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SVEN-ERIK ENNO

Thunderstorm and lightning climatology in the Baltic countries and in northern Europe

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Department of Geography, Institute of Ecology and Earth Sciences,

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II **Enno SE**, Briede A, Valiukas D (2013) Climatology of thunderstorms in the Baltic countries, 1951–2000. Theoretical and Applied Climatology 111:309–325

III Mäkelä A, **Enno SE**, Haapalainen J (2014) Nordic Lightning Information System: Thunderstorm Climate of Northern Europe for the period 2002–2011. Atmospheric Research 139:46–61

IV **Enno SE**, Post P, Briede A, Stankunaite I (2014) Long-term changes in the frequency of thunder days in the Baltic countries, 1950–2004. Boreal Environmental Research 19 (accepted for publication)

Author's contribution

I The author is fully responsible for data analysis and writing of the manuscript.

II The author is fully responsible for data collection and analysis and has written most of the manuscript.

III The author has written most of the results and discussion part of the manuscript.

IV The author is responsible for most of the data collection and analysis. He has also written most of the manuscript.

LIST OF ABBREVIATIONS

CG	–	cloud-to-ground flash
CWT	–	circulation weather type
DE	–	detection efficiency
IC	–	cloud flash
IMPACT	–	improved accuracy from combined technology
LF	–	low frequency (30–300 kHz)
LT	–	local time (UTC + 3 h)
NORDLIS	–	Nordic Lightning Information System
TD	–	thunderstorm day
TH	–	thunderstorm hour
VHF	–	very high frequency (30–300 MHz)
VLF	–	very low frequency (3–30 kHz)
WMO	–	World Meteorological Organization

ABSTRACT

Thunderstorms are hazardous and potentially damaging weather events, which pose direct risk to human lives and property. They are also among the major causes of weather-related damages and economic losses in mid-latitudes.

The present thesis represents the first comprehensive and reliable overview of thunderstorm climate in northern Europe by using different available datasets. Thunderstorm climate and its long-term changes in the Baltic countries are represented on the basis of the data of human observers at weather stations during 1950–2013. Lightning climate of northern Europe and Estonia is analyzed by using automatically registered lightning data of the Nordic Lightning Information System (NORDLIS) during 2002–2013.

In the theoretical part of the thesis, historical human observations of thunderstorms at weather stations as well as modern lightning observations with specific instruments are described as they are the main data sources of the present thesis. Also, a short overview is given about the main properties of thunderstorm climate in global and regional scales.

Results revealed that the average annual ground flash density increased from the north to the south and varied from less than 0.01 to 1.08 flashes km^{-2} yr^{-1} in northern Europe. The lowest values were found along the coast of northern Norway and in the mountains of western Norway. The highest values were concentrated on southwestern Sweden and to the Baltic countries. Annually there were 2–29.5 days with thunderstorms in the study area. Thunderstorm activity in the study area is low on a global scale. On the other hand, it resembles the results in the surrounding areas and also in more distant places in a similar climatic conditions.

Thunderstorm season peaked in summer and roughly 99% of annual lightning occurred from May to September. The diurnal distribution of thunderstorms generally followed the diurnal temperature cycle and peaked between 14 and 19 hours local time (UTC+3 h). However, the large heat capacity of water clearly affected seasonal and diurnal cycles along the coast and over the sea. Thunderstorm season peaked later in August at coastal stations, whereas the maximum was in June or July at inland stations. The diurnal maximum was elongated towards evening and night hours under the influence of the sea as the relatively warmer sea surface sustains convection even when the daytime heating has ceased.

Individual intense storms were found to cause significant fractions of annual total lightning and thus remarkably affect the overall flash statistics. It also came out that such storms may occasionally occur even in the areas, which are usually characterized by low lightning activity.

Cold season thunderstorms appeared to be most frequent along the coast of Norway with up to 8 thunderstorm days from October to April. They are probably caused by the combination of mild humid airflow from the ocean,

coastal effects and the relatively cold winter troposphere. In other areas, like the Baltic countries, such storms are rare events that occur once in many years.

The annual number of thunderstorm days has decreased in the study area during 1950–2004. However, the main descent was concentrated on the period 1960–1990 and after a deep minimum around 1990, the frequency of thunderstorm days has increased during the last two decades. These changes are clearly related to periodic changes in the frequency of days with circulation weather types that enhance and inhibit thunderstorm formation. It is possible that these changes represent some kind of a cycle that is longer than the study period.

Generally there is a good agreement between the thunderstorm and lightning statistics of human observations at weather stations and the automatically registered data of the lightning location network. Properties of thunderstorm climate in northern Europe are similar to those in the surrounding areas. Long-term changes in thunderstorm frequency are in line with changes in synoptic conditions over northern Europe during the thunderstorm season. This indicates that the used datasets and different methods worked well and the results of the thesis could be used as reliable indicators of thunderstorm and lightning climate and its changes in northern Europe.

1. INTRODUCTION

Thunderstorms are hazardous and potentially damaging weather events which are among the major causes of weather-related damages and economic losses in mid-latitudes. Thunderstorms pose direct risk to human lives and property (e.g. López et al. 1995; Curran et al. 2000). Additional economic losses are caused by problems and delays in air traffic (Sasse and Hauf 2003; Mäkelä et al. 2013) and by forest fires ignited by lightning (e.g. Nash and Johnson 1996; Larjavaara et al. 2005).

On the other hand, thunderstorms are an important part of the global electric circuit (Rycroft et al. 2000). Thunderstorm precipitation is an essential source of moisture in many areas (e.g. Changnon 2001b). Lightning is also an important producer of nitrogen oxides and tropospheric ozone (Schumann and Huntrieser 2007).

Today, the question about future changes in the frequency of thunderstorms and lightning has arisen in association with the concept of global warming. Thunderstorms are known to be affected by general changes in climate (e.g. Williams 2005, Price 2009a) and also by natural factors such as solar activity (Brooks 1934; Mullayarov et al. 2009; Siingh et al. 2011). However, the effect of global warming on thunderstorm activity and lightning frequency is still unclear (e.g. Price 2009b; Brooks 2013).

Despite high latitudes, thunderstorms are common summer phenomena in the Baltic countries and in Scandinavia. Lightning, straight-line winds, hail and sometimes even tornadoes have caused serious damages in the Baltic countries (e.g. Merilain and Tooming 2003, Marcinoniene 2003) as well as in Finland (Punkka et al. 2006; Tuovinen et al. 2009; Rauhala et al. 2012).

Climate of thunderstorms and lightning, as well as its long-term changes has been studied in many places around the world (Section 3). In northern Europe, long series of human observations of thunderstorms are available in the Baltic countries (Section 4.2). Scandinavia, Finland and Estonia are covered with the modern NORDLIS lightning detection network during the recent years (Section 4.1). Unfortunately, the potential of the datasets has been used only to a small extent.

As of 2009, only a few papers treated thunderstorms and lightning in northern Europe. These include discussions of the lightning climatology of Sweden (Sonnadara et al. 2006) and Finland (e.g. Tuomi and Mäkelä 2008b). First attempts to analyze the lightning climate of Estonia date back to the 1990s (Taalmann 1995). However, there was no complex lightning climatology for northern Europe, although the necessary data was available. In addition, information about thunderstorm frequency and its long-term changes in the Baltic countries was absent. Most of the thunderstorm data was held only in paper format at different archives in Estonia, Latvia and Lithuania.

This dissertation investigates the thunderstorm and lightning climate and its long term changes in the Baltic countries and in Scandinavia by drawing together different available datasets. It also puts the thunderstorm climate of the study area into a wider context by using synoptic data and comparisons with other similar studies in the world. To achieve that, the following tasks were performed:

1) digital database of annual and monthly numbers of thunderstorm days (TD) in the Baltic countries was constructed on the basis of observational records stored in paper format in Estonia, Latvia and Lithuania (Publications II and IV);
2) thunderstorm climate in the Baltic countries was described by using annual and monthly numbers of TDs registered at weather stations during 1951–2000. (Publication II);
3) long-term changes in thunderstorms frequency in the Baltic countries were investigated on the basis of monthly and annual TD numbers during 1950–2004 (Publication IV);
4) database of circulation weather types was constructed for the study area. Relationships between thunderstorm occurrence and weather types were studied in the Baltic countries during 1950–2004 (Publication IV).
5) software for studying lightning datasets was developed to analyze the NORDLIS lightning data in Estonia (Publication I) and in northern Europe (Publication III).
6) thunderstorm and lightning climate and its long-term changes in the study area were compared with the results of other similar studies carried out in the surrounding areas and elsewhere in mid-latitudes (Publications I, II, III, IV).

2. THUNDERSTORM AND LIGHTNING OBSERVATIONS

2.1. Human observations of thunderstorms

Human observations at weather stations are the oldest available records of thunderstorm activity. Observers usually register monthly and annual numbers of thunderstorm days (TD). According to the WMO definition (1953), a TD is a calendar day on which thunder is heard by the observer. At many stations, the beginning and end times of thunderstorms are also recorded. The beginning of a thunderstorm is registered when the first clap of thunder is heard by the observer whereas the end of the storm is recorded 15 minutes after the last clap (Robinson and Easterling 1988). On the basis of such observations monthly and annual total durations of all thunderstorms can be calculated as thunderstorm hours (TH).

The main advantages of human observations are long data series. The data for annual and monthly numbers of TDs go back for more than 100 years at many stations (e.g. Bielec 2001; Bielec-Bakowska 2003; Changnon and Changnon 2001). Hence it is possible to study not only the present thunderstorm climate but also long-term changes in TD frequency.

Meanwhile, human observations have certain limitations and disadvantages. First of all, a TD does not reflect the real intensity of thunderstorms (Rakov and Uman 2003). Both a weak storm with only one flash and a heavy storm with thousands of flashes give one TD. Although TH data correlates more closely with real lightning activity (Uman 2001), some stations register only TDs. TH data series, if they exist, are often shorter than TD ones.

Furthermore, there are many physical, site-specific and observer-specific factors that affect the observer's chance to record the thunderstorm when lightning has occurred near to the station. The physical properties of the atmosphere affect the propagation of a sound wave. As a result, thunder is seldom heard more than 25 km off the storm (Fleagle 1949). It is also demonstrated by Changnon (1993) that that the cooler air at higher latitudes transmits sound better than the warmer air at lower latitudes. Mountains and large valleys also limit the audibility of thunder (Changnon 2001a).

Site-specific factors include local noise level at the station as well as urban effects on thunderstorm frequency. Local noise at the stations reduces the chance to hear a thunder. It is particularly important at the stations near to big airports (Changnon 1993). Many stations that started their observations in rural conditions are now in the urban environment as a result of the fast growth of cities. Urban heat islands and air pollution are demonstrated to result in an increased thunderstorm and lightning activity (e.g. Westcott 1995; Rivas Soriano and de Pablo 2002; Pinto et al. 2013).

Another related problem is the relocation of stations. As a result, the number of registered thunderstorms may change significantly, especially if the old and new locations are in a sharp climate gradient of storm activity (Changnon 2001a).

It is possible that certain observers have been more attentive to recording thunder than others (Changnon 2001a). Reap and Orville (1990) pointed out that nocturnal storms can be more easily detected because of the lightning flashes against the dark background sky at night. They also demonstrated that stronger storms with a higher frequency of lightning are much more effectively detected by the observer. It is also possible that in the tropics where thunderstorms are very frequent, observers tend to record only overhead storms and ignore more distant ones although the sound of thunder is audible (Brooks, 1925).

All such issues should be addressed when using the data of human observers in order to investigate thunderstorm climate.

2.2. Main properties of lightning and its electromagnetic radiation

The principles of instrumental lightning detection are based on the electromagnetic radiation emitted by lightning. This, in turn, is associated with specific physical processes that occur during a lightning flash. The most important processes in lightning detection and its related data analysis are shortly described below. For more detailed information see Rakov and Uman (2003).

Lightning can be divided into cloud lightning and cloud-to-ground lightning. A lightning discharge within a cloud or between different clouds is termed as a *cloud flash*. A lightning discharge occurring between the cloud and the ground is termed a *cloud-to-ground flash* or simply a *flash* (Poelman 2010). The abbreviations CG and IC are used hereafter to refer to cloud-to-ground and cloud flashes respectively. There are different types of IC and CG flashes. About 90% of CG flashes carry negative charge from the cloud to the ground whereas about 10% carry positive charge (e.g. Baba and Rakov 2009).

A cloud-to-ground flash can consist of one or more strokes. A *stroke* is a sequence of processes including a downward leader, a return stroke, a continuing current and J- and K-components (Poelman 2010). Hereafter, the stroke of a typical CG flash that carries negative charge from the cloud to the ground is described.

The stroke begins to develop when the strength of the electric field in a thunderstorm exceeds the breakdown field. Free electrons join into a leader which develops towards the ground and builds up a conducting path between the cloud charge and the ground. Once the stepped leader approaches the ground, the electric field at the ground locally exceeds the critical value. As a result, positive upwarded leaders develop from the ground objects towards the negative leader (e.g Poelman 2010).

