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Long-term changes in the frequency of thunder days in the Baltic countries

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Long-term changes in the thunderstorm climate of the Baltic countries and their relations with circulation weather types (CWT) during the period 1950–2004 were analyzed. The study area was located in northeastern Europe and encompassed Estonia, Latvia and Lithuania. Thunderstorm day (TD) data series collected by of observers at 40 meteorological stations were carefully checked for artificial inhomogeneities and used as the data source. During the study period, the average annual number of TDs decreased by about 24% in the Baltic countries with a rate of 0.9 TDs per decade. The maximum in thunderstorm frequency was observed during the period 1953–1963, and the minimum during 1990–1994. A long-term decrease in the TD frequency was accompanied by an increased frequency of northerly CWTs that are unfavorable for thunderstorm development. Meanwhile, the frequency of southerly and easterly CWTs that are favorable to thunderstorm formation decreased.

Introduction

Thunderstorms are among the major causes of weather-related damages and economic losses in mid-latitudes. Lightning, as well as straight-line winds, hail and even some rare tornadoes are the main causes of thunderstorm-related damages in the Baltic countries (e.g. Merilain and Tooming 2003, Marcinoniene 2003).

General changes in climate may affect thunderstorm frequency (Williams 2005, Price 2009). In many regional studies on long-term changes in thunderstorm climate, the annual and monthly numbers of thunderstorm days (TD), registered by observers at meteorological stations, are the main data sources.

There are some general similarities in the temporal behavior of thunderstorm frequency in different regions. The main similarity is the relatively high TD frequency in the 1950s and 1960s followed by a downward trend during the last decades of the 20th century. This is characteristic to the United States (Changnon and Changnon 2001), as well as to parts of Russia and Kazakhstan (Gorbatenko and Dulzon 2001). Similar trends are reported for parts of China (Wei *et al.*

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2011, Zhang and Pei 2011) and tropical Africa (Price and Asfur 2006).

Some studies of long-term trends in thunderstorm activity in Europe are inconsistent. Changnon (1985) found an upward trend in the TD frequency over the British Isles, northwestern Russia and southern Europe during 1930–1980, but in western Europe, TD numbers decreased at the same time. More recent, local studies 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). Some increase in the TD frequency was observed in the northern Caucasus region between 1936 and 2006 (Adzhiev and Adzhieva 2009).

Most of the studies mentioned above focused only on changes in thunderstorm climate without discussing their reasons. However, such changes are probably the result of changes in climate (e.g. Price 2009) that affect local and regional environmental conditions. Many studies demonstrated that thunderstorms were associated with specific synoptic conditions and circulation types (e.g. Tomás *et al*. 2004, Kolendowicz *et al*. 2006, Ramos *et al*. 2011).

The Baltic countries are located in the northeastern part of Europe along the eastern coast of the Baltic Sea. The average annual number of TDs in this region is between 12 and 29.5. The main thunderstorm season starts in April, peaks in July and August, and ends in October. Most of the thunderstorms occur in the afternoon and a typical storm last no more than about two hours (Enno *et al*. 2013). The area experienced significant changes in air temperatures and precipitation during the second half of the 20th century (e.g. Jaagus 2006, Rimkus *et al*. 2011, Päädam and Post 2011, Jaagus *et al*. 2013). Much less is known about the temporal behavior of the TD frequency in the Baltic countries. The only paper on the topic so far (Enno 2010) concluded that a statistically significant downward trend in the TD frequency existed during 1950–2000 at some of the 11 Estonian stations under study. However, the number of stations considered was limited and the data series were not checked for artificial inhomogeneities. Therefore, if the Baltic countries experienced some kind of changes in thunderstorm climate, the nature and extent of these changes are still unclear.

The main objective of this study is to give a detailed overview of changes in the thunderstorm climate of the Baltic countries during 1950–2004 based on the series that are checked to be free from artefacts. We also analyzed the relationships between thunderstorms and circulation weather types (CWT) to identify whether the temporal changes in thunderstorm frequency are associated with changes in regional atmospheric circulation. In association with the remarkable warming of winter and spring (Jaagus 2006), changes in the beginning and end dates of the thunderstorm season and in winter thunderstorm frequency were also studied.

Data and method

TD Data

Our study area covered Estonia, Latvia, and Lithuania, and its approximate size was 650 × 495 km. The area lies in the northeastern part of Europe, between 53–60°N and 20–29°E (Fig. 1).

Thunderstorm data from 50 Estonian, Latvian, and Lithuanian meteorological stations were available for the study period. All the stations were manned 24 hours a day. After quality assessment (*see* the next section), data from 40 stations (Fig. 1) were included in the analysis. Monthly and annual numbers of TDs from all stations were obtained from the archives of the Estonian Meteorological and Hydrological Institute, the Latvian Environment, Geology and Meteorology Centre and the Lithuanian Hydrometeorological Service under the Ministry of Environment. Some short gaps in the data series of some Estonian and Latvian stations were filled on the basis of linear regression using the data from the nearby stations (Enno *et al*. 2013).

In addition to the TD data used in the main analysis, more detailed data from 13 stations (Fig. 1) were used. These data included exact dates of thunderstorm occurrence and allowed to assess linkages with circulation weather types.

