 0.05$. This approach was applied in **Papers 1, 3, 4, 5 and 6**. However, for a further inference of the differences in the spatial distributions of trends in the frequency of extreme climate events in Latvia presented in **Paper 2**, the statistically significant values of test statistics were classified as described here. The trend was considered as substantial at a significance level of $p \leq 0.1$ if the test statistic was greater than 1.6 or less than −1.6, as statistically significant at a significance level of $p \leq 0.01$ if the test statistic was greater than 2.6 or less than −2.6 and as very significant at a significance level of $p \leq 0.001$ if the test statistic was greater than 3.3 or less than −3.3.

2.4. Classification of thunderstorm severity levels

For the investigation of thunderstorm severity addressed in **Paper 6** the occurrence and intensity of additional meteorological parameters has been used following an approach comparable to the existing national warning criteria. The national thunderstorm warning criteria are currently based on the intensities of severe weather phenomena associated with thunderstorms, and these are hail, wind gusts and precipitation amount, which, according to their intensity, identify thunderstorms of green, yellow, orange and red warning level in line with the Meteoalarm warning levels (LEGMC, 2017; Meteoalarm, 2017). Due to peculiarities in the available long-term archived data on atmospheric phenomena in Latvia, for the climatological analysis of thunderstorm day severity a slightly different approach regarding severity criteria was used (Table 5). In order to assess hazardous weather phenomena observed on thunderstorm days, the daily accumulated precipitation amount and maximum wind gusts were used as criteria. Due to the relatively small number of historically observed hail events in the meteorological observation stations, all observed hail events were attributed to the yellow–red severity level disregarding the hail diameter. However, within both approaches, severity levels are applied only to cases, where the severity criteria of precipitation and/or hail and/or wind gusts have been observed in 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 observation station (Enno *et al.*, 2013) and thus the associated hazardous phenomena might also take place outside the observation site and vice versa. Another aspect to be considered is the temporal resolution of the historical data used — daily values of meteorological parameters and their combinations might not directly represent individual thunderstorm events, resulting in overestimated thunderstorm day severity levels during particular events.

Table 5

Classification of thunderstorm severity levels according to the national warning criteria and the approach used or the climatic assessment of thunderstorm severity

National thunderstorm warning criteria			
Thunderstorm warning level	**Hail diameter**	**Precipitation accumulation during 12 h**	**Maximum wind gusts**
Green	No hail	< 15 mm in 12 h	< 15 m/s
Yellow	No hail or hail with diameter ≤ 5 mm	< 15 mm in 12 h	15–19 m/s
Orange	Hail diameter 6–19 mm	15–49 mm in 12 h	20–24 m/s
Red	Hail diameter ≥ 20 mm	≥ 50 mm in 12 h	≥ 25 m/s
Thunderstorm severity criteria used for climatological analysis			
Thunderstorm severity level	**Occurrence of hail**	**Precipitation accumulation during 24 h**	**Maximum wind gusts**
Green	No hail	< 15 mm in 24 h	< 15 m/s
Yellow	Hail of any diameter	< 15 mm in 24 h	15–19 m/s
Orange	Hail of any diameter	15–49 mm in 24 h	20–24 m/s
Red	Hail of any diameter	≥ 50 mm in 24 h	≥ 25 m/s

By applying the described criteria, a thunderstorm day severity database has been developed and analysed within the study, presenting both the spatial distribution and frequency of thunderstorm days of different severity levels over the country over a period from 1966 to 2015.

2.5. Severe thunderstorm features in remote sensing observations

In order to assess the applicability of remote sensing observations for the identification of severe thunderstorms in Latvia, several theory-based features were identified and analysed and presented in **Paper 8**.

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 — 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 and hook echo amongst the visual indicators of thunderstorm severity, which can also be addressed to as signatures of a supercell thunderstorm (Stalker and Knupp, 2001; Rigo and Pineda, 2016; Panziera *et al.*, 2016; Lemon and Doswell, 1979).

Meteorological satellite observations provide information on the cloud top features characteristic for severe thunderstorms. Some of such features can be observed in the infrared part of the spectrum, 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 μm) contain the minimum value of cloud top temperatures (hereafter also CTT) and visual features identifiable in the CTT field — such as cold-ring structures or U/V-shaped storm structures. 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. Associated to the vertical extent of convective clouds up to the lower stratosphere is also the occurrence of overshooting tops and gravity waves that can be identified from satellite measurements in the visible part of the spectrum (Setvak *et al.*, 2010; Žibert and Žibert, 2013). Another indicator used for severe thunderstorm detection was a value exceeding 45 obtained from the brightness temperature difference of the spectral channels IR 3.9 μm and IR 10.8 μm. The information retrieved by calculating the brightness temperature difference can be used as a measure of the cloud-top particle size — with small ice particles indicating strong updrafts within the thunderstorm cloud (Putsay *et al.*, 2013; Guehenneux *et al.*, 2015; Mikuš Jurkovic *et al.*, 2015).

The analysis of the described thunderstorm features was performed by developing a database of the occurrence and characteristics of these features on thunderstorm days in Latvia. It is important to note that the selected features and applied identification approach contain a certain level of subjectivity, meaning that the obtained results reflected in the database are dependent on the knowledge and approach of the analyst.

2.6. Atmospheric circulation patterns

The characteristics, transformation and trajectories of an air mass reaching a certain location, as well as its specific weather conditions, are to a large extent determined by the large-scale circulation processes in the atmosphere (Moberg *et al.,* 2003; Jaagus, 2006). For these reasons, 18 large-scale atmospheric circulation patterns for the Baltic Sea region were examined in order to assess the atmospheric conditions favourable for the occurrence of extreme climate events and hazardous hydrometeorological phenomena in Latvia. The basis of this classification method of atmospheric circulation patterns was created by Baur, which formed the foundation for the *Grosswetterlagen* of Hess and Brezowsky, that was later reprocessed by Gerstengarbe and Werner (Gerstengarbe *et al.*, 1999). These patterns were derived from modifications of the circulation patterns created by Gerstengarbe and Werner (Hoy *et al.*, 2013) and made available for scientific research by the European Cooperation in Science and Technology Action 733 (COST733, 2013). This classification approach is based on predefined circulation patterns determined according to the subjective classification of the so-called Central European *Großwettertypes*. It is assumed that these *Großwettertypes* are defined by the geographical position of major centres of action, and that the location and extent of frontal zones can be sufficiently characterized in terms of varying degrees of zonality, meridionality, and vorticity of the large-scale sea level pressure field over Europe. With the help of these circulation patterns, the character of the large-scale atmospheric circulation and the types of synoptic systems determining the weather conditions over a certain area can be derived for each day over the period 1957–2002 (COST733, 2013). Therefore with the aim of describing atmospheric conditions favourable for the occurrence of extreme and hazardous phenomena in Latvia, weather patterns for each day of interest were identified and analysed within **Papers 1 and 4**.

While the previously described classification approach describes atmospheric circulation patterns to a degree comparable to the variable weather conditions associated with the movement of cyclones and anticyclones, another approach was used in order to characterize broader processes determining the onset and duration of the sea ice season. In order to determine relationship of sea ice changes to wide-scale climatic forcing factors, the extended North Atlantic Oscillation (NAO) index (Luterbacher *et al.*, 2002) was used in **Paper 3**. The NAO index data are classified in three categories: high (NAO = 1) or strong westerly, normal (NAO ≥ −1 and ≤ 1) and low (NAO = −1) or weak westerly. To identify climatic turning points, the Baltic winter index (WIBIX) was used (Hagen and Feistel, 2005). This climate index is based on the monthly values of: a) winter anomalies (January — March) of air pressure difference between Gibraltar and Reykjavik to describe the North Atlantic Oscillation, b) sea level anomalies of Landsort (Sweden) to characterise the filling level in the Baltic Proper, and c) maximum Baltic ice cover, to include the influence of continentally dominated alignments of atmospheric centres in action. The resulting values of the index describe alternating severe (continental, WIBIX < 0) and mild (maritime, WIBIX > 0) winter types, with the associated turning points characterising shifts in the climate regime.

3. RESULTS AND DISCUSSION

Climate in Latvia is influenced by its location in the northwest of the Eurasian continent (continental climate impacts) and by its proximity to the Atlantic Ocean (maritime climate impacts). A highly variable weather pattern is determined by the strong cyclonic activity over Latvia. These variable conditions over the territory contribute to differences in the regimes of air temperature and precipitation, and also to the spatial inhomogeneity in the occurrence and long-term trends of extreme climate events and hazardous hydrometeorological phenomena.

3.1. Extreme climate events in Latvia

The assessment of the characteristics and long-term trends of changes in extreme climate events in Latvia is one of the main research topics presented in this thesis. The results of the corresponding investigation have been presented in **Papers 1–2**.

3.1.1. Trends in the frequency of extreme climate events in Latvia

During the analysis, it was found that significant changes in the frequency of extreme climate events have been observed in Latvia. **Paper 1** contains the investigation of the long-term data records (1924–2008) obtained from five major meteorological observation stations in Latvia — Rīga, Liepāja, Alūksne, Saldus and Daugavpils, while **Paper 2** includes the analysis of a larger number of data series (14 meteorological observation stations) over a shorter period of time (1950–2010). Thus the comparison of the obtained results within both of these studies can contribute to an increased understanding of the spatial and temporal differences of the observed changes in extreme climate events in Latvia. The main findings arising from both of these studies are described below.

Both studies confirm a statistically significant increase in the mean values of daily minimum, maximum and mean air temperatures in Latvia. In addition, the long-term data records analysed in **Paper 1** illustrate the gradual character of the changes observed in the values of air temperature since the first part of the 20th century (Figure 2). The mean of daily maximum (TX) and minimum (TN) air temperature showed a statistically significant increasing trend at all meteorological observation stations investigated, while a significant inreasing trend in the lowest values of daily minimum air temperature (TNn) was also detected at 12 meteorological observation stations since 1950. Trends in the frequency of the highest annual value of daily minimum air temperature (TNx), highest (TXx) and lowest (TXn) annual value of daily maximum air temperature demonstrated lower statistical significance of the increasing trends, especially for the observation stations located in the eastern part of Latvia. Such differences reveal the spatial heterogeneity of changes in temperature extremes and the impact of local factors affecting climate at regional/local level.

A detailed study of the character of changes in monthly temperature indices reveals a strongly seasonal character of monthly mean maximum (TX) air temperature increase. On one hand, the increase in maximum air temperature is not even throughout the year, but occurs in some seasons, but on the other hand — it is relatively even for all meteorological stations in Latvia. The increase in the values of maximum air temperature is statistically significant for January till May and again for July and August, but there is a common decreasing trend for June. Similar tendencies are evident also for monthly mean of minimum (TN) air temperatures. The trends of changes observed in Rīga can be considered as alarming, since statistically significant increasing trends are common for nearly full year (except October and December), pointing out the role of the city microclimate (Gabriel and Endlicher, 2011; Lizuma, 2008).

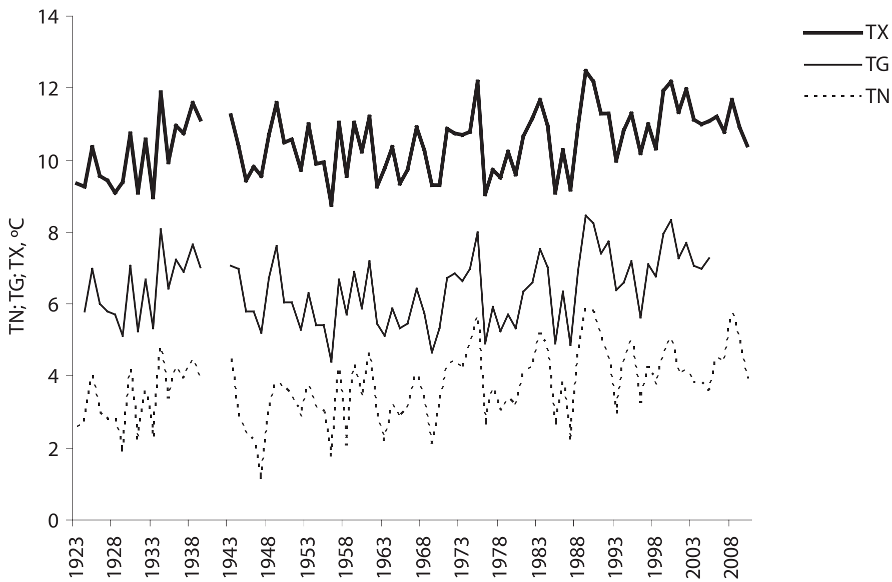


Figure 2. **Changes in the annual daily maximum (TX), mean (TG) and minimum (TN) air temperature in Rīga observation station over the period 1923–2010**

Along with the observed changes in indices describing the mean values of air temperature, significant changes have been observed also in the frequency of days with extreme temperatures. It was found that trends in extreme temperature indices were stronger for the climatic indices relating to the cold seasons: for example, the number of frost days (FD) and number of ice days (ID) both show statistically significant decreasing trends in all the studied stations (Figure 3). However, due to the observed warming in the mean values of air temperature, there has also been an increase in the frequency of extremely hot days and nights. A statistically significant increase in the number of summer days (SU) has been observed in 10 out of 14 meteorological stations, as well a statistically significant increase in the number of tropical nights (TR) in 13 out of 14 meteorological stations. It was found that the changes in the frequency of frost and summer days have shown the greatest anomalies or deviations from the long-term mean since the second part of the 20th century, however significant variability in these extreme climate indicators is evident throughout the length of the available time series of the past ~150 years (observations obtained from the Rīga-University observation station).

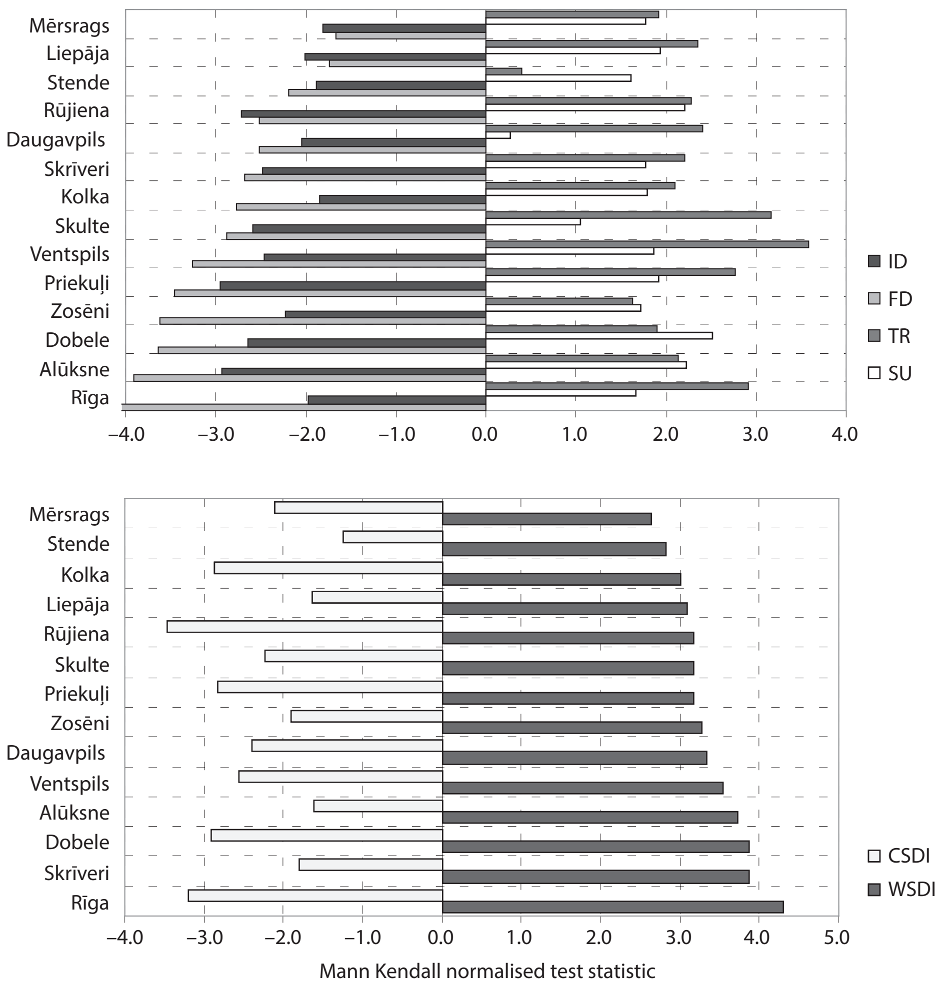


Figure 3. **Long-term trends in the frequency of extreme temperature events and events of prolonged periods of extremely low and high air temperatures in Latvia over the period 1950–2010 (Mann-Kendall test statistics).** The abbreviations correspond to the following climate indices: FD — frost days; ID — ice days; SU — summer days; TR — tropical nights; WSDI — warm spell duration indicator; CSDI — cold spell duration indicator.

Warm spell duration indicator (WSDI) characterizing the length of prolonged heat events has a statistically significant increasing trend all over Latvia, and this can be considered as the most alarming result of this study, because an increase in the frequency and length of the periods of prolonged heat can have a significant negative effect on human morbidity and mortality (Diaz *et al*., 2006; Beniston, 2007; Unkaševica and Tošic, 2009). Even though in Latvia, in the same manner as in other countries of the world, mortality is higher during the cold seasons of the year, in particular cases extremely hot weather can also cause excess mortality during the summer season (Avotniece *et al*., 2011).

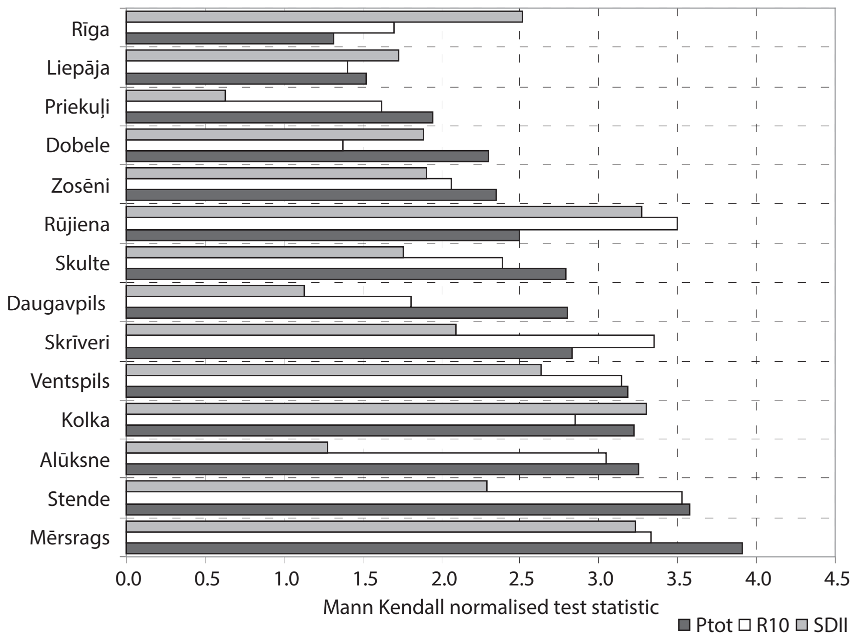


Figure 4. **Long-term trends in the frequency and intensity of precipitation in Latvia over the period 1950–2010 (Mann-Kendall test statistics).** The abbreviations correspond to the following climate indices: Ptot — annual total precipitation amount on wet days; R10 — days with heavy precipitation; SDII — simple daily intensity index.

The analysis of the long-term data records shows statistically significant changes observed in the frequency and intensity of precipitation in Latvia. Precipitation regime is a group of processes controlling hydrology of lakes and rivers, water supply for agricultural and human needs, recreational purposes. At the same time extremes in precipitation amount can be related to floods (including flash floods) or droughts, which both have hazardous effects on several sectors of the economy and human welfare. Trend analysis of changes in precipitation amount and intensity in Latvia at first reveal changes in the precipitation amount distribution on a yearly basis. For example, this study demonstrated a statistically significant increase in the annual total precipitation amount on wet days (Ptot) in most of the observation stations and major changes in a simple daily intensity index (SDII), pointing out significant changes in the character of precipitation intensity and consequently the damaging potential of heavy precipitation events (Figure 4). At the same time the number of consecutive dry days does not show well expressed trends of changes, while the number of consecutive wet days has a statistically significant increasing trend only in 5 out of 14 stations.

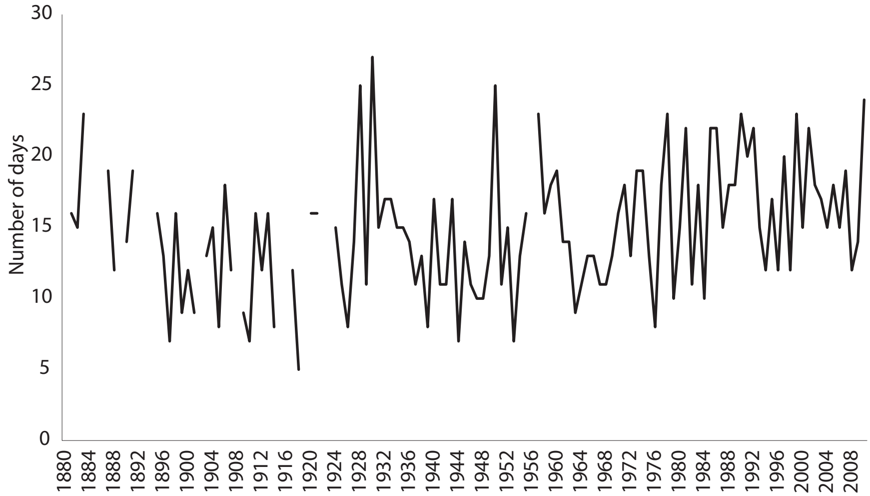


Figure 5. **Long-term changes in the number of days with heavy precipitation (R10) in Rīga-Universitāte observation station over the period 1881–2010**

In all of the meteorological observation stations studied there has been an increase in the number of days with heavy precipitation (R10), and very heavy precipitation (R20) and also in the precipitation amount on very wet days (R95p) and extremely wet days (R99p). For most of the observation stations in the territory of Latvia the trends of precipitation intensity changes are increasing and statistically significant, however, it becomes evident that impacts of regional factors are affecting the precipitation regime, so, for example, the number of extremely wet days in Priekuļi is significantly decreasing, reflecting the importance of the local orography as a factor affecting precipitation regime. Also the well-expressed increase in the number of days with heavy precipitation in Rīga especially evident throughout the past ~80 years (Figure 5) could be associated with the influence of the Gulf of Rīga and the urban climate specifics (Birkmann *et al.,* 2010).

3.1.2. Large-scale atmospheric circulation patterns associated with extreme climate events in Latvia

In order to assess the atmospheric conditions favourable for the occurrence of extreme climate events in Latvia, the daily atmospheric circulation patterns were analysed and presented within **Paper 1**. It was previously identified that changes in extreme climate events have in many cases been much stronger in the capital city Rīga, especially with respect to the number of summer days and tropical nights, but also in the case of days with heavy precipitation. This may be due to an increasing urban heat island effect or other specific urban climate effects (Birkmann *et al*., 2010). Therefore, for the analysis of large-scale atmospheric circulation patterns associated with extreme events, the cases with extreme events observed in Rīga over the period 1957–2002 were analysed.

It was found that the most favourable conditions for the occurrence of extremely hot days and nights in Rīga can be observed under the influence of a southwesterly and southerly anticyclonic flow, in the case of a high pressure area being located over the eastern part of Europe, and with the warmer air flowing into the territory from western Russia. Extremely hot weather in Rīga can also be observed when cyclonic conditions are dominant: southwesterly, southerly and westerly cyclonic flows are associated with the warm sector of a cyclone and an intensive inflow of warm air. The days with heavy precipitation were mainly associated with cyclones, however there were some differences between the synoptic processes responsible for heavy precipitation in the cold and in the warm parts of the year: in the summer, heavy precipitation events were mainly associated with convective processes and the cold fronts of cyclones; in winter these events were mostly the result of prolonged precipitation (Jakimavičius and Kovalenkovienė, 2010; Kriaučiūniene *et al.,* 2008) associated with a warm front. However, when the centre of a low pressure area was situated over Latvia, heavy precipitation was observed at any time of the year.

3.2. Sea ice changes in the Baltic Sea and the Gulf of Rīga near the Latvian coast

The observed increase in the mean values of air temperature and a decrease in the occurrence of extremely cold days has led to a decrease in the occurrence and persistence of sea ice in the coastal areas of Latvia. **Paper 3** describes the characteristics and long-term trends in the formation and persistence of sea ice in the Baltic Sea and the Gulf of Rīga near the Latvian coast over the period 1949–2013.

3.2.1. Climatic characteristics of sea ice in the coastal areas of Latvia

The analysis of the climatic characteristics of sea ice season on the coastal areas of Latvia reveals the basic mechanisms of sea ice development in the coastal areas near the open Sea and the inlet of the Gulf of Rīga. In the coastal areas of Latvia initial ice development usually begins in the bay of Pärnu, where the first new ice formations occur in the middle of December. Thereafter the ice-covered area extends along the Northeastern coast of the Gulf of Rīga, and in the middle of January its width is 5 to 6 nautical miles on average. At the same time some new ice formation near the southern and western coast of the Gulf occurs. The most rapid ice development usually occurs in February, when under favourable conditions the Gulf of Rīga becomes completely ice-covered. During severely cold winters, a solid and rigid ice cover over the Gulf of Rīga may form already in the middle of January, whereas in mild winters, the Gulf may remain mostly ice-free throughout the winter season. During cold winters, the surface water is cooled so much that ice may form also at the coastline of the Baltic Sea. However, the expansion of ice varies widely from year to year, depending on the prevailing weather conditions and the coastal areas of the Baltic Sea are covered with mainly thin and fragile ice only during the most severe winters. With the prevailing westerly winds the ice break-up begins in the western part of the Gulf and gradually progresses to the east. The first area of the Gulf to become ice-free is the Irbe Strait followed by western and southern part of the Gulf, but in the north, northeastern areas the melting and rotten pack ice remains the longest.

The average length of the ice season is the longest in the Bay of Pärnu and in the north part of the Gulf of Rīga — 145 days or almost 5 months. The shortest ice season of ~2 months is characteristic for the southwestern part of the Gulf, the Irbe Strait and the coastal areas of the Baltic Sea. The maximum observed length of the ice season in the Gulf of Rīga has been 168 days, but in the coastal waters of the Baltic Sea — 127 days. The most severe winter during the period of official hydrometeorological observations has been the winter season of 1941/1942, when the thickness of ice in the coastal areas of the Baltic Sea reached 60 cm at particular places.

3.2.2. Long-term changes in the occurrence of sea ice in the coastal areas of Latvia

During the past ~150 years, there has been a significant increasing trend in the values of air temperature, which has been even more obvious during the winter season. The changes in air temperature have also led to significant changes in ice conditions both at the Latvian coastline of the Baltic Sea and in the Gulf of Rīga. A significant decreasing tendency in the length of the ice season over the period 1949–2013 was detected (Figures 6 and 7).

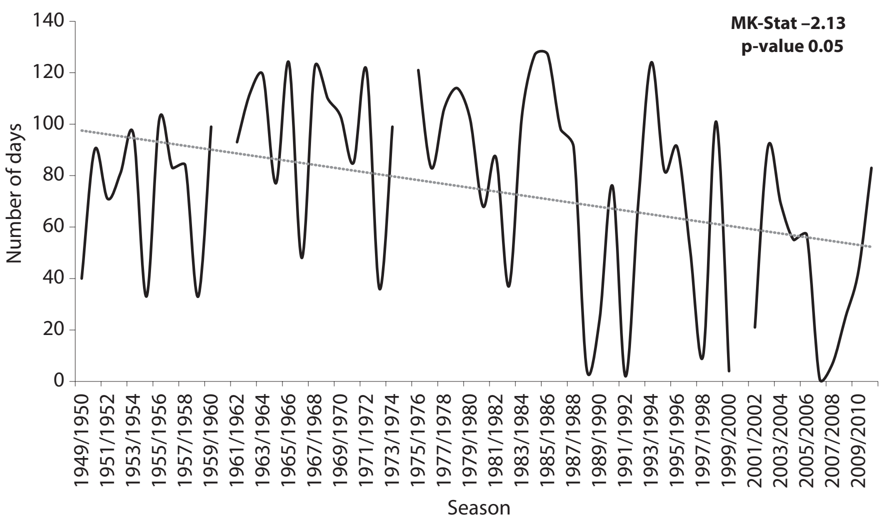


Figure 6. **Long-term changes in the length of the ice season in the Baltic Sea near the Latvian coast (represented by the time-series from the Liepāja observation station) over the period 1949–2013**

Such changes are strongly related to the dynamics and changes in large-scale atmospheric circulation processes taking place over the North Atlantic, which appear to have a significant influence on the climate in the Baltic region, especially during winter seasons. A strong negative correlation between the NAO index and the number of days with ice cover along the coastline of Latvia exists, highlighting the fine linkages between the large-scale NAO forcing factors and the regional scale climate processes in the Baltic region. Moreover, the negative correlation between winter temperatures and NAO index has become stronger during the last 100 years (Marshall *et al.*, 2001; Hagen and Feistel, 2005; de Rham *et al.*, 2008). Another index used in this study was the Baltic winter climate index (WIBIX), which is based on the complex relationships between air pressure and sea level anomalies along with the extent of the maximum ice cover in the Baltic Sea (Hagen and Feistel, 2005). A strong negative correlation between the NAO index, the WIBIX index and the ice-break up events shows that processes over the North Atlantic are the driving force for the sea ice regime at the coastline of Latvia.

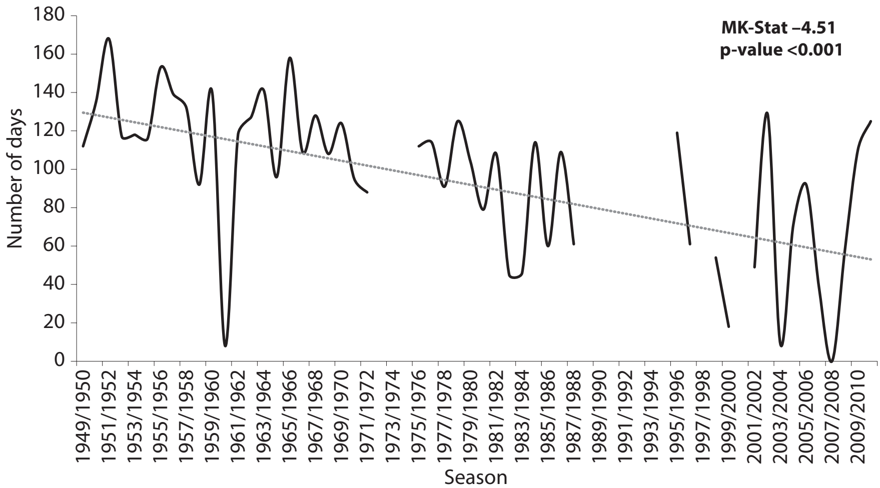


Figure 7. **Long-term changes in the length of the ice season in the Gulf of Rīga near the Latvian coast (represented by the time-series from the Salacgrīva observation station) over the period 1949–2013**

Even though the length of the ice season has significantly decreased in the longer period (Gebre *et al.*, 2014), during the past decade there still have been some winters with significant ice cover over the coastal waters of Latvia. The total number of days with ice cover over the years 2001–2011 has remained rather high: from 452–491 days in the coastline of the Baltic Sea, up to 677–757 days in the Gulf of Rīga, with the average annual length of the ice season of 45–49 and 68–76 days respectively. During the first decade of the 21st century, the mildest winters with the least concentration of ice were the winters of 2001/2002, 2006/2007 and 2008/2009, while the winters of 2002/2003 and 2010/2011 can be considered as the most severe over this period.

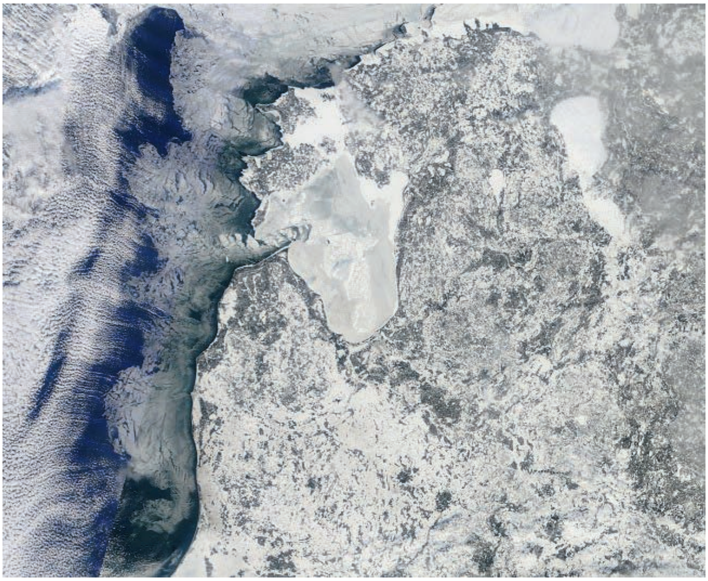


Figure 8. **True color (bands 1-4-3) image of the sea ice cover over the Gulf of Rīga and the eastern coast of the Baltic Sea obtained from the MODIS instrument aboard the Aqua satellite on February 21st, 2011**

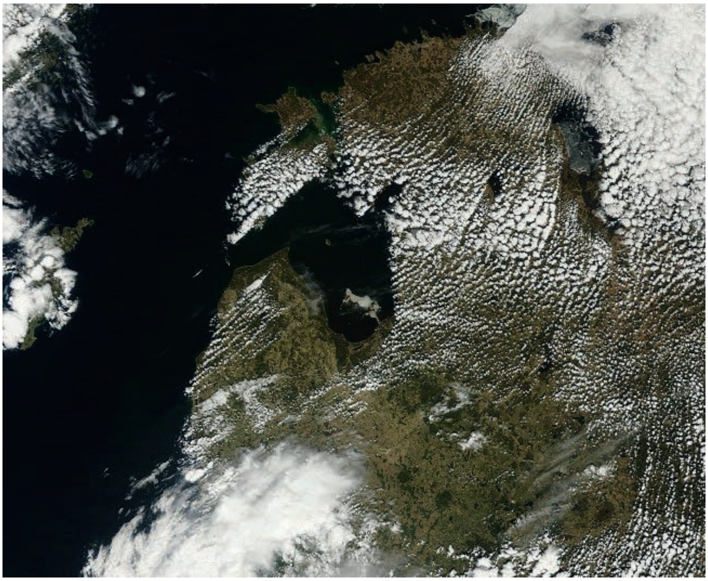


Figure 9. **True color (bands 1-4-3) image of the open water of the Baltic Sea and the Gulf of Rīga obtained from the MODIS instrument aboard the Aqua satellite on May 1st, 2011.** An area of rotten ice can be seen floating in the middle of the Gulf of Rīga.

During the winter of 2010/2011 the cold-spell lasted for a long period of time and resulted in the rapid development of sea ice — by the middle of February the Gulf of Rīga was already completely ice-covered (Figure 8). During this winter the length of the ice season reached 81–83 days in the coastal waters of the Baltic Sea and up to 125 days in the Gulf of Rīga. The observed severe ice conditions, which were unusual for the recent period of comparatively mild winters, resulted in difficulties for the navigation of ships as the fairway from the port of Rīga up to the open Baltic Sea was covered with hummocked ridged ice up to 50 cm in thickness at places. The navigation of ships was possible only with the assistance of an ice-breaker or through the ~20 nautical miles wide polynya of open water which periodically occurred along the western coastline of the Gulf. After a winter of such severity the remains of rotten drifting ice remained in the Gulf for a long period of time — in Figure 9 one can see a small area of drifting ice still evident in the Gulf of Rīga in the beginning of May.

3.3. Climatic characteristics and long-term changes of fog in Latvia

Among the weather hazards affecting the inland and coastal areas of Latvia, fog is a hazardous meteorological phenomenon occurring frequently and affecting all means of transportation. **Papers 4 and 5** contain the analysis of the climatic characteristics of fog occurrence and spatial distribution as well as an in-depth investigation of fog formation at the Rīga Airport.

3.3.1. Climatic characteristics of fog in Latvia

The climatic analysis of fog occurrence and spatial distribution presented in **Paper 4** is based on the long-term data records (1960–2012) obtained from 14 major meteorological observation stations in Latvia. During the analysis, it was found that fog is a comparatively frequent weather phenomenon in Latvia, observed 19–59 days a year on average (Figure 10).

The formation of fog is closely related to the local geographical features of a site, such as orography and slope exposure, proximity to the Baltic Sea and the Gulf of Rīga and the different meteorological processes favourable to the development of fog; therefore, there are significant differences in the annual mean number of days with fog in different regions of Latvia. As a result, fog can be observed most commonly in the western areas of the upland regions of Latvia, while the lowest number of days with fog is observed in the eastern areas of the uplands and in the coastal areas of the Gulf of Rīga. Such a pattern of fog frequency represents the general mechanisms of humidity distribution in Latvia and also the formation of clouds and precipitation, due to prevailing westerly flows over the country. Overall, due to the proximity to the Baltic Sea, fog frequency is greater in the western part of the country. However, it is important to note that there are considerable year-to-year variations in the occurrence of fog in Latvia. Thus the range in the annual number of days with fog in Latvia has varied from 0 days in Zosēni (year 1989) to 110 days in Alūksne (year 1960).

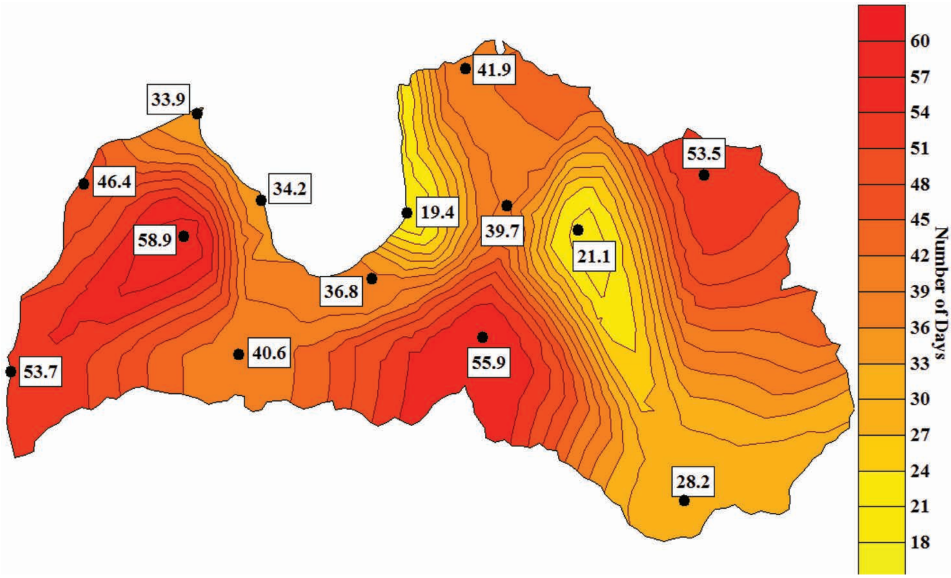


Figure 10. **The annual mean number of days with fog in Latvia over the period 1960–2012**

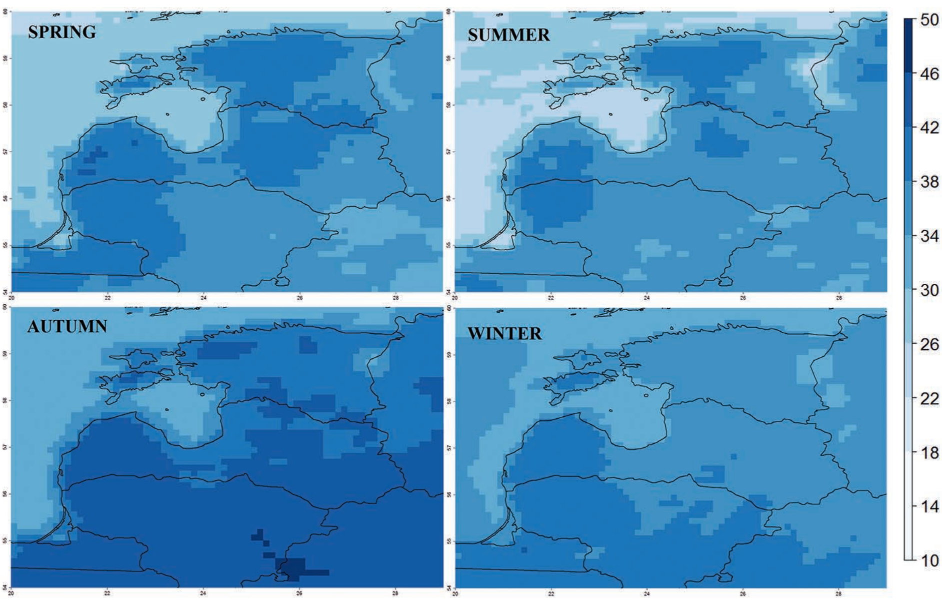


Figure 11. **Mean amount of low clouds (%) in autumn (SON), winter (DJF), spring (MAM) and summer (JJA) obtained from meteorological satellite observations over the period 2008–2013**

Considerable inter-annual variability in fog occurrence has also been detected during the analysis. In the inland stations, the maximum fog occurrence is during the second half of the year — between August and December. During the autumn months, radiation fog forms more frequently, while during winter and spring, advection fog gradually becomes more frequent. Therefore, in the coastal observation stations, the maximum frequency of fog is characteristic in spring, when warm advection from the west triggers the formation of advection fog. Similar distribution has been found during the analysis of satellite-based observations of low cloud cover (Figure 11).