After a contact has been made between the downward and upward moving leaders, the return stroke begins. Negative charges in the lightning channel move with great speed towards the ground, causing large currents. Typically, the peak current of the first return stroke is around 30 kA and it is achieved within some microseconds. As a result of this high current the lightning channel heats up to about 30 000 K (Rakov and Uman 2003). This is accompanied by a bright flash of light and a shock wave, known as the thunder. Return strokes produce the strongest and most easily detectable electromagnetic signatures of cloud-to-ground lightning (Vaisala 2008).

During the end of the stroke, J- and K-processes occur in the cloud. They are associated with the charge transfers between the lightning initiation point and the negative charge region of the cloud. K-processes transport additional negative charge into the existing channel and may finally trigger a subsequent stroke (Poelman 2010).

Most of the negative CG flashes contain more than one stroke. The subsequent stroke process is generally similar to that of the first stroke, except that its peak current and associated electromagnetic radiation is significantly lower. A typical number of strokes per CG flash is 3–5 but flashes with 1–26 strokes have been observed (Rakov and Uman 2003). The number of strokes within a flash is called *flash multiplicity*. Subsequent strokes may hit the same place as the first stroke, but they can also have different ground contact points usually within a few hundred meters to a few kilometers from each other (e.g. Vaisala 2008).

A cloud flash is composed of early (active) stage and late (final) stage. It begins with a bidirectional leader between the negative and positive charge regions in the cloud. Early stage of IC lightning resembles the breakdown and leader processes in negative CG flash. During the late stage processes negative charge is transported to the region of flash origin (Rakov and Uman 2003).

All lightning discharges emit electromagnetic radiation over a wide range of frequencies. Processes that create new channels such as leaders are accompanied by strong emissions in very high frequency (VHF) range. Meanwhile high currents in previously established channels like the return strokes result in the most powerful emission in low frequency (LF) and very low frequency (VLF) (Vaisala 2008). According to Lojou et al. (2009) it is theoretically possible to detect both IC and CG flashes in VHF, as well as in LF and VLF frequencies.

However, the strongest radio frequency radiation of CG flashes is emitted in LF and VLF bands. Their signals peak around 10 kHz (Poelman 2010) where individual large pulses that come from the return strokes could be registered. In contrast, the signals of IC discharges contain hundreds of very fast transient pulses radiated mainly in VHF bands. In the LF range the pulses of cloud flashes are usually very weak and may only occasionally resemble the signals of CG flash return strokes (Vaisala 2008). As a result, different techniques are developed to detect IC and CG lightning.

2.3. Instrumental observations of lightning

Devices that are widely used to register the occurrence of lightning can be divided into flash counters, lightning detection networks and satellite-based instruments. Ground-based flash counters and lightning detection networks mostly rely on the radio emissions from lightning (Drüe et al. 2007), whereas space-based instruments are designed to register optical emission of lightning (e.g. Finke 2009).

Flash counters are the oldest devices that are capable of registering lightning. It is possible to estimate only the total amount of lightning within the effective radius from a flash counter, which is usually in a range of 15 to 30 km. Discrimination between CG and IC lightning is complicated. They were widely used before the advent of lightning detection networks. Flash counters are described in more detail by Cooray (1986).

Lightning detection networks typically encompass many sensors with spatial distances usually tens to hundreds of kilometers between them. The data of individual sensors are collected and analyzed by the central unit of the network. When the measurements of different sensors are combined for the same lightning stroke, it is possible to determine its location, time, type, polarity and peak current. Strokes are then grouped into flashes on the basis of location and time differences and multiplicity of the flashes is determined (e.g. Cummins et al. 1998a).

Lightning detection networks use one or more of the three techniques to locate lightning: magnetic field direction finding, time-of-arrival method and interferometry.

Magnetic field direction finding sensors measure the azimuth between the sensors and the lightning. Two orthogonal magnetic loop antennas are used for the measurements. An optimization procedure to minimize the angle errors of the sensors can be employed if the discharge is registered by at least three sensors. In contrast, if only two sensors register the lightning, significant location errors may occur, especially if the discharge occurs along a line between the two sensors (Rakov and Uman 2003).

Time-of-arrival method bases on the fact that the arrival time of the lightning signal at a sensor reflects the distance of the flash. Sensors that are closer to lightning receive the signal earlier than more distant ones. Each pair of sensors that have registered the flash determines a hyperbolic curve of possible locations of the strike on the basis of difference in the signal arrival time between the sensors in the pair. If at least four sensors and three curves are available then the lightning location can be determined as the intersection point of all the hyperboles. More detailed overview is given by Rakov and Uman (2003).

Improved accuracy from combined technology (IMPACT) method combines magnetic field direction finding and time-of-arrival methods (Fig. 1). Necessary azimuth information comes from direction finding whereas range information is obtained from arrival time of the signal. If the flash occurs along the line between two sensors where direction finding is inaccurate, it can still be accurately located on the basis of the arrival times of its signal. Thus, the IMPACT method allows the determination of time and location of the lighting even if it is detected only by two sensors (Vaisala 2008).

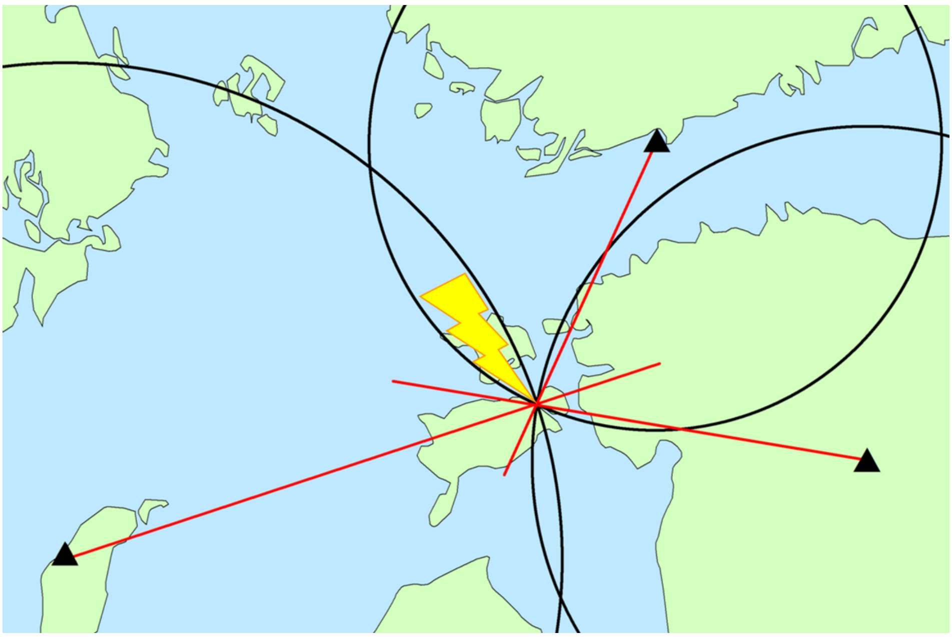

Figure 1. Example of a stroke located by magnetic direction finding (red lines) and the time of arrival method (black curves) by three lightning sensors (black triangles).

Interferometry measures the lightning signals at VHF frequencies. Antennas are placed so that the distances between them are in the order of magnitude of a wavelength, i.e. about one to five meters. As a result, the time difference can be determined as a phase difference of the signals received by the antennas (e.g. Lojou et al. 2009). This allows very high sampling rates and the determination of azimuths and elevation angles of individual lightning sources. Not only the locations, but also the spatial and temporal development of lightning channels can be observed (Hayenga and Warwick 1981).

Most lightning location systems are designed to locate cloud-to-ground flashes (Lojou et al. 2009) as CG lightning is responsible for most of the lightning damage. In addition, its characteristic LF and VLF signals are usually detectable within hundreds of kilometers from the flash (Cummins et al. 2000). Hence, relatively large distances between individual sensors are allowed and the cost of such network is lower.

Other lightning detection instruments are designed to combine different methods such as IMPACT and interferometry to register both CG and IC flashes. However, there are some problematic issues in association with VHF lightning detection. Such signals attenuate relatively fast, so a higher density of sensors with higher costs is needed (Poelman 2010). In addition, VHF detectors are very sensitive to local radio noise and obstacles such as antennas and other large metallic objects (Lojou et al. 2009).

Nowadays, numerous lightning detection networks cover the whole countries (e.g. Schulz et al. 2005; Antonescu and Burcea 2010), regions (e.g. Rivas Soriano et al. 2005; Wapler 2013) and even continents (e.g. Orville et al. 2002). For example, Poelman (2010) described 24 national and international networks only in Europe. Some experimental systems like World-Wide Lightning Location Network have been designed to cover the whole globe (Rodger et al. 2006). Data of the same sensors may be shared between national and international networks simultaneously.

The most widely used spatial measure of lightning incidence is called *flash density*. Flash density is the average number of lightning flashes per area unit per time unit (Rakov and Uman 2003). It may represent all lightning or only CG lightning. Usually the annual number of CG flashes per square kilometer is used to summarize lightning observations. Some authors (e.g. Chronis 2012; Wapler 2013) also use *stroke density*, which means that individual strokes of CG flashes are summarized.

Optimal cell size for calculating flash density depends on the size of the study area and the exact type of analysis (Schultz et al. 2005). Some more widely used cell sizes include 1×1 km (Schulz et al. 2005; Novák and Kyznarová 2011), 10×10km (Watson and Holle 1996; Tuomi and Mäkelä 2008b) and 0.2×0.2 degrees (Orville et al. 2002; Rivas Soriano et al. 2005). Other lightning parameters like peak current and multiplicity may also be averaged over the same grid.

2.4. Advantages and limitations of lightning location networks

Instrumental observations of lighting have certain advantages compared to human observations. Lightning detection networks allow the collection of continuous lightning data with high spatio-temporal accuracy over large areas. Their data are processed and made available in real time (e.g. Cummins et al. 1998a), which help weather forecasters to follow the movement and intensity of storms. In addition, flash density statistics over longer time periods help to estimate lightning risks much more accurately than the traditionally used average annual numbers of TDs and THs (Rakov and Uman 2003). It is possible to derive the annual TD or TH numbers once registered by human observers directly from the lightning detection data (e.g. Huffines and Orville 1999; Rivas Soriano and De Pablo 2002b).

However, there are also many problems in association of automatic lightning detection. First of all, we always miss some lightning even within the theoretical coverage of detection network. This comes from the fact that the signal of lightning received by detectors should match some previously defined criteria in order to be registered (e.g. Cummis et al. 1998a). These predefined criteria are characteristic to a "typical" lightning signal. Hence, if there is a weak stroke for example, it could easily be missed as its signal strength just remains below these criteria.

The ratio of registered to actually occurred flashes or strokes is called the detection efficiency (DE) of a lightning location network (e.g. Tuomi and Mäkelä 2008a). As we never know the actual number of flashes within the range of lightning detection network, we can only approximately estimate the DE. Most of the lightning climate studies apply no correction for DE. However, it has been estimated that within many national lightning detection networks it is possible to detect 90–95% for CG flashes (e.g. Poelman 2010).

In association with signal processing, there are also some problems with discrimination between IC and CG flashes. Usually their signals differ remarkably, but in case of weak flashes (peak current below 10 kA) with positive polarity there is a high risk of misclassification (Cummins 1998b). For that reason, some authors prefer to remove all such CG flashes before calculating flash densities (e.g. Orville et al. 2002; Antonescu and Burcea 2010).

Data of lightning location networks are also associated with spatial accuracy issues. Errors in locating CG lightning are typically in a range of few hundred meters to a few kilometers. However, in some cases the error can be tens or even hundreds of kilometers, i.e. some flashes are wrongly located far away from the actual thunderstorms (e.g. Cummins et al. 1998b).

The available data series of lightning location systems are rather short, the majority of them date back to the 1990s or are even newer. In addition, they are often inhomogeneous as the performance of the networks is frequently changed. Some sensors fail unexpectedly, old sensors are replaced with modern models and new sensors are installed in order to enhance DE (e.g. Mäkelä et al. 2010). Moreover, the signal processing criteria and data algorithms of the central unit of the network may be adjusted (Schulz et al. 2005). All these changes remarkably affect DE whereas the exact magnitude of the effects is often hard to estimate. Hence, issues like long-term changes in thunderstorm frequency are hard to resolve on the basis of lightning location data.

3. CLIMATOLOGY OF THUNDERSTORMS AND LIGHTNING

3.1. Global distribution of thunderstorms and lightning

The highest thunderstorm activity is concentrated to the tropical areas where the annual numbers of TDs as high as 100 to 200 are common (WMO 1956). Average annual TD number reaches 242 at Kampala, Uganda (WMO 1953). Areas with more than 200 TDs annually can also be found in Indonesia (Changnon and Hsu 1984).

Results of flash counters (Mackerras and Darveniza 1994) and the World Wide Lightning Location Network (Virts et al. 2013) generally agree with former TD data. Similar results have also emerged from the global lightning distributions of satellite-based instruments like Optical Transient Detector (e.g. Christian and Latham 1998) and Lightning Imaging Sensor (e.g. Finke 2009).

During 1995-2000, 78% of global lightning was registered between 30°S and 30°N with the highest peak in central Africa and somewhat lower maxima over Amazonia and Indonesia (Fig. 2). Peak mean annual total lightning density (IC and CG flashes) of 80 flashes km^{-2} y^{-1} was found in the Congo basin (Christian et al. 2003).