The study period, 1950–2004, was limited by the availability of data, since many meteorological stations in the Baltic countries started their

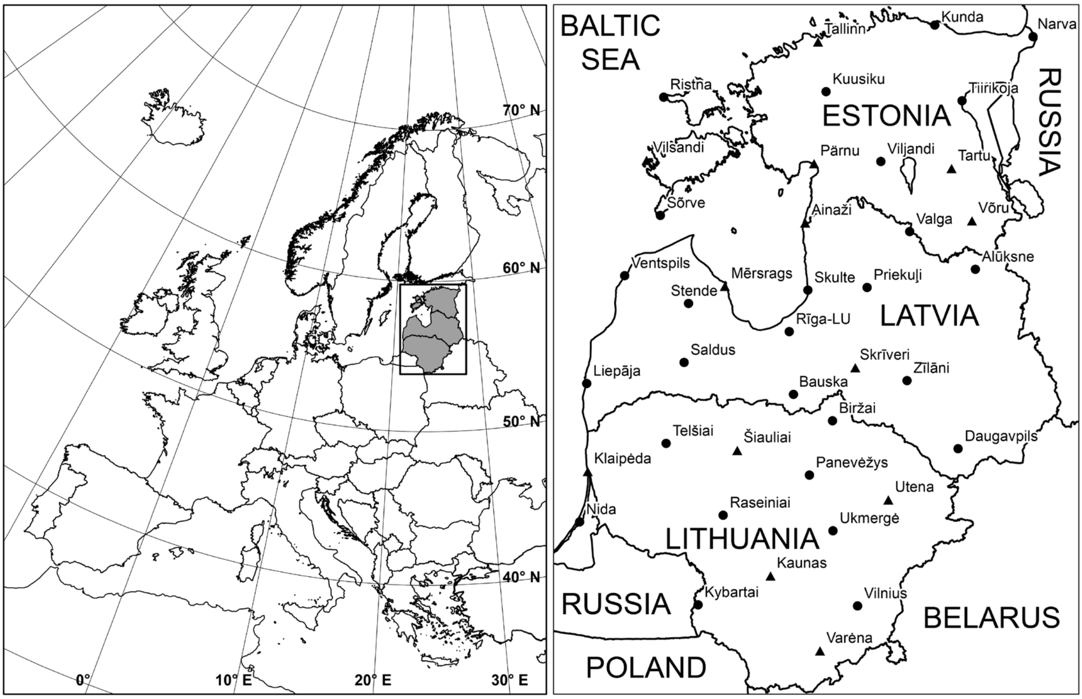

Fig. 1. The study area and locations of meteorological stations. Stations from which only the monthly numbers of thunderstorm days were used are shown with circles and stations from which the dates of thunderstorms were also used are shown with triangles.

observations around 1945–1950. Only scarce data, often of questionable quality and with gaps are available from before 1950. The year 2004 was selected as the end of the study period because of the subsequent automatization of most meteorological stations in Estonia which resulted in significant reduction in numbers of observations carried out by humans.

According to the observation rules, a TD is registered at a meteorological station when a thunder clap is heard by the observer at least once during a 24-h period. Certain problems and ambiguities arise in association with the data obtained at meteorological stations by observers. Physical factors like air temperature and density (Fleagle 1949), as well as major terrain features (Changnon 2001) can remarkably affect audibility of thunder. As a result, thunder is seldom heard at more than about 25 km from the storm location (Fleagle 1949). Urban areas may cause the enhanced frequency of thunderstorms (Changnon 2001, Pinto *et al*. 2013), whereas local noise at the stations reduces the chance to hear thunder (Changnon 1993). Changes in observation methods may result in artificial trends (e.g. Davis and Walsh 2008). It is also possible that certain observers were more attentive to recording thunder than others (Changnon 2001). Hence, it is very important to ensure that the possible influence of artificial factors has been minimized before the long-term changes in the TD frequency are studied. This can be achieved with careful data quality assessment.

Assessment of TD data quality

In the preliminary stage of the data quality assessment, we used the test by Easterling and Peterson (1995) using the AnClim software (Štěpánek 2008) to check for artificial inhomogeneities in the TD data series. The test comprises regression analysis and non-parametric statistics. Easterling and Peterson (1995) demonstrated that this test performs better than other similar tests in detecting artificial inhomogeneities in both the measured and simulated data. Changnon (2001) used that method to check the long-term TD series in the United States.

The test found 43 discontinuities in the TD data from different stations, which were clearly concentrated in certain periods. There were 16 discontinuities during 1960–1964, 9 during 1995–1999 and 8 during 1985–1989. Meanwhile, there were no changes in the observation method, and relocations of stations were rare during these periods. We could conclude that these artificial inhomogeneities were probably caused by sharp natural variations in the TD frequency like a strong maximum around 1960 and a deep minimum around 1990 (*see* Results).

The preliminary assessment demonstrated that the homogeneity test was not able to detect possible artificial changes in TD data when sharp, natural variations existed in the background. On the other hand, even minor artificial factors in the data set may lead to incorrect conclusions, especially when studying long-term changes.

To detect such unnatural changes and biases in the TD data, in the next step we used the comparative analysis. The analysis relies on the assumption that any gradual change or abrupt fluctuation experienced at the candidate station will show up at the nearby reference stations as well. A similar method was applied by Changnon (2001) to assess the quality of TD data at meteorological stations in the United States.

First, we calculated the relative frequency of thunderstorms for each station for every year. Relative frequency means that the annual numbers of TDs at a particular station were expressed as a percentages of the 1950–2004 average at this station. Second, we determined three nearest stations for each of the 50 candidate stations. Relative storm frequencies of a candidate station and the nearest stations were then plotted for a comparison. Third, we visually compared the temporal behavior of storm frequencies at each of the 50 candidate stations with those at the nearest stations. If the candidate station showed any abrupt change or systematic shift in the TD frequency as compared with the nearest stations, we excluded it from further analysis.

In addition to the visual comparison of the temporal behavior of storm frequencies, we also compared the long-term trends in TD frequencies with those found for nearby stations. If the candidate station showed an opposite trend or a trend whose slope was substantially different as compared with the reference stations, we did not use it in further analysis.

Examples of plots used in the comparative analysis are presented in Fig. 2. For better visualization, the relative frequencies of thunderstorms are represented as 5-year averages. It turned out that at the Kaunas station (Fig. 2a), the temporal behavior of TD frequencies generally resembled that at the surrounding reference stations. Some small discrepancies, e.g. during 1975–1979, are probably associated with the stochastic nature of deep convection. So, the station was included in further analysis.