Fog can be classified by its formation in the processes of advection, radiative cooling or a mix of both processes (Ahrens, 2007), and each of these processes can trigger the formation of fog in Latvia throughout the year. As described above, the occurrence of fog in Latvia is closely related to local geographical features; however, the conditions of air humidity and predominant pressure systems also play an important role in the formation of fog. During the analysis it was found that, although meteorological conditions in Latvia are strongly influenced by cyclonic activity, the most favourable conditions for the formation of fog have been observed during the days when a high-pressure area predominates over the country. Thus the most common conditions for the formation of fog in Latvia have been days with westerly or southwesterly air flows under anticyclonic conditions prevailing over the area. In such conditions, with a warm and moist air advection in the western part of an anticyclone, both radiation and advection fog can form. However, a significant proportion of fog cases in Latvia has also formed under cyclonic conditions. In such cases, the formation of fog is usually associated with frontal systems, however, within southerly and southwesterly cyclonic flows, the formation of fog may also be associated with the warm sector of a cyclone. Thus it is evident that the formation of fog in Latvia is mainly associated with the inflow of warm and moist air from the southwest and west, with anticyclonic conditions being the most favourable for fog formation.

3.3.2. Long-term changes in fog frequency in Latvia

The annual number of days with fog in Latvia has decreased significantly during the past 53 years. The stable decreasing tendency from 1960 to 1980 was followed by a more significant decrease during the beginning of the 1990s that could be associated with the rapid decrease in the industrial activities in the country. However, during the past decade, the frequency of fog has increased slightly. Table 6 contains the results of the seasonal and annual trend analysis of fog frequency, performed by applying the Mann-Kendall test.

The observed decrease in fog frequency is evident in all 14 meteorological observation stations, and there has been a significant decrease in the number of days with fog across all seasons in most of the stations; however, the most significant changes have been observed in the winter. Previous studies have shown that there has been a significant increase in the values of air temperatures in Latvia (see **Paper 1** and **Paper 2**), which has been the most significant during the winter and spring seasons. When compared, the trend analysis of fog and air temperature changes show some similar signs: the most significant changes in fog frequency have also been observed in the winter. Therefore, it may be suggested that the long-term decreasing tendency in fog frequency in Latvia could be associated also with the increase in air temperature. However, the correlation between the seasonal and annual mean minimum and maximum temperatures and the number of days with fog do not show a consistent pattern over spatial and temporal scales, suggesting the role of additional meteorological factors, such as for instance humidity, availability of condensation nuclei and atmospheric circulation, in affecting the occurrence and spatial distribution of fog in Latvia.

Table 6

The long-term trends of changes in the seasonal and annual number of days with fog in Latvia (Mann-Kendall test statistics) during the period 1960–2012.

The statistically significant values are highlighted in bold.

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual
Alūksne	**–5.09**	**–5.40**	**–3.87**	**–4.88**	**–6.59**
Daugavpils	**–5.30**	**–4.96**	**–4.41**	**–4.34**	**–6.42**
Dobele	**–2.81**	**–3.67**	**–2.26**	–1.93	**–3.71**
Kolka	**–4.73**	**–3.70**	**–3.45**	**–3.85**	**–4.15**
Liepāja	**–2.92**	–1.91	–0.86	–1.89	**–3.01**
Mērsrags	**–2.84**	–0.67	–1.18	–1.24	**–2.44**
Priekuļi	**–3.48**	**–2.85**	**–3.31**	**–2.15**	**–4.58**
Rīga	**–1.99**	**–3.02**	**–4.22**	**–2.94**	**–4.28**
Rūjiena	**–4.32**	**–4.86**	**–6.17**	**–4.18**	**–6.35**
Skrīveri	**–2.47**	–1.71	**–3.06**	**–1.96**	**–4.01**
Skulte	**–2.82**	**–3.22**	**–4.30**	**–4.29**	**–5.08**
Stende	**–2.98**	**–3.46**	**–4.07**	**–3.13**	**–5.15**
Ventspils	**–3.33**	**–2.19**	**–2.21**	–1.49	**–4.48**
Zosēni	**–2.75**	**–2.54**	**–2.91**	**–2.66**	**–3.24**
Overall in Latvia	**–4.34**	**–3.41**	**–5.20**	**–4.08**	**–5.78**

3.3.3. Characteristics of fog in the Rīga Airport weather station

In spite of the observed decrease in the frequency of fog in Latvia, it is still considered as one of the most dangerous meteorological phenomena affecting transportation, especially air traffic, and causing flight delays and cancellations which lead to great financial loss. Therefore **Paper 5** contains an investigation of the atmospheric conditions associated with the formation of fog at the Rīga Airport.

Rīga Airport lies in a lowland area with increased low-level atmospheric moisture conditions determined by the proximity to wetlands and swamps. The results of the analysis suggest that events of very poor visibility observed at the Rīga Airport have occurred under the conditions of increased atmospheric pressure (Figure 12), which indicates the importance of radiation fog in the area. Radiation fog is common in the lowland area near Rīga Airport, because the wetlands and swamps located to the south of the airport provide extra moisture essential for the development and persistence of thick radiation fog.

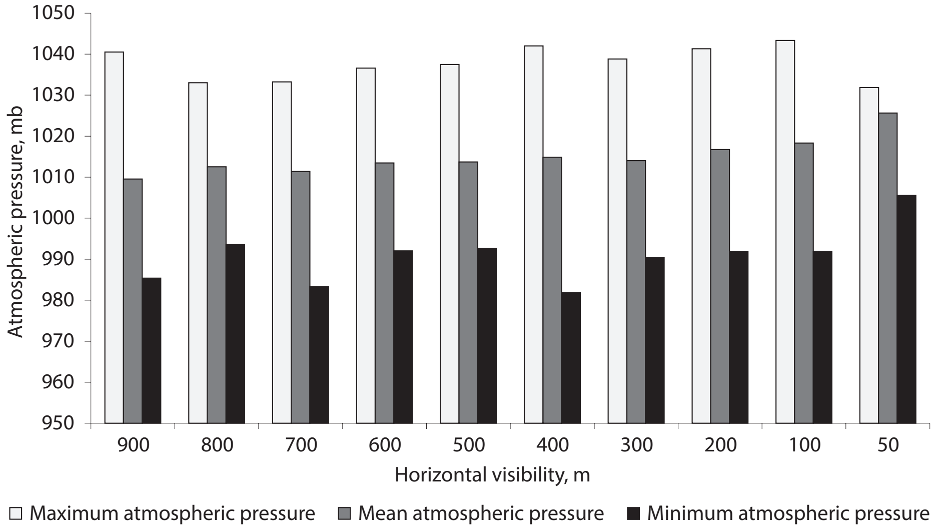


Figure 12. **Atmospheric pressure during fog events at the Rīga Airport over the period 2010–2012**

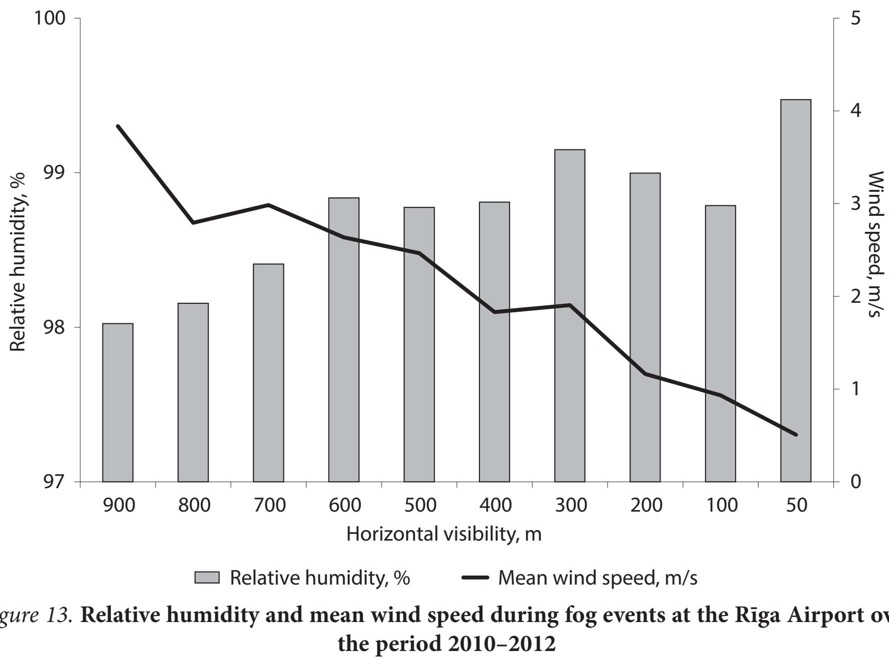


Figure 13. **Relative humidity and mean wind speed during fog events at the Rīga Airport over the period 2010–2012**

The relations between humidity, wind speed and visibility during fog events have an opposite character (Figure 13). An increase in wind speed supports the dissipation of fog, and the most intense fog events happen at low wind speeds as such conditions deteriorate vertical mixing of air near the surface. Relative humidity is a well-known indicator used for the forecasting of fog, since fog most frequently forms under the conditions of relative humidity exceeding 90% (Ahrens, 2007), which is also confirmed by data from the Rīga Airport, since the increase of air humidity supports the increase of fog thickness.

The analysis of fog occurrence during days with precipitation can also be an indicator of the processes of their formation (Figure 14). As radiation fog commonly occurs under conditions of clear skies, usually there is no precipitation observed on days with radiation fog. However, in cases of very thick radiation fog, very small amount of precipitation (up to 0.1–0.2 mm) can be caused by the fog itself. Advection fog is usually associated with frontal systems, so it is frequently accompanied by precipitation. At the Rīga Airport most of the thick fog events have formed during days with no precipitation, which could be associated with the specific local factors associated with the location of the observation station. Nevertheless, advection fog is also commonly observed at the airport, especially in the winter and spring seasons, since the inflow of warm and moist air over the snow-covered ground is favourable for the formation of fog. In some cases in winter and spring fog can be advected to the airport also from the ice-free areas of Gulf of Rīga. It is characteristic for radiation fog to form in the second part of the night or early morning and dissipate soon after sunrise, whereas advection fog can form any time of the day and may persist for a prolonged period of time. Therefore advection fog can be considered as a greater threat for air traffic.

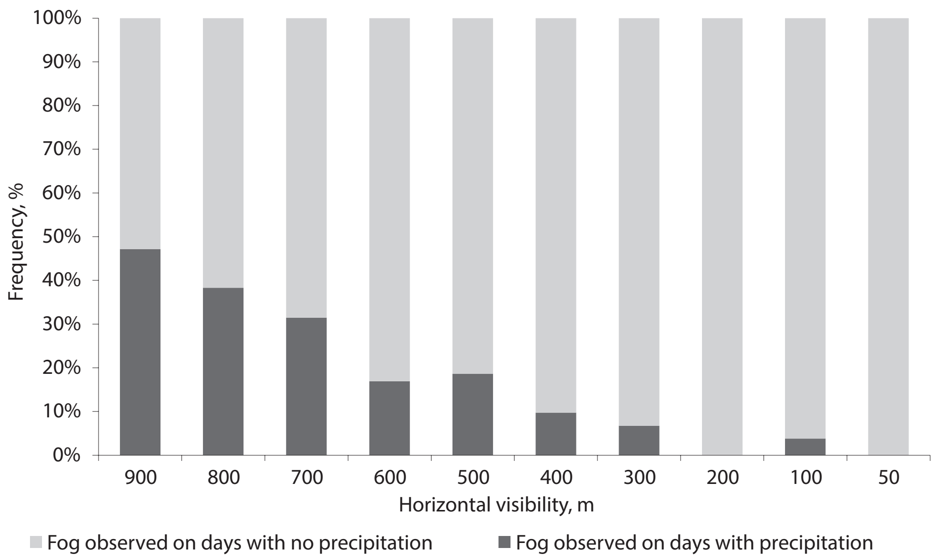


Figure 14. **The frequency (%) of dry days and days with precipitation during fog events at the Rīga Airport over the period 2010–2012**

3.4. Complex analysis of thunderstorms in Latvia

Thunderstorms are one of the most hazardous weather phenomena in Latvia, and they are clearly the most hazardous phenomena affecting the country in the summer season. Therefore studies of thunderstorm occurrence, atmospheric conditions favourable for their development and assessment of options for increasing their observation and forecasting capacity are of a great importance for the development, improvement and delivery of efficient weather surveillance procedures in the country. **Papers 6–8** contain the analysis of long-term data records of thunderstorm observations as well as an in-depth investigation of particularly severe events in line with the assessment of the potential applications of remote sensing observation data for the detection and analysis of thunderstorm events.

3.4.1. Climatic characteristics of thunderstorm frequency and intensity in Latvia

Paper 6 contains the analysis of climatic characteristics of thunderstorm frequency and intensity in Latvia over the period 1960–2015. The study shows, that thunderstorms can be observed in Latvia at any time of the year, however the greatest majority of these hazardous weather events take place between May and September (Figure 15). The two months with the highest annual thunderstorm frequency are July and August, among which July shows significant variability in thunderstorm frequency (2.9 to 6.6 days).

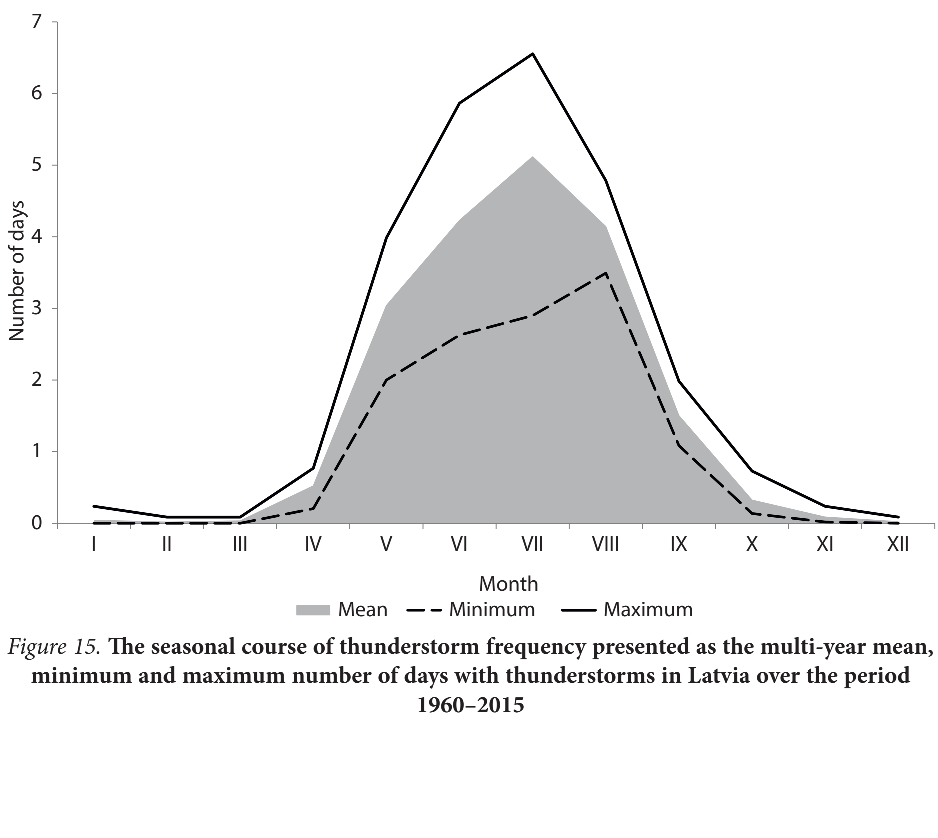


Figure 15. **The seasonal course of thunderstorm frequency presented as the multi-year mean, minimum and maximum number of days with thunderstorms in Latvia over the period 1960–2015**

The annual number of thunderstorm days in the country varies from 14.5 to 16.4 days on average in the coastal areas near the Baltic Sea up to 23 days in the highland areas of the eastern part of the country (Figure 16). The distinct gradient in thunderstorm day frequency from the coastal areas towards inland has been identified also during a similar study carried out in Poland (Bielec-Bakowska, 2003). There has been a great variability in thunderstorm day frequency. During years with the maximum thunderstorm day frequency observed in Latvia, it has well exceeded the long-term mean values, reaching 26 to 46 thunderstorm days per year. Such years have been observed mainly during the first part of the period: 21–46 thunderstorm days in 1961, 19–41 days in 1963 and 17–37 days in 1972. However, also during the recent decades there have been years, for instance, the year 2010, when thunderstorm day frequency was significantly higher than the long-term mean and reached 21–39 days. During the period of 56 years, there have also been periods with relatively low thunderstorm activity observed in Latvia, and the most prominent of these is the period between 1990 and 1994 with a minimum in 1994 when there were only 4–16 thunderstorm days observed in the country.

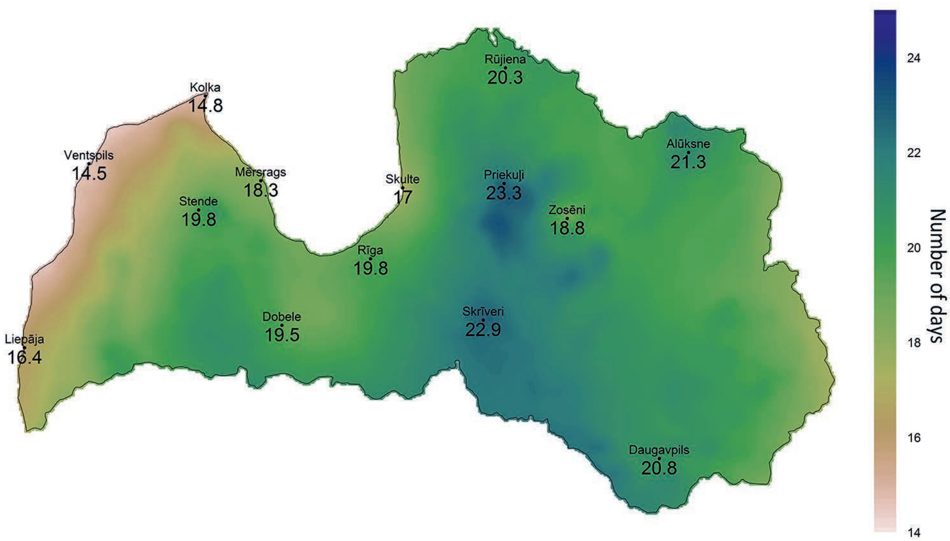


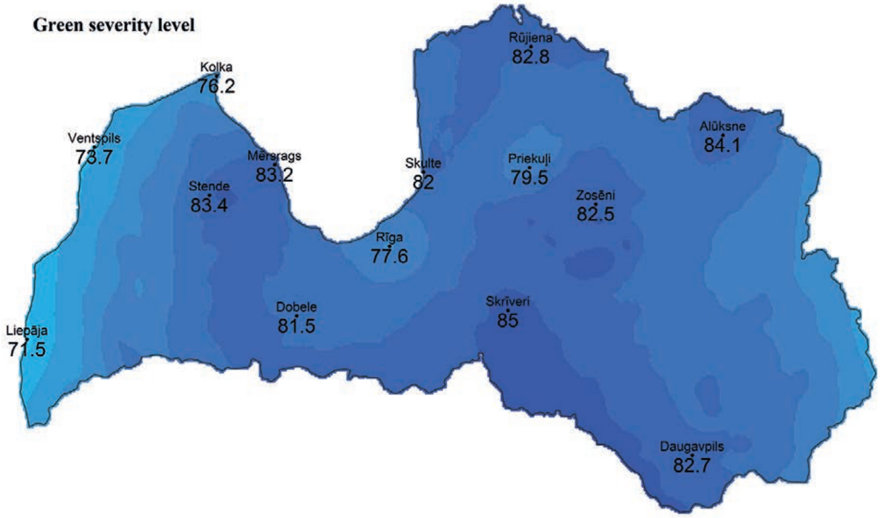
Figure 16. **The annual mean number of days with thunderstorms in Latvia over the period 1960–2015**

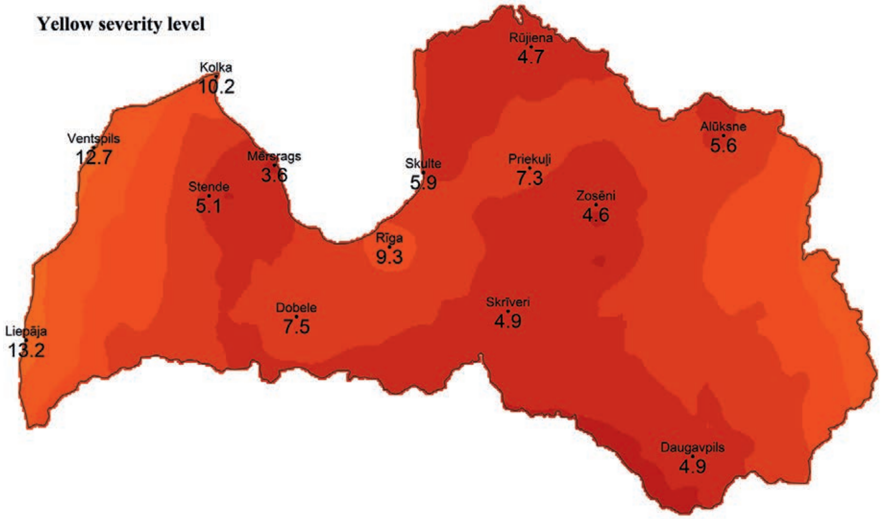
Taking into account the great variability of thunderstorm day frequency both in terms of spatial and temporal distribution, it is important to also assess the long-term characteristics of the intensity of thunderstorm events over the country. For this purpose the climatic characteristics of hazardous weather phenomena associated with thunderstorm days were analysed. Hail is a weather hazard frequently associated with thunderstorm events, however, due to its local nature, poorly represented by the long-term data records of the traditional meteorological observation stations. Therefore, according to the long-term data records in Latvia, there is on average only 0.3 to 1.1 thunderstorm day per year with hail observed at the official observation sites. Precipitation is the most frequent atmospheric phenomenon associated with thunderstorm events, with on average 4.3–9.3 mm of precipitation observed on thunderstorm days during the year, while the multi-year annual maximum precipitation amount on thunderstorm days has been between 25 and 29 mm. The most hazardous impacts of thunderstorms in Latvia are associated with severe straight-line and tornadic convective wind gusts, with maximum wind gusts on average reaching 14 to 20 m/s during thunderstorm days. It is important to note, that on average thunderstorm gustiness is higher in the inland meteorological observation stations.

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 the appropriateness of the warning criteria, a similar approach has been used for thunderstorm day analysis on the climatic time scale. Therefore, all thunderstorm days over the period 1966–2015 were divided into 4 groups according to the intensity of precipitation and wind gusts and occurrence of hail.

Majority of thunderstorm days observed in Latvia since 1966 have not been associated with any hazardous weather and therefore 71–85% of observed thunderstorm days have been classified as of the green level of severity (Figure 17). The overall variability in the fraction of green severity level thunderstorm days has been largest in the coastal regions. Thunderstorm days of yellow severity level are associated with wind gusts exceeding 15 m/s, and therefore there has been a greater fraction of such events in the coastal areas of the Baltic Sea (10–13%), but in the remaining part of the country the fraction of such days varies between 4.6 and 9.3%. The orange thunderstorm severity level is associated with a further increase in wind speed (wind gusts exceeding 20 m/s) and the occurrence of heavy precipitation (15 mm or more within 24 hours). Such events have been more frequent than the less severe yellow level thunderstorm days, reaching 9.7 to 14% of the thunderstorm days observed over the period. The spatial distribution of the mean fraction of orange severity level thunderstorm days identifies several risk-prone regions, such as the coastal areas of the Baltic Sea and the Gulf of Rīga 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 or very heavy rainfall of more than 50 mm during 24 hours — such events have been relatively rare in the country, observed only 0.2 to 1.7% of the events analysed. Even though the frequency of red severity level thunderstorm days in a particular observation station is low, such thunderstorm days have been observed at some site of the country on most years. There have only been 12 years with no thunderstorm days of red severity level observed anywhere in Latvia, while 4 years (1981, 1985, 2005, 2011) of the period have seen such severe conditions observed at 4 observation stations included in the study.

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, which occur more frequently than the less hazardous yellow severity level thunderstorms. This on one hand could be an artefact of the introduced modifications to the severity level criteria used in this


Green severity level
Rūjiena
82.8
Kolka
76.2
Ventspils
73.7
Mērsrags
83.2
Skulte
82
Priekuļi
79.5
Alūksne
84.1
Stende
83.4
Zosēni
82.5
Rīga
77.6
Dobele
81.5
Skrīveri
85
Liepāja
71.5
Daugavpils
82.7


Yellow severity level
Rūjiena
4.7
Kolka
10.2
Ventspils
12.7
Mērsrags
3.6
Skulte
5.9
Priekuļi
7.3
Alūksne
5.6
Stende
5.1
Zosēni
4.6
Rīga
9.3
Dobele
7.5
Skrīveri
4.9
Liepāja
13.2
Daugavpils
4.9

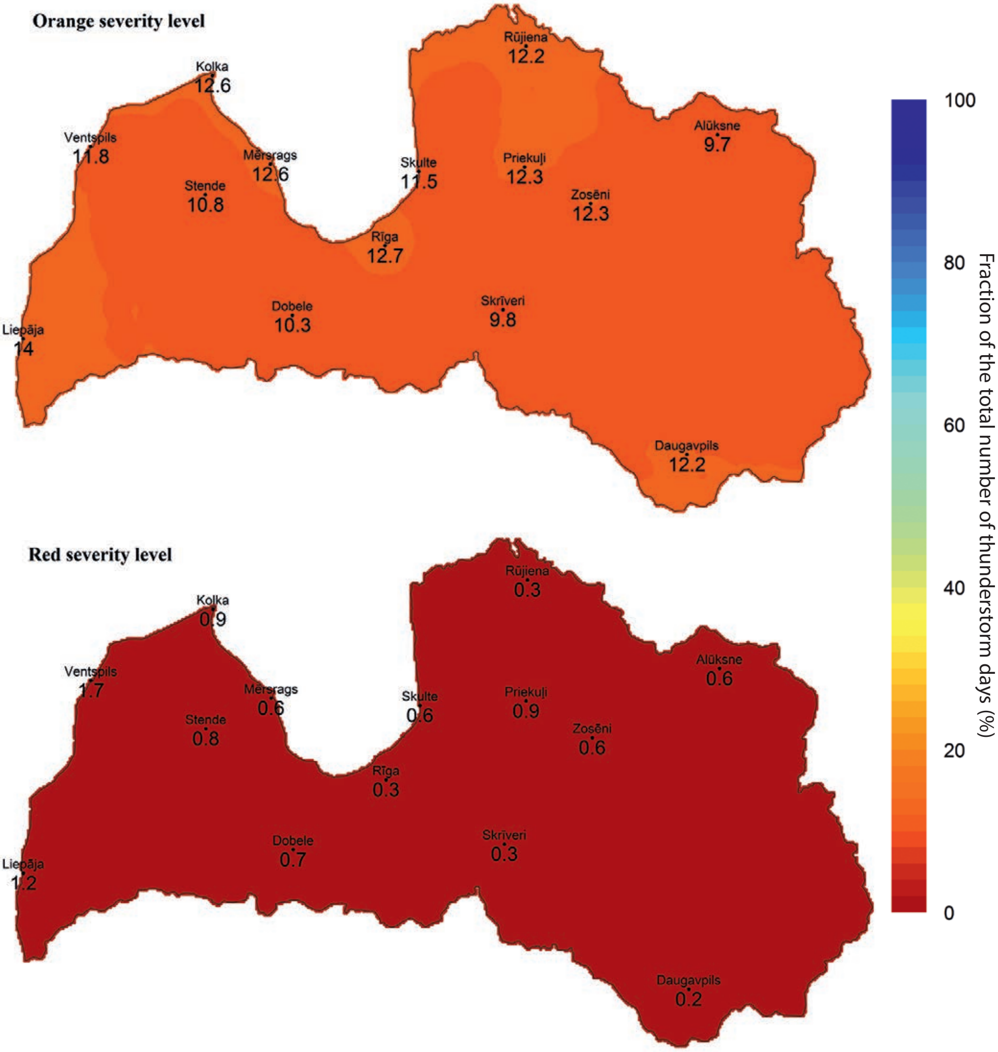


Figure 17. **Multi-year mean fraction (%) of thunderstorms of four severity levels in Latvia over the period 1966–2015**

study: the official warning criteria use precipitation threshold of 15 mm per 12 hours instead of 15 mm per 24 hours, which might create an artificial increase in the frequency of the corresponding severity level thunderstorms. As recent trends in European National Meteorological Services have been towards the introduction of impact-based meteorological warning systems (Rauhala and Schultz, 2009), the results and conclusions arising from this study could be used as a starting point for the modifications and improvement of the national warning system in Latvia.

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

Under the conditions of recent climate change, there have been changes observed in the climatic behaviour of thunderstorm events in Latvia. In comparison to the climatic reference period of 1961–1990, the recent 30-year normal period of 1981–2010 has seen about 2 days less of thunderstorm events per year. The assessment of the long-term changes in the frequency and intensity of thunderstorm days was obtained by applying the Mann-Kendall test (Table 7). The accentuated values show trends considered to be statistically significant at a significance level $p \leq 0.05$. The results of the trend analysis confirm an overall decreasing tendency in thunderstorm day frequency — there has been a significant decreasing tendency in eight out of 14 weather stations included in the study. Such pattern of changes has been also identified for Lithuania and Estonia (Enno *et al.*, 2014), while no significant changes in thunderstorm frequency have been found in Finland (Tuomi and Mäkelä, 2008) and Poland (Bielec-Bakowska, 2003), thus emphasizing the pronounced spatial variability in the dynamics of annual thunderstorm frequency. The changes in frequency and intensity of heavy precipitation and hail events during thunderstorm days have been spatially inconsistent, emphasizing the local distribution of these hazardous weather events. However, the identified significant positive trend in the mean precipitation amount and the frequency of cases precipitation exceeding 50 mm during thunderstorm days has been mainly limited to the coastal areas of the Gulf of Rīga, 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 have been observed for wind parameters on thunderstorm days, with most of the weather stations showing significant increasing tendencies in either the absolute values of wind speed or the frequency of high wind gusts observed during thunderstorm days. It is important to note that this observed increase in wind gusts on thunderstorm days is evident despite the findings of recent studies in Latvia that have revealed a significant decreasing tendency in the mean wind speed in the long-term time scale (Briede, 2016).

Even though thunderstorms in Latvia are not associated with such devastating damage as for instance in the United States or even the southern part of Europe, almost every year there are intense thunderstorms observed causing significant damage and threat to the society. The presented here attempt to analyse the climatic distribution of thunderstorms of different severity levels shows indicators of an overall decrease in thunderstorm day frequency, but at the same time points out a likely increase in their intensity and associated wind-related damage. Even though all available long-term meteorological observation data records have been used in order to obtain representative climatology in both terms of spatial and phenomenological representation, it is important

Table 7

Long-term trends (Mann-Kendal test statistics) in the number of thunderstorm days, fraction of thunderstorms of different severity levels (%), number of hail events, mean and maximum precipitation (mm) and wind gusts (m/s) on thunderstorm days and number of cases exceeding the given precipitation and wind gust intensity thresholds over the period 1960–2015.
The statistically significant values are highlighted in bold.

Parameter	Meteorological observation station														Overall in Latvia
	Alūksne	Daugavpils	Dobele	Kolka	Liepāja	Mērsrags	Priekuļi	Rīga	Rūjiena	Skrīveri	Skulte	Stende	Ventspils	Zosēni	
Thunder-storm days	**−2.3**	**−3.4**	−0.5	**−2.5**	−0.6	−0.7	−1.5	**−3.0**	**−2.5**	**−3.4**	**−3.4**	−0.7	−1.1	**−3.8**	**−2.7**
Green severity level	−1.6	1.9	**−2.8**	**−2.3**	−0.3	−1.0	**−3.2**	**−3.9**	−1.9	**−2.4**	−1.0	0.3	−1.6	−0.7	**−3.6**
Yellow severity level	**2.0**	0.5	**2.6**	1.6	0.5	0.4	**4.7**	**2.0**	**3.3**	**2.3**	0.2	−0.3	1.6	1.4	**3.6**
Orange severity level	0.7	**−2.7**	1.3	0.6	0.1	0.7	0.7	**3.3**	−0.4	0.6	1.1	0.3	0.9	0.2	1.6
Red severity level	1.2	−1.9	0.4	1.3	−0.8	**2.4**	−1.3	−0.8		0.0	−0.1	−1.9	1.4	−0.5	0.1
Hail events	**3.7**	**−2.2**	−0.7	0.8	−0.5	**3.0**	1.3	**−2.7**	1.6	−0.2	**−2.3**	−1.0	0.4	−0.4	−0.0
Mean precipitation	**2.1**	−1.4	1.4	**3.4**	0.2	**2.4**	1.1	**3.1**	1.5	1.3	**2.1**	1.7	0.7	1.4	**3.7**
Maximum precipitation	0.4	**−2.6**	1.5	1.7	−0.6	1.1	−0.3	0.5	0.6	−0.6	−0.5	1.1	−0.3	−1.2	0.7
Precipitation ≥ 15 mm	0.1	−1.7	1.5	1.2	0.3	1.3	−0.8	1.1	−0.7	−0.4	−0.1	0.6	1.0	−1.1	0.2
Precipitation ≥ 50 mm	1.0		−0.3	1.5	−0.3	**3.2**	−0.4	0.2	0.7	−1.6	**2.4**	−0.2	0.0	0.1	0.9
Mean wind gusts	**5.5**	0.0	**5.5**	**4.0**	−0.3	**5.2**	**4.7**	**6.5**	**4.7**	**4.4**	**3.5**	**3.4**	**3.9**	**3.7**	**6.5**
Maximum wind gusts	**2.3**	**−2.0**	**4.1**	0.4	−1.4	−0.0	1.2	**2.7**	1.5	1.8	0.4	−1.4	−1.0	1.4	1.3
Wind gusts 15–19 m/s	**2.0**	−1.4	**4.7**	1.7	−0.3	0.7	**4.1**	**4.6**	**2.4**	**2.4**	0.8	−1.0	0.9	1.0	**2.5**
Wind gusts 20–24 m/s	1.1	**−3.5**	**2.4**	0.3	−0.8		0.0	1.4	−0.0	0.6	−1.5	**−2.3**	−0.3	0.2	−1.1
Wind gusts ≥ 25 m/s	−0.6	−1.5	1.3	−0.7	−0.9		−1.1	−1.2		0.8			1.0		−0.5

to note that the results of the analysis presented here might be biased due to the small-scale spatial distribution and short life span of convective events, since even extremely severe events might be observed at locations not covered by the surface observation network (Doswell *et al.*, 2005). Also, the attempt of classifying observed thunderstorms according to their intensities by using supplementary meteorological parameters might be biased due to the same reasons. Nevertheless, given the complex nature of thunderstorm events, the observed signal of changes in their intensity poses a significant threat to the society and the environment as these high-impact events are associated with the combination of several hazardous meteorological phenomena.

3.4.3. In-depth analysis of two tornado cases in Latvia and Poland

Climatological analysis of thunderstorm events presented before describes the overall activity of convective phenomena and their characteristic intensity and frequency distribution in the country. However, it is particular thunderstorm events that occur in Latvia almost every year and lead to the most devastating damage. Thus in order to mitigate the adverse effects of such events by the provision of timely and effective advisory, it is essential to increasingly investigate the atmospheric conditions , precursors and indicators of increased thunderstorm severity potential. Therefore **Paper 7** focuses on the analysis of mesoscale atmospheric conditions observed during the occurrence of two particular tornadic storms in Latvia and Poland.

The study presents a synoptic analysis of two examples of tornado occurrence in the northeastern part of Europe, which, although occurring in relatively different weather conditions, caused equally disastrous consequences. The first tornado event under analysis, was noted in Latvia on July 29th, 2012, while the second was observed in Poland on July 14th, 2012. The synoptic conditions which produced the tornado (estimated by eye witnesses to be of a F0–F1 intensity) in Latvia were a quite typical example of convective weather, with a convergence line in the warm sector proceeding the cold front. However, in this case the area of positive vorticity advection was neutral or just slightly positive, which, from a theoretical point of view (Gold and Nielsen-Gammon, 2008; Schumann and Roebber, 2010), is a basic component for tornado initiation. The second event occurred in the north of Poland and was associated with a supercell thunderstorm, however the weather situation preceding the onset of the phenomenon was far from favourable for the occurrence of a tornado: the event was associated with a shallow cold front with relatively low cloud cover. Nevertheless, the scale of damage of this particular tornado was estimated to be between the F2 and F3 rating, according to the European Severe Weather Database.

Even though the atmospheric conditions under which both of the tornados developed were considerably different, some common indications favourable for tornado occurrence were identified during the study. In both cases, the main lifting mechanism favourable for thunderstorm development was ensured by the cold front zone. However, in Poland its activity was relatively weak, while in Latvia the convergence line that preceded the front zone was very active. Another common feature of both cases was the presence of the upper-level jet resulting in strong vertical wind shears. However, the crucial difference between these two weather events seems to be the thermodynamic conditions in the troposphere. Thus the analysis presented within **Paper 8** highlights the complexity of the occurrence, dynamics and intensity of convective phenomena as events causing comparably adverse effects can be triggered by different atmospheric processes. Therefore, such case-studies are crucial for developing an increased understanding on the complex atmospheric interactions behind convective phenomena, which are still one of the main challenges in the scientific community.

3.4.4. Assessment of the use of remote sensing observations for the identification and analysis of thunderstorms in Latvia

Nowadays the available remote sensing observations have become a powerful tool in weather forecasting and analysis. However, due to several reasons so far the uptake of remote sensing information, particularly for the purpose of analysis and investigations, has been somewhat limited in Latvia. **Paper 8** presents the first approach towards a comprehensive analysis of thunderstorms in Latvia by using information obtained from meteorological satellite and radar observations. The main aim of the study was the assessment of the applicability of some known theory-based thunderstorm features detectable via remote sensing observations for the identification of increased thunderstorm severity potential in Latvia.

For the analysis of thunderstorm features identified in remote sensing observations, days with more than 10 lightning flashes detected in Latvia were studied. It was found, that during these days, surface in-situ meteorological observations display signs of potentially hazardous weather associated with thunderstorm activity.