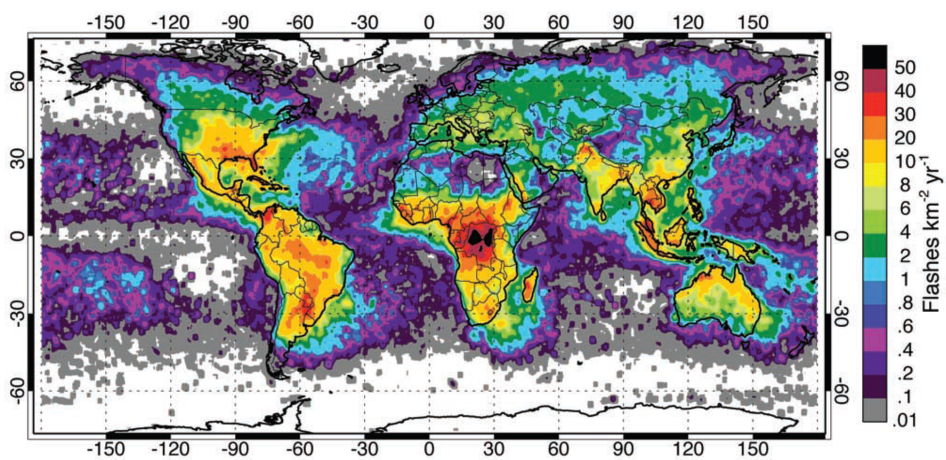

Figure 2. Average global distribution of lightning 1995–2000 represented as a total number of IC and CG flashes km^{-2} y^{-1} (Adapted from Christian et al. 2003).

Global lightning activity is characterized by sharp contrasts between land and ocean areas. The main reason is the more intense thermal heating of land, which results in higher updraft speeds in continental thunderstorms (e.g. Williams and Stanfill 2002). As a result, the annual average land-to-ocean flash ratio is 10:1

(Christian et al. 2003). In addition, continental thunderstorms peak between 16–17 hours local time, whereas oceanic thunderstorms are equally distributed during the day (Price 2006).

As a global average, there are approximately 45 lightning flashes per second (Christian et al. 2003). This rate has an annual variation from 35 to 55 flashes per second with a maximum during the Northern Hemisphere extra-tropical summer. Additional factors like land-ocean differences and diurnal variations cause the actual flash rate to vary from less than 10 to over 80 flashes per second (Christian et al. 2003; Price 2006).

3.2. Regional and local thunderstorm and lightning studies

On the basis of local and regional studies in tropics, the highest CG densities reach 65 flashes km^{-2} y^{-1} on Java Island (Pinto et al. 2007). Typical tropical lightning activity is still lower with mean annual CG flash density of 4.6 in Botswana (Jayaratne and Ramachandran 1998), 3.2 on Java Island (Hidayat and Ishii 1998), 5–15 in South Africa (Gijben 2012) and 6–8 in Brazil (Pinto and Pinto 2003). Average annual TD numbers of human observers are 79–202 in Malaysia (Abidin and Ibrahim 2003), 40–131 in Nigeria (Adegboyega and Odeyemi 2012), 50–140 in Brazil (Pinto and Pinto 2003) and 9–97 in Saudi-Arabia (Shwehdi 2005).

Descending thunderstorm activity towards higher latitudes is obvious from many studies. There are annually 80–97 TDs and 6–8 CG flashes per km^{-2} in northern Australia, whereas the values are 10–20 and below 1 in southern Australia, respectively (Kuleshov et al. 2006). In China, the average annual number of TDs is 60–70 in southern and less than 30 in the northern parts of the country (Zheng et al. 2010).

In North America, the highest thunderstorm activity is concentrated around the Gulf of Mexico (Kucieńska et al. 2010). Mean CG flash densities as high as 9–11 km^{-2} y^{-1} have been reported in Florida (Huffines and Orville 1999; Orville and Huffines 2001; LaJoie and Laing 2008). In contrast, there is less than 1 CG flashes km^{-2} y^{-1} in the northern parts of the United States (e.g. Orville and Hufines 2001) and in most of Canada (Orville et al. 2002; Shephard et al. 2013). On the basis of human observations, the annual number of TDs is 70–88 in Florida and below 10–20 in the northern parts of the United States (Changnon and Changnon 2001). Annual numbers of THs (Changnon 1988a) and thunder events (Changnon 1988b) are roughly 5–10 times lower in the northern parts of the United States than in Florida.

On the basis of European studies, CG lightning density as high as 9 flashes km^{-2} y^{-1} has been registered over a relatively small area in northeastern Italy (Feudale et al. 2013). Other studies in southern Europe have shown maximum lightning frequencies over 2 flashes km^{-2} y^{-1} on the Iberian Peninsula (Rivas

Soriano et al. 2005; Rivas Soriano and de Pablo 2007) and up to 3.06 flashes km^{-2} y^{-1} in Romania (Antonescu and Burcea 2010).

Central Europe is characterized by the annual amount of 0.9–3.2 CG flashes km^{-2} y^{-1} in the Czech Republic (Novák and Kyznarová 2011) and 0.5–4 flashes km^{-2} y^{-1} in Austria (Schulz et al. 2005). In northern Europe, lightning activity is clearly lower with less than 1 CG flash km^{-2} y^{-1} in Finland (Tuomi and Mäkelä 2008b) and Sweden (Sonnadara et al. 2006).

On the basis of human observations, the annual number of TDs is 15–33 in Poland (Bielec-Bakowska 2003), 17–30 in Belarus (Loginov et al. 2010), 4–22 in Sweden (Isaksson and Wern 2010) and 8–18 in central and southern parts of Finland (Solantie and Tuomi 2000). In all the countries, there was an obvious increase in thunderstorm frequency from the north to the south.

3.3. Long-term changes in thunderstorm frequency

Many local and regional studies have published results on long-term changes in thunderstorm climate. Due to limitations of the lightning detection data discussed in section 2.4, such studies are based on the annual numbers of TDs registered by human observers at meteorological stations.

Temporal behavior of TD frequency is usually not uniform in different regions. For example, five to 14 regions with a distinctive temporal behavior of TD frequency have been determined only in the United States on the basis of different study periods and data samples (Changnon 1985; Changnon 1988; Changnon and Changnon 2001).

One general similarity that is reported by many authors for different regions is a relatively high TD frequency in the 1950s and 1960s followed by a downward trend during the last decades of the 20th century. This was characteristic to the United States (Changnon and Changnon 2001) as well as to parts of Russia and Kazakhstan (Gorbatenko and Dulzon 2001). Similar trends have been found in parts of China (Zhang and Niu, 2009; Wei et al. 2011, Zhang and Pei 2011) and in tropical Africa (Price and Asfur 2006).

However, not all the available studies show a peak in TD frequency during the 1950s and 1960s. For example, an upward trend in TD frequency has been observed in Australia since 1940s (Davis and Walsh, 2008; Kuleshov 2012) and in southeast Brazil since 1951 (Pinto et al. 2013).

In Europe, Changnon (1985) found an upward trend in TD frequency during 1930–1980 on the British Isles, northwestern Russia and southern Europe, whereas TD numbers were decreased in western Europe. More recent local studies have found no reliable trends in thunderstorm frequency in Poland during 1949–1998 (Bielec-Bakowska 2003), in southwestern Germany in 1949–2003 (Kunz et al. 2009) and in Bulgaria during 1961–2006 (Simeonov et al. 2009). An increase in TD frequency was observed in the northern Caucasus region between 1936 and 2006 (Adzhiev and Adzhieva 2009).

4. DATA AND METHODS

4.1. NORDLIS lightning observations

4.1.1. Data of NORDLIS lightning detection network

The NORDLIS lightning detection network is covering Norway, Sweden, Finland and Estonia (Fig. 3). During the study period the number of NORDLIS sensors varied from 30 to 34. Most of the sensors apply the IMPACT technology and hence detect mainly CG lightning on the basis of its LF electromagnetic radiation (Section 2.3). The central unit of the system operates in Finland and belongs to the Finnish Meteorological Institute.

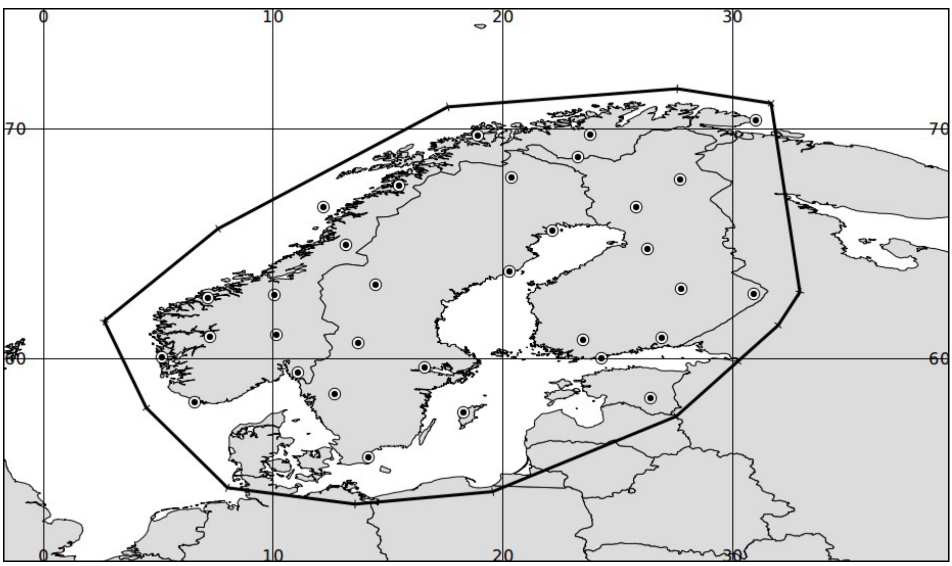

Figure 3. The positions of NORDLIS sensors in 2011 (circles) and their practical range (solid line). (Adapted from Publication III).

The used data set consists of CG flashes, i.e. sequences of strokes that are grouped by the central unit on the basis of predefined spatial and temporal criteria. In case of flashes that contained more than one stroke, the data of the flash actually represents the parameters of its first recorded stroke. For each flash, the dataset contains its located coordinates that are expressed according to the WGS-84 coordinate system. The central processor also provides an estimate for the uncertainty related to each calculated location (location accuracy). In addition, the time of the flash, its peak current, polarity and multiplicity are provided. The data were used without any corrections for DE and location accuracy. Both parameters are estimated to be sufficiently high (Tuomi and Mäkelä 2008a; Mäkelä et al. 2010).

For the Northern Europe lightning climatology (Publication III), the CG data set of the full coverage of NORDLIS during 2002–2011 was used. It consists of 4 121 649 CG flashes. All CGs with positive polarity and peak current less than 10 kA were filtered out from the data set. This was done because many of the positive CGs with low peak currents may actually be misclassified IC flashes (e.g. Cummins et al. 1998b).

For the detailed description of Estonian lightning climate (Publication I) only a small subset of NORDLIS data obtained from the Estonian Environment Agency were used. The subset contained CG flashes in and around Estonia within a predefined spatial domain. The borders of the domain were defined on the basis of Estonian coordinate system LEST97 as follows: X≥335000 m, X≤745000 m, Y≥6381000 m and Y≤6631000 m.

Only the data since 2005 were used as the detection efficiency of the system was significantly lower in Estonia until 2004. There were 149 617 registered CG flashes in the study area in the period 2005–2009. As much more lightning has occurred in Estonia during 2010–2013, an updated statistics for the period of 2005–2013 are represented in the present dissertation. During the nine-year period there were 382 531 CGs in the study area.

4.1.2. Methods for NORDLIS data

A 10×10 km spatial grid was used to calculate flash densities in Estonia (Publication I). *Idrisi 32* and *ArcGIS* software were used in the calculations. Later, the author developed his own scripts in *Python* and *Java* programming languages to deal with NORDLIS data. These scripts were used to prepare the updated spatial and temporal statistics of CG lightning in Estonia during 2005–2013.

In Publication III, Kernel density estimation (Silverman 1986) was used to calculate spatial lightning statistics. The method produces a smoother result than the traditional constant grid, at the same time conserving better the natural mesoscale features of thunderstorms. The study area was divided into a grid of 1 km × 1 km bins. For each bin, the ground flash density within 5.64 km from the bin centre (i.e. within a surface area of 100 km^2) was calculated.

Similar procedure was applied to calculate numbers of TDs on the basis of lightning data. In this case, a TD was defined as a 24-hour period when lightning was registered within 11.3 km from the bin centre. The used radius equals to a surface area of 400 km^2, which has been noted to correlate well with the traditional TD numbers based on human observations (e.g. Tuomi 2001).

In addition, the temporal distribution of lightning was studied month by month and day by day. Diurnal variations in the occurrence of flashes were analyzed hour by hour. The latter was done separately for land and the sea in Publication I.

4.2. Human observations of TDs

4.2.1. Data from meteorological stations

Data of human observations at meteorological stations are used to study thunderstorm climate and its long-term changes in the Baltic countries (Publications II and IV). Monthly and annual numbers of TDs were obtained from the archives of the Estonian Environment Agency, the Latvian Environment, Geology and Meteorology Centre and the Lithuanian Hydrometeorological Service under the Ministry of Environment. All the data, stored in paper format in the archives, were digitized for the computer analysis.