In contrast, the Türi (Fig. 2b) and Virtsu (Fig. 2c) stations were both excluded from the data analysis. While an upward trend in the TD frequency was found for Türi, the downward trends were found at all the reference stations, which probably indicates changes in quality of observations. Virtsu had unusually low TD numbers between 1985 and 1989. It is probably the effect of inadequate observations, as the reference stations showed much higher activity during this period.

As a result of the comparative assessment described above, ten stations were excluded from the main analysis. All of them had unusual biases or abrupt changes in their TD data sets as compared with the reference stations. Consequently, their TD data probably contain artefacts and are therefore not suitable for studying long-term changes in thunderstorm climate.

Circulation weather types

The classification of circulation weather types (CWT) used in the current paper was initially developed by Jenkinson and Collison (1977) as an automatic version of Lamb's classification (Lamb 1972). Later it was successfully used elsewhere in Europe (Linderson 2001, Post *et al.* 2002, Trigo and Da Camara 2000, Jones *et al.* 2013), including a thunderstorm and lightning study in Portugal (Ramos *et al.* 2011). It uses sea-level pressure data values from 16 points

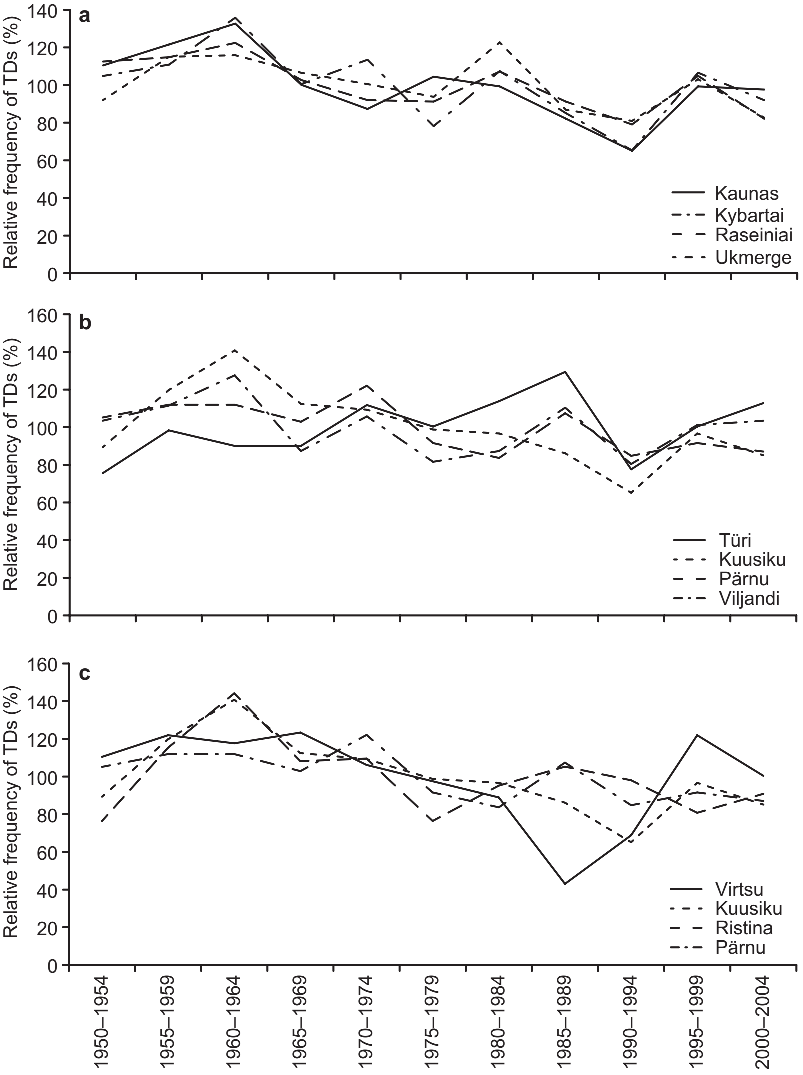

Fig. 2. The temporal behavior of relative storm frequencies at three candidate stations compared with that at the nearest reference stations: (**a**) candidate station Kaunas, (**b**) candidate station Türi, (**c**) candidate station Virtsu.

in and around the study area to calculate the geostrophic airflow (*F*) and the total vorticity (*Z*) indices. CWTs are defined by comparing the numeric values of the indices. If a straight airflow dominates over the vorticity then, depending on the direction of the flow, 8 directional types are specified (W, NW, N, NE, E, SE, S, SW). If the vorticity *Z* is at least two times larger than the geostrophic flow *F*, then the cyclonic (C) or anticyclonic (A) types are determined. The original classification includes also 16 so-called hybrid types, where the direct flow and vorticity play a nearly equal role in atmospheric regional circulation, but our preliminary analysis demonstrated clearer links between CWTs and TDs in those cases where the hybrid types were added to directional ones. As a result, we obtained 10 main circulation types. Mean sea-level pressure (MSLP) fields for these CWTs are represented (Fig. 3).

The MSLP data originated from the NCEP/NCAR reanalysis (Kalanay *et al*. 1996). We chose the classification center to be as close to the center of the study area as possible, with geographic coordinates 57.5°N and 25°E. CWTs were calculated with a daily step on the basis of the MSLP data at 12:00 UTC. This corresponds to the local afternoon, when most of the thunderstorms occur.

Methods

Based on the data from 13 Estonian, 14 Latvian and 13 Lithuanian stations, we calculated the monthly and annual average values of TDs for all of the three countries and for the whole study area.

We used Sen's method in the MS Excel template MAKESENS (Salmi *et al*. 2002) to estimate the directions and magnitudes of changes in the annual numbers of TDs and in the average dates of the first and last thunderstorm of the year during 1950–2004. Sen's method is a method for robust linear regression that chooses the median slope among all lines through pairs of two-dimensional sample points (Sen 1968).