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 (Echo Height EHT product and Maximum Display MAX product) from the weather radar data archive. The analysis of the three components of the Echo height ETH product — echo top height, echo base height and echo thickness — reveal valuable information regarding the vertical extent of convective clouds in Latvia. Over the period 2007–2015, the majority of clouds have had echo base height of ~1–2 km and echo top height of 6–11 km above ground level, while a significant fraction of cases have seen echo top heights 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. In order to assess the intensity and structure of convective clouds, the absolute values, vertical and horizontal extent and structure of the maximum radar reflectivity (dBZ) obtained from the Maximum Display MAX product was used. It was estimated that the majority of thunderstorm clouds have a maximum reflectivity value exceeding 50 dBZ. 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, weak echo region and hook echo. 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 (Figure 18). The occurrence of the weak echo region feature has been more rare, 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.

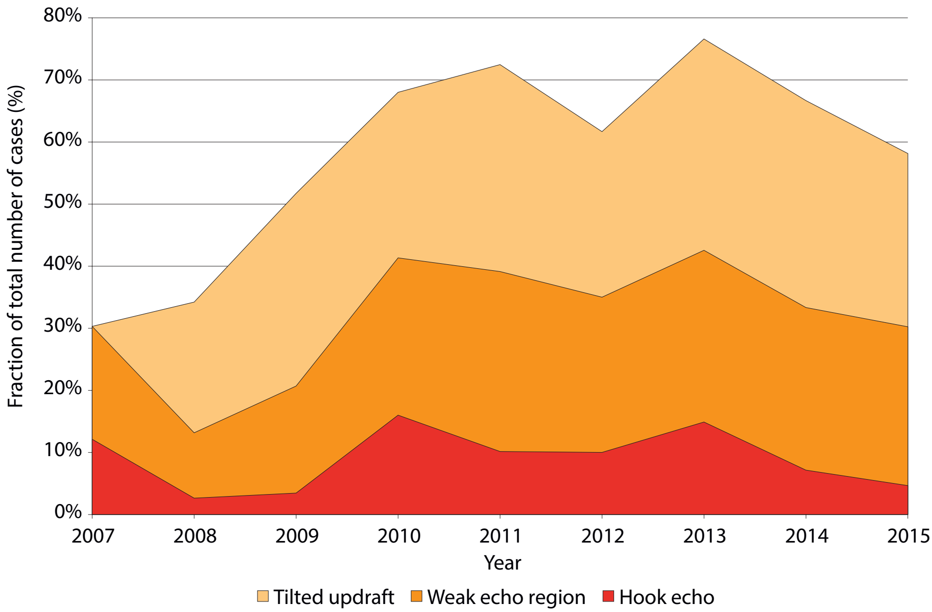


Figure 18. **The fraction of cases (%) with characteristic thunderstorm features identified from weather radar observations on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015**

Satellite observations of thunderstorm features were used within the study in order to describe common thunderstorm cloud top features indicative of increased thunderstorm severity potential. One of the indicators of a potentially severe thunderstorm is its vertical extent indirectly inferred from the satellite observations of surface temperature. Thus for the aim of this study the cloud top temperatures (CTT) depicted by the spectral channel IR 10.8 μm were analysed. The analysis reveals that the majority of thunderstorm cases observed in Latvia have had CTT reaching 210–230 K (–63 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). In addition, several features characteristic for severe thunderstorms were identified from satellite observations (Figure 19). From the CTT field obtained from the IR 10.8 μm channel, the structures of cold-ring storms and V-shaped storms were identified, while exceedances of the threshold of 45 in the brightness temperature difference of the channels IR 3.9 μm and IR 10.8 µm revealed the presence of small ice particles at the top of the cloud. Such features are commonly associated with severe thunderstorms. 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, which is an indicator of intense updrafts and strong vertical motions within the thunderstorm cloud, associated with conditions favourable for the occurrence and growth of hail. The cold-ring and V-shape structures were detected more seldom: 5–28% and up to 10% of the cases accordingly. 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 (Setvak *et al.*, 2010). Valuable information was obtained also from the visible part of the spectrum: overshooting tops could be identified in 22–63% of the cases, while on relatively rare occasions (4–15% of the cases) the presence of gravity waves at the top of convective clouds could be identified.

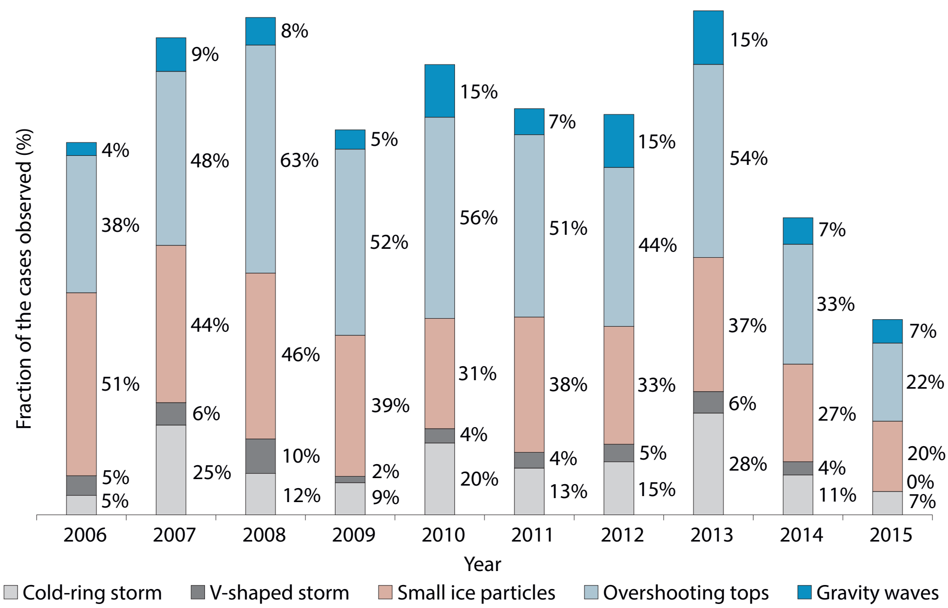


Figure 19. **The fraction of cases (%) with characteristic thunderstorm features identified from weather satellite observations on days with more than 10 lightning flashes detected in Latvia over the period 2006–2015**

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 8 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

Table 8

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 over the period 2006–2015

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

The abbreviations correspond to the following parameters: EHT — radar echo top height (km); ET — radar echo thickness (km); EBH — radar echo base height; Max Z — maximum radar reflectivity (dBZ); CCT — Cloud top temperature (K).

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 these features can serve as an indicator of an increased thunderstorm severity potential.

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 (Lack and Fox, 2012).

CONCLUSIONS

Significant changes in the frequency of extreme climate events have been observed in Latvia since the first half of the 20th century. The trend analysis of extreme climate event indicators shows a significant increase in the number of meteorological events associated with increased summer temperatures and a decrease in the number of extremely low temperature events in winter. There has also been an increase in the frequency and intensity of heavy precipitation, however the magnitude and statistical significance of these trends has shown a spatially inconsistent pattern.

Observed changes in extreme climate events in Latvia show spatial differences, which highlight areas where the most significant changes have taken place. The strongest signal of changes in the frequency and intensity of heavy precipitation has been observed in the coastal areas of the Gulf of Rīga, thus emphasizing the effect of the Gulf on the spatial distribution of precipitation. Trends in the climate indicators were also found to be stronger in the capital city Rīga, which could be associated with the effects of the specific urban climate.

Some regularities in the association of the occurrence of extreme climate events with the prevailing atmospheric circulation patterns were found during the study. It was estimated that the most common synoptic situations for the occurrence of extremely high air temperatures can be found under the conditions of southwesterly, southerly anticyclonic flows and westerly, southwesterly cyclonic flows, while extreme precipitation events were mainly associated with cyclonic activity.

Due to the observed warming, the duration of ice cover on the Baltic Sea and the Gulf of Rīga has been decreasing since the middle of the 20th century, and is related to a later onset and earlier disappearance of the ice cover. However, the trends of sea ice regime are not consistent over different periods of time, and the regime of the sea ice appears to be greatly influenced by large-scale atmospheric circulation processes over the North Atlantic.

Fog is a comparatively frequent hazardous meteorological phenomenon in Latvia, observed on average 19–59 days per year and characterised by a significant spatial and temporal inhomogeneity. However, the occurrence of fog in Latvia has decreased significantly since the middle of the 20th century, which could be associated both with the effects of natural factors as well as the gradual decrease in industrial activities and the resultant improvements of air quality. In spite of the observed decrease in fog frequency, it is still one of the hazardous meteorological phenomena affecting aviation in Latvia.

Even though the majority of fog cases in Latvia have been associated with anticyclonic conditions, fog is commonly accompanied by light precipitation, which could be an indicator for the dominance of advection type of fog in the country. However, the analysis of fog formation in the area of the Rīga Airport revealed that the most intense of the observed fog events can be classified as radiation fog, which, due to its short persistence, is not of as great danger to the aviation traffic as advection fog. Since advection fog plays an important role in the air traffic organization, timely information provided by weather satellites is an essential tool for the forecasting of movement and persistence of the fog and low-cloud areas.

Thunderstorms are one of the most hazardous meteorological phenomena observed in Latvia, and they occur on average 14.5–23 days per year. The spatial distribution of thunderstorm days highlights the role of orography and proximity to the Baltic Sea in the distribution of convective processes in the country.

Thunderstorms are complex meteorological phenomena commonly associated with the occurrence of additional small-scale weather hazards such as heavy precipitation, hail and strong wind gusts. Precipitation is the most frequent atmospheric phenomenon registered on thunderstorm days in Latvia, with daily precipitation amount on thunderstorm days reaching 4.3–9.3 mm on average, and the multi-year maximum values varying between 25 and 29 mm. Hail is rarely observed at the official observation sites in Latvia — only 0.3 to 1.1 thunderstorm days per year on average. Wind gusts on average reach 14–20 m/s on thunderstorm days, with the highest values observed in the coastal areas of the Baltic Sea. However, thunderstorm day gustiness was found to be higher in the inland meteorological observation stations.

The climatological assessment of thunderstorm severity reveals that on average 71–85% of the thunderstorm day cases can be classified as non-severe. Thunderstorm days of yellow, orange and red severity level have been significantly less frequent, with yellow severity level cases on average observed 4.6 to 13%, orange severity level cases 9.7 to 14% and red severity level cases — 0.2 to 1.7% of the time. The obtained results suggest that the currently used national thunderstorm warning criteria represent the climatic distribution of severe thunderstorm events, while the criteria for orange severity level thunderstorms should be reassessed.

In comparison to the climatic reference period of 1961–1990, thunderstorm day frequency in Latvia has decreased by about 2 days in the period 1981–2010. In addition, the trend analysis reveals significant decreasing tendencies in thunderstorm day frequency in 8 out of 14 meteorological observation stations. However, despite the observed decrease in thunderstorm day frequency, 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 Rīga. However, the most prominent changes have been observed for wind parameters, which show significant increasing tendencies in majority of the sites.

In-depth analysis of particular severe thunderstorm events give a much more detailed insight in the processes triggering, driving and characterizing the development of convective processes, which still pose challenges to the scientific community. The analysis of two tornado cases in Latvia and Poland highlights the complexity of the occurrence, dynamics and intensity of convective phenomena as events causing comparably adverse effects can be triggered by different atmospheric processes.

Thoughtful exploitation of remote sensing data undoubtedly gives a more detailed insight in the atmospheric conditions characteristic for the development of thunderstorms. Analysis of weather radar observations suggests that on thunderstorm days in Latvia the radar echo of the thunderstorm clouds on average extends from 1–2 km to 6–11 km above ground level, and maximum radar reflectivities most often reach 50 dBZ, while information obtained from meteorological satellite data reveals that convective cloud top temperatures generally vary between 210–230 K (–63 to –43 °C).

During the analysis, it was found that theory-based remote sensing thunderstorm features under analysis contribute to the assessment of different thunderstorm severity levels as well as inference of the conditions for convective development in Latvia. 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 can be used as indicators of an increased thunderstorm severity potential.

The results obtained within this thesis may contribute to the development and improvement of the national hydrometeorological and climatological service as well as the nowcasting and warning processes and routines at the Latvian Environment, Geology and Meteorology Centre. In addition, the databases and knowledge produced during the research phase might lead to further investigations of extreme climate events and hazardous hydrometeorological phenomena in Latvia.

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PUBLICATIONS ARISING FROM THIS THESIS

Paper 1: **Avotniece, Z.,** Rodinov, V., Lizuma, L., Briede, A., Kļaviņš, M. (2010). Trends in the frequency of extreme climate events in Latvia. *Baltica*, **23** (2), 135–148.

Paper 2: **Avotniece, Z.,** Kļaviņš, M., Rodinovs, V. (2012). Changes of Extreme Climate Events in Latvia. *Environmental and Climate Technologies*, **9** (1), 4–11.

Paper 3: Kļaviņš, M., **Avotniece, Z.,** Rodinovs, V. (2016). Dynamics and Impacting Factors of Ice Regimes in Latvia Inland and Coastal Waters. *Proceedings of the Latvian Academy of Sciences, Section B: Natural, Exact, and Applied Sciences,* **70** (6), 400–408.

Paper 4: **Avotniece**, **Z.,** Klavins, M., Lizuma, L. (2014). Fog Climatology in Latvia. *Theoretical and Applied Climatology*, **122** (1–2), 97–109.

Paper 5: **Avotniece, Z.,** Klavins, M. (2013). Temporal and Spatial Variation of Fog in Latvia. *Environmental and Climate Technologies*, **3**, 5–10.

Paper 6: **Avotniece, Z.,** Aniskevich, S., Briede, A., Klavins, M. (2017). Long-term changes in the frequency and intensity of thunderstorms in Latvia. *Boreal Environment Research,* **22**, 415–430.

Paper 7: Wrona, B., **Avotniece, Z.** (2015). The Forecasting of Tornado Events: the Synoptic Background of Two Different Tornado Case-studies. *Meteorology Hydrology and Water Management*, **3** (1), 51–58.

Paper 8: **Avotniece, Z.**, Klavins, M., Briede, A., Aniskevich, S. (2017). Remote Sensing Observations of Thunderstorm Features in Latvia. *Environmental and Climate Technologies*, **21**, 28–46.

PAPER 1: TRENDS IN THE FREQUENCY OF EXTREME CLIMATE EVENTS IN LATVIA

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Trends in the frequency of extreme climate events in Latvia

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Abstract This study investigated the long–term variability of extreme climate event indicators in Latvia. To assess trends in the frequency of extreme climate events, 14 extreme climate indices, such as number of extremely hot days, number of frost days or number of days with heavy precipitation, were calculated and compared with other indices characterizing mean climate. Trend analysis of long–term changes in the frequency of extreme climate events demonstrated a significant increase in the number of meteorological events associated with an increased summer temperature (for example, the number of summer days and tropical nights) and a decrease in the number of events associated with extreme temperature events in winter (the number of ice days and frost days). Due to the decreasing number of cold days, under the changing climate, the length of the growing season has increased. There were also increases in the number of days with heavy precipitation and in the intensity of heavy precipitation. Finally, influences of the large–scale atmospheric circulation on the occurrence of climate extremes are discussed.

Keywords *Climate extremes, climate change, trends, large–scale atmospheric circulation, Latvia.*

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INTRODUCTION

A significant worldwide increase in the mean temperature near the surface of the Earth has been reported, indicating that climate is changing: the global mean temperature increase over the period 1861–2000 was 0.61°C, with a 90% confidence interval 0.45–0.77°C, while between 1901 and 2000 the observed warming was 0.57°C, with a 90% confidence interval 0.40–0.74°C (Alcamo *et al.* 2007). Climate change can also be characterized by the changes in major indicators of the climate system: precipitation, river runoff, ice and snow cover. However, climate change is not only characterized by changes in the mean values, but also by changes in the variability of climate indicators and extremes (Karl, Trenberth 2003; Kļaviņš *et al.* 2008; Jarmalavičius *et al*. 2007). Just a few examples illustrate the threats and significance associated with extreme climate events: extreme heat events cause heat waves; extreme precipitation causes floods. As has been stated in several studies, an increase in the frequency of extreme climate events can increase the threat to society and individuals (Alexander *et al.* 2007; Beniston 2007; Kysely *et al.* 2010; Unkaševica, Tošic 2009; Jungerius 2008). Compared with existing knowledge on the long–term changes of mean climate indicators, much less is known about the changes of extremes.

Today there is a growing interest in extreme climate events (Easterling *et al*. 2000b). For many impact applications and decisions, extreme events are much more important than the climatic means. The causes of changes in the extremes may be the effects of changes in the mean values, the variance effect or structural changes in the shape of the distribution (Heino *et al.* 2008). Determining the changes of extreme weather events has been the topic of several international projects: ECA&D (Klein Tank *et al*. 2002; Klein Tank, Könen 2003), EMULATE (Moberg *et al.* 2006) and STARDEX (Haylock, Goodess 2004). Often, extreme climate events have been identified using internationally agreed, predefined indices such as number of days exceeding a fixed threshold, percentile threshold, extreme event duration, etc. (Easterling *et al.* 2000). In several studies in Europe, significant increasing trends have been found in a variety of extreme indices over the latter part of the 20th century (Heino *et al.* 1999; Wibing, Glowicki 2002; Klein Tank, Können 2003).

To date, studies of the climate change in Latvia and other Baltic countries have mostly considered changes in mean values. The aim of this study was to determine the long–term variability and trends in the time series of extreme climate events in Latvia, and analyze factors influencing climatic extremes in terms of large–scale atmospheric circulation processes.

DATA SOURCES AND METHODS

Data

The present study is based on daily air temperature and precipitation data series for five meteorological stations (Fig. 1) obtained from the Latvian Environment, Geology and Meteorology Centre[1]. The daily temperature and precipitation data of Rīga University station (observations since 1850) were used to investigate the changes in temperature and precipitation over a period of 156 years. Atmospheric circulation data were obtained from the EU COST program project COST 733 (COST733 2010).

Fig. 1. Major meteorological observation stations in Latvia. Compiled by I. Kokorīte, 2010.

Basic quality and homogeneity control was undertaken for all of the series. Homogeneity of the precipitation and air temperature series was tested using two statistical homogeneity tests: the standard normal homogeneity test (SNHT) (Alexandersson, Moberg 1997) for monthly, seasonal and annual data series; and multiple analysis of series for homogenisation (MASH) (Szentimerey 1996) for daily, monthly, seasonal and annual data series. Only the homogeneous data series were used in this study.

Methods

Trends in the meteorological event time series were analysed using the non–parametric Mann–Kendall test (Libiseller, Grimvall 2002). The Mann–Kendall test was applied separately to each variable at each site at a significance level of $p \leq 0.01$. The trend was considered as statistically significant if the test statistic was greater than 2 or less than -2.

Ensemble climate change indices derived from daily temperature and precipitation data, describing changes in the mean indices or extremes of climate, were computed and analysed. The indices follow the definitions recommended by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI 2009), with a primary focus on extreme events (Table 1).

The data on the climate change indices are available at http://eca.knmi.nl, and gaps found in the data were filled using the original observation data from the Latvian Environment, Geology and Meteorology Centre.

RESULTS AND DISCUSSION

Changes in the frequency of extreme climate events

Climate in Latvia is influenced by its location in the northwest of the Eurasian continent (continental climate impacts), and by its proximity to the Atlantic Ocean (maritime climate impacts). A highly variable weather pattern is determined by the strong cyclonic activity over Latvia.

In this study we used 14 climate indices derived from the daily temperature and precipitation series. Most of these indices measure a type of climatic extreme but a few give information about the mean conditions (for example, growing season length) while at the same time depending on extreme climate events (for example, frost).

The overall results of trend estimates for stations indicated in Fig. 1 are summarized in Figures 2 and 3, and Tables 2 and 3. Visual inspection (Fig. 2, 3) of many indicators of extreme climate events for the last ~80 years reveals clear trends. Changes related to negative temperatures (the annual number of frost days and annual number of ice days) show a decreasing trend,

1 Electronic data base of meteorological observations CLIDATA.

Table 1. List of climate indices used in this study.

Index name	Explanation	Unit
HP	Days with heavy precipitation (number of days with precipitation ≥ 10 mm)	days
VHP	Days with very heavy precipitation (number of days with precipitation ≥ 20 mm)	days
TN	Daily minimum temperature	temperature value
TX	Daily maximum temperature	temperature value
DTR	Mean of diurnal temperature range	temperature value
TG	Daily mean temperature	temperature value
FD	Frost days (number of days TN < 0 °C)	days
ID	Ice days or days without defrost (number of days TX < 0 ºC)	days
CSDI	Cold-spell days	days
CFD	Maximum number of consecutive frost days (TN < 0 °C)	days
TR	Tropical nights (number of days TN > 20 °C)	days
SU	Summer days (number of days TX > 25 °C)	days
GSL	Growing season length (count of days between first span of at least 6 days TG > 5 °C and first span in the second half of the year of at least 6 days TG < 5 °C	days
GD4	Growing degree days (sum of days with TG > 4 °C)	temperature value

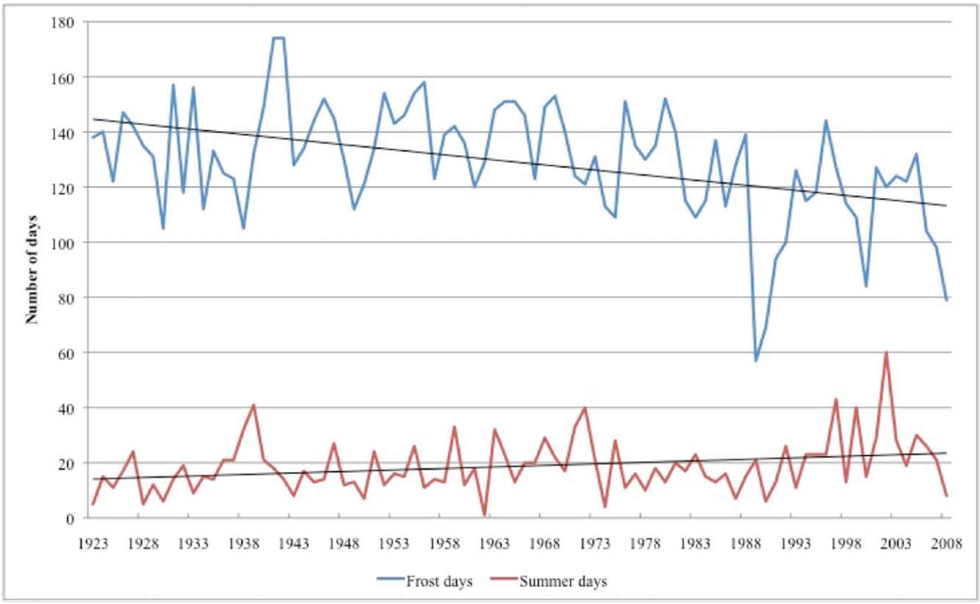

Fig. 2. Trends in the annual number of frost days (daily minimum air temperature < 0°C) and summer days (daily maximum air temperature > +25°C) in Rīga for the period 1923–2008. Compiled by Z. Avotniece, 2010.

but many indicators describing positive temperature extremes demonstrate an increasing trend, for example the annual number of summer days (daily maximum air temperature > +25°C). Also, the number of days with heavy precipitation shows an increasing trend. Patterns of observed trends are consistent between all studied stations, and in many cases the observed trends are statistically significant (Table 2).

In all of the meteorological observation stations there has been an increase in the number of days with heavy precipitation (daily precipitation total ≥

Table 2. Long-term trends in extreme meteorological events (Man-Kendall test statistics).

	HP	VHP	FD	ID	SU	TR	CFD	CSDI
Rīga (1924–2008)	**4.16**	1.25	**-3.57**	-1.78	**2.36**	**3.62**	-0.30	**-2.27**
Liepāja (1924–2008)	**2.18**	0.14	**-3.51**	**-3.63**	0.89	**3.03**	-1.60	-1.36
Alūksne (1946–2008)	**2.86**	-0.51	**-3.98**	**-2.99**	1.92	1.72	**-3.65**	-1.58
Saldus (1946–2008)	1.80	**2.55**	**-3.04**	**-2.24**	1.84	0.43	-1.17	-1.03
Daugavpils (1946–2008)	0.93	0.13	**-2.34**	-1.89	0.49	1.90	-0.25	-1.31

HP – heavy precipitation (≥ 10mm), days; VHP – very heavy precipitation (≥20mm), days; FD – frost day (TN < 0ºC), days; ID – ice day (TX < 0ºC), days; SU – summer day (TX > 25ºC), days; TR – tropical night (TN > 20ºC), days; CFD – maximum number of consecutive frost days (TN < 0ºC), days; CSDI – cold-spell days, days.

The trend was considered as statistically significant at the 5 % level if the test statistic was greater than 2 or less than -2.

10 mm), though only in Rīga, Liepāja and Alūksne this trend was found as statistically significant. The well-expressed increase in the number of days with heavy precipitation in Rīga could be associated with the influence of the Gulf of Riga and urban climate specifics (Birkmann *et al.* 2010). The number of days with very heavy precipitation (daily precipitation total ≥ 20 mm) only shows a significant increasing trend in Saldus, while in Alūksne the trend is negative. Though studies in the United States and elsewhere in the world affirm the increase in the number of days with heavy precipitation during the 20th century (Easterling *et al.* 2000a), the strong local gradient of precipitation (Klein Tank, 2004) makes it hard to make unambiguous conclusions about the long–term trends of changes.

The extreme values of air temperature are increasing along with the increase in the mean values, wherewith there has been an increase in the number of days with extremely high temperatures and a decrease in the number of days with extremely low air temperatures (IPCC, 2007). Trends were stronger for the climatic indices relating to the cold seasons: for example, the number of frost days (TN < 0°C) and number of ice days (TX < 0°C) both show statistically significant decreasing trends in all the studied stations. Studies brought out in Central and Northern Europe show that the decrease in the number of days with negative air temperatures since 1930 is associated with an increase in winter minimum air temperatures (Easterling *et al.* 2000), and the average decrease in the number of ice days over the period 1946–1999 has been 9.2 days (Klein Tank, 2004). The number of maximum consecutive frost days (TN < 0°C) and cold–spell days (unless the statistical significance is not so strong) also demonstrate a decreasing trend. At the same time the climatic indicators of positive temperature extremes, for exam-

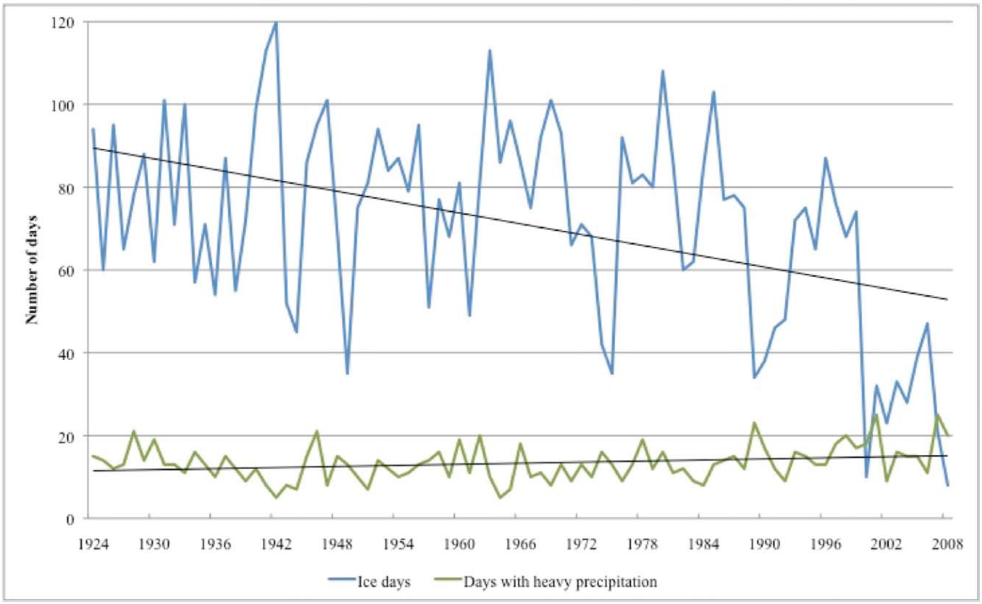

Fig. 3. Trends in the annual number of ice days (daily maximum air temperature < 0°C) and days with heavy precipitation (daily precipitation total ≥ 10 mm) in Liepāja for the period 1924–2008. Compiled by Z. Avotniece, 2010.v

ple the number of summer days (TX > 25°C) and the number of tropical nights (TN > 20°C), demonstrate increasing trends. Besides in the period 1946–1999 in Europe the number of summer days has increased by 4.3 days (Klein Tank, 2004).

Many of the trends in extreme climatic indicators are much stronger in the capital city Rīga, especially in respect to the number of summer days and tropical nights, but also in the case of days with heavy precipitation. This may be due to an increasing urban heat island effect or other specific urban climate effects (Birkmann *et al.* 2010; Lee, Baik 2010; Matzarakis, Endler 2009).

As well as climate extremes, the mean daily mean temperature, the mean daily minimum temperature and the mean daily maximum temperature all showed changes over the study period. As a result of the changes in climate, the number of growing degree-

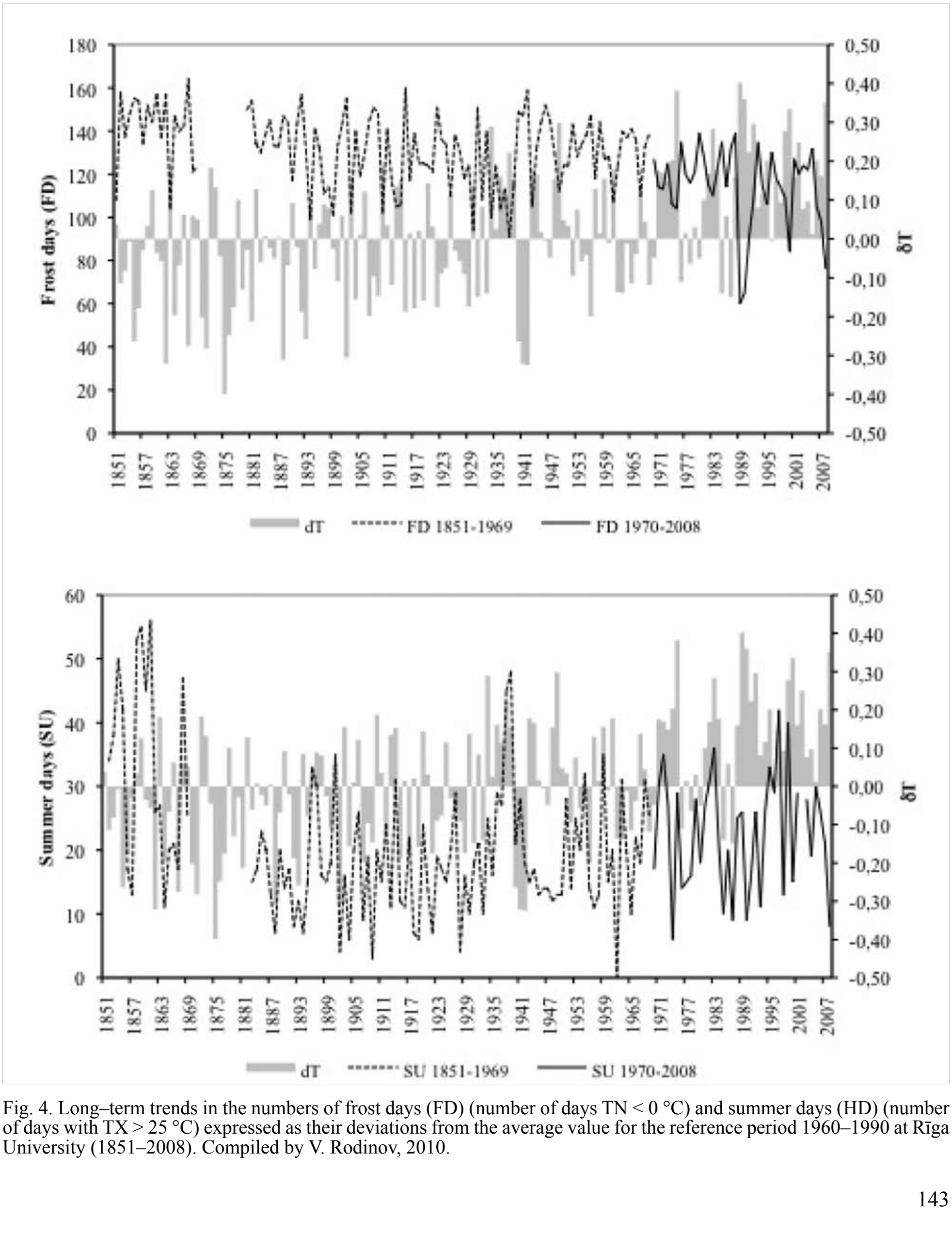

Fig. 4. Long–term trends in the numbers of frost days (FD) (number of days TN < 0 °C) and summer days (HD) (number of days with TX > 25 °C) expressed as their deviations from the average value for the reference period 1960–1990 at Rīga University (1851–2008). Compiled by V. Rodinov, 2010.

days and growing season length are increasing (Table 3). There has been a statistically significant increase in the values of mean daily minimum, mean daily maximum and mean daily mean (except Daugavpils where the trend is of no statistical significance) temperatures. The significant increases in the mean values of air temperature have led to changes in the values of mean diurnal temperature range. In Liepāja and Saldus the diurnal temperature range has increased, which could be associated with a greater increase in the daily maximum air temperatures than in daily minimum air temperatures. In the rest of the stations the diurnal temperature range has decreased, besides in Alūksne and Daugavpils this negative trend is of a statistical significance. These trends of changes are in correspondence with the global decrease in the values of diurnal temperature range (Easterling *et al.* 2000). The well expressed warming observed in many countries in Europe is more associated with the increase in the number of days with extremely high air temperatures than with the decrease in the number of days with extremely low air temperatures (Klein Tank 2004).

Table 3. Long-term trends in meteorological events characterizing climate variability (Man-Kendall test statistics).

	TG	TN	TX	DTR	GD4	GSL
Rīga (1924–2008)	**2.72**	**3.31**	**3.46**	-1.01	**2.33**	**2.06**
Liepāja (1924–2008)	**2.13**	**2.13**	**4.05**	0.19	0.93	1.81
Alūksne (1946–2008)	**2.66**	**2.62**	**2.59**	**-2.00**	1.34	1.03
Saldus (1946–2008)	**2.53**	**2.54**	**3.20**	0.42	1.51	0.30
Daugavpils (1946–2008)	1.61	**2.37**	**2.43**	**-3.14**	-0.23	-0.15

TG – mean daily mean temperature, °C; TN – mean daily minimum temperature, °C; TX – mean daily maximum temperature, °C; DTR – mean diurnal temperature range, °C; GD4 – growing degree days (sum of TG > 4°C), °C; GSL – growing season length, days.

The trend was considered as statistically significant at the 5 % level if the test statistic was greater than 2 or less than -2.

The long–term changes (1851–2006) of the number of frost days and summer days, with respect to the deviation from the average value for the reference period (Fig. 4), clearly indicate the increasing trend in the latter part of the observation period (1960–2006). However, at the same time the analysis of long–term changes demonstrates a significant natural variability of climate indicators for the past 150 years.

Impact of large–scale atmospheric circulation processes on extreme climatic events

The characteristics, transformation and trajectories of an air mass reaching certain locations, as well as its specific weather conditions, are mostly determined by the large–scale circulation processes in the atmosphere (Jaagus 2006). The movement of an air mass is mainly dependent on the location of large–scale synoptic systems and the corresponding air flows in the atmosphere (Moberg *et al.* 2003). For these reasons, 18 large–scale atmospheric circulation patterns for the Baltic Sea region were examined in this study. These patterns were derived from modifications of the circulation patterns created by Gerstengarbe and Werner (Hoy, Matschullat 2010) and made available for scientific research by the European Cooperation in Science and Technology Action 733 (COST733 2010). This classification approach is based on predefined circulation patterns determined according to the subjective classification of the so–called Central European *Großwettertypes*. It is assumed that these *Großwettertypes* are defined by the geographical position of major centres of action, and that the location and extent of frontal zones can be sufficiently characterized in terms of varying degrees of zonality, meridionality, and vorticity of the large–scale sea level pressure field over Europe (Beck 2008). With the help of these circulation patterns, the character of the large–scale atmospheric circulation and the types of synoptic systems determining the weather conditions over a certain area can be derived for each day from 1957 to 2002.

Over the period 1957–2002, 925 cases of summer days (daily maximum air temperature >+25°C), 27 cases of tropical nights (minimum air temperature >+20°C) and 7 cases of the mean daily temperature exceeding +25°C were found (Tables 4–6). It was stated above that any one of the circulation types used in this study could be responsible for extremely hot weather conditions in Rīga, but here we find that seven of them can be defined as dominant. Extremely high air temperatures in Rīga can be observed when the weather conditions are determined by a south–westerly and southerly anticyclones flow (Figs 5, 6), in the case of a high-pressure area being situated over the eastern part of Europe, and with the warmer air flowing into the territory from western Russia. Extremely hot weather in Rīga can also be observed when cyclonic conditions are dominant: south–westerly, southerly and westerly cyclonic flows are associated with the warm sector of a cyclone and an intensive inflow of warm air.

Large–scale atmospheric circulation processes influence extreme precipitation processes (Katz 1999). In the period 1957–2002 there were 732 cases of heavy precipitation (daily precipitation total ≥ 10 mm) in Rīga. The days with heavy precipitation were mainly associated with cyclones, however there were some differences between the synoptic processes responsible

Table 4. Large-scale circulation types during summer days (daily maximum air temperature > +25°C) in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	64	6.92
2	West anticyclonic	85	9.19
3	Southwest cyclonic	97	10.49
4	Southwest anticyclonic	104	11.24
5	Northwest cyclonic	29	3.14
6	Northwest anticyclonic	35	3.78
7	Central Low	24	2.59
8	Central High	47	5.08
9	North cyclonic	15	1.62
10	North anticyclonic	23	2.49
11	Northeast cyclonic	16	1.73
12	Northeast anticyclonic	28	3.03
13	East cyclonic	41	4.43
14	East anticyclonic	66	7.14
15	Southeast cyclonic	38	4.11
16	Southeast anticyclonic	78	8.43
17	South cyclonic	50	5.41
18	South anticyclonic	85	9.19

Table 5. Large-scale circulation types during days with the daily mean air temperature > +25° in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	2	28.57
3	Southwest cyclonic	4	57.14
16	Southeast anticyclonic	1	14.29

Table 6. Large-scale circulation types during tropical nights (daily minimum air temperature > +20°C) in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	2	7.41
3	Southwest cyclonic	3	11.11
4	Southwest anticyclonic	1	3.70
6	Northwest anticyclonic	1	3.70
7	Central Low	1	3.70
12	Northeast anticyclonic	1	3.70
13	East cyclonic	1	3.70
14	East anticyclonic	7	25.93
15	Southeast cyclonic	1	3.70
16	Southeast anticyclonic	4	14.81
17	South cyclonic	4	14.81
18	South anticyclonic	1	3.70

Table 7. Large-scale circulation types during days with heavy precipitation (daily precipitation total ≥ 10 mm) in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	75	10.25
2	West anticyclonic	16	2.19
3	Southwest cyclonic	64	8.74
4	Southwest anticyclonic	19	2.60
5	Northwest cyclonic	59	8.06
6	Northwest anticyclonic	21	2.87
7	Central Low	81	11.07
8	Central High	7	0.96
9	North cyclonic	96	13.11
10	North anticyclonic	28	3.83
11	Northeast cyclonic	70	9.56
12	Northeast anticyclonic	30	4.10
13	East cyclonic	50	6.83
14	East anticyclonic	24	3.28
15	Southeast cyclonic	31	4.23
16	Southeast anticyclonic	10	1.37
17	South cyclonic	44	6.01
18	South anticyclonic	7	0.96

Table 8. Large-scale circulation types during days with heavy summer (June–August) precipitation in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	31	10.37
2	West anticyclonic	6	2.01
3	Southwest cyclonic	27	9.03
4	Southwest anticyclonic	9	3.01
5	Northwest cyclonic	25	8.36
6	Northwest anticyclonic	7	2.34
7	Central Low	42	14.05
8	Central High	2	0.67
9	North cyclonic	29	9.70
10	North anticyclonic	6	2.01
11	Northeast cyclonic	36	12.04
12	Northeast anticyclonic	9	3.01
13	East cyclonic	23	7.69
14	East anticyclonic	13	4.35
15	Southeast cyclonic	10	3.34
16	Southeast anticyclonic	7	2.34
17	South cyclonic	14	4.68
18	South anticyclonic	3	1.00

for heavy precipitation in the cold and in the warm times of the year: in the summer, heavy precipitation events were mainly associated with convective processes and the cold fronts of cyclones; in winter these events were mostly the result of prolonged precipitation associated with a warm front (Jakimavičius, Kovalenkovienė 2010; Kriaučiūniene *et al.* 2008). However, when the centre of a low-pressure area was situated over Latvia, heavy precipitation was observed at any time of the year (Table 7).