Only the stations with long and continuous or almost continuous data series were used. Mostly, meteorological stations in the Baltic countries started their observations around 1945–1950, so only scarce data is available for the earlier years. After 2000, most of the stations in Latvia and Estonia were automated. As a result, the amount of human observations of thunderstorms is very limited after 2004. Due to these limitations, data from 59 stations during 1950–2004 were digitized in total (Fig. 4).

Figure 4. Locations of the used meteorological stations. Stations from where only the numbers of TDs were used are shown with circles and stations from where the beginning and end times of thunderstorm events were also used are shown with triangles.

In addition, data from five Estonian stations (Pärnu, Tallinn, Tartu, Vilsandi and Võru) during 2005–2013 were used in the present dissertation to extend the study of long-term changes in TD frequency. At these stations, human observations of TDs have continued according to the earlier rules.

There were some small gaps (usually a few months with missing TD values) in the data of 8 Estonian and 2 Latvian stations. To fill these gaps, a linear regression model was built and the missing data values were computed on the basis of nearby stations with known TD numbers (Publication II).

As the numbers of THs allow a more accurate analysis than the numbers of TDs (Section 2.1), the beginning and end times of all recorded thunderstorms were also obtained for 15 stations. The number of stations is limited as digitization of such data is time consuming. So, five stations from different parts of each country were chosen.

In order to minimize the influence of unnatural factors, TD data were tested for artificial inhomogeneities. For the general thunderstorm climate study (Publication II), the series were checked only for abrupt artificial changes in association with relocation of stations and changes in observing methods. The Pettitt's test, standard normal homogeneity test and Buishand's test (Costa and Soares 2009) were used. All the 59 stations were found to be free from such major artificial inhomogeneities.

The study of long-term changes in thunderstorm climate (Publication IV) is much more sensitive to even small artificial changes and biases. So the series were checked much more carefully. At first, the Easterling and Peterson test (Easterling and Peterson 1995) was used to check for inhomogeneities in data series. After that, an additional comparative analysis was used. All stations that showed any abrupt changes or systematic shifts in TD frequency compared to the surrounding stations were excluded from further analysis. As a result, 40 stations were found to have series that are suitable for the study.

4.2.2. Methods for thunderstorm data analysis

In Publication II, thunderstorm climate in the Baltic countries during 1951–2000 was described. TD distribution maps were compiled by using the inverse distance weighted interpolation method. Seasonal distribution of thunderstorms was studied by using the average monthly numbers of TDs at all the 59 stations and also on the basis of average daily duration of thunderstorm events at 15 stations. Cluster analysis was performed in order to group the stations based on the monthly distribution of thunderstorms by using Ward's method (Ward 1963).

The durations of all thunderstorm events at 15 stations were summed hour by hour in order to study the diurnal distribution of thunderstorms. On the basis of the diurnal cycles of thunderstorm activity it was possible to cluster the stations into three different groups by using the Euclidean distances (Mimmack et al. 2001) as a distance measure.

Long-term changes in thunderstorm frequency in the Baltic countries during 1950–2004 were studied in Publication IV. In addition, data series of five Estonian stations that are extended until 2013 are represented in the present dissertation. Sen's method (Sen, 1968) was used to estimate the directions and magnitudes of changes in the annual numbers of TDs. Significance of the changes was checked with the Mann-Kendall test (Mann 1945, Kendall 1975). Trends were considered to be statistically significant at $p<0.05$ level.

4.3. Comparison with circulation weather types

4.3.1. Data of circulation weather types

Circulation weather types (CWT) were determined on the basis of the classification that was initially developed by Jenkinson and Collison (1977) as an automatic version of Lamb's classification (Lamb 1972). It has been successfully used elsewhere in Europe, including thunderstorm and lightning studies (e.g. Ramos et al. 2011). It uses the sea level pressure data from 16 points in and around the study area to calculate the intensity of zonal (westerly) and the meridional (southerly) airflow. In addition, shear vorticity is calculated to detect cyclonic or anticyclonic rotation of the atmosphere. CWTs are defined on the basis of the numeric values of the indices. Detailed description of the used classification is given by Post et al. (2002).

The geographic coordinates of the classification center are 57.5°N and 25°E, which is close to the center of the study area. The daily sea level pressure data originated from the NCEP/NCAR reanalysis (Kalnay et al. 1996). CWTs were calculated on the basis of air pressure data at 12 hours UTC for each day. This is 15 hours local time, when most of the thunderstorms occur.

On the basis of the classification, 10 main CWTs were distinguished. Anticyclonic type A means that the center of anticyclone is over the study area. Cyclonic type C means the center of cyclone over the study area. Eight directional types (N, NE, E, SE, S, SW, W and NW) mean airflow from the corresponding direction over the study area. For example, in case of type N, the airflow comes from the north. Mean sea level pressure fields for the used CWTs are represented in Fig. 5.

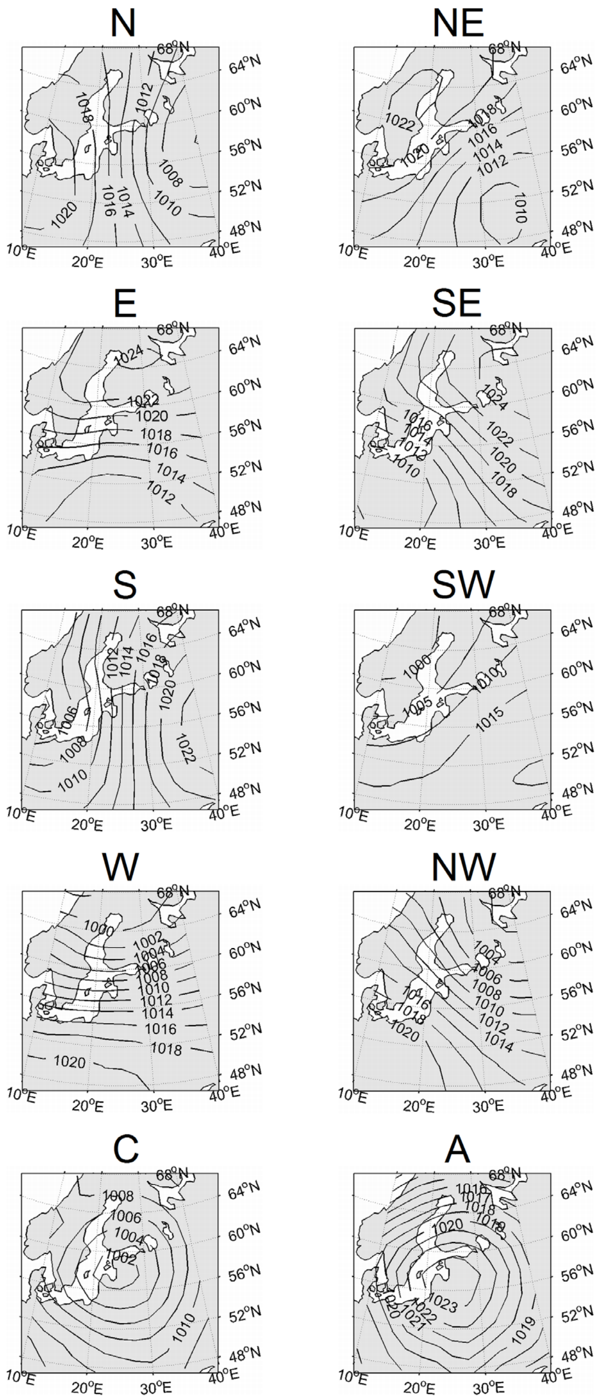

Figure 5. Annual average sea level pressure fields (hPa) for the used 10 circulation types during the period 1950–2004. (Adapted from Publication IV).

4.3.2. Thunderstorm and circulation data comparison methods

The frequencies and TD ratios were computed for each CWT for every month from May to September. TD frequency in the Baltic countries was correlated with the frequency of CWTs during the thunderstorm season. 7-year smoothed average monthly numbers of days with a specific CWT and 7-year smoothed average monthly numbers of TDs at weather stations were used. The correlation coefficient (R) values were calculated with the Pearson correlation method (Rodgers and Nicewander 1988). Significance of correlations was controlled with the Student t-test (Eisenhart 1979). A significance level of $p<0.05$ was used. Series of the frequencies of CWTs with highest correlations were plotted against TD data to explain long-term changes in thunderstorm frequency.

5. RESULTS

5.1. Spatial distribution of thunderstorms and lightning

5.1.1. Thunderstorm statistics in the Baltic countries during 1951–2000

The average annual number of TDs (Fig. 6) increased from the north to the south in the Baltic countries during 1951–2000. The number varied from 12 at the Estonian islands to 29.5 at Varena, southeastern Lithuania. The lowest numbers of TDs were associated with the coastal areas, especially in the western and northwestern parts of Estonia and Latvia. The highest values of TDs were concentrated on inland areas and mostly on uplands (except the strongest maximum in the southern Lithuania). Uplands with enhanced thunderstorm activity include the Pandivere Upland in northeastern Estonia, the Haanja-Alūksne Upland in the southeastern Estonia and northeastern Latvia, the Vidzeme Upland in central Latvia and the Žemaičiu Upland in western Lithuania.

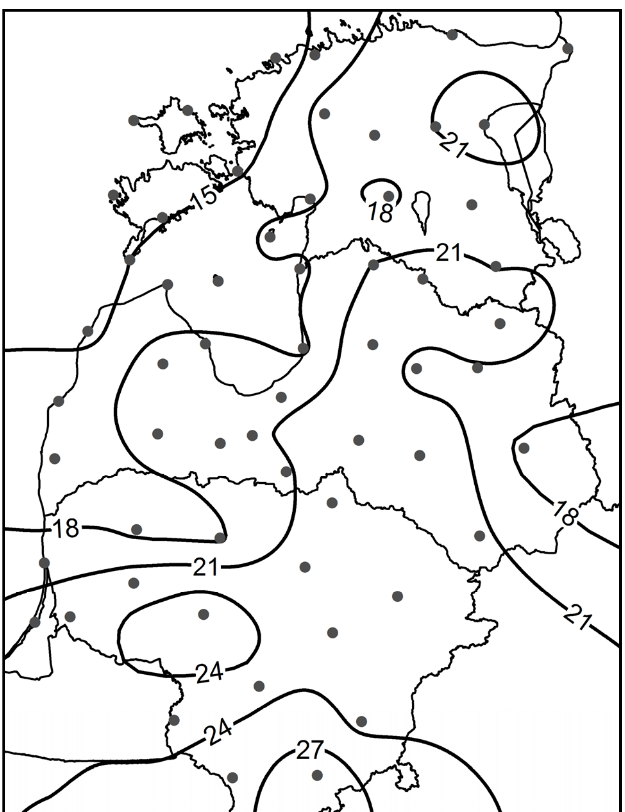

Figure 6. Spatial distribution of TDs in the Baltic countries during 1951–2000. Lines indicate the annual average numbers of thunderstorm days.

5.1.2. NORDLIS lightning statistics in northern Europe 2002–2011

Average annual ground flash density (Fig. 7) and the number of TDs (Fig. 8 in Publication III) generally increased from the northwest to the southeast in northern Europe during 2002–2011. Ground flash density varied from less than 0.01 to 1.08 flashes km^{-2} yr^{-1} and the annual numbers of TDs were 2–20.5 over the study area. The lowest values occurred along the coast of northern Norway and in the mountains of western Norway. The largest values were found in the Baltic countries and in the southwestern Sweden. Rather high lightning frequency has also been detected in the western part of Finland, whereas relatively low flash densities were found over the Baltic Sea and especially over the Gulf of Bothnia.

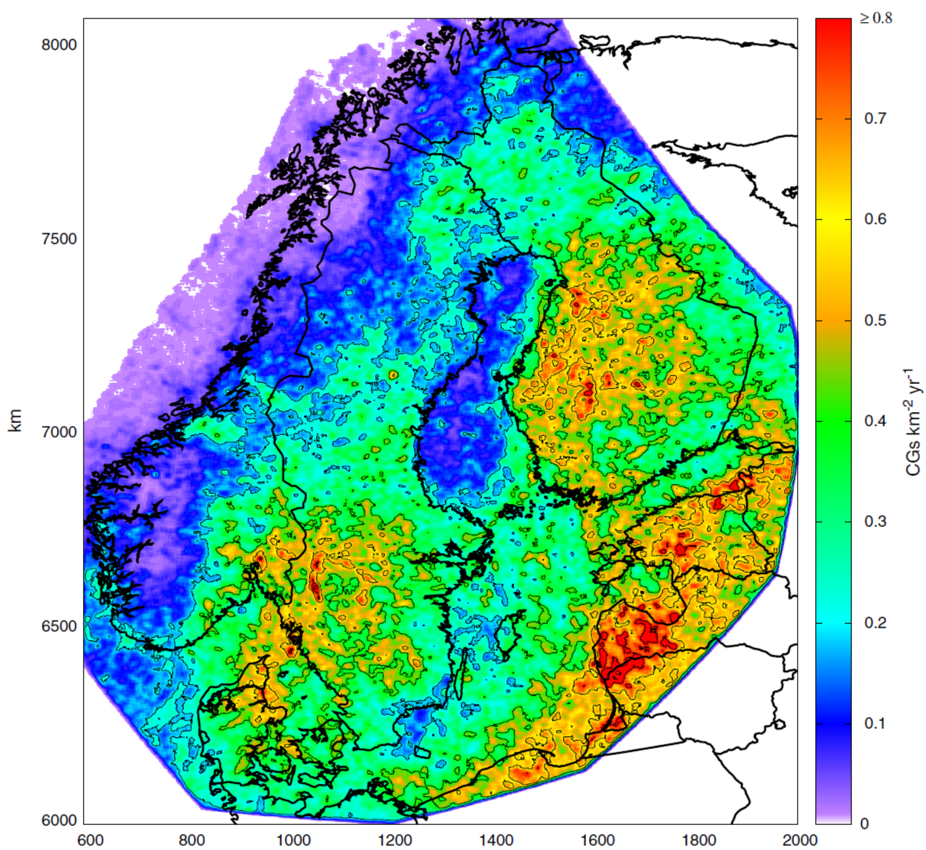

Figure 7. Average annual ground flash density in northern Europe during 2002–2011 (flashes km^{-2} y^{-1}). (Adapted from Publication III).