We checked the significance of these changes for individual stations with a Mann-Kendall test (Mann 1945, Kendall 1975). Considering the average numbers from many stations, we checked the significance of changes using the multivariate Mann-Kendall test in the MS Excel template MULTMK/PARTMK (Libiseller 2002). In calculating the significance of the trends, this test takes into account the standard yearly deviation in the data. Trends were considered to be statistically significant at $p < 0.05$ (two-sided test). For better comparison, we calculated the decadal changes in TD numbers for each station.

We calculated the date of the 10th and 90th percentile of the thunderstorm season in the Baltic countries on the basis of the data from the 13 stations where the dates of thunderstorm occurrence were available. For example, if the total number of TDs at these 13 stations was 200 in a given year, then the 10th percentile was the date when the 20th TD of the year occurred, and the 90th percentile was the date when the 180th TD of the year occurred.

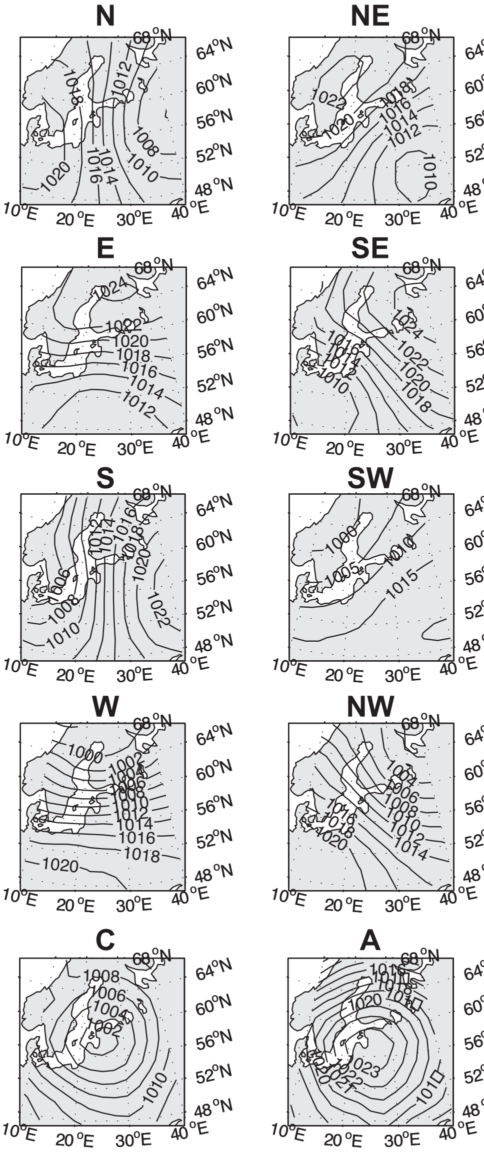

Fig. 3. Annual average sea level pressure field of the 10 circulation weather types during 1950–2004.

We analyzed the relationships between TDs and CWTs during the main thunderstorm season, from May to September, when 93.8% of all TDs during 1950–2004 had been observed. First, the frequencies and thunderstorm probabilities were computed for each CWT. Second, the TD frequency in the Baltic countries was correlated with the frequency of CWTs during the thunderstorm season. We did it separately for each CWT on the basis of the TD data from the 13 stations. Correlations between the 7-year smoothed average monthly numbers of days with a specific CWT and the 7-year smoothed average monthly numbers of TDs at the weather stations were evaluated using regression analysis. CWTs with the highest correlations were used in compari-

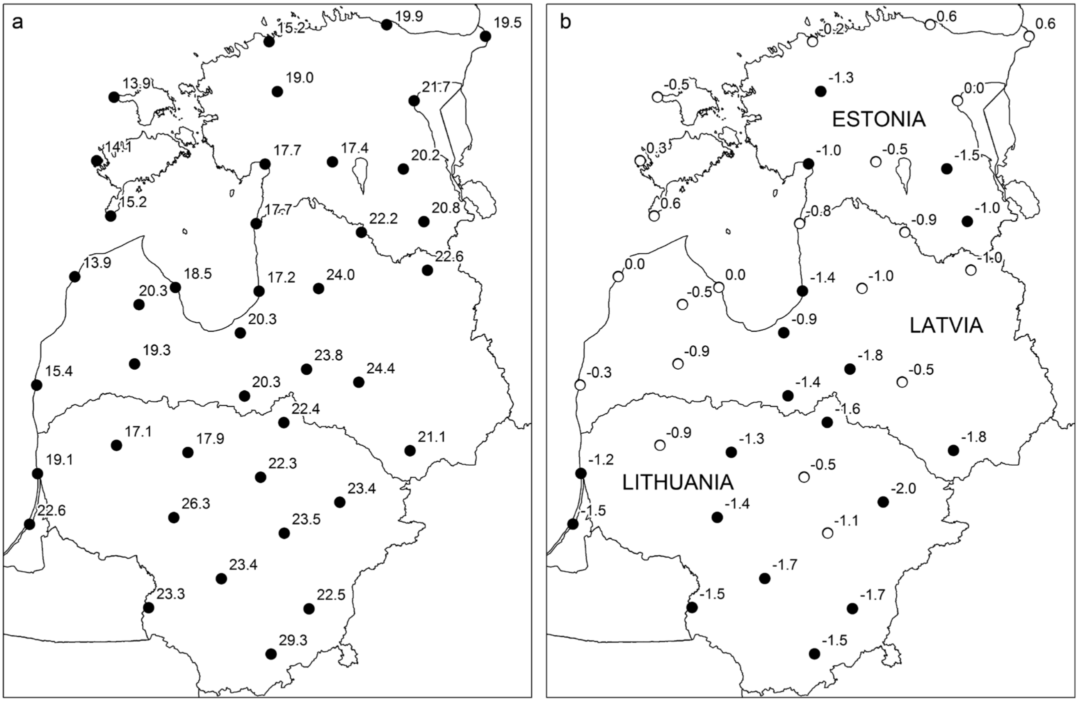

Fig. 4. (**a**) Average annual number of TDs at 40 meteorological stations in the Baltic countries during 1950–2004, and (**b**) decadal changes in the TD frequency (TDs per decade) at the used stations during 1950–2004. Negative values refer to downward trends. Stations with statistically significant trends ($p < 0.05$) are marked with filled circles.

sons with long-term changes in the TD frequency.