Due to the differences in the processes determining the weather conditions favourable to the formation of heavy precipitation (Jakimavičius, Kovalenkovienė 2010) it was necessary to choose a definite season for the analysis. For this purpose the number of days with heavy precipitation for each month during the period 1957–2002 was calculated. The number of days with heavy precipitation was considerably greater in June, July, August, September and October and therefore summer season was chosen for further analysis.

Conditions favourable for the occurrence of heavy precipitation in summer were also mostly associated with cyclonic activity (Table 8). The dominant synoptic conditions characterising days with heavy precipitation in Rīga were westerly, south–westerly (see Figs 5, 6) north–easterly and northerly (Fig. 8) cyclonic flows, and additionally the circulation of air in the centre of a low-pressure area (Fig. 7). In the cases of westerly and south–westerly flows the centre of the low was situated over Scandinavia, and heavy precipitation in Rīga was brought by the weather fronts, especially the cold front. When there was a northerly and north–easterly cyclonic flow, the centre of the low was situated over the western part of Russia, and precipitation in Latvia was associated with the convection caused by the advection of cold air. However, the predominant conditions for the occurrence of heavy precipitation in Rīga occurred when the centre of a low was situated over the region, when the strong convective updrafts intensify the formation of clouds and precipitation.

CONCLUSIONS

There have been significant changes in the extreme climate events in Latvia in the past ~80 years. The trend analysis of extreme climate event indicators showed a significant increase in the number of meteorological events associated with an increased summer temperature (for example, the number of summer days and tropical nights) and a decrease in the number of events associated with extreme temperature events in winter (number of ice days and frost days). Due to the decreasing number of cold days under a changing climate, the length of the growing season has increased. There were also increases in the number of days with heavy precipitation and in the intensity of heavy precipitation. In this study we found the trends of extreme climate event indicators to be much stronger in the capital city Rīga, which could be associated with the impact of the urban heat island and the effects of the specific urban climate.

As a driving factor associated with extreme climate events, large–scale atmospheric circulation processes were identified and the dominant circulation types influencing extreme precipitations and summer temperature extremes were found. Weather conditions are mainly dependent on the location of large–scale synoptic systems and the corresponding air flows in the atmosphere, wherewith during the analysis we found some regularities between the large–scale atmospheric circulations and the weather conditions on the boundary layer. Though any of the 18 atmospheric circulation types can be the cause of extremely high temperatures and heavy precipitation in Rīga, the most common synoptic situations for the occurrence of extremely high air temperatures can be found in the conditions of south–westerly, southerly anticyclones flows causing the advection of warm air from western Russia and in the cases of the warm sector of a cyclone being situated over the territory – in the conditions of westerly, south–westerly cyclonic flows. Extreme precipitation events during the summertime were mainly associated with cyclonic activity, and the predominant conditions of the occurrence of heavy precipitation were found during the days when the centre of a low-pressure area was situated over the region.

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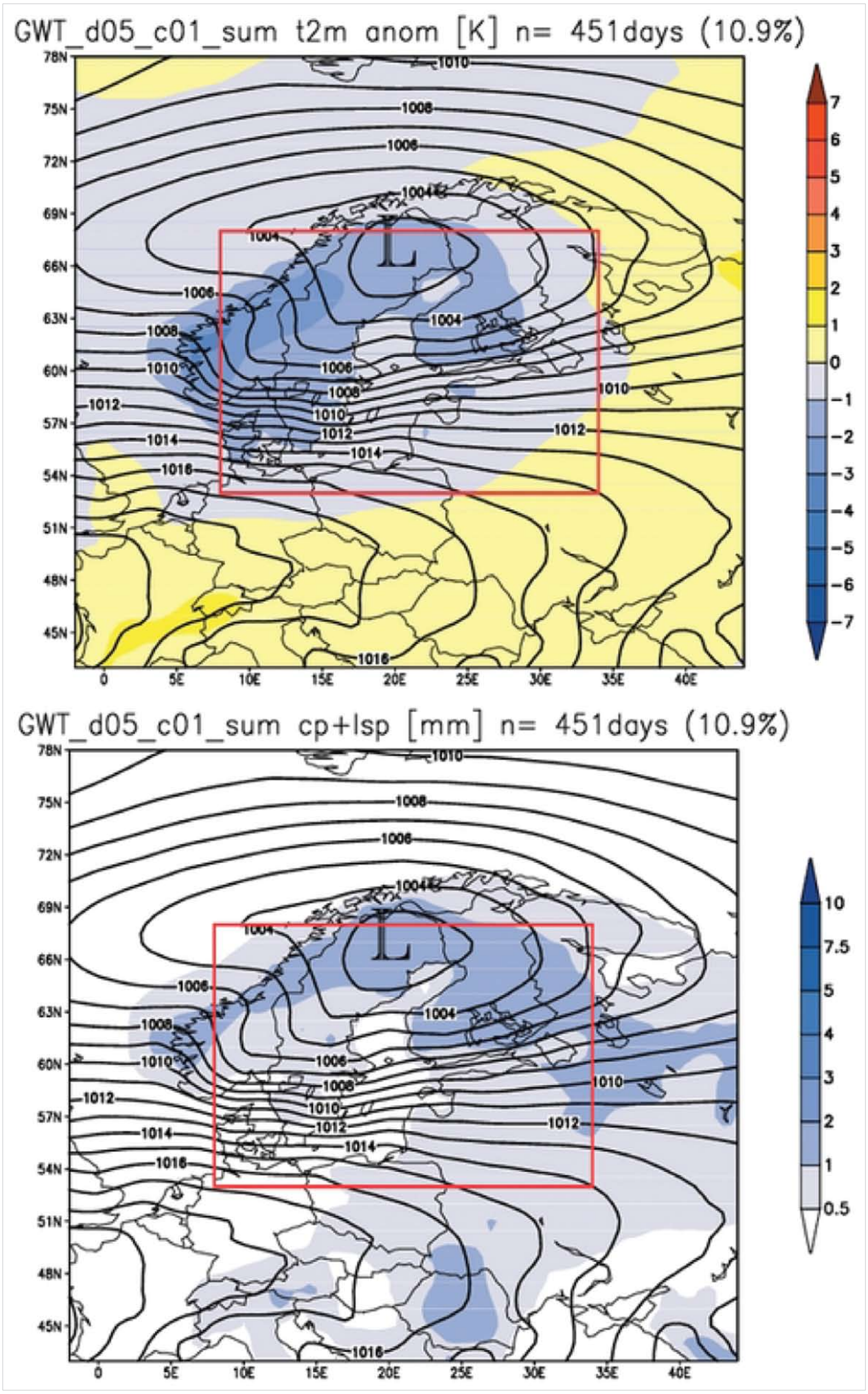

Fig. 5. Circulation type No 1 — westerly cyclonic air flow.

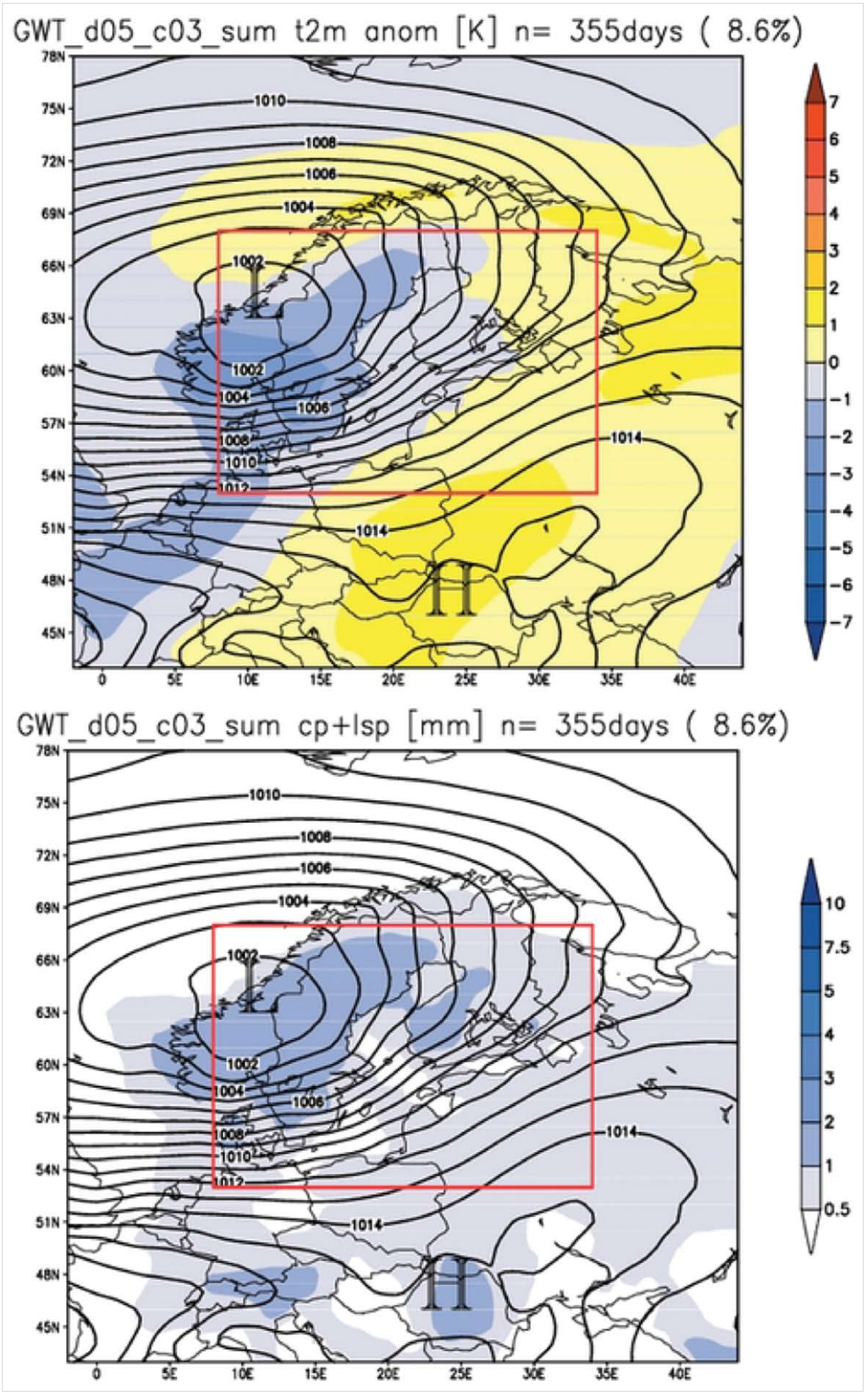

Fig. 6. Circulation type No 3 — southwesterly cyclonic air flow.

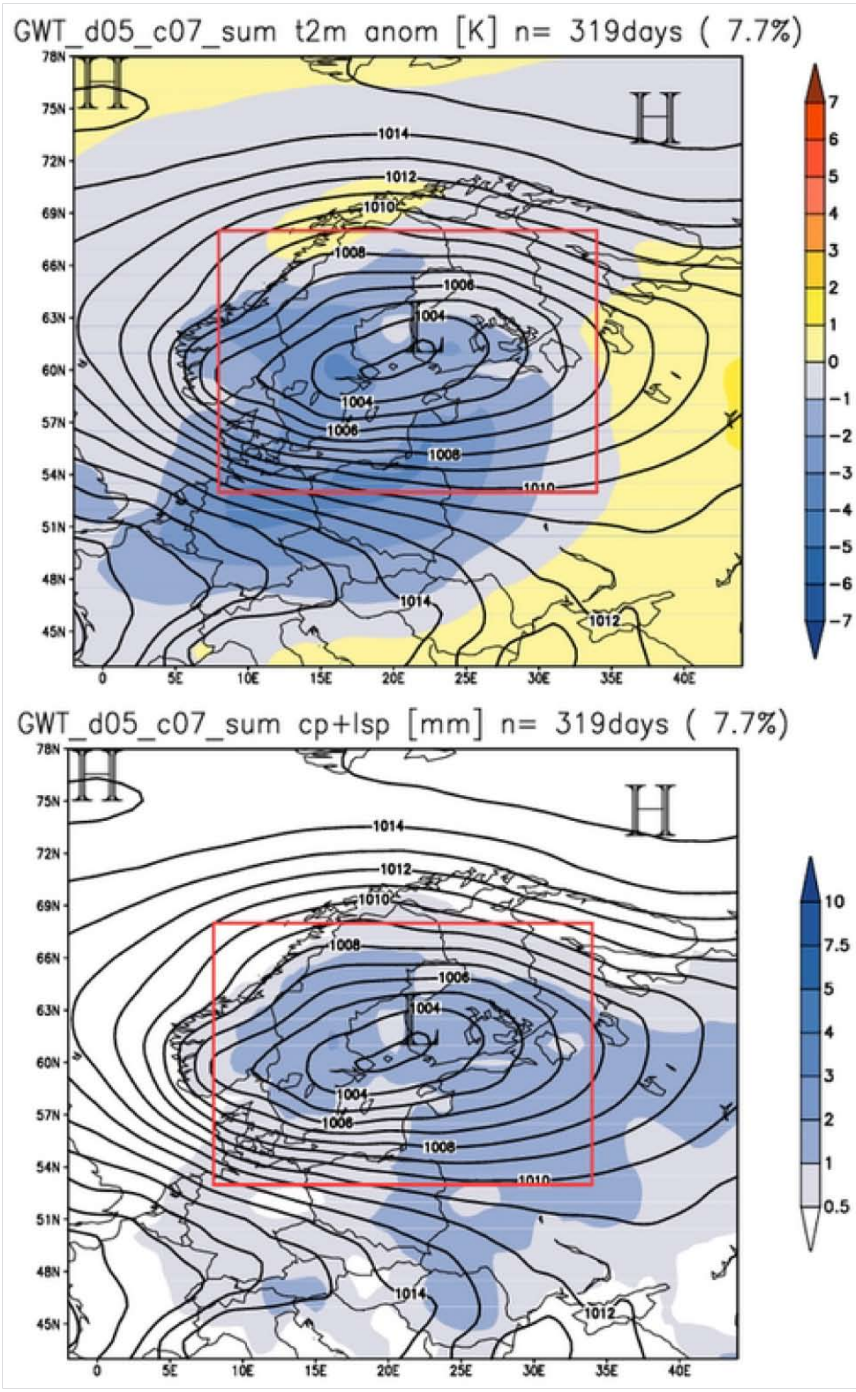

Fig. 7. Circulation type No 7 – air flow in the centre of a low.

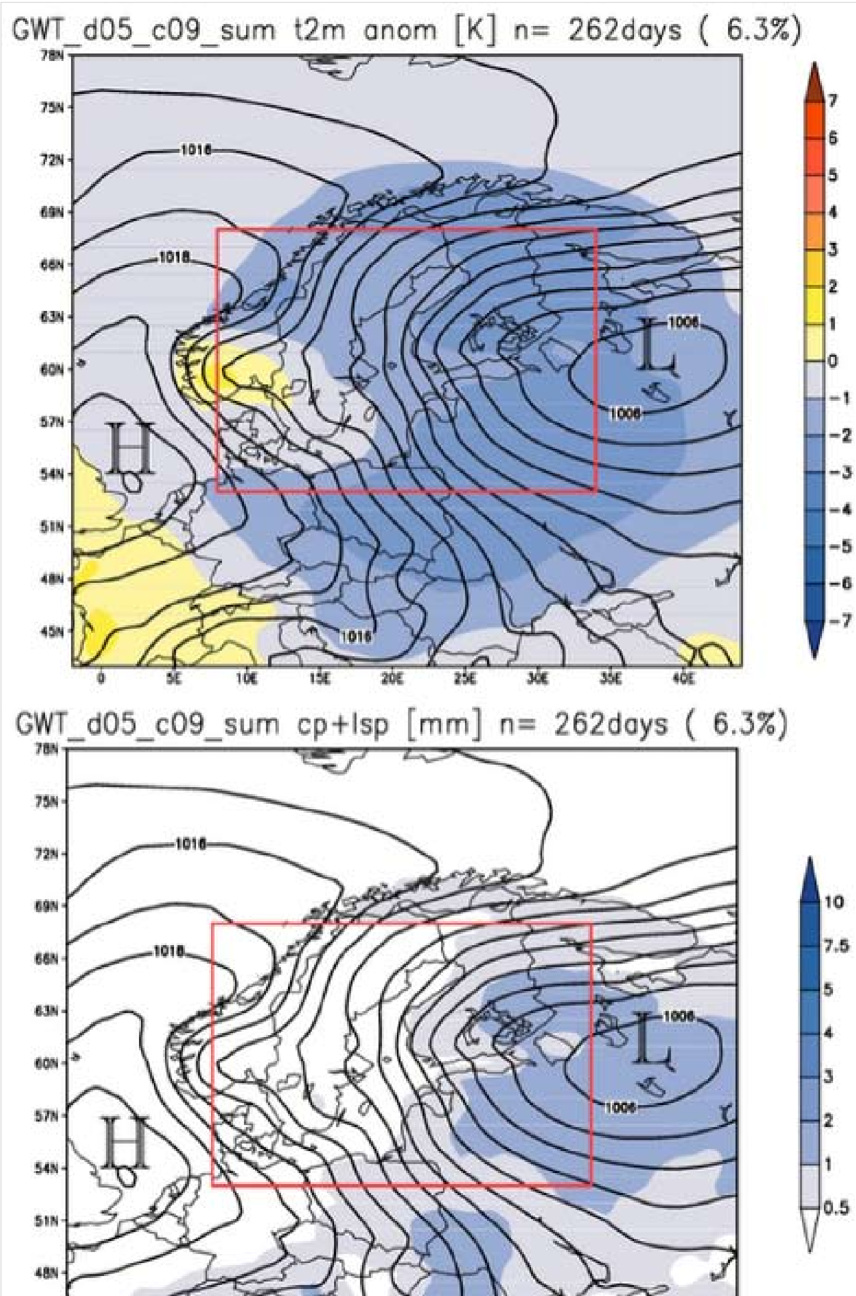

Fig. 8. Circulation type No 9 – northerly cyclonic air flow.

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PAPER 2: CHANGES OF EXTREME CLIMATE EVENTS IN LATVIA

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Changes of Extreme Climate Events in Latvia

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Abstract **- Extreme climate events are increasingly recognized as a threat to human health, agriculture, forestry and other sectors. To assess the occurrence and impacts of extreme climate events, we have investigated the changes of indexes characterizing positive and negative temperature extremes and extreme precipitation as well as the spatial heterogeneity of extreme climate events in Latvia. Trend analysis of long–term changes in the frequency of extreme climate events demonstrated a significant increase in the number of days with extremely high air temperatures and extreme precipitation, and a decrease in the number extremely cold days.**

Keywords **- climate change, trends, temperature extremes, precipitation extremes, Latvia**

I. INTRODUCTION

Climate change has been recognized as a major challenge to human beings and natural ecosystems. Climate change affects all elements of the climate system: air and water temperature, precipitation, river runoff, ice and snow cover and others. A significant worldwide increase in the mean temperature near the surface of the Earth has been reported, indicating that the climate is changing: the global mean temperature increase over the period 1861–2000 was 0.61°C, with a 90% confidence interval of 0.45–0.77°C, while between 1901 and 2000 the observed warming was 0.57°C, with a 90% confidence interval of 0.40–0.74°C [1]. However, climate change is not only characterized by changes in the mean values, but also by changes in the variability of climate indicators and extremes for example, extreme heat events and heat waves, extreme precipitation, floods, [2]. In respect to the damage to the society and natural ecosystems, extreme climate events may pose much more significant threats than climate change itself.

Today there is a growing interest in extreme climate events, [3], [4], [5], [6], [7] and trends of their changes. Changes in extremes may be due to the mean effect, the variance effect or the structural change in the shape of distribution [8]. Determining changes in the behaviour of extreme weather events has been the topic of several international projects ECA&D [9], [10], EMULATE [11], STARDEX [12]. Often extreme climate events have been identified using internationally agreed, predefined indices that is a day count exceeding a fixed threshold, percentile threshold, extreme event duration, etc [13], [14].

In several studies in Europe a significant increasing trend of many extreme indices has been found over the later part of the 20th century [26], [20]. A study based on the analysis of temperature extremes [20] has reported an increment of the warm extremes and a decrease of the cold extremes in Europe. In summer, the increase concerns both daily maximum and daily minimum air temperatures while in winter – mostly daily minimum air temperatures [22]. The countries around the Baltic Sea have also experienced an increase in the number of warm nights and a decrease in the number of cold nights and days in the latter part of the 20th century as well as a slightly increased number of summer days with daily maximum temperatures above +25°C [21]. According to studies brought out in Europe, there are significant spatial differences in the trends of changes for extreme precipitation events [19], [5], though the most significant increasing tendency has been observed in the Baltic Sea region [6], [18]. According to the Fourth Assessment Report (2007) it is very likely that in the northern part of Europe the extremely high temperature events and heat waves as well as extreme precipitation events will continue to become more frequent [15].

So far studies of climate change in Latvia and other Baltic countries have been mostly carried out based on trends of changes of mean values. Climate extreme variability and changes has been studied in several meteorological stations in Latvia and Lithuania [3], [17]. The aim of this study is to determine the long-term variability and trends in the time series of extreme climate events in Latvia.

II. MATERIALS AND METHODS

Daily climate data were provided by 14 major meteorological observation stations in Latvia (Fig. 1). Variable data obtained from the Latvian Environment, Geology and Meteorology Centre included maximum, minimum and average daily temperatures and daily precipitation amount recorded by the weather stations over the period 1950-2010. Data from the Rīga University meteorological station over the period 1852-2010 were used for the analysis of historical changes in the extreme events, but for the case-study of the extremely hot summer of the year 2010 daily observation data of all 23 observation stations in Latvia were used.

Fig. 1. Major meteorological observation stations in Latvia

Ensemble climate change indices derived from daily temperature data describing changes in the mean indices or extremes of climate were computed and analysed. The indices follow the definitions recommended by the *CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices* [29] with a primary focus on extreme events (Table I).

TABLE I

LIST OF CLIMATE INDICES USED IN THIS STUDY

Index name	Explanation	Value
TX	Annual or monthly mean of daily maximum temperature	°C
TN	Annual or monthly mean of daily minimum temperature	°C
TNn	Annual or monthly minimum value of daily minimum temperature	°C
TNx	Annual or monthly maximum value of daily minimum temperature	°C
TXn	Annual or monthly minimum value of daily maximum temperature	°C
TXx	Annual or monthly maximum value of daily maximum temperature	°C
FD	Frost days (annual count when daily minimum temperature <0ºC)	Days
ID	Ice days (annual count when daily maximum temperature<0ºC)	Days
SU	Summer days (annual count when daily maximum temperature >25ºC)	Days
TR	Tropical nights (annual count when daily minimum temperature >20ºC)	Days
CSDI	Cold spell duration indicator (Annual count of days with at least 6 consecutive days when minimum temperature <10th percentile)	Days
WSDI	Warm spell duration indicator (Annual count of days with at least 6 consecutive days when maximum temperature >90th percentile)	Days
Ptot	Annual total precipitation amount in wet days (precipitation amount ≥ 1mm)	mm
SDII	Simple daily intensity index (annual total precipitation divided by the number of wet days (precipitation amount ≥ 1.0mm) in the year)	mm/day
CDD	Consecutive dry days (annual maximum number of consecutive days with precipitation amount <1mm)	Days
CWD	Consecutive wet days (annual maximum number of consecutive days with precipitation amount ≥1mm)	Days
R10	Annual number of heavy precipitation days (precipitation amount ≥10 mm)	Days
R20	Annual number of very heavy precipitation days (precipitation amount ≥20 mm)	Days
R95p	Very wet days (annual total precipitation when precipitation amount>95th percentile)	mm
R99p	Extremely wet days (annual total precipitation when precipitation amount>99th percentile)	mm
Rx1day	Max 1-day precipitation amount (annual or monthly maximum 1-day precipitation)	mm
Rx5day	Max 5-day precipitation amount (annual or monthly maximum consecutive 5-day precipitation)	mm

The climate indices were computed by using The RClimDex 1.0 developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of Meteorological Service of Canada. RClimDex 1.0 was designed to provide a user friendly interface to compute indices of climate extremes. RClimDex 1.0 runs in the R platform and besides the computation of indices it also includes a simple quality control of the data [27].

Trends in the meteorological event time series were analysed by the MAKESENS test, which was developed for detecting and estimating trends in the time series of annual data. The procedure is based on the nonparametric Mann-Kendall test for the trend and the nonparametric Sen's method for the magnitude of the trend. The Mann-Kendall test is applicable to the detection of a monotonic trend of a time series with no seasonal or other cycle [24]. Within this study the Mann-Kendall test was applied separately to each variable at each site. The trend was considered as substantial at a significance level of $p \leq 0.1$ if the test statistic was greater than 1.6 or less than -1.6, as statistically significant at a significance level of $p \leq 0.01$ if the test statistic was greater than 2.6 or less than -2.6 and as very significant at a significance level of $p \leq 0.001$ if the test statistic was greater than 3.3 or less than -3.3.

III. RESULTS AND DISCUSSION

Climate in Latvia is influenced by its location in the northwest of the Eurasian continent (continental climate impacts) and by its proximity to the Atlantic Ocean (maritime climate impacts).

A. Trends in the changes of extreme air temperature in Latvia

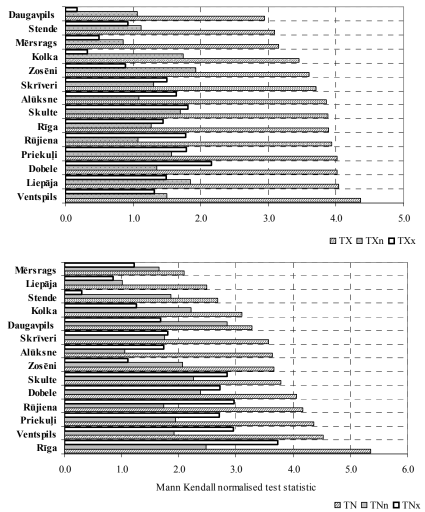

Fig. 2. Long-term trends of mean annual minimum and maximum air temperatures in Latvia over the period 1950-2010 (Mann-Kendall test statistics).TX - Annual or monthly mean of daily maximum temperature; TN- Annual mean of daily minimum temperature; TXn - Annual minimum value of daily maximum temperature; TXx - Annual maximum value of daily maximum temperature. TNn - Annual minimum value of daily minimum temperature; TNx - Annual maximum value of daily minimum temperature.

A highly variable weather pattern is determined by the strong cyclonic activity over Latvia. These variable conditions over the territory contribute to differences in the regimes of air temperature and precipitation, and also to the spatial inhomogeneity in the occurrence and long-term trends of extreme climate events.

The overall results of trend estimates of mean annual minimum and maximum air temperatures for 14 meteorological observation stations in Latvia (the spatial location of the meteorological observation stations can be found in Fig. 1) are summarized in Figure 2. The mean of daily maximum air temperature (TX) and mean of daily minimum air temperature (TN) showed a statistically significant increasing trend at all 14 meteorological observation stations covered by the study, as well as the annual minimum value of daily minimum air temperature (TNn) with statistically significant increasing trend at 12 meteorological observation stations (with the exception of Liepāja and Alūksne). Trends of changes of annual maximum value of daily minimum air temperature (TNx) and annual minimum value of daily maximum air temperature (TXn) as well as the annual maximum value of daily maximum air temperature (TXx) for all stations has a positive character, but the statistical significance is lower, especially for the stations located in the eastern part of Latvia, revealing spatial heterogeneity of temperature extreme changes and impact of local factors affecting climate at regional/local level. An example of trends of changes of daily maximum, mean and minimum temperatures in capital of Latvia – Rīga, demonstrates the impact of city microclimate and visually seen increase of the studied temperature extremes (Fig. 3).

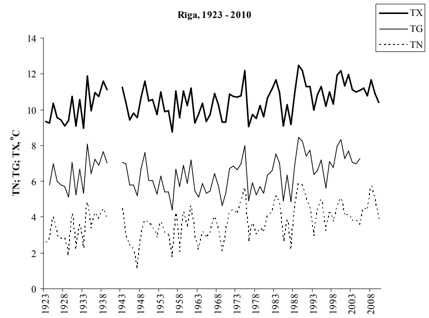

Fig. 3. Trends of annual daily maximum (TX), mean (TG) and minimum (TN) temperature in Rīga for the period from 1923 to 2010

A detailed study of the character of monthly mean of daily maximum temperature changes within a year (Table II) reveal a strongly seasonal character of maximum air temperature increase. On one hand, the daily maximum air temperature increase is not even throughout the year, but occurs in some seasons, but on the other hand is relatively even for all meteorological stations over Latvia. The increase of daily maximum air temperature is statistically significant for January till May and again for July and August, but there is a common decreasing trend for June. Within September till December daily maximum temperature increase is evident unless these changes are statistically insignificant.

TABLE II

LONG-TERM TRENDS OF MONTHLY MEAN OF DAILY MAXIMUM AIR TEMPERATURE (TX) IN LATVIA OVER THE PERIOD 1950-2010 (MANN-KENDALL TEST STATISTICS)

	J	F	M	A	M	J	J	A	S	O	N	D
Alūksne	**2.40**	**1.72**	**2.76**	**2.92**	**1.99**	-0.67	**2.08**	**1.69**	1.05	0.50	1.17	0.45
Daugavpils	**2.10**	1.39	**2.86**	**2.66**	0.82	-1.53	1.08	1.10	0.50	0.48	0.87	0.14
Dobele	**2.23**	**1.79**	**2.71**	**2.92**	**2.55**	0.01	**2.55**	**2.65**	1.23	0.62	**1.81**	0.79

Kolka	**1.86**	**1.93**	**2.19**	**2.50**	**2.81**	-0.35	**1.88**	**2.65**	0.75	-0.45	0.84	0.65
Liepāja	**1.89**	**1.84**	**2.83**	**2.84**	**2.95**	0.88	**2.19**	**2.67**	1.36	0.20	0.88	0.64
Mērsrags	1.40	**1.67**	**2.01**	**2.42**	**2.37**	-0.55	**1.77**	**2.22**	0.11	0.13	0.47	0.19
Priekuļi	**2.21**	**1.81**	**2.79**	**2.73**	**2.23**	-0.32	**2.41**	**1.79**	1.23	0.81	1.08	0.80
Rīga	**1.91**	**1.66**	**2.61**	**1.95**	**2.51**	0.06	**2.58**	**2.15**	0.91	0.06	1.13	0.43
Rūjiena	**2.19**	1.33	**2.66**	**2.56**	**2.10**	-0.53	**2.46**	**1.68**	1.06	0.80	1.47	0.87
Skrīveri	**2.42**	**1.65**	**2.98**	**2.78**	**2.00**	-0.59	**2.35**	**1.80**	1.10	0.73	1.27	0.49
Skulte	**2.29**	**1.72**	**2.94**	**1.85**	**1.66**	-0.26	**2.20**	**1.85**	1.07	0.58	1.27	0.67
Stende	1.64	1.41	**2.26**	**1.89**	**2.05**	-0.76	1.45	1.54	0.12	-0.42	0.87	1.29
Ventspils	**2.10**	**2.00**	**2.74**	**2.30**	**2.44**	0.42	**2.70**	**3.18**	1.46	0.77	**1.69**	1.08
Zosēni	**2.11**	1.31	**3.08**	**2.08**	**2.35**	0.12	**1.93**	**1.74**	0.60	0.32	0.65	0.10

TABLE III

LONG-TERM TREND OF MONTHLY MEAN OF DAILY MINIMUM AIR TEMPERATURE (TN) IN LATVIA OVER THE PERIOD 1950-2010 (MANN-KENDALL TEST STATISTICS)

	J	F	M	A	M	J	J	A	S	O	N	D
Alūksne	**2.63**	1.38	**2.53**	**2.21**	1.54	0.21	**2.36**	**2.08**	0.98	0.06	1.34	0.66
Daugavpils	**2.53**	1.46	**2.66**	**2.01**	1.10	0.12	0.86	1.21	0.29	-0.25	1.05	0.60
Dobele	**2.45**	**1.83**	**2.73**	**2.55**	**2.22**	1.53	**3.15**	**3.38**	**1.80**	-0.06	**1.71**	0.96
Kolka	**2.09**	**1.76**	**2.34**	**1.73**	**2.39**	0.38	**1.69**	**2.10**	0.82	-0.42	1.13	0.28
Liepāja	**1.87**	1.41	**2.02**	1.52	**2.28**	0.63	**1.86**	**2.24**	-0.24	-1.21	0.58	0.48
Mērsrags	**1.84**	1.15	**2.16**	0.92	0.64	0.02	0.42	0.51	-0.16	-0.59	0.19	0.01
Priekuļi	**2.56**	1.52	**2.79**	**2.58**	**2.41**	1.26	**3.58**	**3.38**	1.46	0.27	1.42	0.95
Rīga	**2.74**	**2.07**	**3.29**	**3.39**	**4.41**	**3.53**	**4.99**	**5.66**	**2.99**	1.24	**1.82**	1.13
Rūjiena	**2.63**	1.28	**2.47**	**2.40**	**2.03**	1.29	**3.32**	**3.14**	**1.70**	0.19	1.07	0.98
Skrīveri	**2.58**	1.49	**2.54**	**1.72**	1.17	0.20	**2.40**	**2.08**	0.94	-0.31	1.31	0.68
Skulte	**2.45**	1.60	**2.84**	**2.08**	**2.05**	1.26	**2.71**	**3.47**	1.10	0.09	1.41	0.50
Stende	**1.76**	1.50	**2.09**	1.00	1.03	0.44	0.78	1.42	0.29	-0.66	0.76	0.91
Ventspils	**2.39**	**2.01**	**2.66**	**3.15**	**4.24**	**2.26**	**3.64**	**5.03**	**1.84**	0.55	**2.01**	1.16
Zosēni	**2.19**	1.07	**2.73**	1.27	1.25	1.36	**2.32**	0.76	0.25	-0.65	0.99	0.12

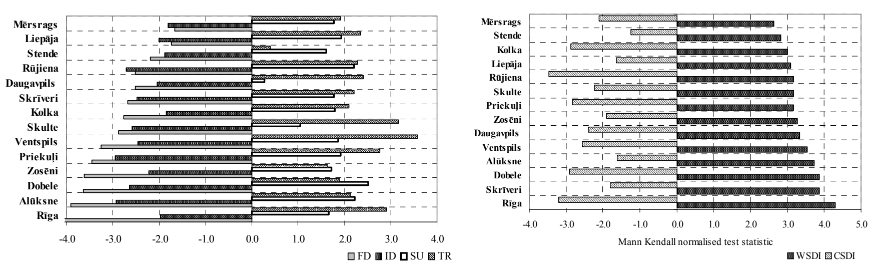

Fig. 4. Long-term trends of extreme temperature events and events of prolonged periods of extremely low and high air temperatures in Latvia over the period 1950-2010 (Mann-Kendall test statistics). FD - Frost days; ID - Ice days; SU - Summer days; TR - Tropical nights; CSDI- Cold spell duration indicator; WSDI - Warm spell duration indicator.

The same trends as for monthly mean of daily maximum air temperature (TX) are common also for monthly mean of daily minimum air temperature (TN) (Table III). However trends for monthly mean of daily minimum air temperature differ, for example, in February in most of the studied meteorological stations. The trends of changes in Rīga can be considered remarkable, where statistically significant increasing trends are common for nearly the whole year (except October and December), stressing the role of the city microclimate [11] as one of the factors affecting climate in general also regionally.

From different climate extreme indicators special attention deserves indices describing number of days with extremely high or low air temperatures, as far as such events pose major threat to human health, productivity in working places, agriculture and other kind of human activities. As there is a significant increase in the mean values of air temperature in all of the meteorological observation stations also the extreme values of air temperature have been increasing along with the increase in the means. Thus also an increase in the number of days with extremely high air temperatures is common for all the studied stations. A statistically significant increase in the number of summer days (TX > + 25°C) has been observed in 10 out of 14 meteorological stations, as well a statistically significant increase of tropical nights (TN > + 20°C) in 13 out of 14 meteorological stations (Fig. 4). However according to the long-term data from the stationRīga -University, the number of summer days was much higher in the 1850-60ies (Fig. 5). The increasing tendency observed from the beginning of the 20th century is caused by warm summers, especially the summer of the year 2002 (with 60 days of maximum air temperatures above +25°C in Rīga - the highest for the whole period of instrumental observations) and the summer of 2010. At the same time, other studies confirm that, similarly to the trends found in the summer day time series in the station Rīga-University, in the period from 1946 to 1999 in Europe, the number of summer days has increased by 4.3 days [19] and that the overall warming tendency is more evident in the central part of Europe, in the mountainous regions and in the north-eastern part of Europe [23].

The warm spell duration indicator (WSDI - annual count of days with at least 6 consecutive days when maximum temperature >90th percentile) characterizing the length of prolonged heat events has a statistically significant increasing trend all over Latvia, and this can be considered as the most alarming result of this study, because an increase in the frequency and length of the periods of prolonged heat can have a significant negative effect on human morbidity and mortality [8], [4], [25]. Overall the most expressed increasing trend of high temperature extremes is common for regions at the coastline of the Baltic Sea, in the more continental stations (Alūksne, Daugavpils and the capital city of Latvia – Rīga (Fig. 4)).

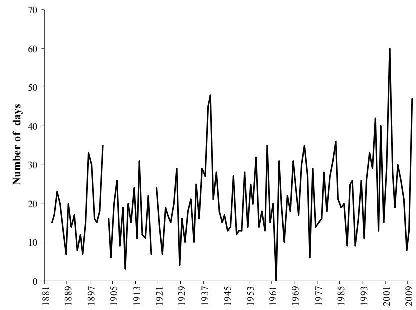

Fig. 5. The annual number of summer days in Rīga-University observation station over the period 1881-2010

On the other hand, extremes associated with negative air temperatures (despite relatively cold winters in 2009/2010, 2010/2011) have a statistically significant negative trend of changes all over Latvia (Fig. 4). Indices of climate extremes associated with negative air temperatures are cold spell duration indicator (CSDI - annual count of days with at least 6 consecutive days when minimum air temperature <10th percentile), frost days (FD - annual count when daily minimum air temperature <0ºC), ice days (ID - annual count when daily maximum air temperature <0ºC). According to the analysis of the World Meteorological Organization [31], the year 2010 along with the years 2005 and 1998 globally has been the hottest year since the beginning of the instrumental meteorological observations in 1850. In Latvia, due to the extremely low wintertime temperatures, the average air temperature of the year 2010 was close to the reference (+5.6°C), ranking the year as the coldest of the 21st century, however during the summer the air temperatures were extremely high (Fig. 6), the excessive heat lasted for a long period of time, and in most of the meteorological observation stations of Latvia the maximum temperature records were broken. Such extremely hot conditions were observed due to a south-easterly air flow that was established over the area for a prolonged period of time [28].