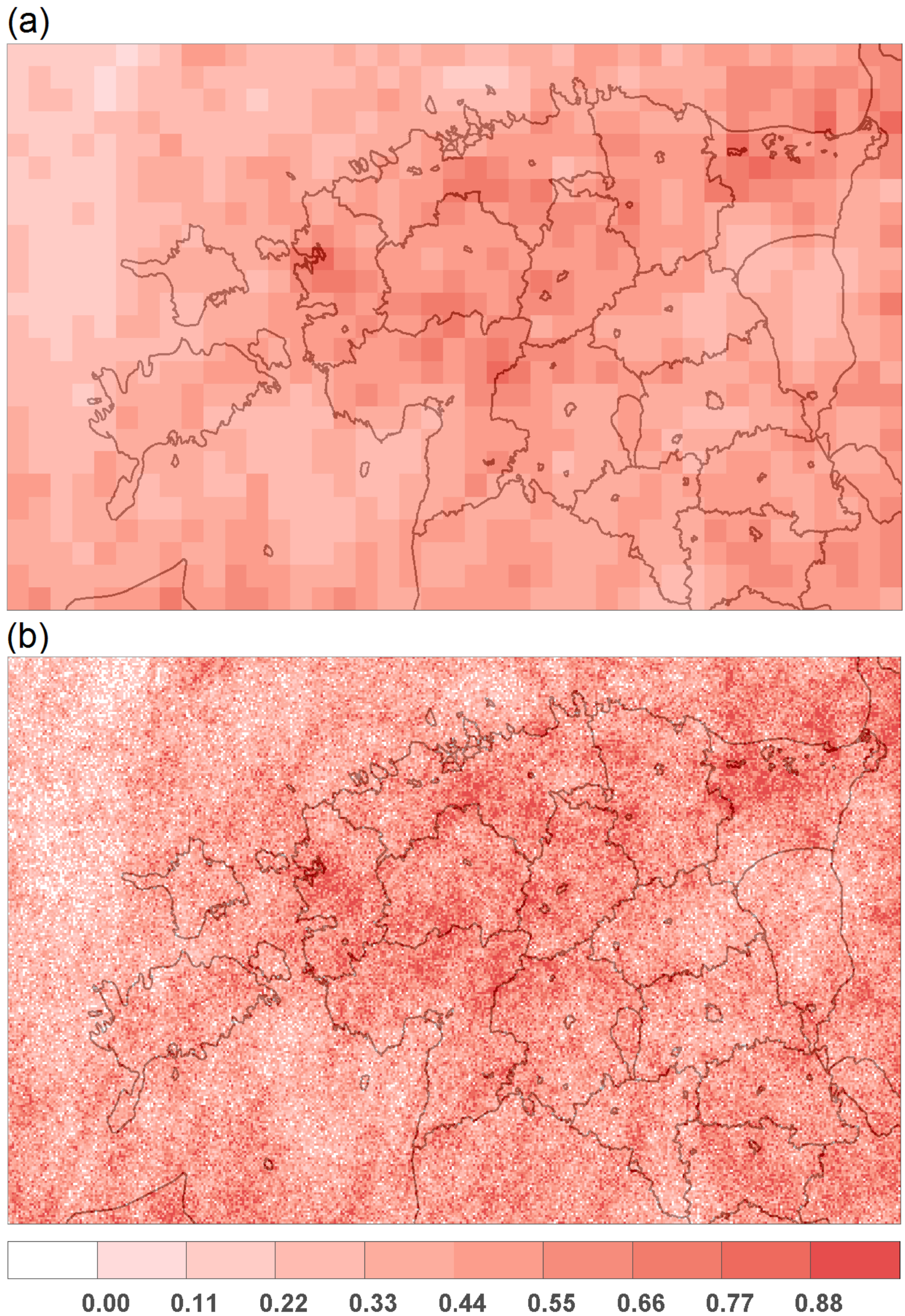

Figure 8. Annual average ground flash density (flashes km^{-2} y^{-1}) in the Estonian domain during the period 2005–2013 in a 10 km grid (a) and 1 km grid (b).

5.1.3. NORDLIS statistics in the Estonian domain 2005–2013

CG density in the Estonian domain during 2005–2013 varied from 0.10 to 0.84 flashes km^{-2} yr^{-1} in case of 10×10 km grid cells (Fig. 8a). If 1×1 km grid cells were used, 4.6% of cells had no lightning and 1.7% of cells had more than 1 flash km^{-2} yr^{-1} (Fig. 8b). The highest lightning activity was concentrated on the zone that extended from the western coast over central Estonia to the northeastern part of the country. The strongest maximum is located just south of the towns Kiviõli and Püssi in Ida-Virumaa county, northeastern Estonia. The lowest values were found over the sea, especially over the Baltic Proper in the westernmost part of the domain.

5.2. Seasonal and diurnal cycles and their land-sea contrasts

5.2.1. Thunderstorms in the Baltic countries during 1951–2000

The seasonal distribution of TDs with a monthly step showed a strong summer maximum (Fig. 9b). It was possible to divide the used stations into three different clusters on the basis of the exact timing of the maximum with 32 continental, 11 maritime and 16 transitional stations (Fig. 9a). The latter maximum was characteristic to maritime stations. The same was confirmed by the seasonal distribution of TDs with a daily step at 15 stations (Fig. 5 in Publication II).

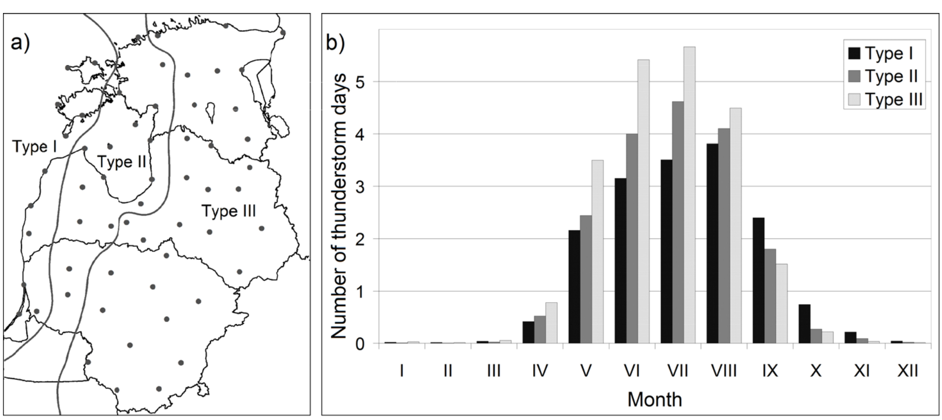

Figure 9. Clusters of stations on the basis of the annual pattern of TDs with a monthly step (a) and monthly average numbers of TDs of the stations in each cluster (b) during 1951–2000. (Adapted from Publication II).

The diurnal distribution of thunderstorms peaked between 14 and 18 hours LT and the lowest thunderstorm activity was found between 4 and 10 hours LT (Fig. 6 in Publication II). The shape of the distribution was similar at the continental and transitional stations whereas the amplitude was lower at the transitional stations. The maritime stations showed the diurnal distribution of thunderstorms with the lowest amplitude and specific shape. A long period with high activity lasted from around 14 to 1 hours LT, with two weak maxima around 15 to 18 hours LT and 22 to 1 hours LT (Fig. 7 in Publication II).

5.2.2. Lightning in northern Europe and in Estonia during 2002–2013

Roughly 99% of annual CGs occurred during the warm season (May-September) in northern Europe during 2002–2011. The average monthly percentages of CGs as well as daily variations in lightning frequency showed a well-defined thunderstorm season from May to September with the peak activity in July (Fig. 4b and Fig. 5 in Publication III).

Hourly variation showed a clear diurnal cycle in the ground flash frequency (Fig. 10). In northern Europe (Fig. 6 in Publication III), maximum activity occurred between 15 and 18 hours LT, whereas a long period with low activity lasted from 2 to 11 hours LT. The frequency of flashes differed about 4.5 times between daily maximum and morning minimum.

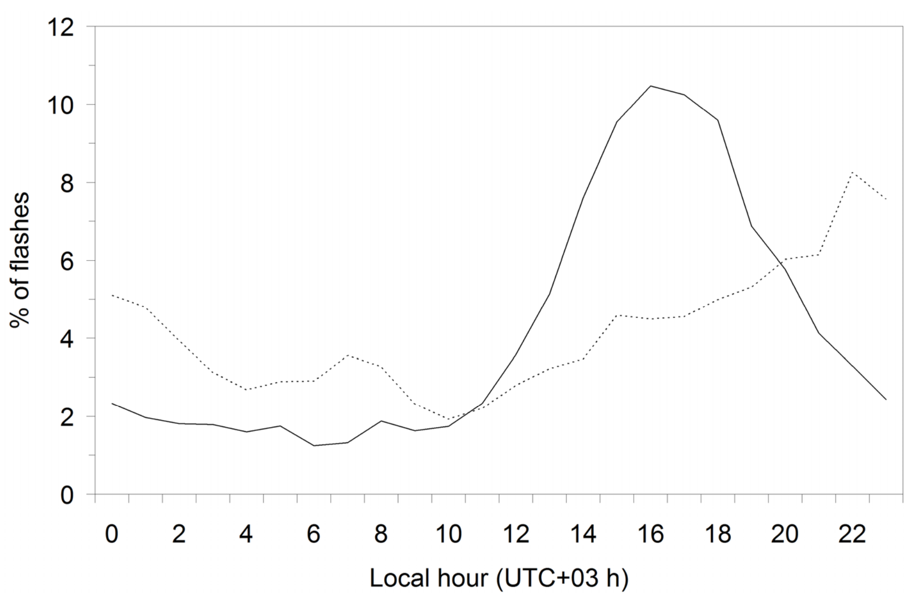

Figure 10. Diurnal distribution of ground flashes over the land (solid line) and over the sea (dotted line) in the Estonian domain during the period 2005–2013.

Results were generally similar in the Estonian domain. However, the diurnal cycle of flashes was studied separately over the land and sea areas. It came out that the diurnal distribution of lightning differed remarkably in the land and sea areas (Fig. 10 and Fig. 6 in Publication I). A strong peak between 14 and 19 hours LT and low activity between 23 and 11 hours LT appeared in the land areas. In the sea areas, lightning activity peaked around 22–24 hours LT, whereas it was low from 2 to 15 hours LT (Fig. 10).

5.3. Extreme events

On the basis of human observations at weather stations, it is only possible to estimate the extremity of a thunderstorm regarding its duration. The average duration of a thunderstorm event at 15 stations in the Baltic countries during 1951–2000 was 112 min. Generally, the coastal stations had longer thunderstorm events (118–145 min) than the inland stations (69–116 min). It came out that 23 % of all thunder events lasted 0.5–1 h and 20 % lasted 1–1.5 h. About 90 % on the storms were shorter than 3.5 h, 95 % did not last over 5 h and only 1 % of all registered thunderstorm events lasted over 7.5 h (Fig. 8 in Publication II).

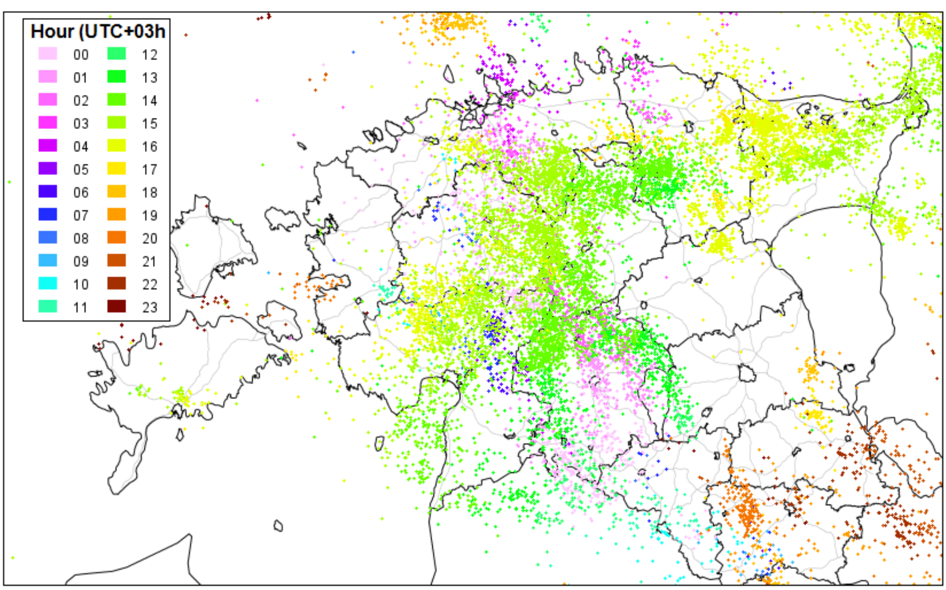

Figure 11. Spatial distribution of CG lightning in the Estonian domain on July 28th 2011. Flashes are marked with different colors according to the hours of their occurrence.