Results

Long term changes in the TD frequency

The mean annual TD number calculated for all the 40 stations included in the study together decreased significantly at a rate of 0.9 TDs per decade (Mann-Kendall statistics = –2.443, p = 0.015) which is 4.4% of the annual average number of TDs (20.2) in the study area. Thus, during the whole study period of 1950–2004, the TD frequency in the study area decreased by approximately 24% (Fig. 4).

While there was no clear trend in the average annual TD number at 13 Estonian weather stations, the mean TDs of 14 Latvian and 13 Lithuanian stations decreased significantly at a rate of 1.0 and 1.3 TDs per decade, respectively. Downward trends tended to become more pronounced and statistically more significant towards the southern part of the Baltic countries. In Estonia, statistically significant downward trends in the annual number of TDs were found for four stations only, whereas in Latvia and Lithuania the respective number of stations were five and ten. For some Latvian and Lithuanian stations, a decadal change as large as 7%–9% of the long-term average was found. This amounts to ~47% decrease in the TD frequency during the whole study period.

Thunderstorm activity in the Baltic countries was characterized by a remarkably large inter-annual variability (Fig. 5). For example, the highest average TD number in the study area during 1950–2004 was 31.8 in 1972, whereas the lowest, 12.5, was reported only four years later in 1976.

It can also be seen that the main decrease in the TD frequency was in the period between 1960 and 1990 (Fig. 5). The highest thunderstorm activity during the study period was recorded between 1953 and 1963, the annual TD

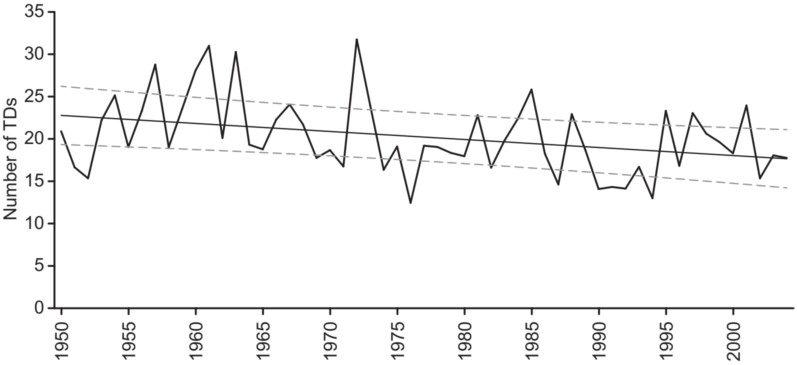

Fig. 5. Average annual numbers of TDs in the Baltic countries with the linear trend (black line) and its 95% confidence intervals (grey, dashed lines) for 1950–2004 (p = 0.015).

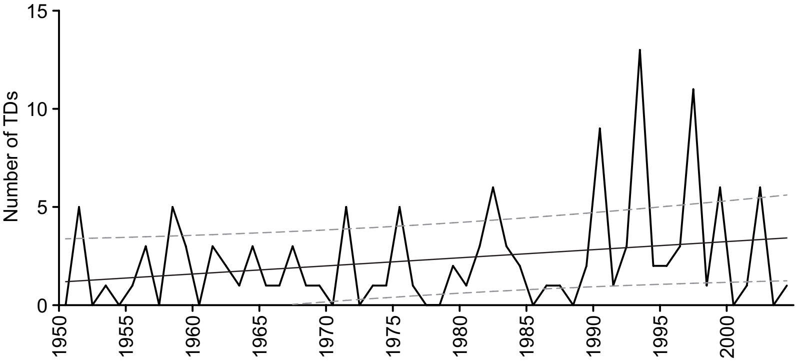

Fig. 6. Total numbers of winter TDs (December to February) at 40 weather stations in the Baltic countries with the linear trend (black line) and its 95% confidence intervals (grey, dashed line) (p = 0.078).

numbers being 20–30. In contrast, during 1990–1994 there were only about 15 TDs annually, so that the period was characterized by the lowest thunderstorm activity between 1950 and 2004.

Throughout the study period, winter thunderstorms were rare in the Baltic countries, with usually fewer than five reports per 40 stations annually (Fig. 6). However, it was also found that the frequency of such storms was clearly higher during the 1990s with peaks in 1990, 1993 and 1997. A related upward trend in the winter TD frequency was still statistically insignificant (Mann-Kendall statistics = 1.763, $p = 0.078$).

The average date of the 10th percentile of the thunderstorm season in the Baltic countries was 18 May. Among the years it varied between 23 April and 13 June (Fig. 7a). Large inter-annual variations appeared throughout the study period; however, no statistically significant trend was found.

The average date of the 90th percentile of the thunderstorm season in the Baltic countries was 30 August. It varied from 17 August to 16 September during most of the study period (Fig. 7b). Regardless of two extremely early cases on 2 August at the end of the period, in 1996 and 2002, no statistically significant trend emerged.

Relationships with circulation weather types

It appeared that the most frequent CWT in the Baltic countries during the thunderstorm season was the anticyclonic type A, characterizing 21.9% of days. The less frequent types included NE, E, SE and S, which occurred on 4.4%–7.6% of days. It is also noticeable that the frequency of the northerly and easterly flow types generally decreased from spring towards autumn. The opposite was true for the westerly flow types (Table 1).