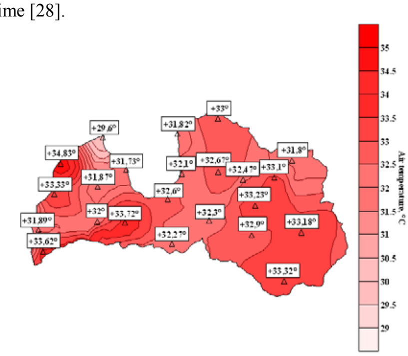

Fig. 6. The maximum values of air temperature in Latvia during the summer 2010

Figure 6 shows the maximum air temperatures of the summer 2010 recorded in 23 meteorological observation stations in Latvia. One can see that in all meteorological stations except Kolka the maximum air temperature exceeded +30°C. The pattern of the maximum air temperature distribution was not directly related to geographical factors such as the distance from the Baltic Sea or the Gulf of Riga – due to prevailing south-east winds the highest air temperature of +34.83°C has been observed in Ventspils.

B. Trends in the changes of extreme precipitation in Latvia

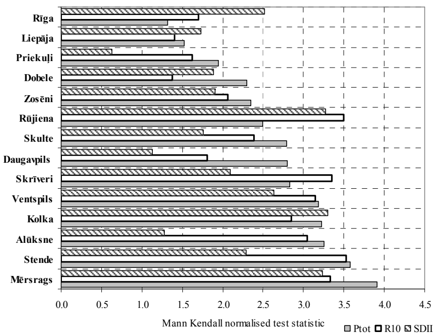

Fig. 7. Long-term trends of changes in precipitation amount and heavy precipitation events in Latvia over the period 1950-2010 (Mann-Kendall test statistics). Ptot - Annual total precipitation amount in wet days; R10 - Annual number of heavy precipitation days; SDII - Simple daily intensity index.

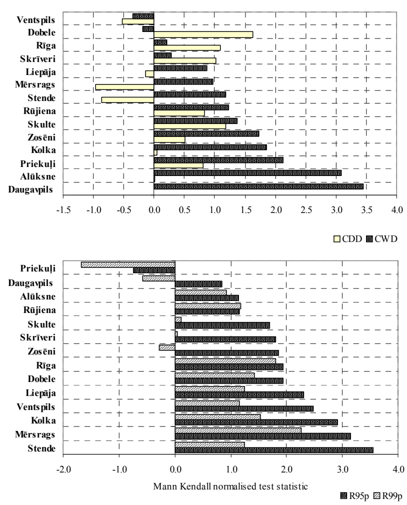

Fig. 8. Long-term trends of prolonged dry and wet periods and extremely heavy precipitation in Latvia over the period 1950-2010 (Mann-Kendall test statistics).CDD - Consecutive dry days; CWD - Consecutive wet days; R95p - Very wet days; R99p - Extremely wet days.

Another group of meteorological events may be related to precipitation regime. Precipitation regime is a group of processes controlling hydrological processes in lakes and rivers, water supply for agricultural and human needs, recreational purposes. At the same time extremes in precipitation amount can be related to floods (including flash floods), but also droughts. Trend analysis of changes in precipitation amount and intensity in Latvia (Fig. 7, 8) at first reveal changes in the precipitation amount distribution on a yearly basis. For example, our study demonstrated a statistically significant increase (in most of the meteorological stations) in annual total precipitation amount (Ptot) in wet days (precipitation amount ≥ 1mm) and major changes in a simple daily intensity index (SDII - annual total precipitation divided by the number of wet days (precipitation amount ≥ 1.0mm) in the year) stressing significant changes in the precipitation intensity character and consecutively in the damaging potential of the heavy precipitation events. At the same time, the number of consecutive dry days (CDD - annual maximum number of consecutive days with precipitation amount <1mm) does not have well expressed trends of changes at all, but the number of consecutive wet days (CWD - annual maximum number of consecutive days with precipitation amount ≥1mm) has a statistically significant increasing trend only in 5 stations (out of 14) ((Fig. 8).

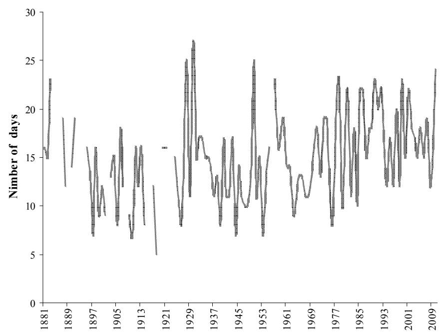

Fig. 9. Long-term trends in the number of days with heavy precipitation (daily precipitation amount ≥ 10 mm) in Rīga-University observation station over the period 1881-2010

In all of the meteorological observation stations studied there has been an increase in the number of days with heavy precipitation (R10 - daily precipitation total ≥ 10 mm), and very heavy precipitation (R20 - precipitation amount ≥20 mm) and also in the number of very wet days (R95p - annual total precipitation when precipitation amount>95th percentile) and extremely wet days (R99p - annual total precipitation when precipitation amount>99th percentile). For most of the observation stations in the territory of Latvia the trends of precipitation intensity changes are increasing and statistically significant (Fig. 8), however, it becomes evident that impacts of regional factors are affecting the precipitation regime. Thus, for example, the number of extremely wet days in Priekuļi is significantly decreasing (Fig. 10), reflecting the importance of the local relief as a factor affecting precipitation regime. Also the well-expressed increase in the number of days with heavy precipitation in Rīga (Fig. 9) especially evident throughout the past ~80 years could be associated with the influence of the Gulf of Rīga and the urban climate specifics [7].

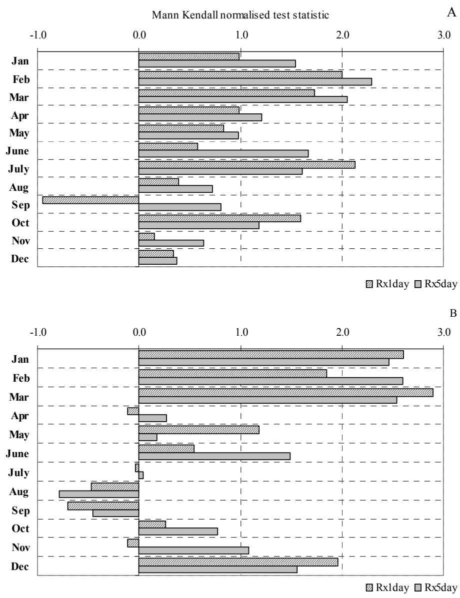

Fig. 10. Long-term trends of monthly maximum 1-day and 5-day precipitation amount in Mērsrags and Priekuļi observation stations over the period 1950-2010 (Mann-Kendall test statistics).Rx1day - Max 1-day precipitation amount (monthly maximum 1-day precipitation); Rx5day - Max 5-day precipitation amount (monthly maximum consecutive 5-day precipitation). A – Mērsrags (3.2 m a. s. l.); B – Priekuļi (117 m a. s. l.)

Also maximum 1-day precipitation amount (Rx1day - annual or monthly maximum 1-day precipitation) and maximum 5-day precipitation amount (Rx5day - annual or monthly maximum consecutive 5-day precipitation) demonstrate the overall redistribution of the precipitation intensity, but changes from station to station (Fig. 10).

IV. Conclusions

The analysis of the long-term trends in the occurrence of extreme temperature and precipitation events demonstrates significant changes in climate variables throughout the territory of Latvia. There has been a significant increasing tendency in the number of days with high temperature extremes and a decrease in the number of days with extremely low air temperatures in most of the observation stations included in this study. The overall warming tendency evident in both the mean values and extremes of air temperature as well as the increased occurrence of heat waves that is even more significant in the major cities of Latvia should raise the awareness of the necessity for adaptation actions, as extreme heat can have a significant negative effect on human mortality and morbidity. The increase in extreme precipitation has a local character, however such events can also have a strong negative influence to both human health and infrastructures. It is expected that future climate change will result in a further increase in both extreme precipitation and heat events in Latvia.

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PAPER 3: DYNAMICS AND IMPACTING FACTORS OF ICE REGIMES IN LATVIA INLAND AND COASTAL WATERS

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DYNAMICS AND IMPACTING FACTORS OF ICE REGIMES IN LATVIA INLAND AND COASTAL WATERS

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The sea ice regime is considered to be a sensitive indicator of climate change. This study investigates long-term changes in the ice regimes of the Gulf of Riga along the coast of Latvia in comparison with those of inland waters. The ice regime of the studied region indicates the impact of climate change related to increasing air and sea water temperatures. Ice cover duration on both the sea and inland waters has decreased during recent decades. In addition, long-term records on ice break in the studied region exhibit a pattern of periodic changes in the intensity of ice regime, while trends of the sea ice regime are not consistent between periods of time. Alternating mild and severe winters also occur. The ice regime was shown to be strongly influenced by large-scale atmospheric circulation processes over the North Atlantic, as indicated by close correlation with the North Atlantic Oscillation index.

Key words: *ice regime, coastal waters, large-scale atmospheric circulation, climate change.*

INTRODUCTION

Records of the dates of ice freeze-up and break-up are good indicators to assess inter-annual and seasonal climate variability, especially in relation to long-term climate change (Beltaos and Burrell, 2003; Johannessen *et al*., 2004; Saucier *et al*., 2004; Laidre and Jorgensen, 2005; Granskog *et al*., 2006; Sooaar and Jaagus, 2007; Sarauskiene and Jurgelenaite 2008). There are three major reasons for studying sea ice regimes: a) the calendar dates of formation and thawing of ice cover have been recorded for a long period, b) ice conditions are sensitive and reliable indicators of climate, and c) sea and coastal ice regimes affect ship transport, fishery, and other aspects of the economy (Takács and Kern, 2015).

Temperature change and ice regimes have been observed to be related with the North Atlantic Oscillation (NAO) pattern (Hurrell and van Loon, 1997; Osborn *et al*., 1999) of large-scale anomalies in North Atlantic atmospheric circulation. Similarly, Southern Oscillation has been argued to exert influence over the ice regime in the Northern Hemisphere (Robertson *et al*., 2000). The so-called positive phases of NAO (associated with strong westerly winds and increased flow of warm and moist air to Western Europe) cause warmer winters, their later start and early springs (Chen and Hellström, 1999; Paeth *et al*., 1999). Changes in air temperature and in the occurrence of rainfalls influenced by airflow from the North Atlantic (indicated by NAO) significantly affect the ice regime (Loewe and Koslowski, 1998). In addition, a major factor possibly affecting the ice regime is global warming (Morse and Hicks, 2005; Lind *et al*., 2016). The records made during the last two centuries on ice break-up dates on rivers in the Northern Hemisphere provide consistent evidence of later freezing and earlier break-up (Magnuson *et al*., 2000). Several studies have analysed ice regime trends for inland waters (Beltaos, 1997; Benson *et al*., 2000; Hodgkins *et al*., 2002). Such studies are facilitated by the fact that easily identifiable parameters describing ice break-up have been recorded for a long period of time. These studies have clearly shown long-term changes in climate and have also argued that natural processes and the ice regime in Northern Europe are related to changes in NAO (Yoo and D'Odorico, 2002). The ice conditions of the Baltic Sea have been previously studied using a historical time series of ice break-up at the port of Rīga (Jevrejeva, 2001) and along the coastline of Estonia (Sooaar and Jaagus, 2007). However, the ice regime of inland waters in Latvia, especially in association with changes of the regime in coastal waters, has not been studied, and the factors affecting major fluctuations of the ice regime have not been identified.

The aim of this study was to determine the character of long-term changes of the sea ice regime along the coastline of Latvia, in relation to long-term climate change (temperature) and large-scale atmospheric circulation processes (the North Atlantic Oscillation, NAO).

DATA SOURCES AND METHODS

Data on ice regime (formation of permanent ice cover, ice break-up, and calculated length of ice cover) were extracted from bulletins of hydrological observations (1925–2013) at the Latvian Centre of Environment, Geology, and Meteorology. The time series of the River Daugava ice break-up dates were first published by P. Stakle (1931). Air temperature records at the Rīga–University Meteorological Station were obtained for the period from 1795 to 2013. During the studied period (1925–2013), the sampling and observation methods followed standard approaches and historical observations were re-evaluated to adjust them to the existing principles of time measurement (Stakle, 1931). This study used only observation data, and no data were substituted. The locations of sampling sites and regular monitoring stations are shown in Figure 1.

Fig. 1. Locations of stations for observation of sea ice (•) (1949–2013) and inland ice (▲) (1949–1999) regimes in Latvia.

To determine relationship to wide-scale climatic forcing factors, we used the extended North Atlantic Oscillation (NAO) index (Luterbacker *et al*., 2002). The NAO index data are classified in three categories: high (NAO 1) – strong westerly, normal (NAO ~ 1) and low (NAO –1) – weak westerly. To identify climatic turning points, the recently suggested Baltic winter index (WIBIX) (Hagen and Feistel, 2005) was used. This derived climate index is based on monthly values of the first principal components of: a) winter anomalies (January – March) of air pressure difference between Gibraltar and Reykjavik to describe the North Atlantic Oscillation, b) sea level anomalies of Landsort (Sweden) to characterise the filling level in the Baltic Proper, and c) maximum Baltic ice cover, to include the influence of continentally dominated alignments of atmospheric centres in action. The resulting time coefficients are regressively computed by corresponding winter anomalies in air temperature over central England. Severe (continental, WIBIX < 0) and mild (maritime, WIBIX > 0) winter types alternate, and the associated turning points characterise climate regime shifts.

The non-parametric Mann–Kendall test for monotone trends in time series of data grouped by sites, plots and seasons was chosen for determination of trends, as this is a relatively robust method concerning missing data and has no strict requirements regarding data heteroscedasticity. The Mann–Kendall test was applied separately to each variable at each site at a significance level of $p < 0.05$. A trend was considered as statistically significant at the 5% level if the test statistic was greater than 2 or less than –2. The COND/MULTIMK code (Libiseller and Grimvall, 2002) was used for trend analysis.

RESULTS

The beginning of ice formation. Ice development begins in Pärnu Bay, where the first new ice formation occurs in the middle of December (Table 1). Thereafter, the ice-covered area extends along the north-eastern coast of the Gulf of Riga. In mid-January, its width is 5 to 6 nautical miles on average. At the same time, new ice formations near the southern and western coasts of the gulf occur.

The most intensive ice development occurs in February, when, under favourable conditions, the Gulf of Riga becomes completely ice-covered. In the middle of the month, the pack ice brought by currents freezes and covers Irbe Strait with rigid and ridged ice. At the same time, the width and thickness of the fast ice increases along the rest of the gulf coastline, and various ice forms intensively develop

Table 1

BASIC CHARACTERISTICS AND ICE REGIME OF THE STUDY SITES IN LATVIA AND ITS COASTLINE

River-sampling station	Length of observations, years	Mean date of freeze-over	Mean date of break-up	Average number of days with ice cover	Decrease, day/10year $p = 0.17$ (95%)
Baltic Sea – Liepāja	1949–2013	24 Dec	03 Mar	71	2.8
Baltic Sea – Ventspils	1949–2013	26 Dec	27 Mar	76	3.0
Baltic Sea – Kolka	1950–2013	03 Jan	22 Feb	58	2.5
Gulf of Rīga – Mērsrags	2000–2013	24 Dec	03 Mar	53	0.7
Gulf of Rīga – Jūrmala	2000–2013	02 Jan	05 Mar	52	0.2
Gulf of Rīga – Salacgrīva	1949–2013	12 Dec	12 Mar	64	2.7
Venta – Kuldīga	1926–2013	02 Dec	22 Mar	65	3.2
Gauja – Sigulda	1939–2013	01 Dec	30 Mar	78	4.1

also in the central part of the gulf. In moderate winters, the Gulf of Riga and Irbe Strait become completely ice-covered by the end of the month. However, during severely cold winters, a solid and rigid ice cover over the Gulf of Riga may form already in the middle of January, whereas in mild winters, the gulf may remain mostly ice-free throughout the winter season.

The development of pack ice usually begins in coastal waters and extends in parallel to isobaths. However, its development is uneven, reflecting alterations of the cold and warm spells. The pack ice maximum occurs in late February to early March, and, during moderate and severe winters, pack ice completely covers both the Gulf of Riga and Irbe Strait.

During winters, the surface water is cooled so much that ice may form also at the coastline of the Baltic Sea. However, the expansion of ice varies widely from year to year, depending on whether the weather is mild or cold. The water territories concerned are mostly ice-free and are covered with ice only during the most severe winters. However, the ice is mostly thin and fragile, and, if the wind direction is favourable, the ice rapidly floats from the shore into the open sea. In the coastal waters of the Baltic Sea, the ice development begins at the end of December, sometimes in the middle of November.

The disappearance of ice. With the prevailing westerly winds, the ice break-up begins in the western part of the Gulf of Riga and gradually progresses to the east. The first area of the gulf to become ice-free is Irbe Strait, followed by the western and southern parts of the Gulf. In the north and north-eastern areas, in turn, the melting and rotten pack ice remains for the longest periods.

During late and cold springs, there can be some differences in the disappearance of ice: at first, the ice disappears in the comparatively shallow north-eastern part of the Gulf of Riga, as the water temperature begins to rise due to the river inflow. In this case, the pack ice remains in the central part of the gulf for longer.

The length of the ice season. The average length of the ice season is the longest in Pärnu Bay and in the northern part of the Gulf of Riga, where it is 145 days or almost five months. The shortest ice season of two months is characteristic of the south-western part of the Gulf of Riga, Irbe Strait and near the Latvian coast of the Baltic Sea. In the southern part of the gulf, as well as in the area near Kolka, the average ice season is two to three months long. The maximum observed ice season length in the Gulf of Riga is 168 days, and in the coastal waters of the Baltic Sea — 127 days. The most severe winter during the observation period was in 1941/1942. During this winter, the maximum ice cover at the coastline of the Baltic Sea was observed at the end of March to beginning of April, with ice thickness of about 60 cm. The ice thickness was 55.7 cm, 6.4 km from the coast near Liepāja and 48.6 cm at distance 14.5 km from Ventspils.

Changes in the length of the ice season at the coastline of Latvia. The ice conditions are observed in six marine observation stations in Latvia (Fig. 1). The stations of Ventspils and Liepāja, which are situated east of the central part of the Baltic Sea, represent the ice conditions characteristic for the open part of the sea, where usually the concentration of ice is the smallest and the length of the ice season — the shortest. The Kolka station represents ice conditions in the shallow Irbe Strait, and the Mērsrags station represents conditions of the western part of the gulf. These two stations are situated in an area of comparatively rapid changes in the concentration of ice, as the ice tends to break up and drift to the east with the prevailing westerly winds, forming ice-free areas. The Jūrmala observation station represents the shallow southern coast of the gulf. The Salacgrīva station represents the north-eastern part of the gulf, where ice expansion usually is the greatest and the ice season is the longest.

During the past ~150 years, there has been a significant increasing trend in the values of air temperature, which is even more obvious during winter seasons (Klavins *et al.* 2002). The changes in air temperature have also led to significant changes in ice conditions both at the Latvian coastline of the Baltic Sea and in the Gulf of Riga (Jevrejeva, 2001). A significant decreasing tendency of the length of ice season for the period of 1949–2013 was observed (Table 2) at the coastline of the Baltic Sea (Fig. 2), and even a more significant decreasing trend was observed in the Gulf of Riga (Fig. 3).

Ice conditions during the first decade of the 21st century (2001–2011). Although the length of ice season has significantly decreased over a longer period (Gebre *et al.*, 2014), during the past decade, there still have been some winters with substantial ice cover over the coastal waters of Latvia (for example, in winter 2012/2013). The total number of days with ice cover for the past ten years remains rather high: from 452–491 days at the coastline of the Baltic Sea up to 677–757 days in the Gulf of Riga (Fig. 4), with average annual ice season length of 45–49 and 68–76 days, respectively. During the past decade, the mildest winters with the lowest abundance of ice cover were in winters of 2001/2002, 2006/2007 and 2008/2009, when the development of sea ice was of a short range and present only in some areas of the coastal waters. In contrast, the winters of

Table 2

LONG TERM TRENDS OF ICE COVER DURATION ACCORDING TO THE MANN–KENDALL NORMALISED TEST STATISTICS

River-sampling station	Period of observation	Normalised test statistic	*p*-value (one-sided test)
Baltic Sea – Liepāja	1949–2013	–2.61	0.009
Baltic Sea – Ventspils	1949–2013	–3.34	0.009
Baltic Sea – Kolka	1950–2013	–2.85	0.014
Gulf of Rīga – Salacgrīva	1949–2013	–4.42	0.001
Venta – Kuldīga	1926–2013	–1.21	0.113
Gauja – Sigulda	1939–2013	–2.87	0.002

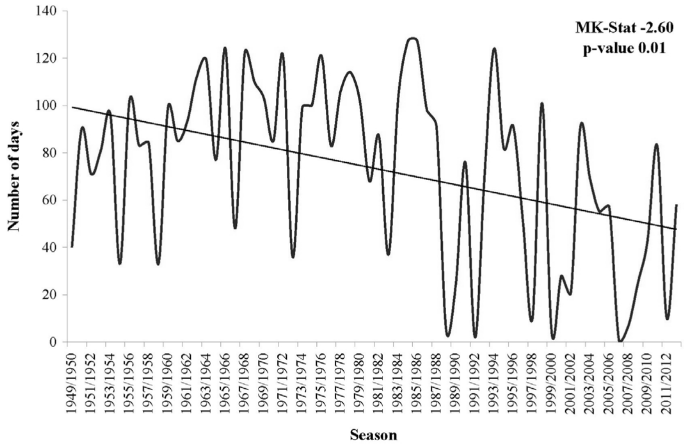

Fig. 2. Trend in the length of ice season in the coastal areas of the Baltic Sea (Liepāja) for the period of 1949–2013.

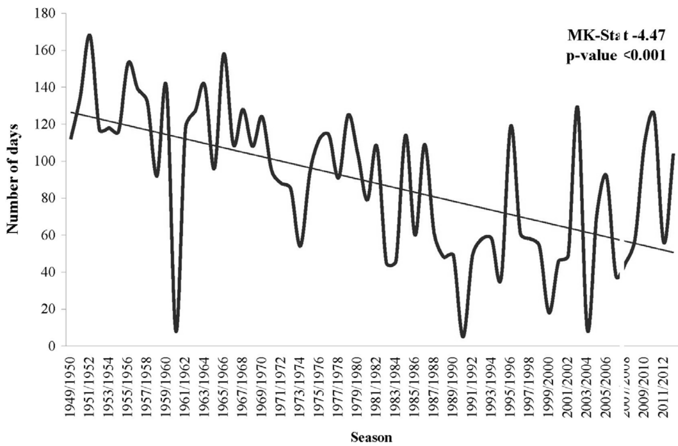

Fig. 3. Trend in the length of ice season in the coastal areas of the Gulf of Riga (Salacgrīva) for the period of 1949–2013.

2002/2003, 2010/2011 and 2012/2013 were the most severe during the past decade.

During the winter of 2010/2011, the cold spell lasted for a long period of time. In many observation stations of Latvia, the minimum temperature records were broken. The development of ice occurred rapidly, and the Gulf of Riga was completely ice-covered already by the middle of February (Fig. 5).

The changes in the duration of ice cover can be strongly associated with the changes in its formation time. In the last decades, a stable ice cover (except in severely cold winters) appeared later (Fig. 6) and melted earlier (Fig. 7).

DISCUSSION

A comparison of the ice regime on Latvian inland rivers and the ice regime along the coastline of Latvia (Figs. 8, 9) indicates that it is longer on inland water bodies, but these values are significantly correlated. However, in case of rivers, processes in their basins also play an important role, and, therefore, the correlations are far from 100%.

During the last decades, a significant increase in air temperature has been recorded in the Baltic region and Latvia. The seasonal air temperatures, according to the records of the Rīga-University meteorological station, have changed substantially over the last 200 years (1795–2013). The annual mean temperature has increased by 1.1 ^{o}C, and the trend is significant (test statistic 4.37; $p = 0.0000$). However, the increase in temperature has not been similar among seasons. The highest increase in air temperature was observed for spring (2.1 ^{o}C, test statistic 5.18; $p = 0.000$) and winter (1.9 ^{o}C, test statistic 2.77; $p = 0.0028$) seasons. A smaller increase in temperature (by 0.5 ^{o}C, test statistic 1.81; $p = 0.03$) was typical for the autumn season. There was no trend observed for summer temperatures covering the entire pe-

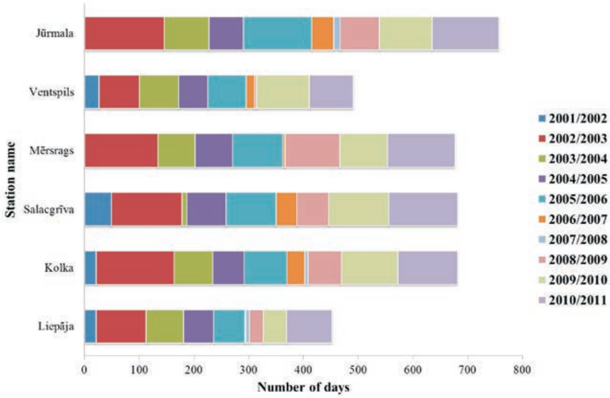

Fig. 4. Annual and total lengths of ice season at six marine observation stations of Latvia for the period of 2001–2013.

riod from 1795 to 2002. Compared to the 30-year mean (1961–1990), the lowest mean temperature occurred for annual and seasonal temperatures (autumn, spring and summer) during the period from 1830 to 1930. Winter season temperatures have been increasing gradually since the 19th century, and the long-term minimum was not reached during the 1830–1930 period. Notable increases in winter and spring air temperatures have been observed since the 1970s (Lizuma *et al*., 2007).

Furthermore, not only air temperature but also water temperature in the Baltic Sea and the Gulf of Riga has increased significantly (Fig. 10), evidently affecting the sea ice regime. Similar trends have been found at all studied stations for changes in both maximal and minimal water temperatures, especially for changes in water temperatures in the autumn (September, October, November) and winter seasons (December, January, February).

Processes over the North Atlantic appear to have a significant influence on the climate in the Baltic region, especially during winter (December, January, and February) and cold seasons (October–April) (Figs. 11, 12).

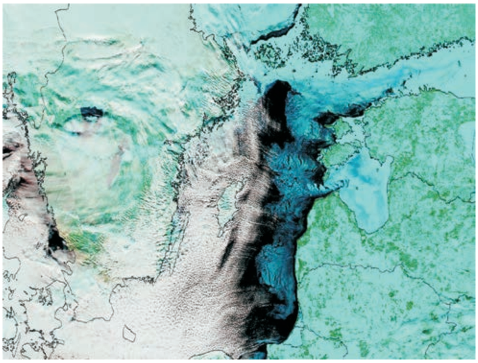

Fig. 5. Ice conditions in the coastal areas of Latvia on 21 February 2011 (MODIS Aqua image; channel combination 7–2–1; spatial resolution 1 km).

Figures 11 and 12 depict the winter period series of the NAO index during the second half of the 20th century and the number of days with ice cover. A strong negative correlation between the NAO index and the number of days with

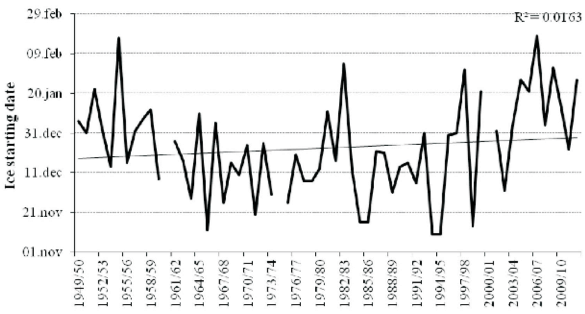

Fig. 6. Long-term changes in the starting date of ice cover appearance at Liepāja.

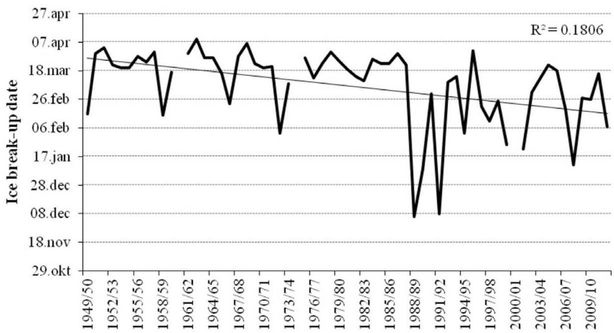

Fig. 7. Long-term changes in the break-up date of ice cover at Liepāja.

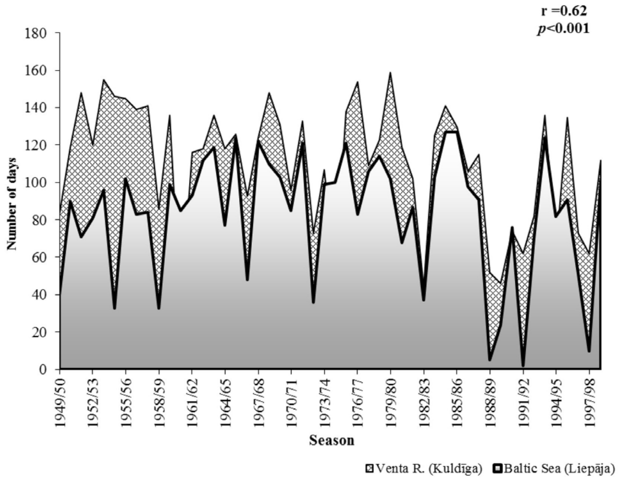

Fig. 8. Correlation of the duration of ice cover in a coastal zone of the Baltic Sea (at Liepāja)

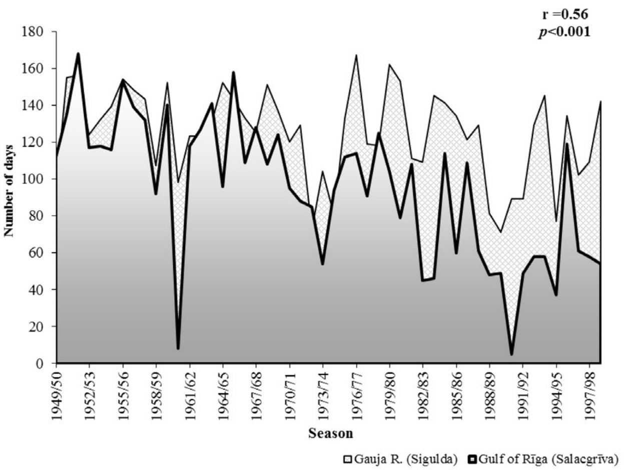

Fig. 9. Correlation of the duration of ice cover in a coastal zone of the Gulf of Riga (at Salacgrīva) and the River Gauja (Sigulda).

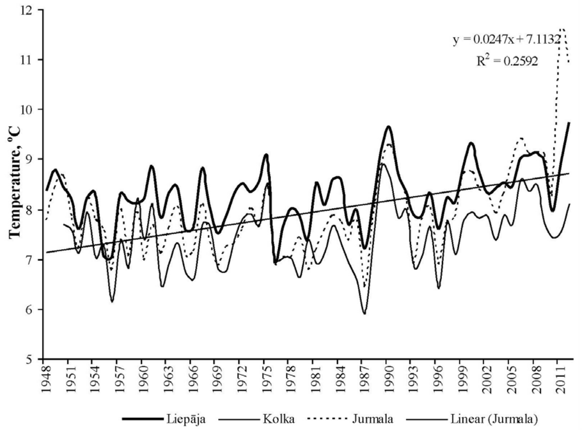

Fig. 10. Changes in the annual average water temperature at Liepāja, Kolka, and Jūrmala.

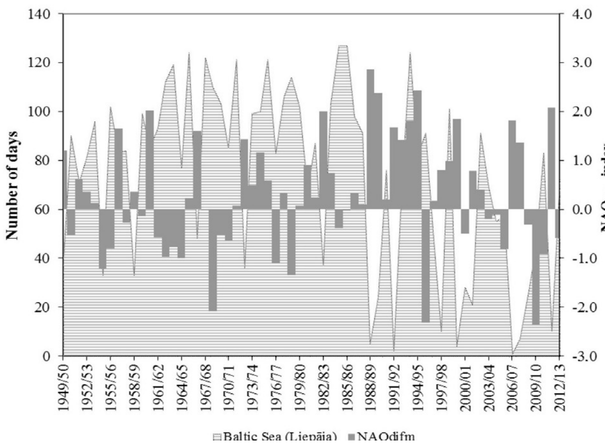

Fig. 11. Correlation (r = –0.44, *p* 0.001) between the prolongation of ice cover duration on the Baltic Sea at the coastline of Latvia (Liepāja) and the NAO winter index.

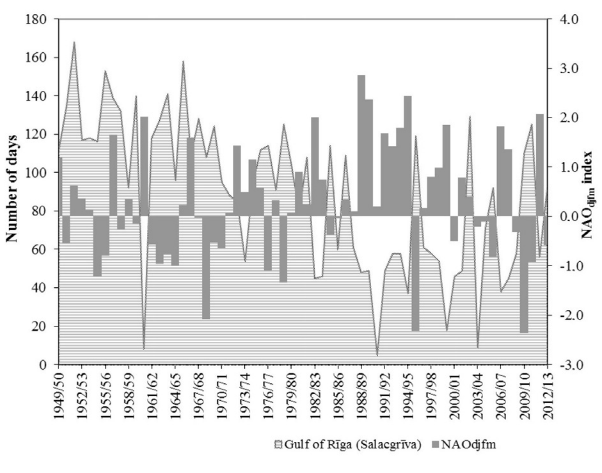

Fig. 12. Correlation (r = –0.51, *p* 0.001) between the prolongation of ice cover on the Gulf of Riga at the coastline of Latvia (Salacgrīva) and the NAO winter index.

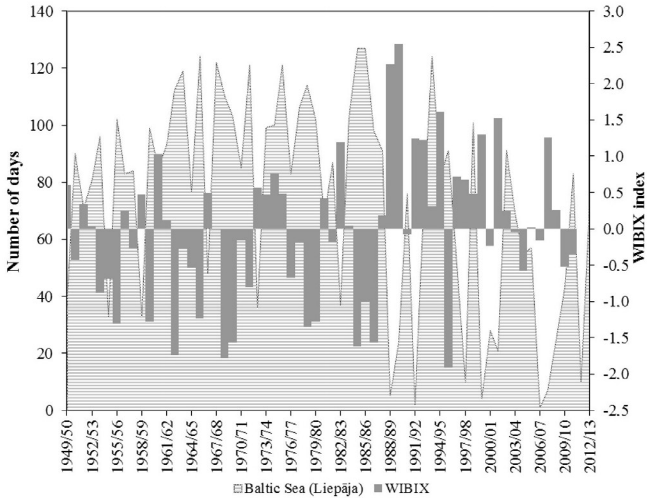

Fig. 13. Correlation (r = –0.64, $p < 0.001$) between the prolongation of ice cover on the Baltic Sea at the coastline of Latvia (Liepāja) and the WIBIX index.

ice cover along the coastline of Latvia exists, indicating that large-scale atmospheric circulation processes over the North Atlantic greatly influence the winter climate in the Baltic region. NAO has been observed to influence winter precipitation with varying intensity along the Norwegian coast, in northern Sweden and in southern Finland, where terrain plays an important role (Uvo, 2003). The strong correlation found in our study highlights the fine linkages between the large-scale NAO forcing factors and the regional scale climate processes in the Baltic region. Moreover, the negative correlation between winter temperatures and NAO indexes has become stronger during the last 100 years (Marshall *et al*., 2001; Hagen and Feistel, 2005; de Rham *et al*., 2008). Changes in ice regime can also be directly related to the recently suggested (Hagen and Feistel, 2005) derived Baltic winter climate index (WIBIX) (Fig. 13), which is better correlated with the parameters describing ice regime than the NAO winter index.

A strong negative correlation between the NAO index, the WIBIX index and the ice-break up events shows that processes over the North Atlantic are the driving force for the sea ice regime at the coastline of Latvia. In winter, an intense westerly circulation moves fronts and air masses through the mid-latitudes, while it weakens considerably during the warm period, and the majority of precipitation events occur due to different processes.

CONCLUSIONS

The duration of ice cover on the Baltic Sea and the Gulf of Riga has been decreasing during the last 60 years and is related to later start and earlier melt of the ice cover. There are significant differences in respect to ice cover in the Gulf of Riga and at the coastline of the Baltic Sea. The time of ice break-up depends on global climate change and can be related to increasing air and sea water temperatures. However, the trends of sea ice regime are not consistent over different periods, and there are also alternating mild and severe winters. The sea ice regime appears to be greatly influenced by large-scale atmospheric circulation processes over the North Atlantic.

ACKNOWLEDGEMENTS

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LATVIJAS IEKŠZEMES UN PIEKRASTES ŪDEŅU LEDUS REŽĪMA DINAMIKA UN TO IETEKMĒJOŠIE FAKTORI

Jūru ledus režīms uzskatāms par klimata pārmaiņu jutīgu indikatoru. Pētījuma mērķis ir analizēt Latvijas piekrastes un Rīgas līča ledus režīmu, salīdzinot to ar iekšzemes ūdeņiem. Latvijas iekšzemes un piekrastes ūdeņu ledus režīms uzrāda globālās sasilšanas ietekmes, un tā pārmaiņas ir saistāmas ar gaisa un jūras ūdens temperatūras izmaiņām. Latvijas iekšzemes un piekrastes ūdeņu ledstāves ilgums pēdējās desmitgadēs ir samazinājies, bet vienlaikus iezīmējas klimatisko pārmaiņu periodiskuma ietekme. Ledus režīmu raksturo gan maigu, gan aukstu ziemu periodiska nomaiņa, un to ietekmē liela mēroga atmosfēras cirkulācijas procesi virs Atlantijas okeāna, ko pierāda cieša korelācija ar Ziemeļatlantijas oscilācijas indeksu.

PAPER 4: FOG CLIMATOLOGY IN LATVIA

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ORIGINAL PAPER

Fog climatology in Latvia

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Abstract Fog has been recognised as a hazardous weather phenomenon that can cause accidents and affect urban air quality negatively. Therefore, assessing the characteristics of fog formation, as well as the changes in fog frequency and intensity as a result of climate change is of high importance. This study covers a 52-year period and contains an analysis of the frequency of fog occurring, long-term changes in fog frequency and atmospheric conditions that favour the occurrence of fog events in Latvia. During the analysis, two inter-annual maxima of fog frequency were identified in the spring and autumn; the seasonal differences in the formation of fog were also confirmed using satellite observations of low-level cloudiness. However, the long-term changes of fog frequency showed a decrease tendency of fog to form, which may be associated with improvements in air quality since industrialization and the observed increase of air temperature.

1 Introduction

Fog has been recognised as a hazardous weather phenomenon worldwide; it can cause accidents and negatively affect urban air quality, especially in combination with the impact of air pollutants (Lange et al. 2003; Singh and Dey 2012). The total economic loss associated with the impact of fog can be comparable to losses caused by tornadoes or, in some cases, winter storms and hurricanes (Niu et al. 2010). Problems with traffic flow such as flight delays, and automobile and marine accidents due to poor visibility can be considered as the most common negative effects of fog (Cermak and Bendix 2008; Heo et al. 2010). At the same time, fog can be associated with critical conditions in air pollution, resulting from air pollutants becoming trapped in the fog droplets and reaching high concentrations, causing the formation of smog or in some cases acid fog (Bendix 2002; Błas et al. 2002; Witiw and LaDochy 2008; Syed et al. 2012). However, fog, acting as a source of humidity, is also very important to the health of ecosystems and humans (Sachweh and Koepke 1997; Cereceda et al. 2002; Lange et al. 2003; O'Brien et al. 2012). In addition, fog has an important role in maintaining radiation balance and, as a result, long-term changes in the frequency of fog can play an important role in the accuracy of climate model predictions (Bendix 2002).

Fog is a very local phenomenon that can form as a result of advection, radiative cooling or a weather front moving over an area; its frequency and spatial distribution is closely related to orography and proximity to the sea (Błas et al. 2002; Witiw and LaDochy 2008; Syed et al. 2012; O'Brien et al. 2012). The high fog frequency at higher elevations is usually a product of orographic cooling (Lange et al. 2003), and the most frequent category of fog observed at these sites is slope fog, which forms as humid air ascents mountain slopes to an altitude of 1,000–1,600 m above sea level (Błas et al. 2002). However, over higher mountain ranges, such as the Alps, a reduced frequency of fog or a lack of fog coverage are observed, owing to a decrease in humidity (Bendix 2002). The occurrence of fog is also related to atmospheric circulation and the local geographical features of a site, so it differs in different parts of the world (Cereceda et al. 2002); for example, fog frequency in Taipei is the highest during March, which is the month when

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the minimum fog frequency can be observed in Mexico (Tsai et al. 2007; Garcia-Garcia and Zarraluqui 2008). Under the influence of diurnal changes in air temperature, the maximum occurrence of fog is characterised as being between 4–6 a.m. and the minimum during 1–3 p.m. To assess the intensity of fog, the measurements of horizontal visibility or the persistence of fog can be used (Sachweh and Koepke 1997; Błas et al. 2002).