NORDLIS data allows the estimation of the average intensity of thunderstorms as the average ground flash density per TD (Fig. 3 in Publication III). It is also possible to find out the characteristics of extreme storms such as the maximum daily and annual ground flash density (Fig. 10 and Fig. 11 in Publication III). All the mentioned parameters generally increased from the northwest to the southeast in northern Europe during 2002–2011. Meanwhile, relatively large values extended much further to the north and the west than the high values of average annual CG frequency. Some small regions that have experienced extreme storms with remarkably high flash densities can be found even north of the Arctic Circle.

During 2005–2013, about 16% of annual total amount of CGs in the Estonian domain were registered during the most active day of the year. This fraction varied from 8 to 32% in individual years. The most intense storms over Estonia were registered on July 28th 2011 with 13 098 CGs within 24 hours (Fig. 11).

5.4. Cold season thunderstorms and lightning

Winter thunderstorms during December to February were generally rare in the Baltic countries from 1951 to 2000. Most of them occurred at Lithuanian stations where there was about one TD during 10 years. Maximum was observed on the western coast of the country with the average of one winter TD in 3 years at the Klaipėda station (Publication II).

During 2002–2011, the cold season thunderstorms (from October to April) occurred mainly along the western coast of Norway and south of the 60th latitude in northern Europe (Fig. 8 and Fig. 9 in Publication III). The highest annual numbers of cold season TDs (up to 8) have been registered over the North Sea west of Norway and on the western coast of Denmark. Meanwhile, the largest average ground flash densities from October to April (more than 0.1 ground flashes $km^{-2}\ yr^{-1}$) were registered in the Baltic area.

5.5. Relationships between thunderstorm days and circulation weather types

The most frequent CWT in the Baltic countries during the thunderstorm season was anticyclonic, which was characteristic to 21.9% of days (Table 1 in Publication IV). It was followed by westerly and northerly types whereas southerly and easterly CWTs were the least frequent. Thunderstorms were most common in case of southerly and easterly types and also in case of the cyclonic type C (Table 2 in Publication IV). Their frequency was the lowest in case of anticyclonic and northerly CWT.

A comparison of TD and CWT series showed the strongest negative correlation in case of the type N during summer and the types NE and E in September (Table 3 in Publication IV). The strongest positive correlations between TD and CWT series appeared in case of anticyclonic, E and SE types.

5.6. Changes in the frequency of thunderstorms and lightning

Thunderstorm activity in the Baltic countries during 1951–2000 was characterized by remarkably large inter-annual variability and abrupt changes (Fig. 12). For example, the highest average TD number of the study area was 31.8 in 1972, whereas the lowest average number 12.5 was reported only four years later in 1976.

Remarkable inter-annual variations were also obvious in the annual numbers of located ground flashes in northern Europe (Fig. 4a in Publication III). The period of 2005–2009 was characterized by lower thunderstorm activity, whereas the beginning and end of the study period showed roughly two times larger annual flash counts. The highest lightning activity was registered in 2003 and the lowest in 2008.

Yearly variations in the Estonian domain were even larger. Lightning activity was the lowest in 2006 with about 17 thousand registered ground flashes and the highest in 2010 with more than 77 thousand located CGs.

It appeared that TD frequency in the Baltic countries has fluctuated throughout the study period. The 7-year smoothed average TD number indicated slight maxima and minima in TD frequency in every 10–15 years (Fig. 12).

The average annual TD number of the 40 studied stations showed a statistically significant downward trend with a decreasing rate of 0.9 TDs per decade in the Baltic countries during 1950–2004. As a result, the TD frequency has decreased approximately 24% in the Baltic area during the study period. Despite a more frequent presence of winter TDs during the 1990s (Fig. 5 in Publication IV), no statistically significant trend emerged.

Downward trends were larger and statistically more significant in the southern part of the Baltic countries (Fig. 3 in Publication IV). In Estonia, only four stations showed a statistically significant downward trend in the annual number of TDs, whereas in Latvia the number was five and in Lithuania it was ten.

It can also be seen that the main descent in TD frequency was concentrated to the period of 1960–1990. Since the beginning of the 1990s, an upward trend has prevailed in TD frequency. It is especially obvious from the extended data series of five Estonian stations (Fig. 13). This trend has balanced the descent in TD frequency prior 1990. As a result, TD frequency at these stations has been statistically stable during 1950–2013.

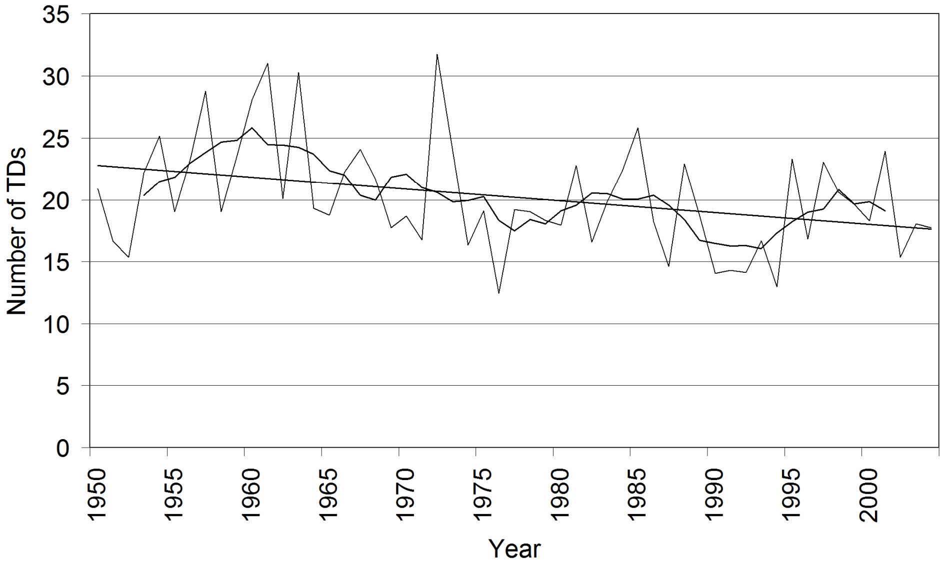

Figure 12. Average annual number of thunderstorm days in the Baltic countries, its 7-year smoothed average and linear trend during 1950–2004.

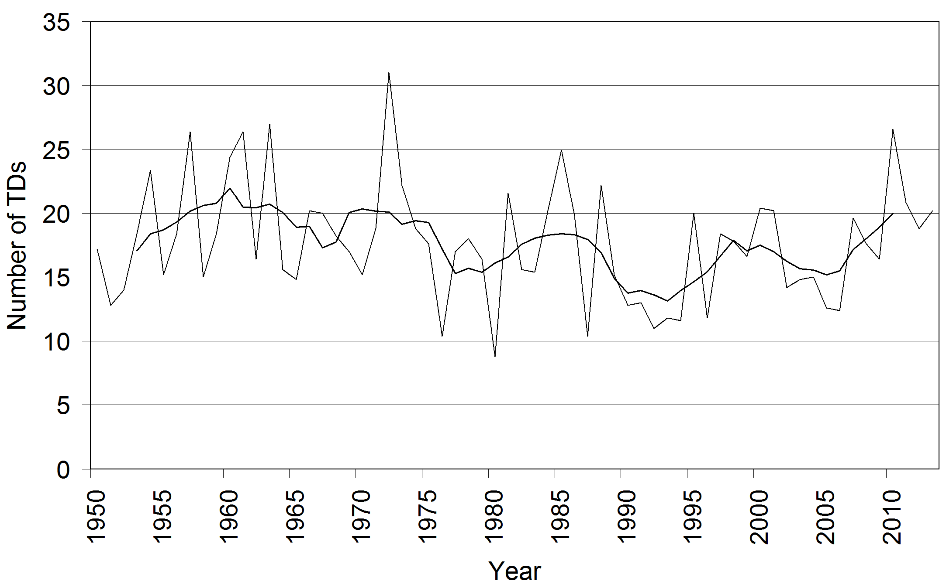

Figure 13. Average annual number of thunderstorm days at five Estonian stations and its 7-year smoothed average during 1950–2013.

Clear opposite phase behavior is obvious if TD series are plotted against the series of CWTs unfavorable for thunderstorm development (type N from May to August and types NE and E in September). The mentioned CWTs explain more than 66 percent of the variations in thunderstorm frequency in the Baltic countries during 1950–2004 (Fig. 14). The numbers of days with CWTs that are positively correlated with thunderstorm frequency (types A, E and SE from May to August, types W and NW in September) explain more than 51 percent of the variations in TD frequency in the Baltic countries during the study period (Fig. 15). Similar temporal behavior of the series is especially obvious since 1970.

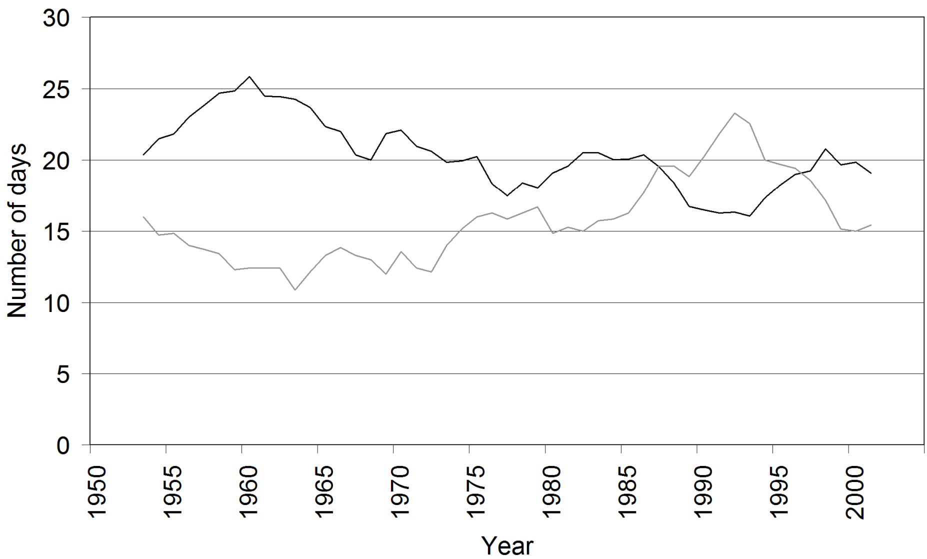

Figure 14. Average annual number of thunderstorm days in the Baltic countries (black line) and the number of days with the circulation type N from May to August plus days with the circulation types NE and E in September (gray line). The values are 7-year smoothed averages. Pearson correlation coefficient r=–0.817. (Adapted from Publication IV).

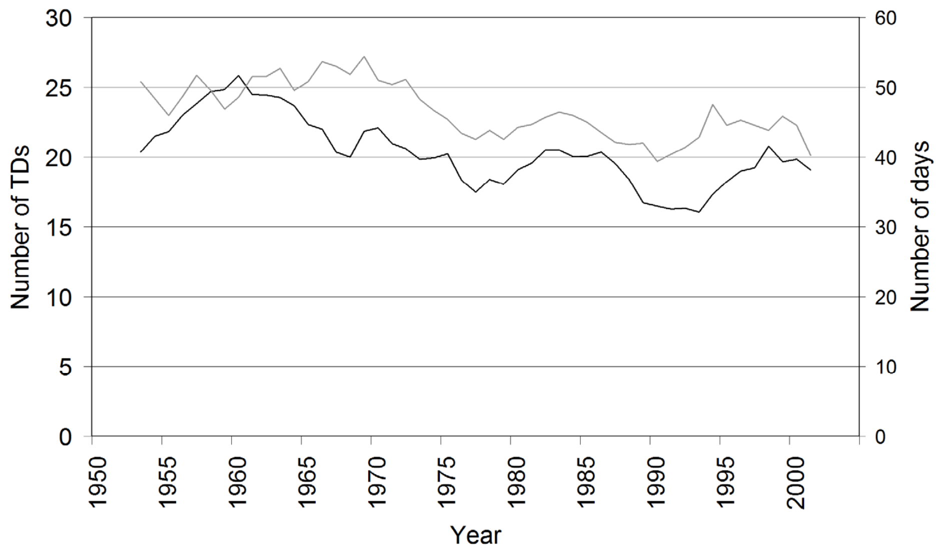

Figure 15. Average annual number of thunderstorm days in the Baltic countries (black line) and the number of days with the circulation types E, SE and A from May to August plus days with the circulation types W and NW in September (gray line). The values are 7-year smoothed averages. Pearson correlation coefficient r=0.719. (Adapted from Publication IV).