Thunderstorms were most common during the flow types E, SE, S, SW, and also during the cyclonic type C (Table 2). Their frequency was the lowest during the types A, N and NW.

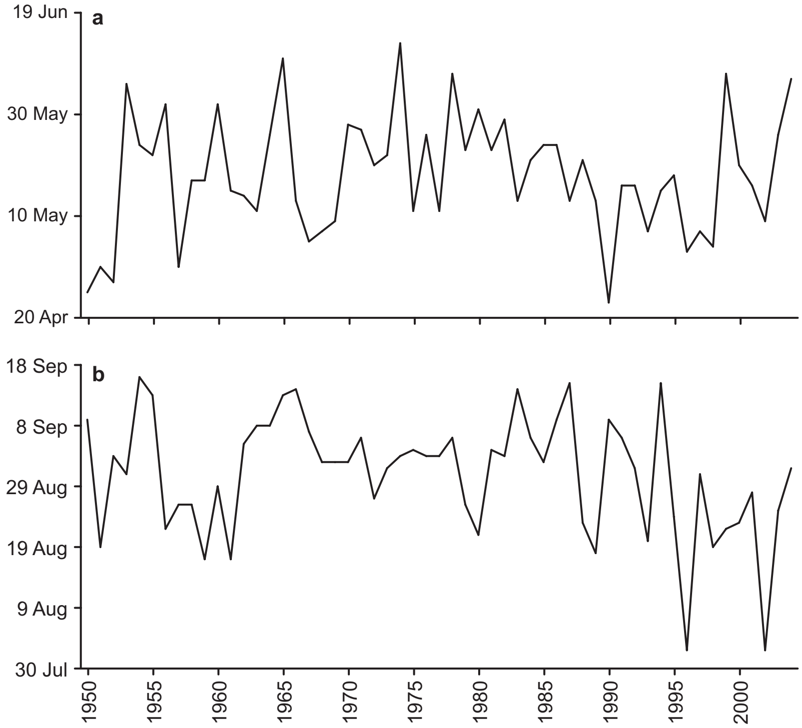

Fig. 7. Date of (**a**) the 10th percentile, and (**b**) the 90th percentile of thunderstorm season in the Baltic countries during 1950–2004.

Seasonal changes were evident. Thunderstorms became much less frequent in September during the cyclonic and anticyclonic type. From May to July, the southerly and easterly flow types were most favorable to thunderstorm formation. From August onwards, the westerly types like SW and

Table 1. Circulation weather type (CWT) monthly and seasonal frequencies (%) form May to September 1950–2004.

	N	NE	E	SE	S	SW	W	NW	C	A
V	10.6	11.3	9.1	6.7	7.1	6.9	8.6	7.9	9.4	22.4
VI	13.0	8.1	5.5	3.9	4.7	9.5	10.4	13.0	10.0	21.9
VII	12.0	7.1	4.7	3.0	5.5	10.1	13.3	11.1	12.1	21.0
VIII	8.9	6.9	5.1	4.8	5.6	11.0	12.7	10.7	10.9	23.5
IX	7.5	4.4	2.7	3.4	8.1	14.7	14.2	12.6	11.7	20.7
V–IX	10.4	7.6	5.4	4.4	6.2	10.4	11.8	11.0	10.8	21.9

Table 2. Monthly and seasonal TD ratios (%) for different circulation weather types (CWT) form May to September 1950–2004.

	N	NE	E	SE	S	SW	W	NW	C	A
V	4.7	6.1	12.3	15.7	18.6	14.2	8.4	5.8	16.0	4.2
VI	8.7	16.7	24.7	29.8	27.9	23.1	11.9	9.1	23.1	6.4
VII	9.9	13.0	23.4	29.3	30.5	23.1	16.8	10.2	26.1	7.2
VIII	10.3	12.2	14.9	15.4	20.1	19.5	12.8	12.6	19.9	6.1
IX	3.3	2.5	5.5	5.2	8.3	8.9	8.2	6.1	8.3	0.9
V–IX	7.7	10.3	16.5	18.4	19.7	17.2	11.8	8.9	18.8	5.0

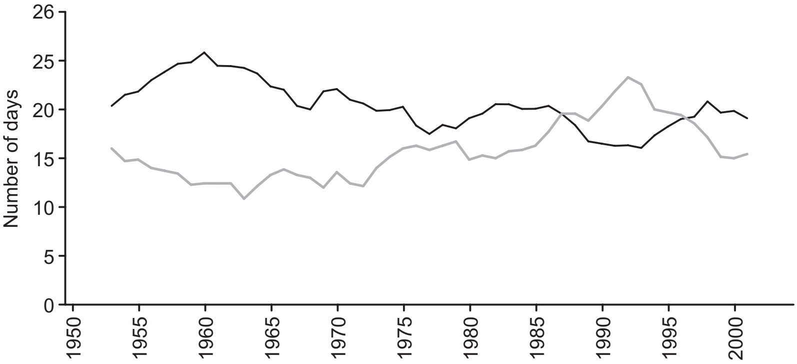

Fig. 8. Average annual number of TDs in the Baltic countries (black line), and the number of days with circulation type N from May to August as well as days with circulation types NE and E in September (gray line). The values are 7-year smoothed averages.

W became more important whereas the role of the easterly types decreased.

The comparison of the TD and CWT frequency series showed the strongest negative correlation with the frequency of the flow type N (Table 3). This was especially evident in July and August whereas in September, a strong negative correlation appeared with the types NE and E. At the seasonal scale, a significant negative correlation also with the type SW was found, but the relationship was weaker. A clear opposite phase behavior was limited to the first 15 years of the study period.

The strongest positive correlation was found between the series of TDs, and the anticyclonic type A (Table 3). Based on the monthly data, the relationship was stronger in spring. A positive correlation with the flow types E and SE was strongest in July.