In many sites in the industrialised world, the most intense fogs, in both persistence and density, were observed in the 1940s and 1950s, when some famous low-visibility episodes occurred in combination with heavy air pollution, such as the Great Smog of London in 1952 (Met Office 2005). During this event, visibility below 10 m lasted for nearly 48 h in Heathrow; such intense and persistent low visibility is almost unheard of today (Met Office 2005; Witiw and LaDochy 2008). Since this time, owing to the introduction of clean air legislation and a decrease in total suspended particulates, fog climatology has changed considerably and many sites have experienced a decrease in fog frequency (Bendix 2002; Witiw and LaDochy 2008; Shi et al. 2008). Owing to the anthropogenic factors influencing the climate in urban areas, studies have demonstrated a decrease in the annual number of fogs in big agglomerations, which could be connected with the growth of cities and the resulting decrease in natural surfaces (Sachweh and Koepke 1995; Shi et al. 2008). However, in developing countries such as India, with rapidly growing industry and rising anthropogenic emissions, the frequency of fog events has increased and visibility has rapidly decreased over the past 30 years (Singh and Dey 2012; Syed et al. 2012).

This study investigates the climatic characteristics of fog occurrence in Latvia. In general, the climate in Latvia is influenced by its location in the northwest of the Eurasian continent (continental climate impacts) and by the proximity of the Atlantic Ocean (maritime climate impacts). A highly variable weather pattern is a result of the strong cyclonic activity over Latvia. These variable conditions over the territory contribute to differences in the regimes of air temperature and humidity (Avotniece et al. 2010; Klavins and Rodinov 2010; Lizuma et al. 2010) and to the spatial heterogeneity in the occurrence of fog. Fog can be classified by its formation through the processes of advection, radiative cooling or a mix of both processes (Ahrens 2007), and throughout the year, each of these processes can trigger the formation of fog in Latvia. Radiation fog forms most frequently in the morning before sunrise, during conditions of high atmospheric pressure and clear skies, when small water droplets form a layer of fog near the Earth's surface due to radiative cooling and condensation processes. It is common for radiation fog to dissipate gradually as the sun rises above the horizon. Advection fog forms in conditions of warm advection over an area; in particular, in Latvia, dense and persistent advection fogs form in the cold half of the year, when the ground is covered with snow. Frequently, advection fogs form due to a warm front moving over a colder area, and these can be accompanied by light precipitation. However, in specific, much rarer conditions, fog can also form under the influence of cold air advection. Such conditions can be observed in Latvia during the summer, when the inflow of cold air triggers the cooling and condensation of the still warm air near the Earth's surface, which can sometimes result in very dense fogs forming that spread over large areas. A common feature of both warm and cold advection fogs is their persistence in comparison to the more temporary radiation fogs and their ability to form during any time of the day. However, in some cases, radiation fogs can gain advective features and spread over large areas for a prolonged period of time.

High-quality observational data of various parameters describing fog are not available in many countries owing to sparse observation networks and, consequently, it is practically impossible to carry out a reliable and spatially coherent analysis of fog distribution based only on the surface observation data (Bendix 2002). However, satellite data can provide important information on the spatial distribution, dynamics and properties of fog (Cermak and Bendix 2008). Despite the importance of fog both from an applied research perspective and in respect to a better understanding of extreme climate events, there have been no studies of fog climatology carried out in the Baltic region. Therefore, the aim of this article is to analyse fog climatology, the trends of changes of fog events and the impact of atmospheric conditions (especially large-scale atmospheric circulation processes) on the occurrence of fog in Latvia, as well as to study the possibility of using satellite data for the climatic characterisation of fog occurrence.

2 Data sources and methods

Daily observation data of fog events and precipitation amount were provided by 14 major meteorological observation stations in Latvia (Fig. 1). The data obtained from the Latvian Environment, Geology and Meteorology Centre covered a 52-year period from 1960 to 2012. Fog is commonly classified by its intensity; however, there are differences in the classifications applied between countries. The classification of fog in Latvia follows the criteria established by the Stare Fire and Rescue Service, which marks three classes of fog: fog with horizontal visibility of 500–1,000 m, fog that reduces the visibility to 100–500 m and fog reducing visibility below 100 m, which is classified as very poor visibility (Latvian Environment, Geology and Meteorology Centre 2011).

In addition to the surface observations, satellite data were also used in the analysis. For the climatological characterisation of the occurrence of fog, satellite observations of low clouds for the period 2008–2013, provided by the Satellite Application Facility on Climate Monitoring (CM SAF), were used as an indicator of the most favourable sites for the formation of fog (CM SAF 2009). Monthly and seasonal

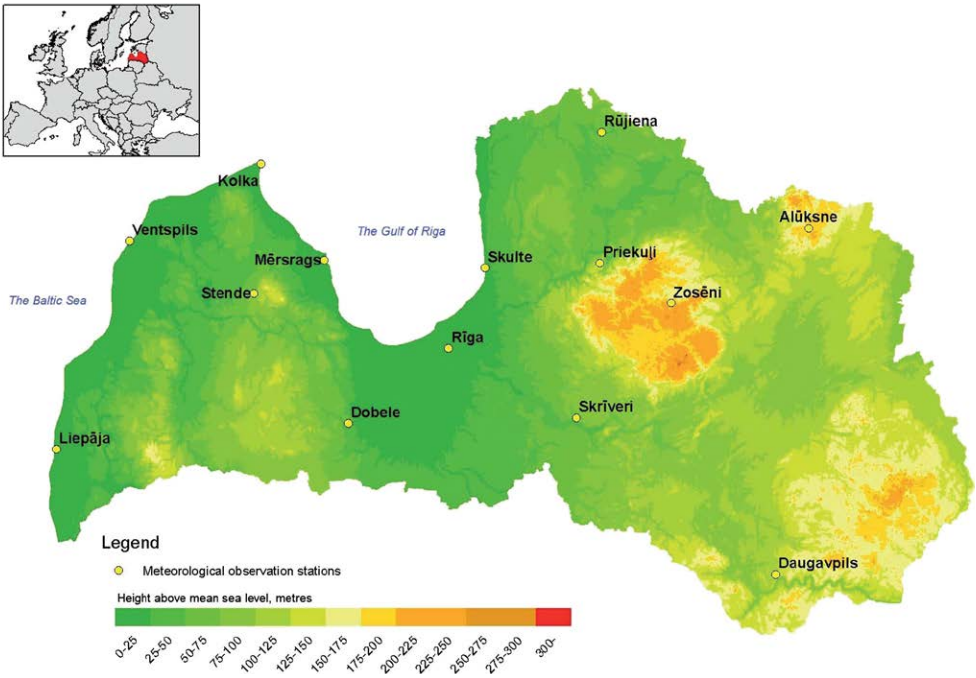

Fig. 1 Geographical locations of 14 major meteorological observation stations in Latvia. The *colours* of the map represent the height above mean sea level, with a maximum of 311.5 m in the eastern part of Latvia

mean amounts of low clouds were calculated from the satellite data with software tools CDO (*Climate Data Operators*) and R and were compared to the surface observation data.

For the characterisation of atmospheric conditions favourable for the occurrence of fog, 18 large-scale atmospheric circulation patterns for the Baltic Sea region, covering the period 1960–2002, were examined. The basis of this classification method of atmospheric circulation patterns was created by Baur, which formed the foundation for the 'Grosswetterlagen' of Hess and Brezowsky that was later reprocessed by Gerstengarbe and Werner (Gerstengarbe et al. 1999). The atmospheric circulation patterns used in this study were derived from modifications to the circulation classification of Gerstengarbe and Werner (Hoy et al. 2013) that have been made available for scientific research by the European Cooperation in Science and Technology Action 733. This classification approach is based on predefined circulation patterns determined according to the subjective classification of the so-called Central European Großwettertypes. It is assumed that these Großwettertypes are defined by the geographical position of major centres of action, and that the location and extent of frontal zones can be sufficiently characterised in terms of varying degrees of zonality, meridionality and vorticity of the large-scale sea level pressure field over Europe (COST733 2012). The abbreviations of circulation type names presented in this study consist of the first letters describing the direction from which the air flows, and the second part describes the synoptic system (cyclone or anticyclone), so, for example, the abbreviation SW-A stands for south-west anticyclonic flow.

Trends in the annual number of days with fog were determined by applying the nonparametric Mann–Kendall test (Libiseller and Grimvall 2002; Salmi et al. 2002). The Mann–Kendall test was applied separately to each variable at each site, at a significance level of $p \leq 0.05$. The trend was considered statistically significant if the test statistic was greater than 1.96 or less than −1.96.

3 Results and discussion

3.1 Climatic characteristics of fog occurrence in Latvia

Fog is a rather frequent weather phenomenon in Latvia, and it can be observed on 19–59 days a year on average (Fig. 2). The

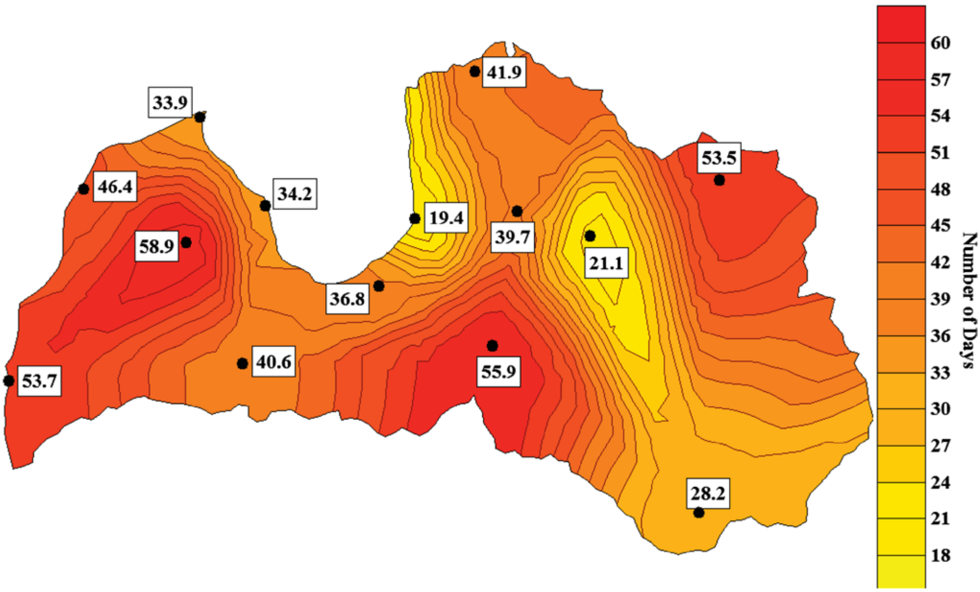

Fig. 2 Annual mean number of days with fog in Latvia during the period 1960–2012. The values over the country are represented by *interpolation on a triangular grid*

formation of fog is closely related to the local geographical features of a site, such as orography and slope exposure, proximity to the Baltic Sea and the Gulf of Riga and the different meteorological processes favourable to the development of fog; therefore, there are significant differences in the annual mean number of days with fog in different regions of Latvia. As a result, fog can be observed most commonly in the western areas of the upland regions of Latvia, while the fog is observed on the lowest number of days in the eastern areas of the uplands and in the coastal areas of the Gulf of Riga. Such a pattern of fog frequency represents the general mechanisms of humidity distribution in Latvia and also cloud formation and precipitation, due to prevailing westerly flows over the country. Overall, to the proximity to the Baltic Sea, fog frequency is greater in the western part of the country.

Figure 3 illustrates the long-term variation in fog frequency in Latvia. The range in the annual number of days with fog in Latvia varies from 0 days in Zoseni (1989) to 110 days in Aluksne (1960); additionally, the annual variations within each station are considerable. For 9 out of 14 observation stations, the data distribution is somewhat positively skewed. In general, the graph shows significant differences in the spatial and temporal distribution of the annual number of days with fog in Latvia.

The inter-annual variability of fog (Table 1) shows significant differences in the months with the maximum occurrence of fog between coastal and inland observation stations. In the inland stations, the maximum fog occurrence is during the second half of the year—between August and December. During the autumn months, radiation fogs form more frequently, while during winter and spring advection fogs gradually become more frequent. Therefore, in the coastal observation stations, the maximum frequency of fog occurs in spring—during March, April and May—when warm advection from the west triggers the formation of advective fogs.

Satellites are considered to be a powerful tool for the observation of fog, as satellite observations provide both wide spatial and temporal coverage, which is essential for the detection and characterisation of such a variable phenomenon. In essence, fog is very similar to low stratus clouds, and it differs from low clouds only by its base being located near the ground (World Meteorological Organization 1992); therefore, for the climatic characterisation of fog occurrence, it is possible to compare the surface observations of fog to the low cloud observations from satellites provided by the CM SAF. If the surface observations of fog and the satellite observations of low clouds in the autumn season (Fig. 4a) during a 6-year period are compared, one can see similar features. The greatest amount of low cloud (up to 47 %) can be observed in the south and west regions of Latvia, while in the coastal areas, the amount of low clouds is smaller. In the winter season, the low cloudiness in Latvia is smaller in general, and it does not

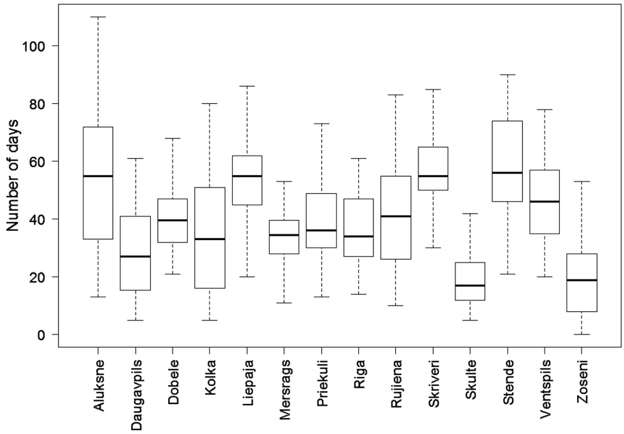

Fig. 3 Variations in the annual number of days with fog in Latvia during the period 1960–2012. The *bold lines* represent the median of the annual number of days with fog, the *upper* and *lower sides of the boxes* describe the upper and lower quartiles, the *whiskers* represent the greatest and smallest annual number of days with fog

exceed 42 % (Fig. 4b). During winter, a more expressed formation of fog is evident, in particular, over the west regions of Latvia, where it may be triggered by the influence of periodic thaws.

In spring, some differences in the low cloud and fog formation processes appear (Fig. 4c). In the western regions, where, under the influence of warm advection from the west, advection fogs form more frequently, the mean amount of low clouds is higher than in other parts of the country and reaches 40–42 %. However, at the same time, in the upland areas of Latvia, a gradual increase in the occurrence of radiation fog begins. In addition, during summer (Fig. 4d), the low cloudiness is greatest over the upland areas, where it reaches up to 40 % of the total cloudiness, owing to the dominance of radiation fogs.

The analysis of fog occurrence during the days with precipitation can also be an indicator of the formation process. As radiation fog commonly occurs in conditions of clear skies, there is usually no precipitation during days with radiation fog. However, in cases of very dense radiation fog, a very small amount of precipitation (up to 0.1–0.2 mm) can be caused by the fog itself. Advection fogs are usually associated with frontal systems, so such fogs are frequently accompanied by precipitation. Figure 5 illustrates the pattern of the

Table 1 Monthly mean number of days with fog during the period 1960–2012. The long-term monthly mean number of days with fog is presented, and for each observation station, the three months with the highest frequency of fog are highlighted in *pink*

	J	F	M	A	M	J	J	A	S	O	N	D
Aluksne	4.9	4.6	4.7	4.2	2.4	1.2	2.5	4.0	5.5	7.3	9.2	7.0
Daugavpils	1.5	2.0	2.4	1.8	2.0	1.3	1.9	3.3	4.3	4.5	3.1	2.6
Dobele	4.2	3.4	4.1	2.9	1.7	1.1	1.6	2.8	4.5	5.3	4.3	4.8
Kolka	2.7	3.3	5.4	5.9	4.6	2.1	1.7	1.9	1.9	2.3	2.6	2.0
Liepaja	3.9	4.6	6.5	7.3	7.1	5.2	3.7	3.7	2.8	4.1	3.7	4.4
Mersrags	2.3	2.4	3.6	4.5	3.4	1.8	2.8	3.6	3.2	3.2	3.2	2.3
Priekuli	3.9	3.9	3.8	3.2	2.7	1.3	2.2	3.8	4.2	4.5	4.8	4.8
Riga	3.3	3.3	3.8	3.0	2.3	1.4	2.3	3.0	3.5	4.2	5.0	4.4
Rujiena	3.6	3.7	3.7	3.1	2.2	1.7	3.0	4.8	5.0	5.2	4.8	4.5
Skriveri	5.2	4.5	4.5	3.1	2.4	2.2	3.5	6.2	4.8	7.3	7.1	6.8
Skulte	1.7	2.3	3.0	2.7	2.5	0.9	0.7	1.3	1.3	1.8	2.0	1.6
Stende	5.5	5.1	5.9	4.9	3.8	3.5	5.3	6.3	4.7	5.5	6.6	6.5
Ventspils	3.7	3.6	5.8	6.8	6.2	4.6	3.4	2.9	2.3	3.0	3.3	3.3
Zoseni	1.3	1.5	1.6	1.6	1.0	0.8	1.4	2.2	2.9	3.1	3.4	2.0

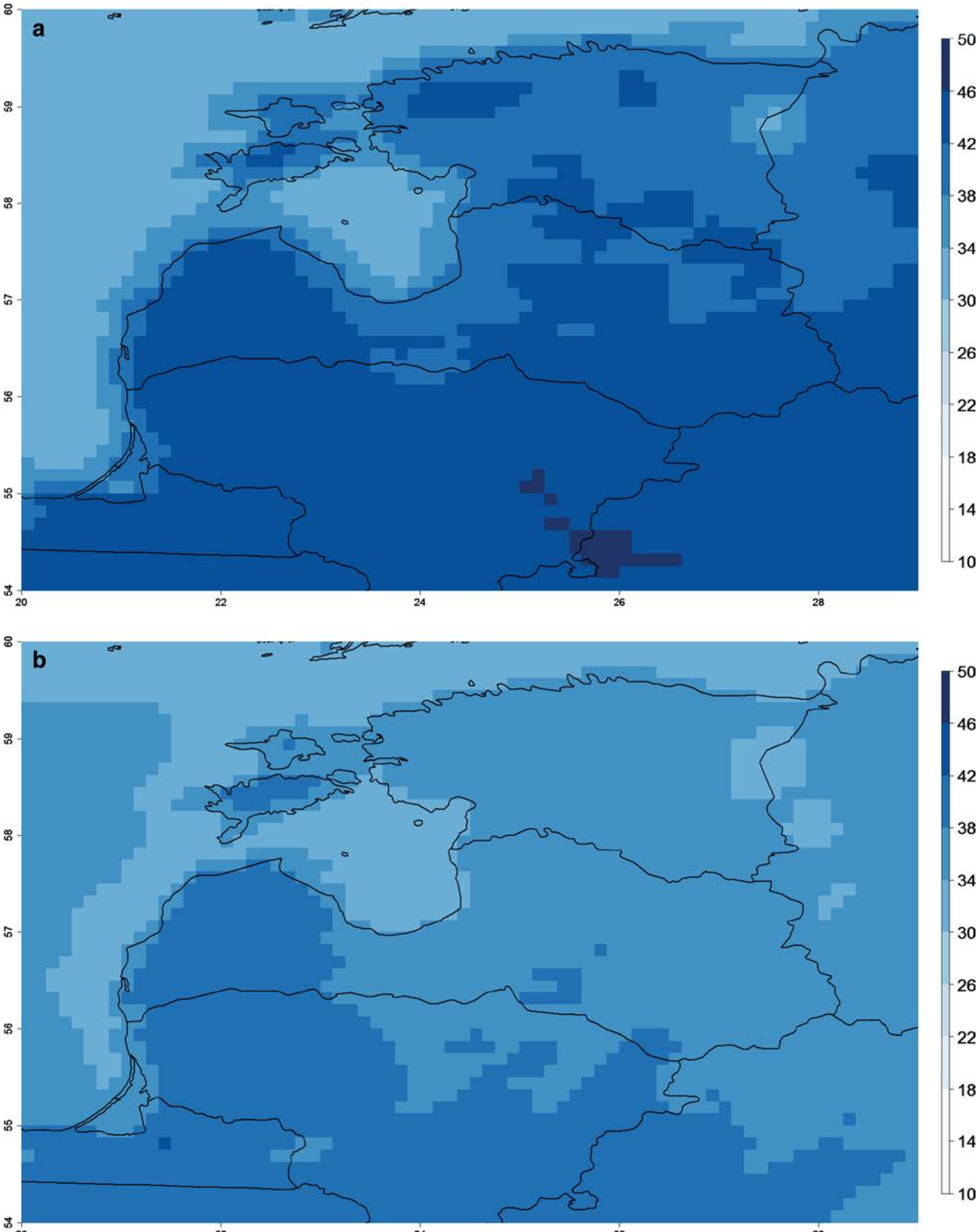

Fig. 4 Mean amount of low clouds (%) **a** in autumn (SON), **b** in winter (DJF), **c** in spring (MAM) and **d** in summer (JJA) during the period 2008–2013. Data obtained from the SEVIRI instrument onboard the MSG satellite with a spatial resolution of 15×15 km

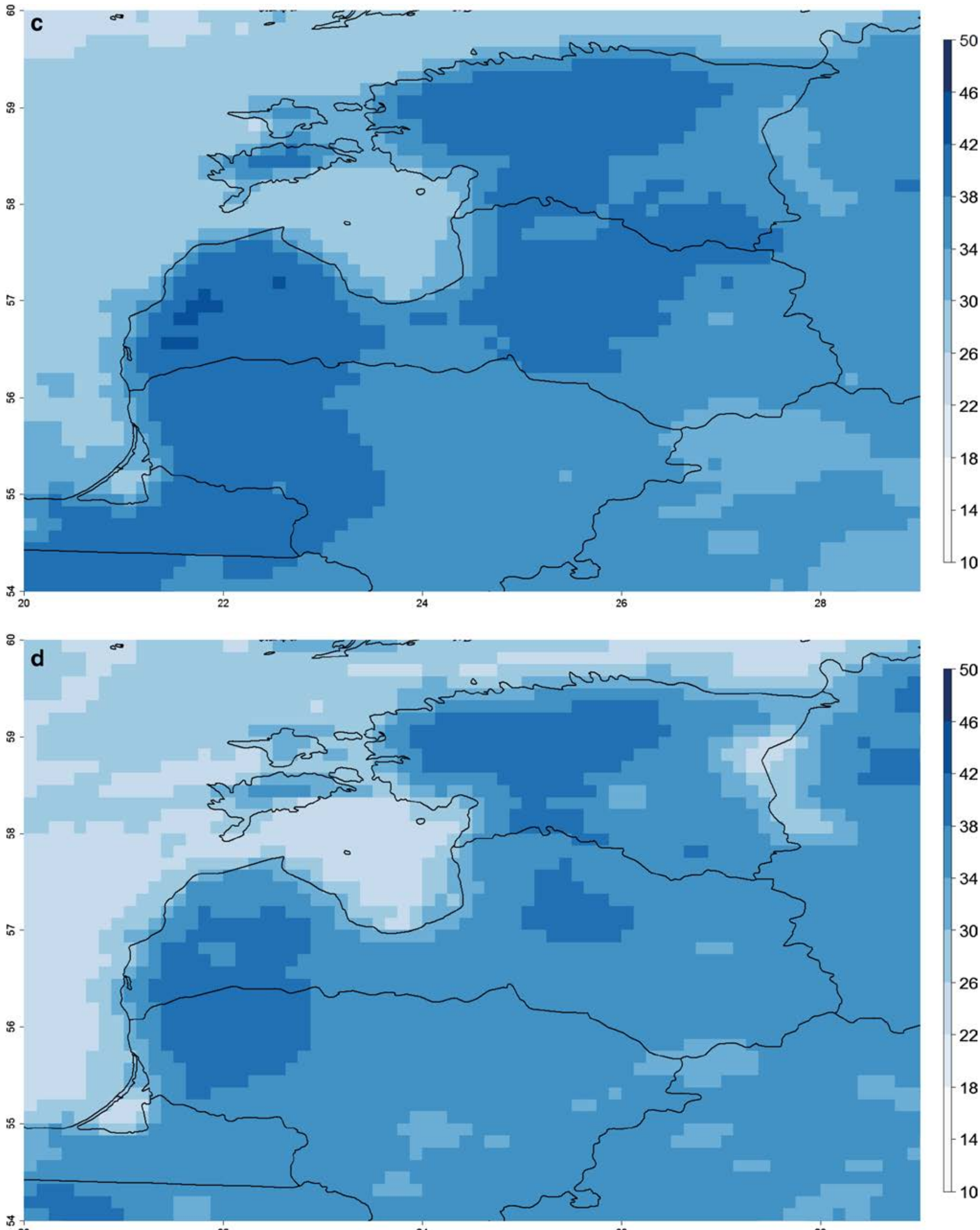

Fig. 4 (continued)

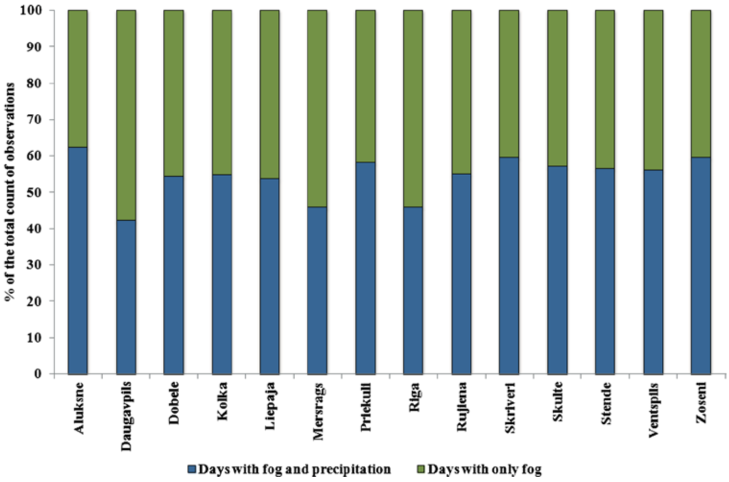

Fig. 5 The formation of fog on days with precipitation during the period 1960–2012. The number of fog on days with total precipitation of 0.1 mm or greater were counted and presented as a percentage of the total number of days with fog. The percentage of days with fog only is shown in *green* and the days when fog was accompanied by precipitation is shown in *blue*

formation of fog during days with precipitation. Overall, in Latvia, days with fog occurring together with precipitation predominate and consequently it is probable that advection fogs are, in general, more frequent. It is only in Mersrags, Riga and Daugavpils that most of the observed fogs occur during days with no precipitation, which could be associated with the specific local environmental factors of these observation stations. For example, at the Daugavpils observation station, which is located in the valley of the river Daugava, the formation of valley fogs could be a significant influence. In the capital city of Riga, air pollution with aerosols and particulate matter could be a reason for the higher frequency of radiation fog, while in the observation station of Mersrags, fog with no precipitation can be observed because of cold advection from the Gulf of Riga.

The annual number of days with fog in Latvia has decreased significantly during the past 53 years (Fig. 6). The stable decreasing tendency from 1960 to 1980 was followed by a more significant decrease during the beginning of the 1990s that could be associated with the rapid decrease in the industrial activities in the country. However, during the past decade, the frequency of fog has increased slightly.

Table 2 contains the results of the seasonal and annual trend analysis of fog frequency, performed by applying the Mann–Kendall test. The observed decrease in fog frequency is evident in all 14 meteorological observation stations, and there

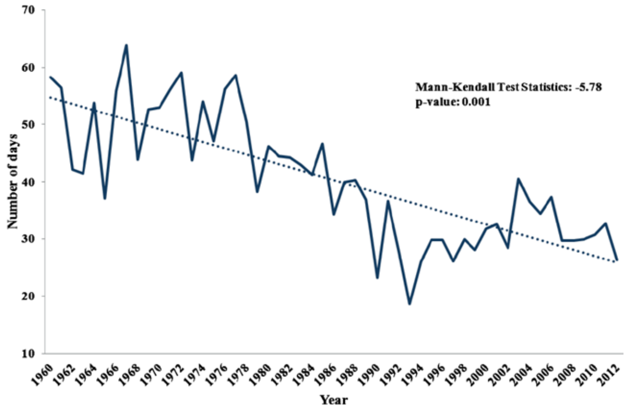

Fig. 6 Time series showing the annual number of days with fog in Latvia during the period 1960–2012. The annual mean number of days with fog over Latvia was calculated as the mean of data from 14 observation stations, and the Mann–Kendall test was applied at a significance level of 0.001 %

Table 2 The long-term trends of changes in the seasonal and annual number of days with fog in Latvia (Mann–Kendall test statistics) during the period 1960–2012. The statistically significant values are highlighted in bold

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual
Aluksne	**−5.09**	**−5.4**	**−3.87**	**−4.88**	**−6.59**
Daugavpils	**−5.3**	**−4.96**	**−4.41**	**−4.34**	**−6.42**
Dobele	**−2.81**	**−3.67**	**−2.26**	−1.93	**−3.71**
Kolka	**−4.73**	**−3.7**	**−3.45**	**−3.85**	**−4.15**
Liepaja	**−2.92**	−1.91	−0.86	−1.89	**−3.01**
Mersrags	**−2.84**	−0.67	−1.18	−1.24	**−2.44**
Priekuli	**−3.48**	**−2.85**	**−3.31**	**−2.15**	**−4.58**
Riga	**−1.99**	**−3.02**	**−4.22**	**−2.94**	**−4.28**
Rujiena	**−4.32**	**−4.86**	**−6.17**	**−4.18**	**−6.35**
Skriveri	**−2.47**	−1.71	**−3.06**	**−1.96**	**−4.01**
Skulte	**−2.82**	**−3.22**	**−4.3**	**−4.29**	**−5.08**
Stende	**−2.98**	**−3.46**	**−4.07**	**−3.13**	**−5.15**
Ventspils	**−3.33**	**−2.19**	**−2.21**	−1.49	**−4.48**
Zoseni	**−2.75**	**−2.54**	**−2.91**	**−2.66**	**−3.24**
Overall in Latvia	**−4.34**	**−3.41**	**−5.2**	**−4.08**	**−5.78**

has been a significant decrease in the number of days with fog across all seasons in most of the stations; however, the most significant changes have been observed in the winter. At the same time, in some stations in the western part of the country (Liepaja, Mersrags, Ventspils, Skriveri, Dobele) the decrease in fog frequency during spring, summer and, especially autumn, has not been significant.

Previous studies have shown that there has been a significant increase in the minimum and maximum temperatures in Latvia (Avotniece et al. 2013) that are especially pronounced

Table 3 Pearson correlation coefficients between the mean seasonal and annual minimum and maximum air temperatures and the number of days with fog over the period 1960–2012. The coloured cells show moderate correlation (0.3…0.5 for positive and −0.3…−0.5 for negative correlation), but strong correlation (0.5…0.8 for positive and −0.5…−0.8 for negative correlation) is highlighted in bold

Observation Station	Summer (JJA)		Autumn (SON)		Winter (DJF)		Spring (MAM)		Annual	
	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Aluksne	-0.25	-0.33	0.02	0.00	-0.12	-0.11	-0.09	-0.27	-0.36	-0.37
Daugavpils	0.03	0.00	0.04	0.16	-0.13	-0.12	-0.07	-0.23	-0.34	-0.29
Dobele	0.32	0.19	0.40	0.47	0.06	0.01	0.35	0.31	0.32	0.32
Kolka	-0.37	-0.45	0.05	0.06	-0.26	-0.27	-0.29	-0.46	-0.47	**-0.50**
Liepaja	-0.33	-0.16	0.06	0.11	0.01	-0.03	-0.24	-0.39	-0.29	-0.34
Mersrags	-0.01	-0.01	0.19	0.37	-0.07	-0.08	0.06	-0.10	-0.21	-0.16
Priekuli	-0.11	-0.15	0.09	0.13	-0.08	-0.09	-0.04	-0.14	-0.29	-0.22
Riga	-0.18	-0.40	0.13	0.18	-0.12	-0.15	-0.07	-0.17	-0.24	-0.31
Rujiena	-0.20	-0.36	0.19	0.16	-0.05	-0.08	0.07	-0.26	-0.23	-0.33
Skriveri	-0.15	-0.48	0.13	0.24	-0.04	-0.01	0.08	-0.11	-0.09	-0.09
Skulte	-0.34	-0.27	-0.08	-0.04	0.00	-0.03	-0.37	**-0.50**	-0.42	-0.43
Stende	-0.13	-0.25	0.17	0.21	-0.08	-0.09	-0.09	-0.44	-0.27	-0.35
Ventspils	-0.47	-0.37	0.08	0.12	-0.24	-0.22	-0.30	-0.28	**-0.52**	-0.49
Zoseni	0.01	0.07	0.19	0.25	-0.17	-0.17	-0.25	-0.11	-0.23	-0.16
Overall in Latvia	-0.25	-0.36	0.18	0.24	-0.11	-0.12	-0.12	-0.32	-0.37	-0.39

in the winter and spring, while in the autumn, the changes of temperature have been the least significant. The trend analysis of fog and air temperature changes shows some similar signs when compared; the most significant change in fog frequency has also been observed in the winter, but the least significant change has been observed in the autumn (see Table 2). Therefore, it might be suggested that the long-term decreasing tendency in fog frequency in Latvia could be associated also with the increase in air temperature. However, the correlation coefficients between the seasonal and annual mean minimum and maximum temperatures and the number of days with fog do not show a consistent pattern over the country (Table 3). The lowest correlations between the frequency of fog and values of air temperature are found in autumn and winter, which are the seasons with the least (autumn) and most (winter) significant changes in fog frequency. Therefore, there might be other significant meteorological factors that favour the formation of fog during these seasons. The strongest correlations between air temperature and fog frequency can be found in spring and especially summer, when in most cases, there is a negative correlation—increasing temperatures are associated with fewer fog cases. This pattern is also evident for the correlations between the annual mean temperatures and number of days with fog. However, in some seasons (see autumn) and observation stations (see observation station Dobele), there has been a different relation—increasing temperatures correlate with the number of fog positively. Therefore, it can be concluded that the changes in air temperature are only one of the factors triggering the decrease in fog frequency, and changes in other factors, such as humidity, availability of condensation nuclei and atmospheric circulation, could have a stronger effect on the spatial and temporal distribution of fog.

3.2 Atmospheric circulation processes associated with the formation of fog in Latvia

The characteristics, transformation and trajectories of an air mass reaching a certain location, as well as its specific weather conditions, are mostly determined by large-scale circulation processes in the atmosphere (Jaagus 2006). The movement of an air mass is mainly dependent on the location of large-scale synoptic systems and the corresponding air flows in the atmosphere (Moberg et al. 2003). For these reasons, 18 large-scale atmospheric circulation patterns following the GWT (Großwettertypes) classification for the Baltic Sea region were examined in this study (COST733 2012). With the help of these circulation patterns, the character of large-scale atmospheric circulation and the types of synoptic systems determining the weather conditions over Latvia was derived for the days with fog during the period 1960–2002.

Fog is a frequent weather phenomenon in Latvia, and, as described above, its occurrence over the country is closely related to local geographical features; however, the conditions of air humidity and predominant pressure systems also play an important role. In addition, the long-term changes in atmospheric circulation conditions have a significant effect on climatic conditions (Cahynova and Huth 2010). As an example, the observed increase in the persistence of atmospheric circulation patterns since the 1980s could have led to changes in climatic conditions in the boundary layer, such as the increase in the persistence of both heat and cold waves (Kysely 2008)

Although meteorological conditions in Latvia are strongly influenced by cyclonic activity, the most favourable conditions for the formation of fog have been observed during the days when a high-pressure area determines the weather conditions across the country.

Table 4 The three most dominant atmospheric circulation types occurring on the days with fog during the period 1960–2002, presented as a percentage of the total number of days with fog

Observation station	Dominant atmospheric circulation types, frequency of their occurrence (% from the total number of observations)		
Aluksne	W-A	SW-C	SW-A
	12.40 %	11.27 %	10.97 %
Daugavpils	W-A	SW-A	S-A
	15.93 %	15.49 %	8.22 %
Dobele	SW-A	W-A	S-A
	15.42 %	11.53 %	11.53 %
Kolka	SW-A	W-A	S-C
	11.93 %	9.71 %	9.65 %
Liepaja	W-A	SW-C	SW-A
	13.64 %	11.58 %	10.62 %
Mersrags	SW-A	W-A	S-A
	14.07 %	11.80 %	9.80 %
Priekuli	W-A	SW-A	W-C
	14.71 %	10.83 %	8.57 %
Riga	W-A	SW-A	SW-C
	14.84 %	13.99 %	8.27 %
Rujiena	W-A	SW-A	W-C
	13.80 %	13.46 %	9.28 %
Skriveri	W-A	SW-A	W-C
	16.02 %	11.97 %	10.38 %
Skulte	W-A	SW-A	W-C
	14.50 %	12.79 %	9.87 %
Stende	W-A	SW-A	W-C
	13.62 %	10.51 %	8.97 %
Ventspils	W-A	SW-A	SW-C
	13.60 %	11.53 %	10.94 %
Zoseni	SW-A	W-A	SW-C
	13.39 %	10.98 %	7.85 %

Table 4 contains information on the most favourable atmospheric circulation patterns occurring on days with fog in Latvia during the period 1960–2002. The most common conditions for the formation of fog in Latvia are the days with westerly or south-westerly air flow and, less often, southerly air flow, with anticyclonic conditions prevailing over the area. In such conditions, with a warm and moist air advection in the western part of an anticyclone, both radiation and advection fogs can form. However, a significant proportion of fogs in Latvia also forms in cyclonic conditions—forming with southerly, south-westerly and westerly cyclonic flows. In these cases, the formation of fog is usually associated with frontal systems, and such fogs can be called frontal fogs. However, within southerly and south-westerly cyclonic flows, the formation of fog may also not be associated with frontal systems, but instead with the warm sector of a cyclone where, in conditions of increased moisture, warmth and light winds, dense and persistent advection fogs can form.