6. DISCUSSION

6.1. Spatial distribution of thunderstorms and lightning

The frequencies of CG lightning (Publications I and III) and TDs (Publication II) in northern Europe are low on the global scale. For a comparison, about 10 times higher CG flash densities have been registered in southern Europe (Feudale et al. 2013) and in Florida (e.g. Huffines and Orville 1999). However, ground flash densities around 1 km^{-2} yr^{-1} and less, and annual TD numbers up to 20–30 have been reported at other places with a similar climate. Such are the northern parts of the United States (e.g. Changnon and Changnon 2001; Orville et al. 2002), Canada (e.g. Shephard et al. 2013) and Northern Russia (Christian et al. 2003).

Thunderstorm activity estimations of the present research are also in line with previous similar analyses in and around the study area. Lightning and TD frequency over Finland and Sweden (Fig. 7) are similar to the findings of Solantie and Tuomi (2000), Tuomi and Mäkelä (2008b), Sonnadara et al. (2006) and Isaksson and Wern (2010). Lithuania and southern Latvia had similar annual numbers of TDs (Fig. 6) to the northern half of Belarus (Loginov et al. 2010). In addition, the TD frequency in southern Lithuania was similar to that in northern Poland (Bielec-Bakowska 2003). Such good agreements indicate not only similar climate conditions but also suggest a good quality of the used TD and lightning data.

The frequency of TDs and lightning generally increases from the north to the south in the study area. This finding is in line with a global increase in thunderstorm frequency towards lower latitudes. The main reason is that the southern parts of the study area are more frequently affected by warm humid air masses that are favorable for thunderstorms development.

Regional maxima and minima in thunderstorms frequency are probably associated with topographic features such as large water bodies and uplands. The sea and coastal areas are characterized by a lower frequency of TDs and lightning (Figs. 6, 7 and 8). This represents a global contrast that appears in tropics as well as at mid latitudes. As sea surface is usually cooler than the land during the warm season, updrafts over the sea are weaker and do not sustain the development of thunderstorms (e.g. Williams and Stanfill 2002).

Higher thunderstorm frequency over uplands was most obvious from the 50-year TD data series in the Baltic countries (Fig. 6). Uplands force the horizontal airflows to rise and thus the development of convective clouds, precipitation and thunder is favored especially along the windward sides of such areas. It has been demonstrated that many local precipitation maxima in the Baltic countries are also associated with uplands (Jaagus et al. 2010).

In contrast, the western windward side of the much higher Scandinavian mountain range was characterized by a very low lightning activity (Fig. 7). This finding is remarkable since the main mountain ranges in Central and Southern Europe such as the Alps (Bernardi and Ferrari 2004; Schulz et al. 2005), the Carpathians (Antonescu and Burcea 2010) and the Pyrenees (Rivas Soriano et al. 2005) are all found to be associated with local lightning maxima.

It can be assumed that there is not enough potential energy for the development of thunderstorms in the air masses that move from the Atlantic Ocean to Norway. Such air is often moist and its rising causes strong precipitation maxima along the western side of the Scandinavian mountains. Probably, the factor that prevents the formation of thunderstorm producing convective clouds is a relatively low temperature of the high-latitude oceanic air. In such conditions, the development of convection and thunderstorms is inhibited, especially during summer when the troposphere is relatively warm.

In case of lightning data (Publications I and III), the influence of relatively short series and edge effects of the lightning detection network should also be taken into account. Such effects seem to be more relevant in case of small study domains especially near the edges of the network range. The Baltic countries are a good example. Unlike TD data (Fig. 6), the lightning data (Fig. 7 and Fig. 8) do not show clear maxima over uplands and an increase in thunderstorm frequency from the northwest to the southeast in the Baltic countries.

In case of a short study period, the effect of relatively low uplands on the spatial distribution of lightning is probably much smaller than the influence of individual intense storms. For example, intense storms over the western and central parts of Estonia explain the high lightning incidence in these areas with generally plain landscape and low elevation (Fig. 8). Some paths of such storms are still visible in case of 1×1 km grid (Fig. 8b) despite the fact that the data are averaged over 9 years. Meanwhile, the lightning maximum over the Haanja Upland in southeastern Estonia is only hardly visible although Haanja is the highest upland in the Baltic countries.

Due to the edge effect of the lightning location system, many weaker flashes probably remain undetected in southeastern Estonia, as well as in the central parts of Latvia and Lithuania. Lower mean numbers of strokes per flash and higher average peak currents over these areas (Fig. 13 and Fig. 14 in Publication III) support this assumption. They indicate that mostly, the stronger strokes are registered there. Hence, the lightning frequency over these areas is probably somewhat underestimated.

6.2. Seasonal and diurnal cycles and their land-sea contrasts

The mid-latitude specific thunderstorm season with the peak in summer was obvious from the TD data of the Baltic countries (Fig. 9b) as well as from the lightning data of northern Europe (Fig. 4b in Publication III). Similar results with a vast majority of thunderstorms and lightning during the warm season are found in many countries e.g. in Austria (Schulz et al. 2005), Romania (Antonescu and Burcea 2010) and Canada (Burrows et al. 2002).

The exact timing of the peak in the seasonal cycle of thunderstorm activity was demonstrated to be governed by the distance from the sea (Fig. 9). An earlier June-July maximum was characteristic to continental stations whereas a later August maximum emerged along the coast. The main reason for the differences between the maritime and continental stations is the much larger heat capacity of the sea compared to that of the land. From April to July, when the land warms up rapidly but the sea remains relatively cooler, the TD numbers were clearly higher at continental stations. From August onwards, the land cools faster than the sea and higher thunderstorm activity moves to the coastal areas (Fig. 9b, Fig. 4d in Publication II).

The results show that the lightning maximum in July (Fig. 4b in Publication III) is much more pronounced than the TD maximum (Fig. 9b). This probably indicates that not only the frequency but also the intensity of storms is the highest in July. As discussed earlier, the TD peak in July is characteristic to the inland areas. Hence, the main contribution to the remarkably high lightning activity in July comes from storms over the land areas. This is in a good agreement with global observations of much more intense lightning activity over the land (e.g. Christian et al. 2003).

The diurnal cycle of thunderstorms and lightning generally showed the afternoon peak and minimum during the night and morning hours (Fig. 6 in Publication II and Fig. 6 in Publication III). Such a distribution is a global feature over the land areas (Price 2009a) that is driven by the diurnal temperature cycle.

However, it appeared that the coastal and sea areas were also characterized by a specific diurnal cycle of thunderstorms (Fig. 10; Fig. 6 in Publication I; Fig. 7 in Publication II). Its maximum was elongated towards the evening hours and in all cases there was at least a slight peak around midnight. Another slight peak earlier in the afternoon was noticeable in the Estonian domain during 2005–2009 (Fig. 6 in Publication I) and in the Baltic countries during 1951–2000 (Fig. 7 in Publication II).

The earlier afternoon peak in the diurnal cycle of thunderstorms over the sea is probably associated with the maximum activity of inland storms during that time. At coastal stations, observers report also the storms that actually occur over the land. In addition, at least some of such storms move to the sea and produce CGs there.

The later peak around midnight is probably associated with some properties of the sea, namely, its relatively warmer surface during the night hours. Hence, storm systems over the sea may stay active for a much longer time than storms over the land, which dissipate as a result of evening cooling. This idea is supported by the generally longer duration of thunderstorm events at coastal stations (Section 5.3). It is also possible that land breezes during the late evening and night hours further sustain the development of convective storms over the sea areas (e.g. Virts et al. 2013). Some previous studies have indicated a similar nighttime peak in thunderstorm frequency along the coast of the United States (Orville and Huffines 2001) and over the oceans (Dai 2001).

One additional interesting feature in association with the influence of the sea on thunderstorm activity appeared in the Baltic countries. The influence is obvious along the western coast of the countries, whereas it is absent on the northern coast of Estonia (Publication II). This can be explained with a dominant southwesterly airflow. As a result, the western coast is more affected by storms that originate from the sea or develop in the coastal zone. Meanwhile, the northern coast of Estonia is mostly influenced by storms that have formed over the inland areas of Estonia and are later carried to the northern coast by southwestern airflow. Hence, it is not surprising that they have characteristics typical to inland storms.

6.3. Extreme events

Extreme thunderstorms that produce exceptionally large numbers of lightning and/or last unusually long are especially hazardous to human life and property. In addition, they have a significant impact on lightning statistics, particularly if the study period is relatively short.

On the basis of human observations in the Baltic countries during 1951–2000, 5% of the registered storms lasted over 5 and 1% lasted over 7.5 hours. TH and flash density relations (e.g. Rakov and Uman 2003) hint that total flash counts of such storms are probably high. Possible causes of very long thunderstorms include the persistent warm and humid air masses and slowly moving or stationary fronts.

In case of a warm humid air mass, so many local thunderstorms may develop during afternoon and early evening that the sound of thunder can be heard at stations even between individual storms. Slow moving or stationary fronts may sometimes lead to a widespread thunderstorm activity from afternoon to the early morning of the next day. Such situations are probably responsible for the longest recorded thunderstorms that had the durations of 11–14 hours at most of the stations.

It came out that individual intense storms may occasionally occur over most of northern Europe, including the areas where the annual average flash density and TD number is low (Fig. 10 and Fig. 11 in Publication III). The explanation is that in some cases, warm and humid air may reach to the areas where they are usually rare, for example, north of the Arctic Circle. When they meet the much cooler local air masses, intense thunderstorms may occur. Possibility of occasional heavy storms in areas with relatively low average thunderstorm activity is in line with the finding of Mäkelä et al. (2011) for Finland and the United States.

Individual heavy storms may have a significant impact on lightning statistics. During 2005–2013, about 16% of the annual total amount of CGs in the Estonian domain was registered during the day of the year with the highest flash count. As such storms usually encompass only a part of the study area, the accumulation of CGs is especially high there. Paths of such storms are frequently recognizable on the annual flash density maps and, as discussed earlier, some of them are still visible in 9-year statistics (Fig. 8b).

Preliminary investigation in the Estonian domain has shown that such extreme storms have developed in warm air masses and along cold fronts. This is generally in line with the findings of Tuomi and Mäkelä (2008b) for Finland. Individual intense storms produce a significant fraction of annual total lightning also in Canada (Burrows et al. 2002). So, it can be assumed that lightning climate is significantly affected by such storms elsewhere in high latitudes.

6.4. Cold season thunderstorms and lightning

Cold season thunderstorms in northern Europe (Fig. 8 and Fig. 9 in Publication III) are usually registered in the areas where the cold season is either relatively warmer (coast of Norway) or shorter in duration (southern part of the study area). However, a large number of TDs in combination with low flash density show that these storms are often weak.

Western coasts of Norway and Denmark, where such storms are most frequent are open to western winds from the Atlantic Ocean, which carry mild and humid air. Meanwhile, the troposphere is generally colder during winter. Hence, the convection is enhanced especially along the coastline with mountains. In addition, graupel and ice crystals that are needed for charge separation and cloud electrification can form in cold winter troposphere even if the vertical extent of the clouds is not very large. This explains the formation of relatively large number of weak storms.

The southern part of the study area is characterized by a relatively longer thunderstorm season. It means that the period from October to April is also affected by some early and late main season thunderstorms there. These storms may be much stronger than typical cold season thunderstorms and hence they may have a significant impact to lightning statistics. This effect is clearly expressed in the Baltic Sea region where small areas with remarkably high flash densities exist (Fig. 8 in Publication III). Most of them were caused by the heavy frontal storms on 1 October 2006. These storms were the main season storms by their character.

The TD statistics (Fig. 9 in Publication III) are less influenced by such occasional main season storms and should thus better represent the distribution of winter thunderstorms. This is true at least in the Baltic countries where the TD data of NORDLIS agree with the long-term winter TD statistics that are based on human observations at weather stations with the maximum on the coast of Lithuania.

6.5. Relationships between thunderstorms and CWTs

It came out that southerly and easterly CWTs were most favorable for thunderstorm development during spring and summer (Table 2 in Publication IV). The same was found in Finland by Tuomi and Mäkelä (2008b). Such airflows bring warm humid air from lower latitudes which create good conditions for thunderstorm formation. Frequent occurrence of TDs in association with the cyclonic type C can be explained with the rising air in the central region of cyclones, which support convection.

In September, the westerly flow types were most conductive to thunderstorm formation. This is not surprising as the land cools faster than the sea in autumn. Hence the warm humid maritime air carried by westerly winds is more favorable for deep convection than the cooler and drier continental air masses carried by the types E and SE.

Rare occurrence of thunderstorms in case of anticyclonic CWT is associated with the descent of the air in the central region of high pressure areas that inhibit convection. In case of northerly flow types, thunderstorms are infrequent as such air flows carry cooler air from higher latitudes, which has no potential energy for thunderstorm formation.

Long-term TD series generally show a positive correlation with CWTs conductive to thunderstorm formation and a negative correlation with weather types that inhibit convection (Table 3 in Publication IV). The anticyclonic type is an interesting exception. Although the thunderstorm probability is the lowest in case of the type A, the frequency of the type is positively correlated with the frequency of TDs during 1950–2004. Two probable indirect relationships between the presence of the type A and TD frequency are discussed hereafter.