The number of days with circulation types unfavorable to thunderstorms (type N from May to August and types NE and E in September) were plotted against TD frequencies. The opposite phase behavior is clear and the frequency of the CWTs explained 67% ($r = –0.817$, $n = 49$, $p < 0.05$) of the variation in the thunderstorm frequency in the Baltic countries during 1950–2004 (Fig. 8). Because of the above-mentioned weaker relationship, the type SW was not included regardless of a significant negative correlation at the seasonal scale.

The number of days with the circulation types that were positively correlated with thunderstorm occurrence (types A, E and SE from May to August, types W and NW in September) were plotted against TD frequencies. A similar temporal behavior of the series is especially evident since 1970 (Fig. 9). The frequency of the CWTs explained 52% ($r = 0.719$, $n = 49$, $p < 0.05$) of the variations in the thunderstorm frequency in the Baltic countries during the study period.

Discussion

Long term changes in the TD frequency

The most obvious feature of the TD frequency

Table 3. Pearson's correlation coefficients for lirear regressions (r) between 7-year smoothed average monthly numbers of days with different CWTs and 7-year smoothed average monthly numbers of TDs at 13 weather stations from May to September 1950–2004. Statistically significant correlations ($n = 49$, $p < 0.05$) are given in boldface.

	N	NE	E	SE	S	SW	W	NW	C	A
V	**–0.405**	**–0.531**	–0.039	**0.332**	**0.320**	0.079	–0.215	–0.257	**0.450**	**0.395**
VI	–0.060	**–0.301**	–0.153	–0.078	0.099	0.184	–0.054	0.008	–0.026	**0.271**
VII	**–0.797**	0.257	**0.660**	**0.690**	**0.310**	–0.055	**–0.409**	**–0.268**	–0.004	0.109
VIII	**–0.553**	**0.432**	0.202	**0.280**	–0.027	0.014	–0.007	–0.216	–0.073	0.003
IX	0.045	**–0.763**	**–0.749**	**–0.277**	0.047	**0.307**	**0.553**	**0.745**	–0.019	**–0.400**
V–VIII	**–0.731**	–0.007	**0.409**	**0.405**	0.126	**–0.498**	**0.280**	–0.149	–0.206	**0.633**
V–IX	**–0.644**	–0.162	0.132	**0.344**	0.181	**–0.462**	–0.045	0.261	–0.256	**0.591**

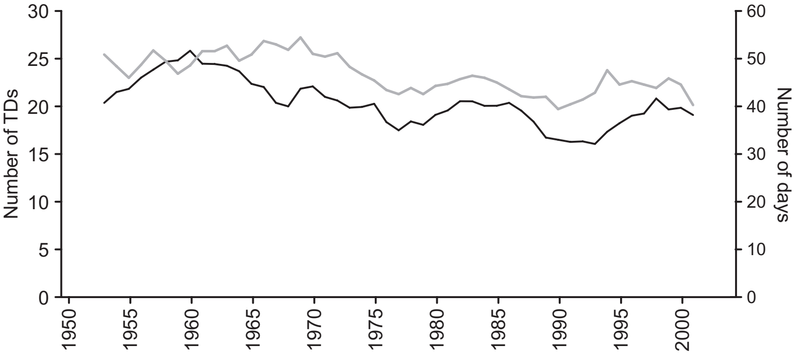

Fig. 9. Average annual number of TDs in the Baltic countries (black line) and number of days with circulation types E, SE and A from May to August as well as with circulation types W and NW in September (gray line). The values are 7-year smoothed averages.

in the Baltic countries during 1950–2004 is a statistically significant downward trend with the rate of change of 0.9 TDs per decade. Worldwide, similar downward trends in thunderstorm frequencies during the second half of the 20th century were reported for parts of the United States (Changnon, 1985, Changnon and Changnon 2001), Russia and Kazakhstan (Gorbatenko and Dulzon 2001) and China (Wei *et al*. 2011).

At the regional scale, thunderstorm climate was more stable in Finland and Poland. In Finland, which is just north of our study area, no clear changes in TD and lightning frequencies were observed between 1960 and 2007 (Tuomi and Mäkelä 2008). This is in line with our finding that the downward trends in average TD frequencies become more pronounced and statistically more significant towards the south.

In Poland, there were no significant trends in the TD frequency during 1949–1998 (Bielec-Bakowska 2003). It is interesting that there is no trend even in the Mazursko-Podlaski region in northeastern Poland, which borders Lithuania where a clear downward trend in the TD frequency was found. This can be associated with the relatively large spatial extent of the Mazursko-Podlaski region, which encompassed stations not only near the Lithuanian border but also in central Poland.

The above-mentioned differences indicate a probable presence of areas with a different temporal behavior of thunderstorm frequency in northeastern Europe. This is generally in line with the findings of some previous studies. For example, the continental United States can be divided into 5 to 14 distinctive zones on the basis of long-term changes in thunderstorm climate (Changnon 1985, Changnon 1988, Changnon and Changnon 2001). Changnon (1985) studied also European data and found three regions with an upward trend and one region with a downward trend in the TD frequency during 1930–1980. This study did not include the Baltic countries, Finland and Poland. However, an upward trend in TD activity was found for northwestern Russia, east of our study area.

Despite the differences in long-term trends, there are also similarities between the temporal behavior of thunderstorm activity in the Baltic countries, Finland and Poland. Similarities are more common in case of extremes in the thunderstorm frequency. For example, the lowest annual average TD number in the Baltic countries in 1976 coincides with that in Poland (Bielec-Bakowska 2003). In Finland, the lowest annual average TD numbers during 1960–2007 were registered in 1976 and 1996 (Tuomi and Mäkelä 2008). The highest annual TD number in the Baltic countries in 1972 coincides with the maximum TD frequency in northeastern Poland (Bielec-Bakowska 2003) and a record high lightning activity in Finland (Tuomi and Mäkelä 2008). This indicates that remarkable anomalies in the TD frequency are probably caused by atypical weather conditions over large areas.