As one can see from Table 1, there are two maxima in fog frequency in Latvia; a maximum in spring is evident in the coastal stations while the maximum in autumn is characteristic for the inland stations. The most favourable conditions for the formation of fog (Table 5) in spring in the inland stations are south-westerly and westerly anticyclonic flows, but in the coastal stations, fogs can form in westerly and south-westerly flows during a predominance of both cyclonic and anticyclonic conditions. During springtime, all of these weather patterns are associated with an advection of warm air over cool and, in many cases, still snow-covered land, thus triggering the formation of persistent advective fogs. In autumn, in the whole territory of Latvia, westerly and south-westerly anticyclonic flows are the most favourable conditions for the

Table 5 The three most dominant atmospheric circulation types occurring on days with fog in spring (MAM) and autumn (SON) during the period 1960–2002, given as a percentage of the total number of days with fog during these seasons

Observation station	Dominant atmospheric circulation types and the frequency of their occurrence (% from the total number of observations)					
	Spring			Autumn		
Aluksne	SW-C	SW-A	W-A	W-A	SW-C	SW-A
	10.71 %	10.34 %	8.83 %	13.66 %	12.08 %	11.98 %
Daugavpils	SW-A	S-A	W-A	W-A	SW-A	S-A
	15.47 %	10.43 %	9.35 %	19.73 %	17.77 %	9.57 %
Dobele	SW-A	S-A	SE-A	SW-A	S-A	W-A
	12.75 %	11.88 %	8.12 %	16.25 %	13.75 %	12.97 %
Kolka	SW-A	SW-C	S-C	SW-A	W-A	S-C
	10.23 %	9.83 %	9.02 %	16.83 %	15.56 %	13.02 %
Liepaja	SW-C	W-C	W-A	W-A	SW-A	SW-C
	12.88 %	12.21 %	10.41 %	20.39 %	16.45 %	11.84 %
Mersrags	S-A	SW-A	E-C	SW-A	W-A	S-A
	10.52 %	9.69 %	9.28 %	20.20 %	15.66 %	11.11 %
Priekuli	SW-A	W-A	W-C	W-A	SW-A	S-A
	10.64 %	9.22 %	8.98 %	16.36 %	13.83 %	7.25 %
Riga	SW-A	W-A	A center	W-A	SW-A	SW-C
	13.16 %	10.63 %	8.35 %	18,79 %	15.43 %	9.93 %
Rujiena	SW-A	W-A	W-C	W-A	SW-A	SW-C
	12.77 %	9.88 %	9.16 %	16.37 %	15.77 %	9.76 %
Skriveri	W-A	SW-A	SW-C	W-A	SW-A	SW-C
	11.83 %	11.37 %	11.37 %	16.94 %	14.54 %	10.16 %
Skulte	W-A	W-C	SW-A	SW-A	W-A	SW-C
	10.54 %	10.26 %	9.69 %	18.55 %	18.15 %	10.08 %
Stende	W-A	SW-A	SW-C	W-A	SW-A	S-A
	11.06 %	10.59 %	9.19 %	16.42 %	13.51 %	8.48 %
Ventspils	W-C	SW-C	W-A	W-A	SW-A	SW-C
	11.78 %	11.41 %	10.55 %	21.60 %	18.40 %	10.93 %
Zoseni	SW-A	E-A	SW-C	SW-A	S-A	W-A
	11.67 %	9.44 %	8.33 %	17.13 %	11.59 %	10.33 %

formation of fog when, owing to radiative cooling, radiation fogs are more frequent. It is evident that the formation of fog in Latvia is mainly associated with the inflow of warm and moist air from the south-west and west, with anticyclonic conditions being the most favourable for fog formation.

4 Conclusions

Fog is a frequent weather phenomenon in Latvia and is characterised by a significant spatial and temporal variability in its occurrence. Fog most commonly forms owing to the inflow of warm and moist air from the south-west and west in conditions of anticyclonic circulation over the area. However, the general pattern of fog frequency over the country is mainly associated with the distribution of humidity; consequently, owing to the prevailing westerly flows, fog is more frequent in the western part of the upland areas, while in the eastern (leeward) part of the uplands, the frequency of fog is considerably lower. Fog has also been observed more frequently in the western part of the country, where the impact of the maritime climate of the Baltic Sea is the greatest. Although a significant majority of the observed fog cases have been associated with anticyclonic conditions, fog is commonly accompanied by light precipitation; this could be an indicator of the dominance of advective fog formation processes in the country.

Since the middle of the past century, the annual mean number of days with fog has decreased significantly; this could be associated with both the gradual decrease in industrial activities and the resultant improvements of air quality and the observed increase in air temperature. The warming has been the most significant in the winter and this might have triggered a decrease in the formation of advective fogs, which in this season usually form when warm and moist air flows over a cool or snow-covered surface. However, in spite of this observed decrease, fog is still one of the most dangerous and harmful meteorological phenomena affecting aviation in Latvia.

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PAPER 5: TEMPORAL AND SPATIAL VARIATION OF FOG IN LATVIA

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Temporal and Spatial Variation of Fog in Latvia

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Abstract **- Fog is a hazardous weather phenomenon, which can impact traffic (especially air traffic) and air quality. The aim of this study is to analyse fog climatology, the trends of long-term changes of fog events and factors affecting them in general, in Latvia, but especially at Riga airport. For a 50-year period of observations, the analysis of fog frequencies, long-term changes and atmospheric conditions favourable for the occurrence of fog events in Latvia has been studied. During the analysis, two inter-annual maxima of fog frequency were found in spring and autumn, and the seasonal differences in the formation of fog were also approved by the satellite data on low cloud cover.**

Key word **- fog, aviation, long-term trends, occurrence**

I. Introduction

Fog is a hydrometeor consisting of a visible aggregate of minute water droplets or ice crystals, suspended in the atmosphere near the Earth's surface and reducing horizontal visibility below one kilometre [1]. Fog is a hazardous weather phenomenon worldwide, which can cause accidents and affect urban air quality, especially in combination with impacts of air pollutants [2, 3]. Traffic obstacles such as flight delays, automobile and marine accidents due to poor visibility can be considered as the most common negative effects of fog [4, 5]. At the same time, fog can be associated with critical conditions of air pollution (especially with particulate matter), because air pollutants can be trapped in the fog droplets and can reach high concentrations, causing the formation of smog or in some cases acid fog [6, 7]. On the other hand, fog as a source of humidity is also very important to the health of ecosystems and humans [8], and as fogs have an important influence on the radiation balance, the long-term changes in their frequency can play an important role in the accuracy of the climate model predictions [6].

Fog is a very local phenomenon, which can form as a result of advection, radiative cooling or a weather front moving over an area, and its frequency and spatial distribution are closely related to orography and proximity to the sea [7, 9-11]. The occurrence of fog is related to the atmospheric circulation and local geographical features of a site and thus fog climatology studies are of especial importance for airports, where local meteorological conditions (lowland and flatland territories) may support increased occurrence of fogs, but the impacts might have serious consequences. To assess the intensity of fog, the measure of horizontal visibility or the persistence of fog can be used [9, 12]. The most intense fogs in both persistence and density were observed in many sites of the industrialized world in the 1940s and 1950s, when some famous low visibility episodes in combination with heavy air pollution such as the Great Smog of London in 1952 occurred [13]. During that event visibility below 10 m lasted for nearly 48 hours in Heathrow - such intense and persistent low visibility is almost unheard of today [7, 13]. Since then, due to the introduction of clean air legislation and a decrease in total suspended particulates, fog climatology has changed considerably and many sites have experienced a decrease in the fog frequency [6, 7, 14], also in Riga. However the presence of particulates in the air still remains high where presence of particulates in air remain high [15]. High quality observation data of various parameters describing fog are not available in many countries because of the sparse observation networks, and consequently it is practically not possible to carry out a reliable and spatially coherent analysis of fog distribution based only on the surface observation data [6]. However, satellite data can provide important information on the spatial distribution, dynamics and properties of fog [4]. Despite the importance of fog both from the applied research point of view, and in respect to a better understanding of extreme climate events, there have been no studies of fog meteorology carried out in the Baltic region. The aim of this study is to analyse fog climatology, the trends of long-term changes of fog events and factors affecting them in general, in Latvia, but especially at Riga airport, as well as to evaluate possibilities to use satellite data for the detection of fog.

II. Data Sources and Methods

Daily observation data on fog events and precipitation amount were provided by 15 major meteorological observation stations in Latvia (Figure 1). Data obtained from the Latvian Environment, Geology and Meteorology Centre covered a 52-year period from 1960 to 2012. The methods of fog observations vary depending on the meteorological stations – in automatic observation stations, such as Riga airport, horizontal visibility is observed automatically by the use of sensors, while in other observation stations in Latvia observations of horizontal visibility and fog are performed visually by the meteorologist. Visual observations of horizontal visibility are performed by evaluating the distance between the observer and predefined existing objects such as trees, buildings, towers etc., or objects established specially for this purpose [16].

In addition to the surface observations, satellite data were also used for the analysis. For the climatological characterisation of the occurrence of fog, satellite observations of low clouds for the period 2005-2011 provided by the Satellite Application Facility on Climate Monitoring (CM SAF) were used as an indicator of the most favourable sites for the formation of fog [17]. Monthly and seasonal mean amounts of low clouds were calculated from the satellite data with statistical programmes CDO (*Climate Data Operators*) and R, and compared with the surface observation data.

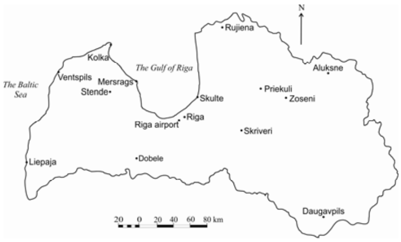

Fig. 1. Major meteorological observation stations in Latvia

The visualization of the location of meteorological observation stations used in this study (Fig. 1) was performed by using Corel Draw, but the spatial distribution of fog in Latvia (Fig. 2) was visualised by using the FiSynop software with linear interpolation on a triangular grid.

Trends in the annual number of days with fog were analysed by using the non–parametric Mann–Kendall test [18, 19]. The Mann–Kendall test was applied separately to each variable at each site at a significance level of $p \leq 0.01$. The trend was considered as statistically significant if the test statistic was greater than 2 or less than -2.

III. Results and Discussion

A. Fog climatology in Latvia

Climate in Latvia is influenced by strong cyclonic activity over Latvia and location in the northwest of the Eurasian continent (continental climate impacts) and by its proximity to the Atlantic Ocean (maritime climate impacts). These variable conditions over the territory contribute to differences in the regimes of air temperature and humidity [20-22], and also to the spatial inhomogeneity in the occurrence of fog.

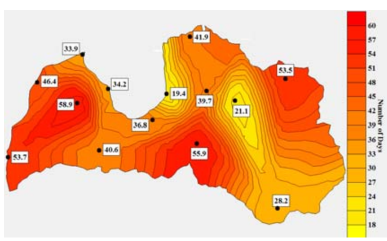

Fig. 2. Annual mean number of days with fog in Latvia over the period 1960-2012

Fog can be classified by its formation in the processes of advection, radiative cooling or a mix of both processes [23], and each of these processes can trigger the formation of fog in Latvia throughout the year. Fog is a rather frequent weather phenomenon in Latvia, and it can be observed 19-59 days a year on average (Figure 2). The formation of fog is closely related to the local geographical features of a site, such as orography and slope exposure, proximity to the Baltic Sea and the Gulf of Riga, and the different meteorological processes favourable for the occurrence of fog; therefore, there are significant differences in the annual mean number of days with fog in Latvia. As a result, fog most commonly can be observed in the western parts of the highland areas of Latvia, while the lowest number of days with fog is observed in the eastern parts of highlands and in the coastal areas of the Gulf of Riga. Overall fog frequency is larger in the western part of the country.

Figure 3 illustrates the long-term variability of fog in Latvia. The bold line represents the median of the annual number of days with fog, the upper and lower sides of the boxes are the upper and lower quartiles, the whiskers represent the greatest and lowest annual number of days with fog, but the dots represent outliers, which are more than 1.5 times greater or smaller than the quartiles. The range of the annual number of days with fog in Latvia varies from 0 days in Zoseni to 110 days in Aluksne, and also the annual variations within each station are considerable. For most of the stations, the data distribution is positively skewed, which means that there are more years with the annual number of fogs exceeding the long-term average than years with a smaller number of days with fog. Under the influence of the highly variable weather pattern in three observation stations of the western part of the country – Liepaja, Mersrags and Dobele - outliers of both minimum and maximum annual number of days with fog can be found. In general, the graph shows significant differences in the spatial and temporal distribution of the annual number of days with fog in Latvia.

The inter-annual variability of fog (Table 1) shows significant differences in the months of the maximum occurrence of fog in coastal and inland observation stations. The coloured cells indicate 3 months with the greatest frequency of fogs in each observation station. In the inland stations the maximum of fog occurrence is characteristic for the second half of the year - beginning from August to December. During the autumn months the radiation fogs form more frequently, but during winter and spring advection fogs gradually become more frequent. Therefore in the coastal observation stations the maximum frequency of fog occurs in spring – during March, April and May, when warm advection from the west triggers the formation of adjective fogs.

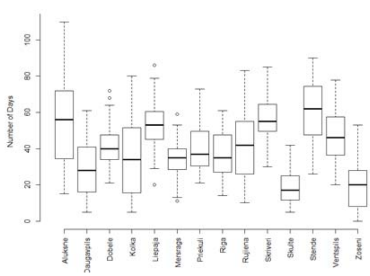

Fig. 3. Variations in the annual number of days with fog in Latvia over the period 1960-2012.

TABLE 1

MONTHLY EAN NUMBER OF DAYS WITH FOG OVER THE PERIOD 1960-2012

	January	February	March	April	May	June	July	August	September	October	November	December
Aluksne	4.9	4.6	4.7	4.2	2.4	1.2	2.5	4.0	5.5	7.3	9.2	7.0
Daugavpils	1.5	2.0	2.4	1.8	2.0	1.3	1.9	3.3	4.3	4.5	3.1	2.6
Dobele	4.2	3.4	4.1	2.9	1.7	1.1	1.6	2.8	4.5	5.3	4.3	4.8
Kolka	2.7	3.3	5.4	5.9	4.6	2.1	1.7	1.9	1.9	2.3	2.6	2.0
Liepaja	3.9	4.6	6.5	7.3	7.1	5.2	3.7	3.7	2.8	4.1	3.7	4.4
Mersrags	2.3	2.4	3.6	4.5	3.4	1.8	2.8	3.6	3.2	3.2	3.2	2.3
Priekuli	3.9	3.9	3.8	3.2	2.7	1.3	2.2	3.8	4.2	4.5	4.8	4.8
Riga	3.3	3.3	3.8	3.0	2.3	1.4	2.3	3.0	3.5	4.2	5.0	4.4
Rujiena	3.6	3.7	3.7	3.1	2.2	1.7	3.0	4.8	5.0	5.2	4.8	4.5
Skriveri	5.2	4.5	4.5	3.1	2.4	2.2	3.5	6.2	4.8	7.3	7.1	6.8
Skulte	1.7	2.3	3.0	2.7	2.5	0.9	0.7	1.3	1.3	1.8	2.0	1.6
Stende	5.5	5.1	5.9	4.9	3.8	3.5	5.3	6.3	4.7	5.5	6.6	6.5
Ventspils	3.7	3.6	5.8	6.8	6.2	4.6	3.4	2.9	2.3	3.0	3.3	3.3
Zoseni	1.3	1.5	1.6	1.6	1.0	0.8	1.4	2.2	2.9	3.1	3.4	2.0

The annual number of days with fog in Latvia has decreased significantly during the past 50 years (Figure 4). The most significant decrease in the frequency of fog is evident for the 20 year period between the years 1980 and 2000 and could be associated with the rapid decrease in the industrial activities in the country, but in the past decade the frequency of fog has again increased slightly.

In spite of the observed decrease in the frequency of fog in Latvia, it is still considered as one of the most dangerous meteorological phenomena negatively affecting transportation, especially air traffic, and causing flight delays and cancellations which lead to great financial loss.

Especially low visibility (intensive fog) events have been observed under the conditions of increased atmospheric pressure (Figure 5), which indicates the great importance of radiation fogs in the area. Radiation fogs are common in the lowland area near Riga airport, because the wetlands and swamps located to the south of the airport provide extra moisture essential for the development and persistence of dense radiation fogs.

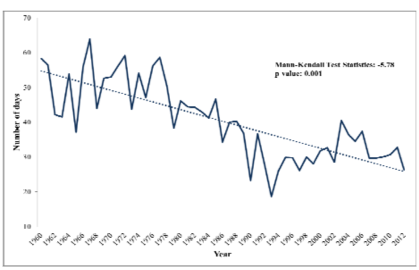

Fig. 4. Time series in the annual number of days with fog in Latvia overall over the period 1960-2012

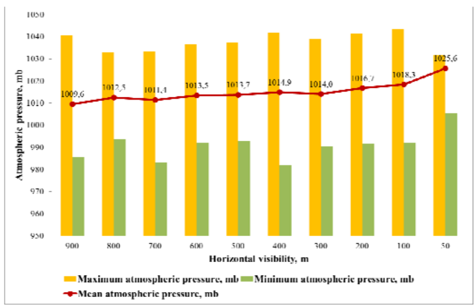

Fig. 5. Atmospheric pressure during fog events at Riga airport over the period 2010-2012.

In-depth analysis of fog climatology at Riga airport indicates several major factors affecting fog occurrence (Figure 5 – 7), such as atmospheric pressure, air humidity and wind speed, as well as presence of atmospheric precipitation during fog events.

The relations between humidity and wind speed on visibility during fog events have an opposite character – increase of wind speed supports the dissipation of fog, and the most intensive fog events happen at low wind speeds as such conditions deteriorate vertical mixing of air near the surface (Figure 6). Relative humidity is a well-known indicator used for the forecasting of fog, since fog most frequently forms in the conditions of relative humidity exceeding 90% [23], which is also approved by data from the Riga airport, since the increase of air humidity supports the increase of fog thickness.

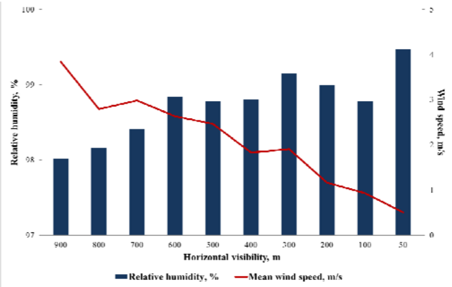

Fig. 6. Relative humidity and mean wind speed during fog events at Riga airport over the period 2010-2012.

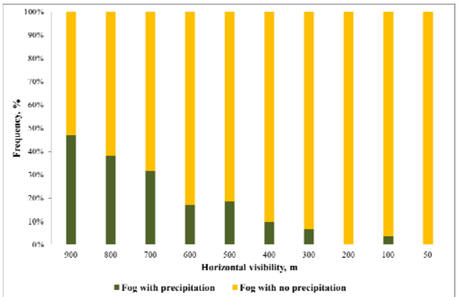

Fig. 7. The frequency of dry days and days with precipitation during fog events at Riga airport over the period 2010-2012.

The analysis of fog occurrence during days with precipitation can also be an indicator of the formation process. As radiation fog commonly occurs in the conditions of clear skies, usually there is no precipitation during days with radiation fog. However in cases of very dense radiation fog, very small amount of precipitation (up to 0.1-0.2 mm) can be caused by the fog itself. Advection fogs are usually associated with frontal systems, so such fogs are frequently accompanied by precipitation. Figure 7 illustrates the relation between patterns of formation of fogs during days with precipitation. At Riga airport most of the most intensive observed fogs have formed during days with no precipitation, which could be associated with the specific local factors of the observation station favourable for the development of radiation fogs. Nevertheless, advection fogs are also observed commonly at the airport, especially in the winter and spring seasons, since the inflow of warm and moist air over the snow-covered ground is favourable for the formation of fog. In some cases in winter and spring fog can be advected to the airport also from the ice-free areas of Gulf of Riga. It is characteristic for the radiation fogs to form in the second part of the night or early morning and dissipate soon after sunrise, however advection fogs can form any time of the day and may remain for a prolonged period of time, therefore advection fogs can be considered as a greater danger for the air traffic.

B. Use of satellite data for identification of fog

Nowadays satellites are considered as a powerful tool for the observations of fog, as satellite observations provide both wide spatial and temporal coverage which is essential for the detection and characteristics of such a variable phenomenon. In essence, fog is very similar to low stratus clouds, and it differs from low cloudiness only by its base being located near the ground [1]; therefore, for the climatic characterisation of fog occurrence, it is possible to compare the surface observations of fog to the low cloud observations from satellites provided by the CM SAF. If compared the surface observations of fog and the satellite observations of low clouds in the autumn season (Figure 8) over a six-year period, one can see similar features: the greatest amount of low clouds (up to 47%) can be observed in the south and west regions of Latvia, while in the coastal areas the amount of low clouds is the smallest (38-44%). In the winter season, the low cloudiness in Latvia is smaller in general, and it does not exceed 44% (Figure 9). In winter, a more expressed formation of fog is evident over the valley of the river Daugava and especially over the west regions of Latvia, where it could be triggered by the influence of periodic thaws.

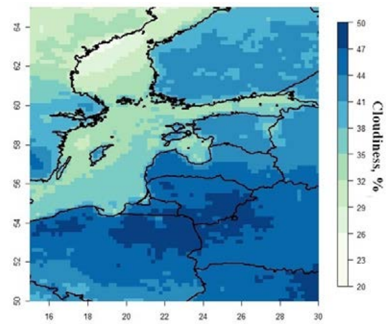

Fig. 8. Mean amount of low clouds (%) in autumn (SON) over the period 2005-2011.

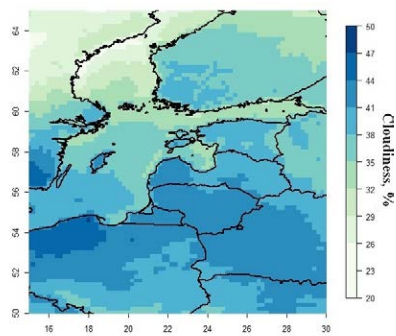

Fig. 9. Mean amount of low clouds (%) in winter (DJF) over the period 2005-2011.

In spring, some differences in the low cloud and fog formation processes appear (Figure 10). In the western regions, where, under the influence of warm advection from the west, advection fogs form more frequently, the mean amount of low cloudiness is higher than in other parts of the country and reaches 40-42.5%. But at the same time in the highland areas of Latvia, a gradual increase in the occurrence of radiation fogs begins. Also in summer (Figure 11) the low cloudiness is the greatest over the highland areas, where it reaches up to 40% of the total cloudiness due to the dominance of radiation fogs.

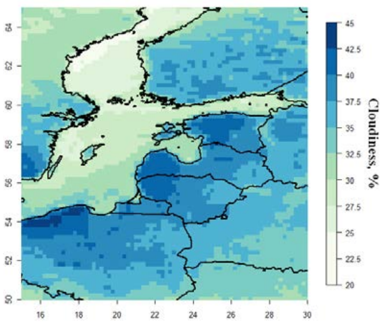

Fig. 10. Mean amount of low clouds (%) in spring (MAM) over the period 2005-2011.

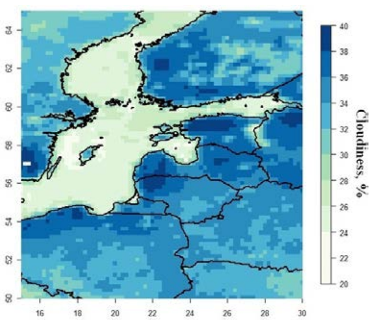

Fig. 11. Mean amount of low clouds (%) in summer (JJA) over the period 2005-2011.

Satellite information can be also efficiently used to evaluate development of fog conditions locally, for example at Riga airport on the 25th of October in 2011 when a wide area of dense fog approached Latvia from the south, and moved over the central regions of the country to the Gulf of Riga (Figure 12). The south-east regions of Latvia were covered with clouds, but in the central regions at night the skies were clearing and a dense radiation fog formed. In the conditions of a strong low-level inversion the fog remained throughout the whole day, slowly moved to the north and in the evening covered the Gulf of Riga. During the fog in the morning in Riga the visibility was reduced to 100 m, but in the middle of the day in Dobele to 70 m, besides in Dobele visibility below 500 m remained for 28 hours. In this case satellite data were an essential source of information on the spatial coverage, movement and characteristics of fog, providing much wider view on the process than the surface observation network.

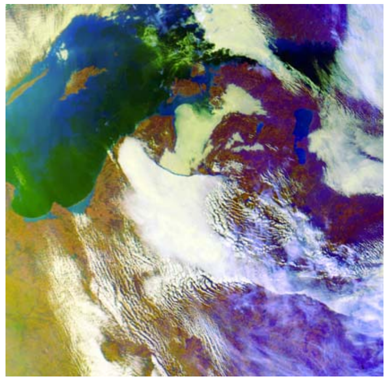

Fig. 12. NOAA satellite image (channel combination 2-1-4, fog and low stratus appears as light yellowish area) at 11:10 UTC 25.10.2011.

In spite of the observed decrease in the frequency of fog in Latvia, it is still considered as one of the most dangerous meteorological phenomena negatively affecting transportation, especially air traffic, and causing flight delays and cancellations which lead to great financial loss. Therefore, in the conditions of ever increasing demand for air transport, it is essential to be aware of the general climatic characteristics of fog occurrence and synoptic patterns favourable for their development.

IV. Conclusions

Fog is a frequent weather phenomenon in Latvia, which is characterised by a significant spatial and temporal inhomogeneity in its occurrence. Since the middle of the past century, the annual mean number of days with fog has decreased significantly but, in spite of the observed decrease, fog is still one of the most dangerous and harmful meteorological phenomena affecting aviation in Latvia. The analysis of fog formation in the area of the Riga airport revealed that the majority of fog events observed can be classified as radiation fogs, which due to their short persistence are not of as great danger to the aviation traffic as advection fogs. Since advection fogs play an important role in the air traffic organization, timely information provided by satellites is an essential tool for the forecasting of movement and persistence of the fog and low-cloud areas.

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PAPER 6: LONG-TERM CHANGES IN THE FREQUENCY AND INTENSITY OF THUNDERSTORMS IN LATVIA

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

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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

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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-

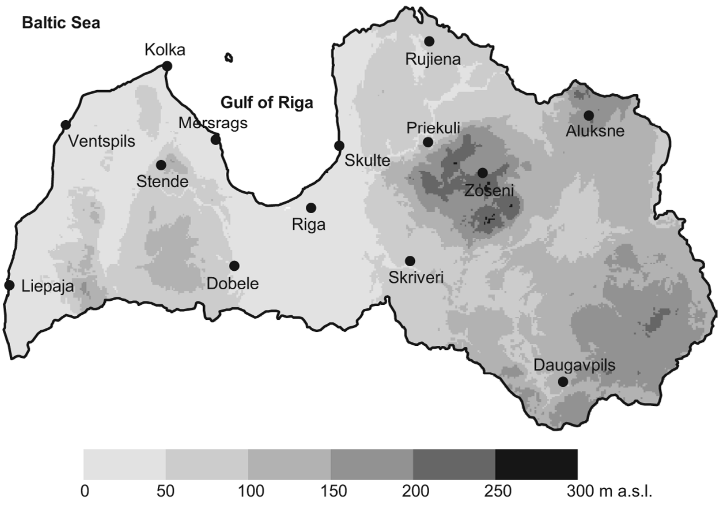

Fig. 1. Location of the 14 meteorological stations in Latvia.

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

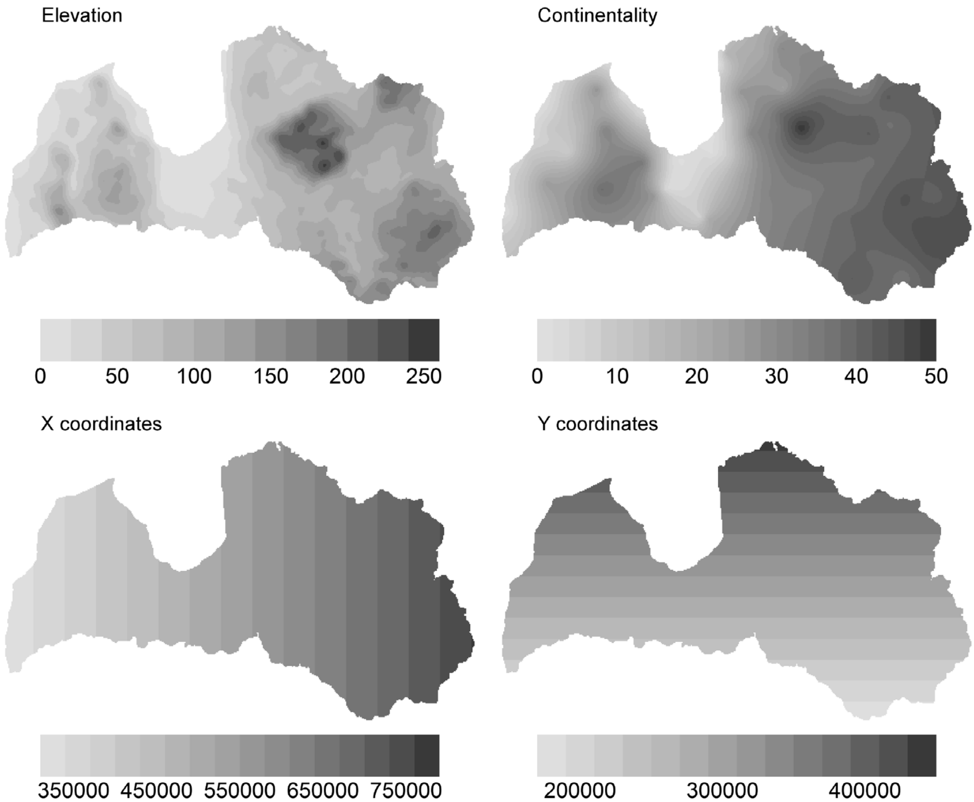

Fig. 2. Explanatory variables used in the interpolation routine: mean elevation (m a.s.l.) of 5 km^2 moving window and Gams' continentality index; X and Y coordinates in LKS-92 TM.

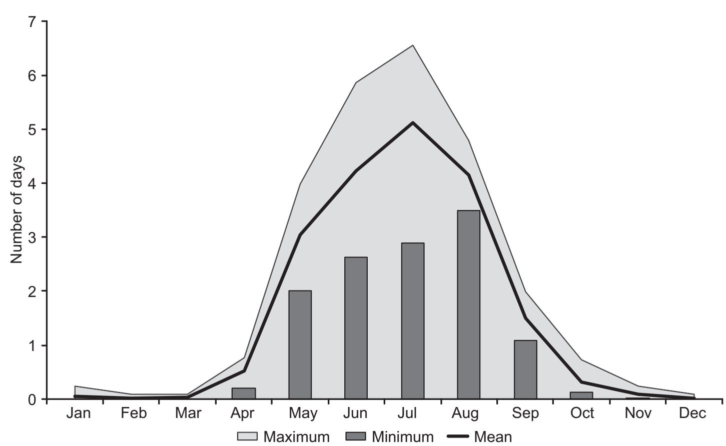

Fig. 3. Frequency of thunderstorm days in Latvia during 1960–2015.

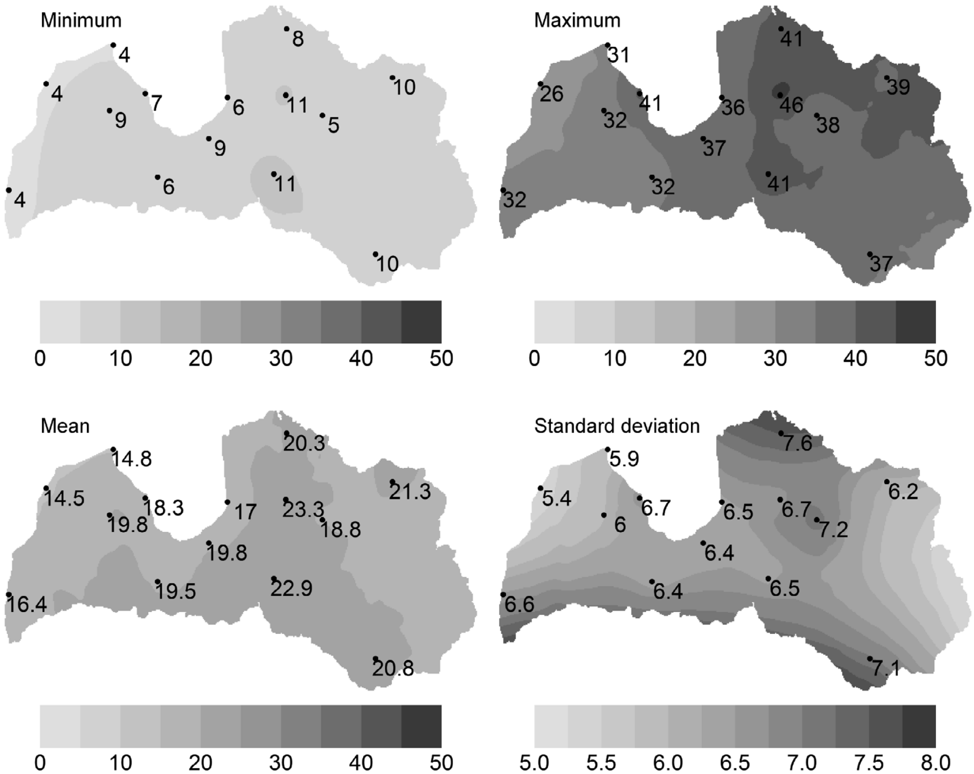

Fig. 4. Thunderstorm day frequency and variability in Latvia during 1960–2015. Top panels: minimum and maximum annual number of thunderstorm days; bottom panels: mean annual number of thunderstorm days and variability in annual thunderstorm day frequency expressed as standard deviation.

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

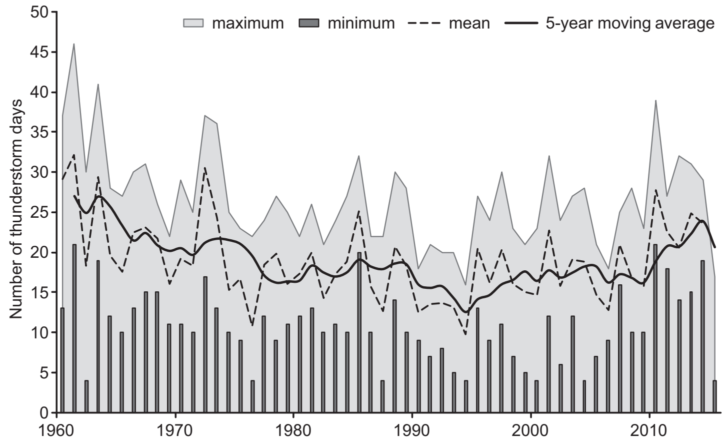

Fig. 5. Number of thunderstorm days in Latvia (data from 14 weather stations; *see* Fig. 1 and Table 1).

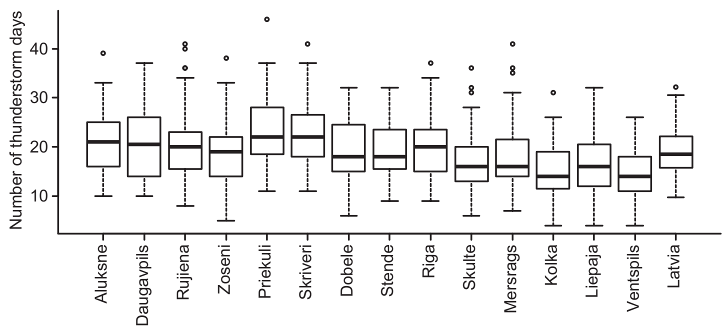

Fig. 6. Number of thunderstorm days in Latvia during 1960–2015. Thick line inside the box = median, top and bottom of the box = upper and lower quartiles, respectively, whiskers = minimum and maximum (excluding outliers), circles = outliers (more than 1.5 times greater than the quartiles).

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).

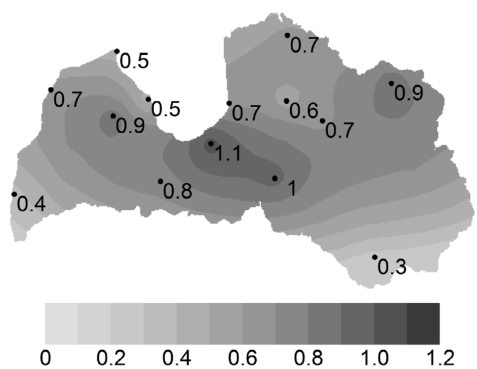

Fig. 7. Mean number of hail events on thunderstorm days in Latvia during 1960–2015.

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

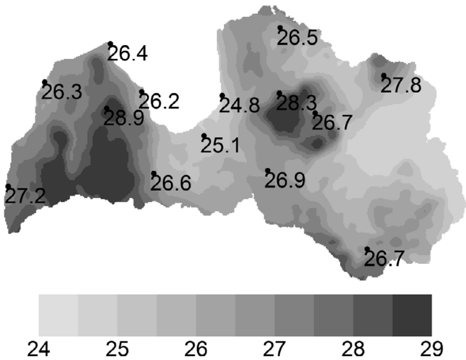

Fig. 8. Maximum precipitation amount (mm) per thunderstorm day in Latvia during 1960–2015.

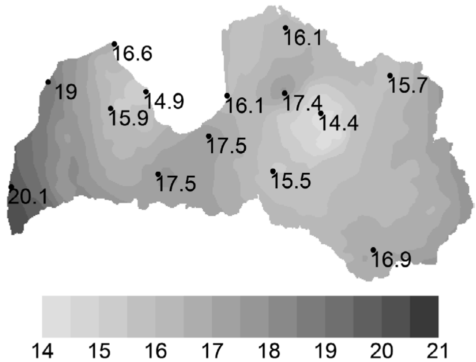

Fig. 9. Annual maximum wind gusts (m s^{-1}) during a thunderstorm day in Latvia during 1966–2015.

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

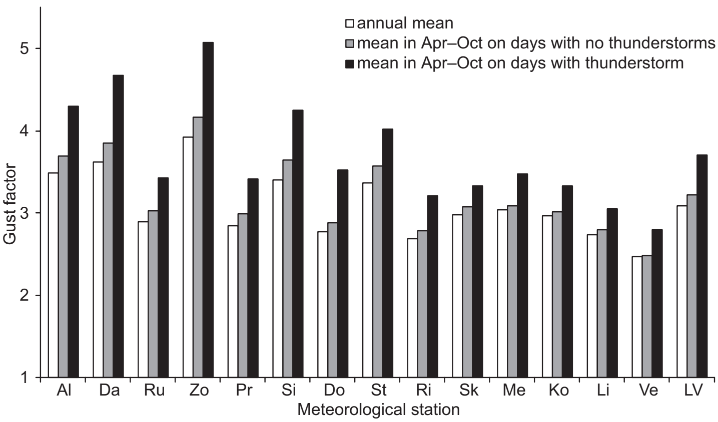

Fig. 10. Mean gust factor in Latvia during 1966–2015.

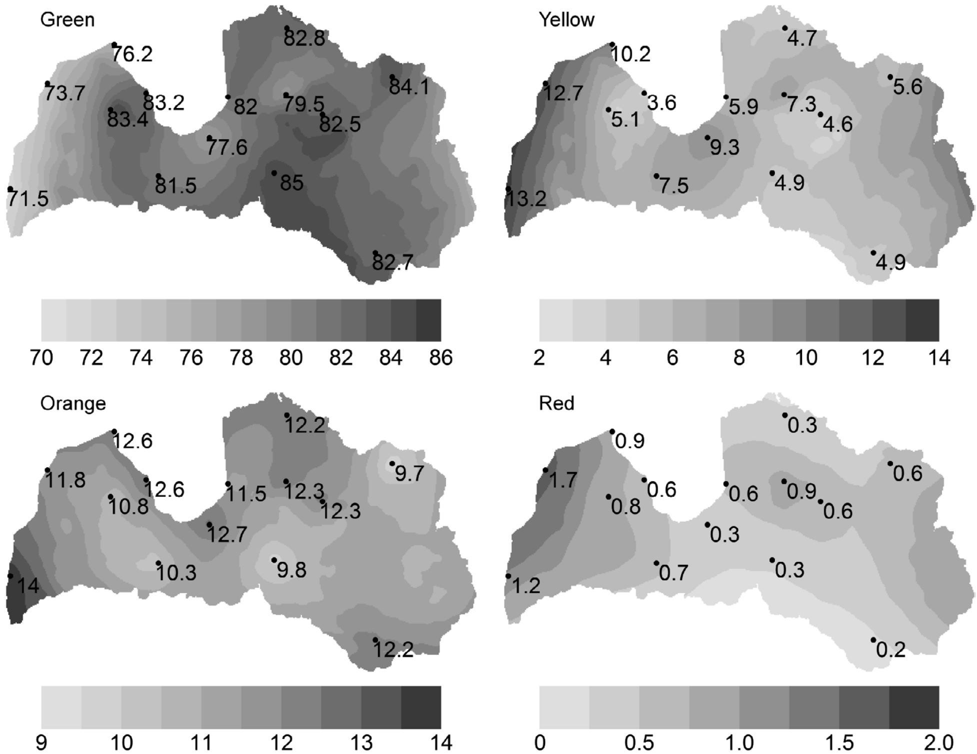

Fig. 11. Mean proportions (%) of thunderstorm days of four severity levels in Latvia in 1966–2015.