First, it was found that the frequency of the anticyclonic type is positively correlated with the frequencies of types SE ($R=0.374$, $p<0.05$) and S ($R=0.471$, $p<0.05$). This could be explained with the prevailing eastward motion of weather systems at mid-latitudes. As a result, the high pressure centers that form in northern Europe frequently move eastward. Finally they reach western Russia and the Baltic countries start to be affected by southerly and southeasterly airflows in the western part of anticyclone. This results in the advection of warm humid air with high probability of thunderstorms.

Second, high pressure favors cloudless sky with a lot of sunshine. The resulting fast warming of sea surface may enhance thunderstorm activity. Typically, the TD frequency in the Baltic countries is low in the vicinity of the Baltic Sea, especially during spring when the water is still cool (Publication II). A lot of days with the anticyclonic type A in May and June with faster warming of the sea may increase TD frequency at coastal stations. This, in turn, means higher annual numbers of TDs. This hypothesis is supported by the fact that the positive correlation between the frequency of anticyclonic CWT and TDs is the strongest in May and June.

6.6. Changes in the frequency of thunderstorms and lightning

The frequency of thunderstorms and lightning vary remarkably between individual years in northern Europe where the annual flash counts differed more than two times during 2002–2011 (Fig. 4a in Publication III). In case of the much smaller Estonian domain the variation was even more pronounced.

As the changes in the configuration and detection efficiency of NORDLIS have been relatively small during the study period, such sharp changes in lightning frequency are probably associated with natural factors. This assumption is supported by the fact that a similar high variability appeared also from much longer series of human observations of TDs in the Baltic countries (Fig. 12). In addition, large inter-annual variations in TD frequency are characteristic not only to the Baltic countries, but also to other areas like Poland (Bielec-Bakowska 2003), southwestern Germany (Kunz et al. 2009) and Bulgaria (Simeonov et al. 2009).

Abrupt changes in the annual frequency of TDs are associated with remarkable year-to-year variations in prevailing synoptic conditions during the thunderstorm season. For example, in 1972 when the annual number of TDs was the highest in the Baltic countries, there were only four days with the circulation type N from May to August. In 1976, when the annual number of TDs was the lowest, there were 23 days with the type N that is unfavorable for thunderstorm formation.

Fluctuations with the periodicity of 10–15 years appeared in the TD series of the Baltic countries (Fig. 12) and also in the series of five Estonian stations (Fig. 13). The latest peaks around 2000 and 2010 with lower TD frequency between them are similar to changes in lightning activity in northern Europe during 2002–2011 (Fig. 4a in Publication III). These fluctuations are related to periodic changes in general circulation over northern Europe. Periods with higher numbers of TDs were characterized by more frequent presence of CWTs favorable for thunderstorm formation and lower frequency of the types that inhibit convection (Fig. 14 and Fig. 15).

Long-term descent was characteristic to the TD frequency in the Baltic countries during 1950–2004 with the most obvious downward trend during the period 1960–1990. In contrast, thunderstorm climate has been more stable in the surrounding areas like Finland (Tuomi and Mäkelä 2008b) and Poland (Bielec-Bakowska 2003). These differences indicate a probable presence of areas with different temporal behavior of thunderstorm frequency in northern Europe, which is generally in line with the findings by Changnon (1985).

Long-term changes in CWT frequency (Fig. 14 and Fig. 15) explain well the trends in the TD frequency in the Baltic countries. Years around 1960 when the highest TD frequency was observed were characterized by the lowest frequency of northerly flow types unfavorable for thunderstorm formation. Meanwhile, the frequency of types conductive to thunderstorms was high.

During 1960–1990, when the main descent in TD frequency occurred, the frequency of northerly CWT increased. It peaked around 1990, when the lowest TD frequency was observed (Fig. 14). The frequency of types that favor thunderstorms decreased during 1960–1990 and the deepest minimum occurred around 1990 (Fig. 15).

The last two decades and especially the last five years or so have remarkably affected the general picture of the long-term changes in TD frequency. After a minimum around 1990, TD frequency has rapidly increased and during the last years it has almost re-achieved the level of the strongest maximum noted around 1960 (Fig. 13). This relatively fast rise explains the claims about the possible more frequent presence of thunderstorm-related damages in Estonia during the last years. However, on the basis of long series it can be said that thunderstorms have not been exceptionally frequent during the last years, but they have been much more frequent than 10–20 years ago.

The recent increase in TD frequency is accompanied by a remarkably lower number of days with northerly CWTs. Around 2010, the annual number of such days has been almost as low as around 1960. Meanwhile, the frequency of days with CWTs favorable for thunderstorms has remarkably increased.

It is probable that the TD maximum around 1960, minimum around 1990 and recent increase in TD frequency represent some kind of a longer cycle in summer circulation conditions in northern Europe. The period of this cycle may be longer than the study period. Longer series in the future will confirm or disconfirm this assumption.

7. CONCLUSIONS

This thesis investigates the thunderstorm climate with its long-term changes in the Baltic countries and the lightning climate of northern Europe. The main conclusions are as follows.

1. This thesis combines different available thunderstorm and lightning databases in northern Europe. Although human observations of thunderstorms and automatic lightning observations are very different methods, it was found that they give similar results in northern Europe. Both datasets show similar annual numbers of thunderstorm days and an increase in thunderstorm frequency from the north to the south. They also indicate almost identical seasonal and diurnal distributions of storms. This is a very important conclusion as there are no parallel human and automatic observations that could be used to compare the methods directly.
2. The average annual lightning frequency varied from less than 0.01 flashes $km^{-2}\ yr^{-1}$ in the northern and western parts of Norway to 1.08 flashes $km^{-2}\ yr^{-1}$ in southwestern Sweden and in the Baltic countries. The average annual number of thunderstorm days varied from 2 in northern Norway to 29.5 in southern Lithuania. All these values are in line with the findings in the surrounding areas like Belarus, Finland and Poland. This further demonstrates that the general quality of the used datasets is good and the results could be trusted. Furthermore, similarities with the results of Belarus, Finland and Poland also confirm the findings of these studies.
3. It came out that the spatio-temporal distribution of thunderstorms in northern Europe is in a good accordance with the influence of main climatic factors such as solar heat flux and peculiarities of the underlying surface. The thunderstorm season peaks in summer and the diurnal maximum in thunderstorm frequency is between 14 and 18 hours local time (UTC+3 hours) when the solar heating is most intense. Meanwhile the cold season thunderstorms are generally rare, often weak and usually occur in the areas where the cold season is either relatively warmer (coast of Norway) or shorter in duration (southern part of the study area). Thunderstorms are more frequent over inland areas as the land is usually warmer surface than the sea. In the Baltic countries, some local maxima in thunderstorm frequency were clearly related with upland areas that force the air to move upward and hence enhance convection.
4. Although high thunderstorm activity is more concentrated to the southern part of the study area, occasional intense storms are possible practically everywhere in the study area. Such storms have been registered even north of the Arctic Circle. They may cause a remarkable fraction of total annual lightning within less than 24 hours and hence their impact to lightning statistics is significant.
5. High correlations between the series of thunderstorm and circulation data indicate that the observed changes in thunderstorm frequency such as the

maximum around 1960 and the minimum around 1990 generally reflect natural changes and variations. The sea level pressure data that was used to determine circulation weather types is much more independent of human errors than thunderstorm observations. Hence, high correlations with circulation series also indicate the high quality of thunderstorm series. This in turn confirms that the methods used to eliminate thunderstorm series with artificial inhomogeneities worked well.

The above-mentioned conclusion confirms that the used datasets and different methods worked well and the results of the thesis could be used as reliable indicators of thunderstorm and lightning climate and its changes in northern Europe. However, the lightning series are still short and the data of the following years will allow an even more precise estimation of the spatial distribution of lightning. Developed methods and software solutions are suitable for continuous monitoring. It would also be useful to install additional lightning sensors in Estonia and Latvia and incorporate the sensors of Lithuania into the NORDLIS lightning detection network. It would allow higher spatial accuracy and detection efficiency of lightning over the Baltic countries. It would also be interesting to apply more precise convection indices in the future studies of the relationships between thunderstorms and synoptic conditions.

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SUMMARY IN ESTONIAN

Baltimaade ja Põhja-Euroopa äikese- ning välgukliima

Äikesetormid kujutavad endast olulist ohtu nii inimeste elule kui varale. Välk ja teised ohtlikud äikesenähtused põhjustavad parasvöötmes igal aastal olulise osa ilmaga seotud majanduslikest kahjudest. Samas on välk oluline faktor atmosfääri elektrilistes protsessides. Äikesepilvedega seotud sademed on mitmel pool äärmiselt vajalikuks niiskuse allikaks. Globaalse kliimamuutuse kontekstis on oluliseks küsimuseks saanud muutused ekstreemsete ilmanähtuste, sealhulgas äikese esinemissageduses. Kuigi äikese- ja välguandmed on Põhja- ja Baltimaade kohta olemas, puudusid vastavasisulised laiemad uuringud.

Käesoleva väitekirja eesmärgiks on uurida äikese ja välgu ajalis-ruumilist jaotust Baltimaades ning Põhja-Euroopas, samuti äikesekliima pikaajalisi muutusi. Kasutatakse erinevaid olemasolevaid andmeid, mis on kogutud meteoroloogiajaamade ja välgudetektorite võrgustiku NORDLIS poolt. Töö eesmärkideks on

1) Baltimaade meteoroloogiajaamade kuude ja aastate äikesepäevade arvude digitaliseerimine ja ühisandmebaasi koondamine;
2) Baltimaade äikesekliima uuring meteoroloogiajaamades perioodil 1951–2000 kogutud vaatlusandmete põhjal;
3) Baltimaade äikesekliima pikaajaliste muutuste kirjeldus ja analüüs meteoroloogiajaamades perioodil 1950–2004 kogutud andmete põhjal;
4) tsirkulatsioonitüüpide andmebaasi koostamine ning äikese ja tsirkulatsioonitüüpide vaheliste seoste uurimine Baltimaades perioodil 1950–2004;
5) äikesedetektorite võrgustiku NORDLIS andmete analüüsiks vajaliku tarkvara arendamine ja ülevaate andmine Põhja-Euroopa ja Eesti välgukliimast;
6) uurimisala äikese- ja välgukliima võrdlemine sarnaste uuringutega naaberaladel ja teistes sarnase kliimaga piirkondades.

Tulemustest ilmnes, et kuigi meteoroloogiajaamade ja välgudetektorite puhul on tegemist erinevate vaatlusmeetoditega, on saadud põhijäreldused äikesekliima kohta väga sarnased. Mõlemad meetodid näitasid äikeselise aktiivsuse kasvu lõuna suunas. Äikeste sesoonne ja ööpäevane jaotus ei sõltunud oluliselt kasutatud andmestikust. See näitab, et ehkki paralleelsed andmestikud meetodite otseseks võrdluseks peaaegu puuduvad, annavad mõlemad usaldusväärseid andmeid.

Keskmine aastane pilv-maa-välkude sagedus varieerus 0,01 löögist km^{-2} a^{-1} Norra põhja- ja lääneosas 1,08 löögini km^{-2} a^{-1} Rootsi edelaosas ja Baltimaades. Keskmine aastane äikesepäevade arv ulatus 2 päevast Põhja-Norras 29,5-ni Leedu lõunaosas. Need arvud on sarnased naabermaades Soomes, Poolas ja Valgevenes saadud tulemustega ja kinnitavad seega nii antud töös kui ka nimetatud uuringutes kasutatud andmete kvaliteeti.

Äikese ajalis-ruumiline jaotus Põhja-Euroopas on vastavuses oluliste klimaatiliste tegurite (päikesekiirgus ja aluspind) mõjudega. Kõige enam on äikest suvel ja pärastlõunasel ajal, kui päikesekiirgus on kõige intensiivsem. Lisaks on äikest selgelt enam maismaa kohal, kuna see soojeneb tugevamalt kui meri. Baltimaades on mitmed kohalikud äikesemaksimumid seotud kõrgustikega, mis sunnivad õhuvoole tõusma ja soodustavad konvektsiooni.

Kuigi äikest ja välku esineb sagedamini uurimisala lõunaosa kohal, võib üksikuid intensiivseid torme ette tulla praktiliselt kõikjal. Neid on vaadeldud isegi polaarjoonest põhja pool. Sellised tormid võivad väikestel aladel anda mõne tunniga suure osa aastasest välkude koguarvust ning seega mõjutavad nad oluliselt ka üldist välgustatistikat.

Äikesepäevade andmeread korreleerusid hästi tsirkulatsiooniandmetega. Sellest võib järeldada, et pikaajalised muutused Baltimaade äikesekliimas, näiteks maksimum 1960. aasta paiku ja miinimum 1990. aasta paiku, on tingitud klimaatilistest varieeruvustest. Tsirkulatsiooni klassifikatsiooni aluseks olevad õhurõhu andmed on võrreldes äikesepäevade registreerimisega palju vähem mõjutatud vaatlusvigadest. Seega peegeldab hea korrelatsioon tsirkulatsiooniandmetega ka äikeseandmete head üldkvaliteeti. See omakorda näitab, et ebausaldusväärsete andmeridade tuvastamiseks ja eemaldamiseks kasutatud meetodid olid efektiivsed.

Põhja-Euroopa äikesekliima kohta on koostatud ulatuslik ja usaldusväärne ülevaade. Kasutatud meetodeid ja väljatöötatud tarkvara saab kasutada äikese ja välgu edasiseks seireks Põhja-Euroopas.

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