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.

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PAPER 7: THE FORECASTING OF TORNADO EVENTS: THE SYNOPTIC BACKGROUND OF TWO DIFFERENT TORNADO CASE-STUDIES

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The forecasting of tornado events: the synoptic background of two different tornado case studies

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Abstract: The synoptic analyses of two different tornado cases, observed in Latvia and Poland in the summer of 2012, are examined in this paper. The first of them, the tornado in Latvia seemed to be a "textbook example" of tornado occurrence. Its development took place in the contact zone of the warm, tropical air, characterized by a very high CAPE (Convective Available Potential Energy), with cold and moist polar marine air mass behind the convergence line that determined very good conditions for convective updraft. Additionally, the moderate environmental wind shear favoured the sufficient condition for concentrating the atmosphere's vorticity into well-organized strong rotating upward motions that produced the supercell structures and tornado. Thus, from the forecaster's point of view, the occurrence of this severe convective event was not a surprise. This phenomenon was predicted correctly more than a dozen hours before the tornado occurred.

The second event occurred in the north of Poland and was associated with a thunderstorm where a supercell was formed in conditions of low CAPE but favourable wind profile, both vertical and horizontal. Helical environments (characterized by large shear vectors that veered with height in the lowest three kilometres, especially the nearest one kilometre) were arguably the most important factor that determined the Polish tornado's occurrence. In this case the analysis of the synoptic situation was not so clear and the superficial analysis, even post factum, regarding radar, satellite or detection maps might have suggested "quite a normal" summer thunderstorm. However, the detailed examination showed the reasons why tornado genesis took place. The potential conditions for the occurrence of this severe phenomenon were indicated by forecasters, although the forecasts were less exact with regard to the place of occurrence and the heaviness of the strike.

Keywords: tornadoes, synoptic background, forecasting, nowcasting

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1. Introduction

Tornadoes are often the subject of in-depth stu-dies and extensively discussed in scientific literature (Maddox et al. 1980; Brooks, Doswell 2001; Dotzek 2003; Marcinoniene 2003; Setvák et al. 2003; Davies-Jones 2006; Agee, Jones 2009; Wurman et. al. 2010; Brazdil et al. 2012; Rauhala et al. 2012). This paper presents a synoptic analysis of two examples of this phenomenon which, although occurring in relatively different weather conditions, caused equally disas-trous consequences. The first discussed tornado, called locally "virpuļstabs", was noted in Latvia on July 29, 2012, and the second was the whirlwind in Poland which occurred two weeks earlier, on July 14, 2012. The synoptic conditions which produced the tornado in Latvia were a quite typical example of convective weather connected with a warm sector ahead of the cold front preceded by a convergence line, except for the fact that the area of positive vorticity advection was neutral or just slightly positive, which, from a theoretical point of view (Gold, Nielsen-Gammon 2008; Schumann, Roebber 2010), is one basic component for tornado initiation. The question is, what was the compensation for this? The second event occurred in the north of Poland and was associated with a supercell when the weather situation preceding the tornado was far from what seemed to be "favourable conditions" for tornado genesis. It was related to a shallow, eastwardly moving cold front with relatively low cloud cover, towered by the supercell that spawned the tornado. Its scale of damage was measured between the F2 and F3 rating, according to ESWD (European Severe Weather Data). A detailed synoptic analysis, containing both the large-synoptic scale as well as the detailed mesoscale analysis of these two similar (in terms of process) and yet different (in terms of origin) extreme meteorological phenomena aims to identify common features crucial for their formation.

2. Synoptic Backgrounds

There are many case studies that reveal similar synoptic preconditions for the formation of tornadoes. Some main synoptic flow patterns favourable for the occurrence of a tornado have been distinguished: upper-level trough the west of the location of the tornado that contributes to deepening of a surface low; sufficient instability commonly associated with the presence of low level moisture in a warm sector; upper level jet streak collocated with a centre of rapid decrease in surface pressure contributing to intensification of the synoptic cyclone; and increasing vertical wind shear (Rotunno, Klemp 1982; Schafer, Doswell 1984; Houze 1993; Corfidi et al. 2010; Mercer et al. 2012). Although the conditions in the larger synoptic scale create a favourable thermodynamic environment, the formation of deep convective phenomena is determined by mesoscale conditions. Three factors are necessary for the development of deep moist convection: low-level moisture, conditional instability and source of lift. Other factors like vertical wind profile may determine the type of convection which forms (Doswell 1987). Helical environments, understood as "ones with large shear vectors that veer with height in the lowest few kilometres" are conducive to tornadoes (Kerr, Darkow 1996; Davies-Jones 2006). Thus, the goal of this paper is to analyse both of these tornado cases by analysing at the conditions in which they developed.

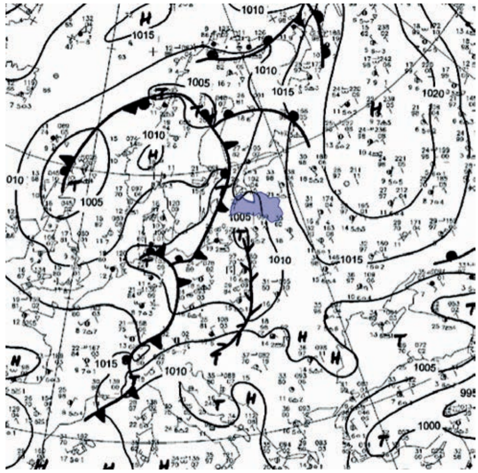

Fig. 1. The surface weather map; July 29, 2012; 12:00 UTC (source: DWD)

Fig. 2. Temperature and mean wind speed at 15:00 in Latvia; July 29, 2012 (source: LEGMC)

2.1. Tornado in Latvia, July 29, 2012

The tornado in Latvia resulted from the formation of a supercell in the conditions of deep convection connected with the slow movement of atrough with a convergence line preceding a cold front (Fig. 1). During the days prior to the event, an extensive warm sector of a cyclone located over the North Sea caused a gradual inflow of warm and humid tropical air from the south which, on July 29, resulted in temperatures as high as 20°C at 850 hPa causing maximum surface temperatures to increase up to 33°C in many places (Fig. 2).

In the afternoon of July 29, 2012, a shallow trough with a cold front zone was slowly approaching Latvia from the west of Europe, and it waspreceded by a convergence line – this formed a classic scenario for intense convection. At the same time, in the middle and upper troposphere, an extended ridge covered the territory of Eastern Europe.

The nearest sounding indicators from Tallinn (Estonia; 29.07.2012 at 00:00 UTC), located almost at the same longitude as Riga, combined with NWP DWD data (Deutscher Wetter Dienst Numerical Model Prediction) showed that instability and low-level humidity conditions were favourable for tornado formation in this region. The specific humi-dity of the warm sector of an air mass that struggled over Latvia was potentially very moist, and oscillated between 12 g/kg and 14 g/kg, which corresponded to mean precipitable water content (PW) of about 34-40 mm (max PW = 44 mm). Convective available potential energy (CAPE) increased up to 2200 J/kg, the values of lifted index (LI) were also high: -5°C. Convective inhibition energy (CIN) decreased totally from -156J/kg during the 14 hours preceding the occurrence of the tornado. These conditions created a low lifting condensation level (LCL) of about 280 m AGL. At the vertical wind profile, in the middle and upper troposphere, an almost steady flow from the south (210-220°), with a speed of about 36-40 kt, was observed. Despite a lack of vertical shear in the middle troposphere, some veer shear was observed between the surface and 850 hPa level. The wind changed direction and speed, from 090°/05 kt near the surface to 220°/25 kt at the height of about 2000 m. This vertical and directional shear in the low level atmosphere, combined with the existing conditions of deep convection, created a favourable basis for the development of vorticity at ground level – a situation conducive to the development of supercells and tornadoes.

The vorticity at 500 hPa and 300 hPa at 12:00 UTC showed that the whole region was in an area of neutral or slightly positive vorticity advection, as mentioned above, in the periphery of the upper ridge. Although there was no significant positive vorticity observed, the strong low-level warm advection connected with the high low-level moisture field was big enough to release and sustain the energy needed to maintain upward motion (Maddox et al.

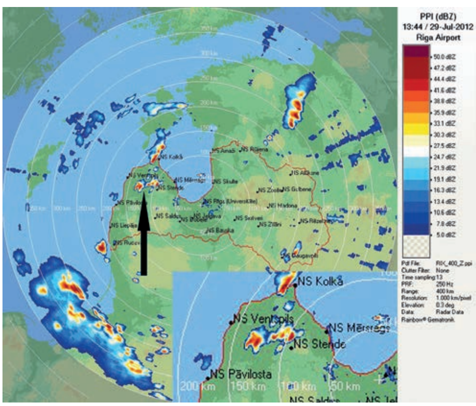

Fig. 3. Dopper-radar data from Latvia, July 29, 2012; PPI: 13:44 UTC. Yellow arrows indicate the supercell's position with hook echo (source: LEGMC)

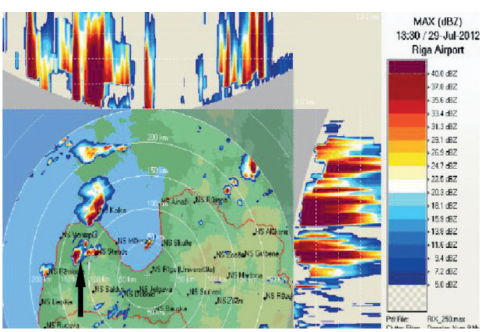

Fig. 4. Dopper-radar data from Latvia, July 29, 2012; MAX CAPPI: 13:30 UTC. Yellow arrow indicates the position of supercell in Talsi region, the most affected by the tornado (source: LEGMC)

1980; Maddox, Doswell 1981; Boustead et al 2013). Moreover, the area of western Latvia remained under the influence of the upper level divergence connected with the right-entrance of a jet stream at 300 hPa. The jet was moving to the north above the Baltic Sea and Scandinavia. The upper divergence zone emphasized the upward motion within the lower and middle troposphere and caused an outflow of air in the upper troposphere, thus strengthening the low-level moisture, instability and convergence interaction (Uccelini, Johnson 1979). The mechanism that initiated the upward lifting in the atmosphere was the convergence in the cold front line which was moving over the area of Latvia in the afternoon hours.

The first thunderstorms were noted around 13:00 UTC, however, the main activity developed in the late afternoon, extending mostly over western Latvia. In the afternoon (14:00 UTC) severe thunderstorms with hail, and strong wind gusts at the seaboard of up to 24 m/s were noted. At about 13:00 UTC, near Stende meteorological observation station, a huge Cb started to develop. During 20 to 40 min. it converted into a supercell with a hook echo visible with radar imagery (Fig. 3) and then transformed into tornadic thunder. The maximum reflectivity on radar in Riga showed that the tops of clouds exceeded 15 km (Fig. 4). The tornado hit the city of Talsi, which was the place most affected by the tornado despite the fact its intensity was about F0-F1 at this point, according to reports of eye witnesses.

2.2. Tornado in Poland, July 14, 2012

The weather conditions of the tornado occurrence in Poland, only two weeks prior to the tornado in Latvia, were different. On July 14, 2012, Western and Central Europe was under the influence of a shallow low pressure area with its centre over Norway (995 hPa), while the eastern part of the continent was covered by a high with its centre over Russia. Poland remained in the warm sector of the secondary low from over Denmark, which featured quite a warm maritime-polar air mass. The undulated line of cold front covering Germany in the morning hours was to move over the area of Poland in the afternoon (Fig. 5).

In the lower and central troposphere, nearly the whole of Europe was under the influence of a wide trough from the Norwegian Sea. The temperature at the 850 hPa varied from 6°C to 8°C, while the maritime-polar air mass, following the cold front, was slightly colder – by only 3°C to 4°C. Thus, it is even difficult to distinguish on the map where the frontal lines and warm sector were (Fig. 6.)

The NWP analysis of the July 14, 2012, morning forecast materials did not show many factors indicating the occurrence of such an extreme weather phenomenon as a tornado within just a few hours. As mentioned above, the relatively warm maritime-polar air mass struggling over Poland on that day was not significantly unstable or humid – something that would be warning signal for intense convective phenomena, as was the case with the tornado in Latvia. Thermal conditions were quite "average" for this season and the maximum temperature on that day reached values of 25°C in north-west Poland. Furthermore, the surface thermal contrast in the frontal zone was small, not exceeding 5°C. However, there were some symptoms of potential conditions for tornado formation. The analysis of air mass humi-dity showed that in the lower atmosphere, up to the altitude range of 2000-2500 m, the relative humidity was higher than 90%, and the precipitable water (PW) indicator increased from 19 mm to 24 mm. Atmospheric instability was identified as conditionally unstable. In the near ground layer of the atmosphere, up to 3000 m, the air was characterized by low instability (CAPE: 200-600 J/kg according to nearby soundings from 12:00 UTC in Wrocław and Gdańsk) but it was relatively humid, while in the upper parts of the vertical profile of the atmosphere the air was dry with generally neutral stratification and was sepa-rated by an inversion layer present at the altitude of about 3000 m (Fig. 7.2). Such a vertical profile of the atmosphere usually causes the inversion layer to suppress the development of convective phenomena above the inversion level, unless it is "forced" as the result of the presence of an atmospheric front or another factor that releases this potential energy.

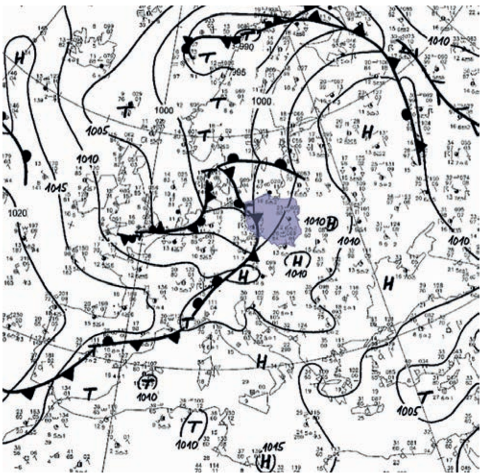

Fig. 5. The surface weather map; July 14, 2012; 12:00 UTC (source: DWD)

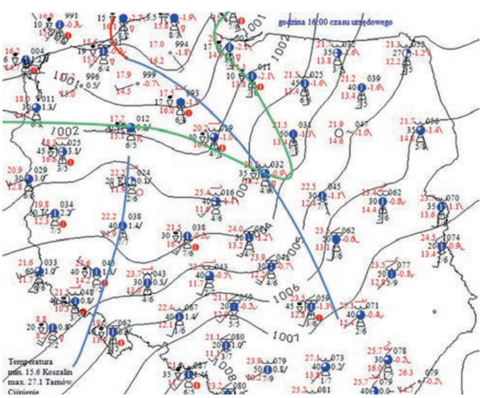

Fig. 6. The surface chart on July 14, 2012; 14:00 UTC. Blue lines show the cold fronts (main and secondary) while green line shows the area of higher humidity (dew points above 15ºC); source: Institute of Meteorology and Water Management, National Research Institute (IMGW-PIB)

Another, and indeed the most significant factor that should have caused concern for a forecaster on duty in the afternoon of July 14, 2012, was the vertical wind profile. Both a wind veer in the layer closest to the ground and a vertical speed shear in the middle troposphere were observed (Fig. 7.1, 7.2). The wind veer in the layer of up to 1 km was significant. Wind speed and direction at the ground level was 160°/5 kt, while in the 0-3 km layer it increased and turned to 240°/37 kt. As we know, helical environments, especially with veer in the lowest 1 km, are very conducive conditions to producing the tornado genesis process (Davies-Jones 1984). Furthermore, also in the middle troposphere, a strong vertical shear was present so that, in the layer up to 5 km, the wind speed increased further, by 15 kt, reaching the speed of 50 kt. These conditions, conducive to the development of horizontal vorticity in the lower troposphere and wind shear favourable for vortex tube formation in the atmosphere, created a solid basis for the development of a mesocyclone of supercell (Kerr, Darkow 1996; Wurman, Kosiba 2013).

However, as mentioned earlier, the conditions for the development of strong convection currents in the morning of this day were not favourable and, for that reason, the phenomena occurring in the cold front zone, which in the afternoon started to move from north-west Poland towards the east, showed relatively little activity. The first thunderstorms were noted after 10:00 UTC and they were accompanied by light rain showers and wind gusts not exceeding 11-13 m/s. The intensification of convective phenomena occurred only in the north part of Poland in the late afternoon when convective activity had been strengthened by the influence of the upper level divergence connected with the jet stream movement over central Poland and the convective day-lift (Fig. 8.1). During the afternoon, the loca-

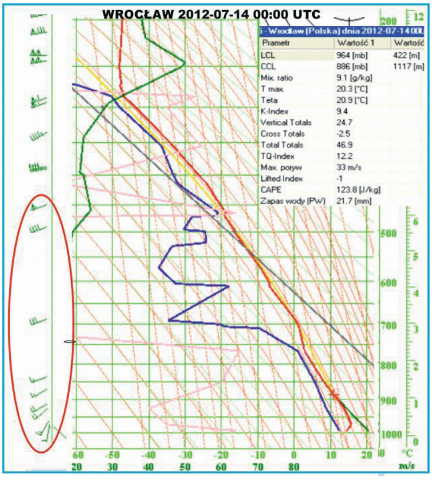

Fig. 7.1. Sounding from Wroclaw on July 14, 2012, 00:00 UTC. Red ellipse highlights vertical wind profile (source: IMGW-PIB)

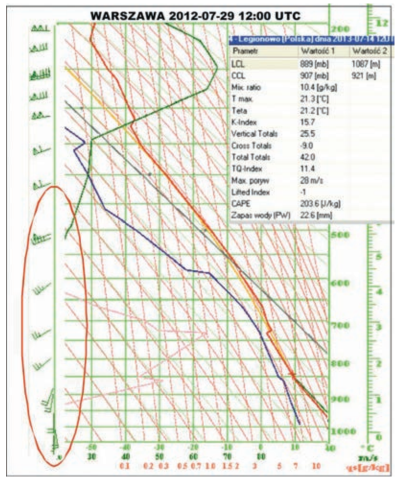

Fig. 7.2. Sounding from Warsaw on July 29, 2012, 12:00 UTC. Red ellipse highlights vertical wind profile (source: IMGW-PIB)

tion of the jet stream over Poland was such that its northwest part was below the left-exit of the jet, and therefore, divergence in the upper troposphere caused the outflow of air in the upper layers of the troposphere, thus strengthening the vertical air movements below. At the 300 hPa level, the increase of air divergence could be seen clearly between 06:00 UTC and 12:00 UTC – this confirms the described conditions (Fig. 8.1). Interestingly the temperature of the average CB tops at this afternoon oscillated just below -50ºC, which indicates that the CB tops were at the height of about 6-8 km (this was obtained both from radar and satellite images). There were no overshooting tops visible, even during the highest convective activity through all the time the cold front passed across the area of Poland (Fig. 8.2).

However, the supercell's top towered 3-4 km above the tops of the surrounding clouds and reached a height of between 11-12 km. We can see its peak on the MAX CAPPI (Maximum Constant-Altitude Plan Position Indicator) radar reflectivity at 15:30 on July 14, 2012 (Fig. 9.1). The PPI (Plan Position Indicator) radar imagery shows cumulonimbus (Cb) clouds with the "hook echo" which was associated with a mesocyclone and indicated favourable conditions for tornado formation over Warmia and Pomerania at around 15:30 UTC, as registered by the radar located in Gdańsk (Fig. 9.2).

Thus, even with the knowledge that the wind shear conditions were so favourable to tornado genesis supported by the upper-level jet, it is surprising that these weak convective circumstances created such an interaction between the environment and the Cb cloud, which resulted in the formation of a column of whirling air mass moving within a 7-8 km long, and ca. 300 m wide (Fig. 10) belt (causing the greatest damage in the villages of Stara Rzeka and Łączek in the Pomeranian Voivodeship, NW Poland).

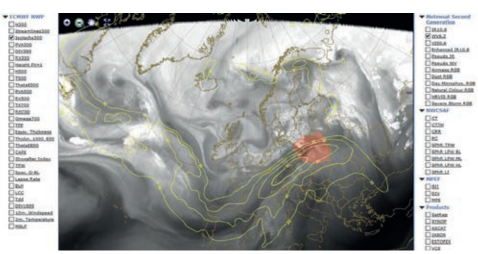

Fig. 8.1. Isotachs (yellow lines) and divergence (blue points) at 300 hPa level; WV 6.2 image, July 14, 2012, 12:00 UTC (source: EUMeTrain)

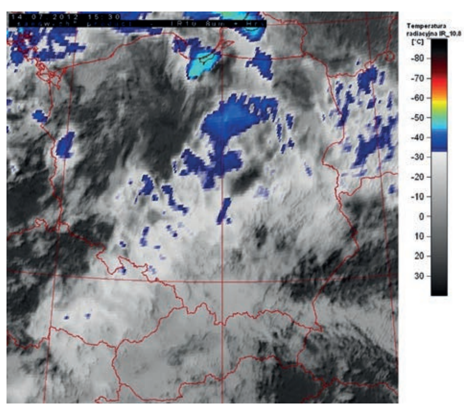

Fig. 8.2. "Sandwich" satellite indicates a temperature of top clouds over Poland and The Czech Republic; 14, 2012, 15:30 UTC (source: IMGW-PIB)

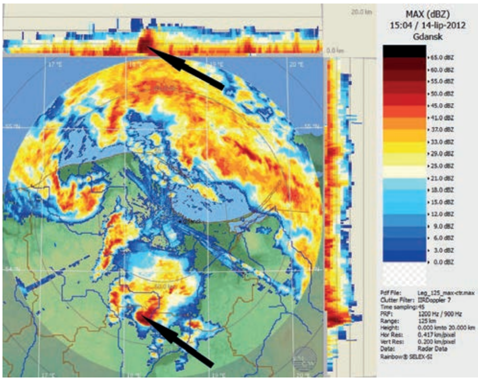

Fig. 9.1. MAX CAPPI image on 14 July 2012 at 15:34 in Gdańsk, Poland. The arrow shows the position of supercell (source: IMGW-PIB)

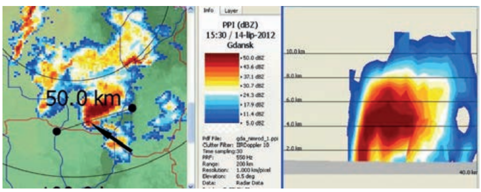

Fig. 9.2. PPI image on 14 July 2012 at 15:30 in Gdańsk, Poland that shows hook echo (indicated by an arrow) and vertical cross-section of supercell (source: IMGW-PIB; Irena Tuszyńska)

3. Results and Discussion

The synoptic situations presented here of tornado occurrences in Poland (July 14, 2012) and in Latvia (July 29, 2012) were different in terms of origin, but the impact they resulted in was catastrophic in both cases. Some of the numerous reports from the media and the ESWD (European Severe Weather Database) gave information about damage done by the Polish tornado: 1 fatality, 4 injured people, some roofs lost, Bory Tucholskie Forest was seriously damaged (Fig. 10). The worst damage (F2-F3 category) was reported in Smętowo Graniczne. The tornado in Latvia (F0-F1 category) hit the city of Talsi, causing local damage in the city centre and two fatalities due to flying roof parts and a falling tree. About 10 000 houses were also left with no electricity.

Fig. 10. The path of the tornado and damage done to the forestry (fot. K. Kowalski/FORUM)

In both cases, the cause that triggered the updraft in the atmosphere was the cold front zone. However, in Poland its activity was relatively weak, while in Latvia the convergence line that preceded the front zone was very active and the tornado occurrence that preceded two hours before the main front was connected just with its activity. Another common feature of both cases was the presence of the upper-level jet. It is known to focus primarily in the lower troposphere in cases of tornado occurrence, however, the influence of upper and middle flow on the low level storm relative flow and storm relative helicity is significant (Droegemeier et al. 1993; Kerr, Darkow 1996).The west-north area of Poland on that afternoon was under the right-entrance jet in the area of increased upper-level divergence, while the left-exit covered Latvia.

The crucial difference between these two weather events seems to be the thermodynamic conditions in the troposphere for creating of a favourable environment for tornadic thunderstorm. In the Polish case, the thermal circumstances were quite weak, with a low environmental CAPE (below 200-600 J/kg) that did not lead to strong convective updraft. However, the environmental vertical wind shear profile, amplified by the upper-level jet, prepared the perfect condition for tilting and rotation in the low/middle troposphere, and this produced the vortices (Rotunno 1981; Davies-Jones 1984). The veer in the layer up to 1 km was significant. Wind at the ground level 160°/5 kt increased and turned to 240°/37 kt in the 0-3 km layer. The relationship between storm structure and the environmental storm-relative flow resulted in the creation of a mesocyclone that yielded in tornado transition (Weisman, Klemp 1982; Lilly 1986a, b). It seems accurate to suppose that just this strong interaction between the environmental storm-relative flow and the relatively weak Cb updraft led to its transformation into a tornadic supercell structure, which was the basic reason for tornado occurrence in Poland.

In Latvia the situation was totally different. This tornado developed in a humid and very hot air mass of tropical origin. The specific humidity of the warm sector of an air mass that struggled over Latvia was very moist, and oscillated between 12 and 15 g/kg, which corresponded to a mean precipitation water content (PW) of about 40 mm (max PW = 44 mm). Convective available potential energy (CAPE) increased on the morning up to 2200 J/kg, and the values of lifted index (LI) were also high: -5°C. Convective inhibition energy (CIN) decreased totally from -87 K/kg during the 12 hours preceding the occurrence of the tornado, which suggests that strong enough static stability in the morning was overcome by high instability during the day, supported by the approaching convergence line. The favourable conditions for deep convection resulted in the formation of supercell the bases of which began at 300 m (LCL about 280 m AGL) and expanded through the tropopause into the lower stratosphere in the form of overshooting tops higher than 15 km (Fig. 4).The environmental wind profile also showed the proper hodograph clockwise curvature for a supercell (from 090°/05 kt near the surface to 220°/25 kt at about 2000 m height). This wind shear was strong enough to provide two distinctive kinds of thunderstorm – multicell and supercell. The latter developed in the convergence line, quickly developed above the troposphere, then weakened and disappeared. All this process occurred in no longer that one hour. The multicell structures appeared in the cold front zone about two hour later. They were also characterized by very strong reflectivity detected by the weather radar located at Riga airport. Thus, inside the land hail (2-4 cm size) strong wind gusts and downdrafts of these huge Cb multicells caused damage of even the same severity as that caused by a tornado. This was because the huge potential energy of the updrafts was converted into the kinematic energy of the horizontal wind.

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PAPER 8: REMOTE SENSING OBSERVATIONS OF THUNDERSTORM FEATURES IN LATVIA

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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].

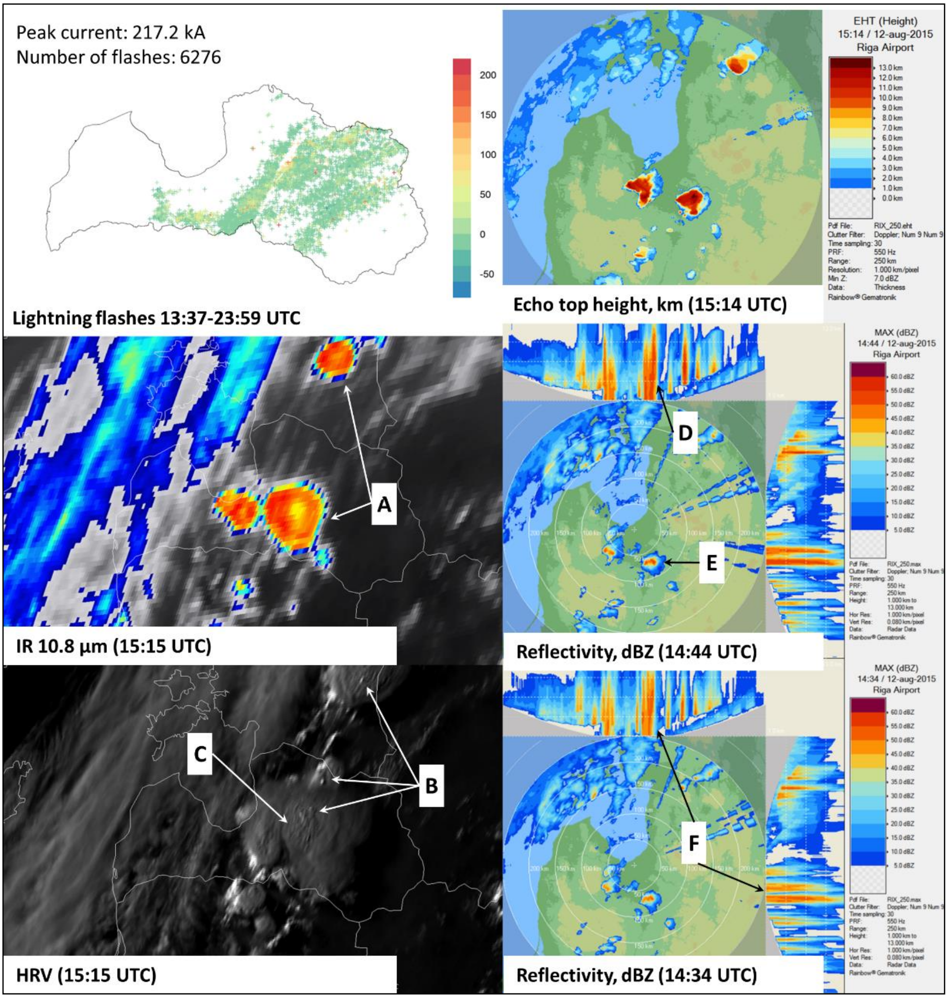

Fig. 1. Example of the thunderstorm features identified for a severe convective storm observed in Latvia on the 12th August 2015. The identified features are marked with letters A–F as follows: A – cold-ring structures; B – overshooting tops; C – gravity waves; D – tilted updraft; E – hook echo; F –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

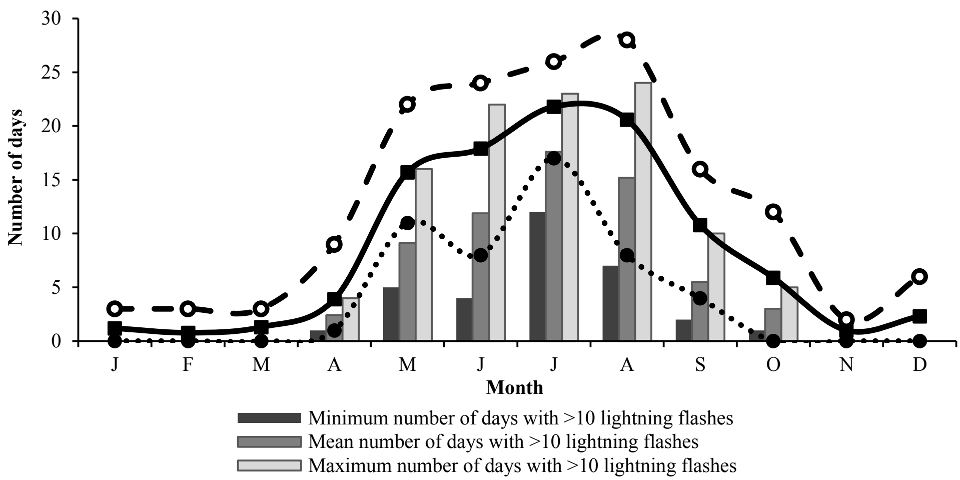

Fig. 2. The seasonal course of the frequency of days with lightning flashes presented as the multi-year mean, minimum and maximum number of days with at least 1 lightning flash and more than 10 lightning flashes detected in Latvia over the period 2006–2015.

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.

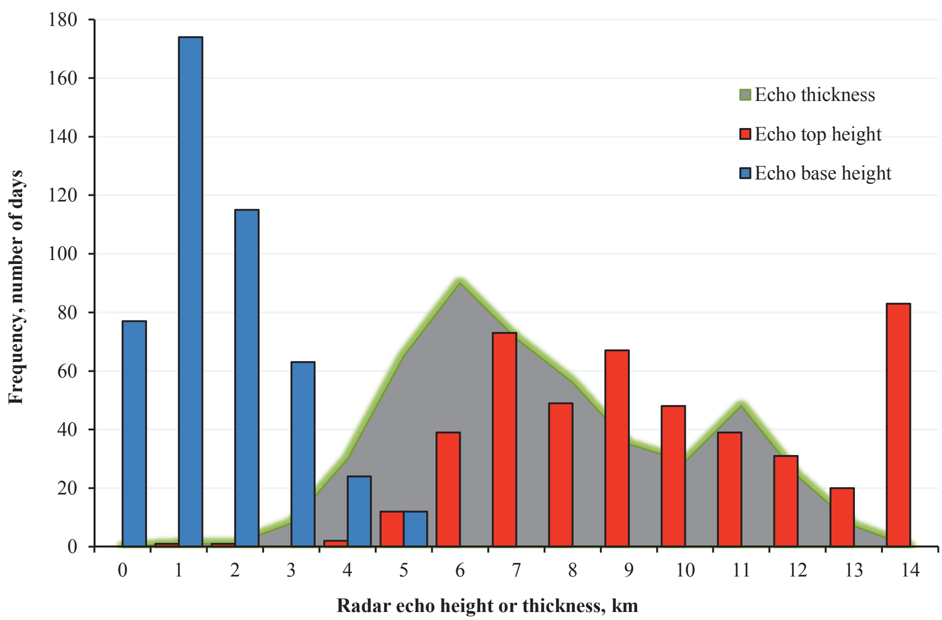

Fig. 3. The frequency distribution of weather radar Echo height EHT product parameters on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015.

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).

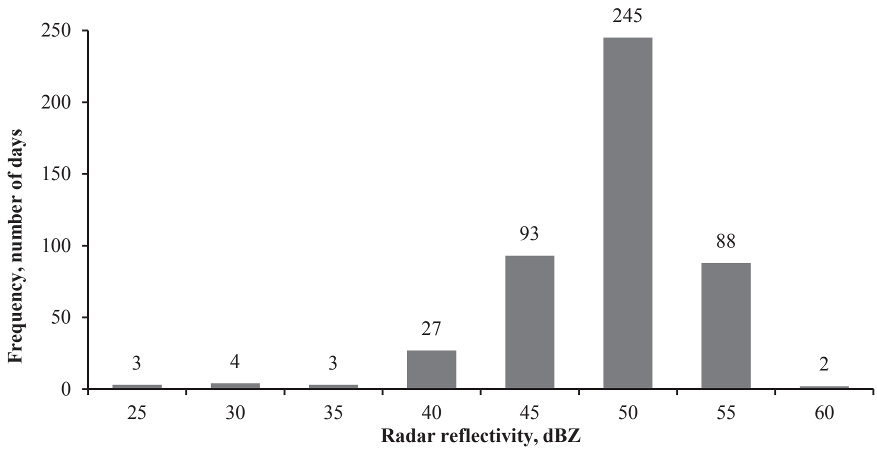

Fig. 4. The frequency distribution of reflectivity values (dBZ) obtained from the weather radar Maximum Display MAX product on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015.

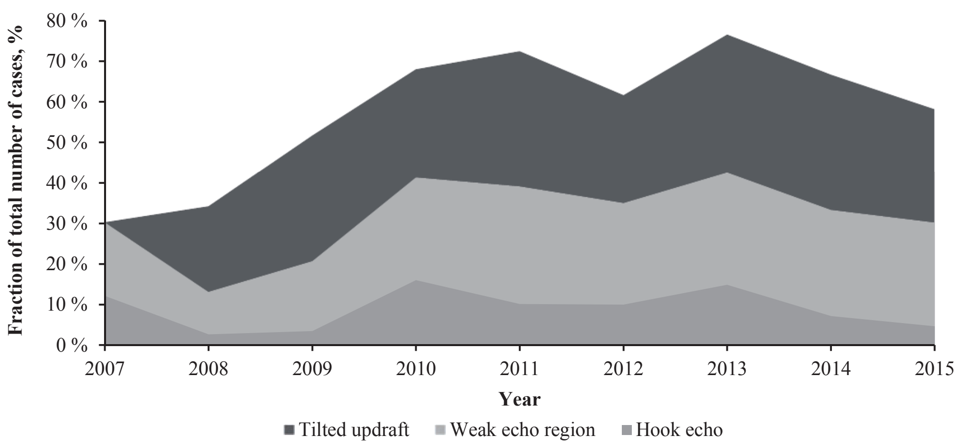

Fig. 5. The fraction of cases (%) with characteristic thunderstorm features identified from weather radar observations on days with more than 10 lightning flashes detected in Latvia over the period 2007–2015.

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).

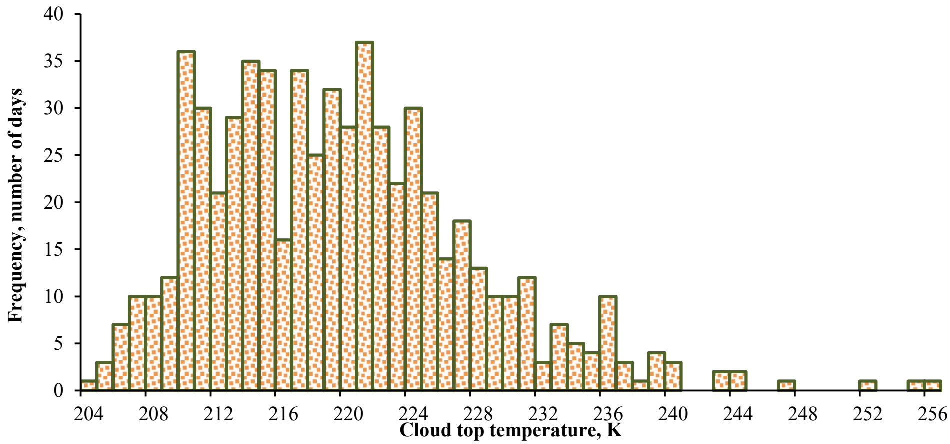

Fig. 6. The frequency distribution of CTT (K) identified from IR 10.8 spectral channel of the SEVIRI instrument aboard the *Meteosat* satellites on days with more than 10 lightning flashes detected in Latvia over the period 2006–2015.

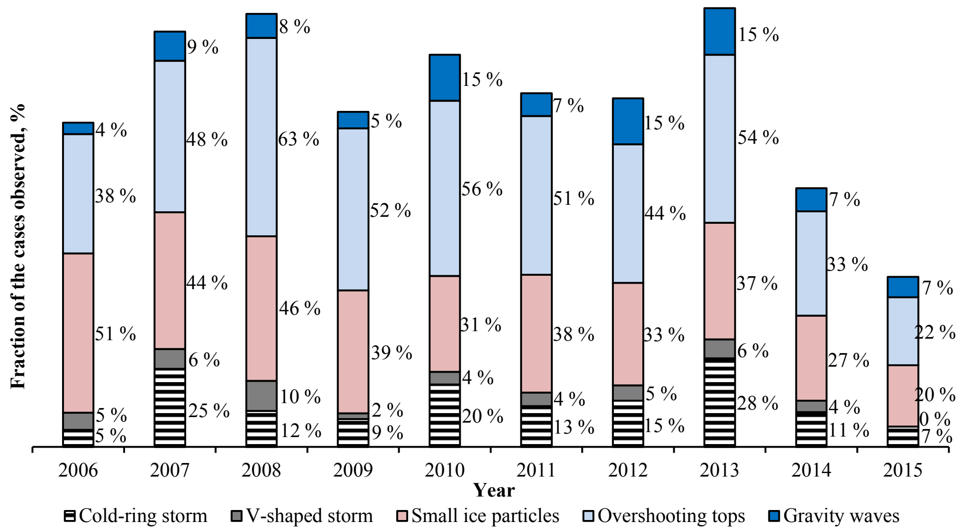

Fig. 7. The fraction of cases (%) with characteristic thunderstorm features identified from weather satellite observations on days with more than 10 lightning flashes detected in Latvia over the period 2006–2015.

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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