Inter-annual variations in the TD frequency (Fig. 5) are large not only in the Baltic countries, Finland and Poland, but also elsewhere in Europe: e.g., southwestern Germany (Kunz *et al*. 2009) and Bulgaria (Simeonov *et al*. 2009). Modern lightning detection networks have also confirmed large year-to-year variations in the thunderstorm activity over Estonia (Enno 2011), as well as over the neighboring countries like

Finland (Tuomi and Mäkelä 2008) and Sweden (Sonnadara *et al*. 2006).

Considering the overall downward trend in the TD frequency, winter thunderstorms were more frequent at the end of the study period (Fig. 6). Although the trend was statistically insignificant, the highest activity of winter thunderstorms is clearly concentrated in the 1990s. In that decade, there was about three times more winter TDs than in the previous decades. This is probably associated with unusually warm winters accompanied by intense westerly airflow and frequent passages of cyclones and fronts during the 1990s (Jaagus 2006).

These findings are generally in line with the results for Poland and central Europe. Bielec (2001) pointed out that since the mid-20th century, the average annual number of days with winter thunderstorms (October to March) has increased in Cracow, Poland. Meanwhile, Bielec-Bakowska (2003) showed that during the cold season a significant increase in the TD frequency was found for only a few of the analyzed 56 Polish stations. For both the Czech Republic (Munzara and Franc 2003) and Slovakia (Racko *et al*. 2002), the more frequent occurrence of winter thunderstorms during the recent years has been mentioned. However, the existence of statistically significant trends remains a question.

Although the overall frequency of TDs has decreased during the study period, no significant change in the dates of the 10th and 90th percentile of the thunderstorm season was found (Fig. 7). It is somewhat surprising that the date of the 10th percentile of the thunderstorm season was stable considering significant warming of spring (Jaagus 2006). This is probably related to the fact that warming is most intense in early spring, especially in March, when long-term average temperature is around 0 °C. Despite warming, temperatures are still too low for significant thunderstorm activity.

Relationships with circulation weather types

Our results demonstrate that during the thunderstorm season, the weather in the Baltic countries is most frequently affected by the anticyclonic circulation type (Table 1). Flow types showed mid-latitude specific distribution with a more frequent presence of westerly CWTs. These types are frequently associated with North Atlantic cyclones, which are characteristic to northern Europe.

It appears that thunderstorms are much more frequent in case of southerly and easterly types during spring and summer (Table 2). Such air flows are the source of warm, humid air from lower latitudes, thus being favorable to thunderstorm formation. This is in line with the results of Tuomi and Mäkelä (2008) in Finland. Thunderstorms occur frequently with the cyclonic type C as well. This is probably the effect of cyclonic fronts that are favorable to thunderstorm formation.

Different situation appeared in September, when westerly flow types were most favorable to thunderstorm formation. This follows from the fact that in autumn land cools faster than the sea. Westerly winds carry warm, humid air from the North Atlantic and the Baltic Sea in September. This air is more favorable for deep convection than the cooler and drier continental air masses carried by the types E and SE.

Thunderstorms are most rarely associated with the anticyclonic type and northerly flow types. Convection is inhibited by the descending air in the central region of high pressure areas. Northerly flow types carry cooler air masses from higher latitudes, which are characterized by the lack of potential energy for thunderstorm formation.

When we correlated the TD series with the frequency of CWTs, the most surprising feature that we noted was a significant positive correlation between the TD frequency and the presence of the anticyclonic type A (Table 3). This seems to be inconsistent with the fact that the probability of thunderstorm occurrence is the lowest during the type A. However, it is possible that the type A is associated with CWTs that are more favorable for thunderstorms.

We checked this assumption and found that the frequency of the anticyclonic type A is positively correlated with the frequencies of the types SE ($r_P = 0.374, p < 0.05, n = 49$) and S ($r_P = 0.471, p < 0.05, n = 49$). This could be explained with the prevailing eastward motion of weather systems at mid-latitudes where the centers of high pressure areas frequently move east after having affected the study area. When they reach western Russia, the Baltic countries come under the influence of southerly and southeasterly air flows in the western part of the anticyclone with a high probability of thunderstorms.

The anticyclonic type with its mainly cloudless sky and plenty of sunshine also favors fast warming of the sea surface, which may enhance thunderstorm activity. The TD frequency in the Baltic countries is clearly lower in the vicinity of the Baltic Sea, especially during spring when the water is still cool (Enno *et al.* 2013). Plenty of days with anticyclones in May and June lead to a more rapid warming of the water. As a result, the thunderstorm development conditions over coastal and sea areas improve at the beginning of the storm season. If this results in an increased TD frequency at coastal stations then the overall annual number of TDs is also higher. Results (Table 3) support this hypothesis as a positive correlation between the frequencies of the anticyclonic weather type A and thunderstorms is indeed strongest in May and June.

CWT and TD relationships discussed above explain most of the long-term changes in the TD frequency. The years around 1960, when the highest TD frequency was observed, were characterized by the lowest frequency of northerly flow types unfavorable to thunderstorm formation. The frequency of such CWTs peaked around 1990, when the lowest TD frequency was observed (Fig. 8).

Relationships of TDs with CWTs favorable to thunderstorms (Fig. 9) are most clear since 1970. The lowest TD frequency around 1990 is associated with the infrequent presence of such types. The more complicated situation before 1970 includes a clear peak in thunderstorm activity around 1960 during a relatively stable frequency of favorable CWTs during 1950–1970. This indicates that the relationships between CWTs and thunderstorms may have been different before 1970. For example, the data revealed a remarkably high frequency of TDs in case of the cyclonic type C around 1960. A further study is needed to explain this fact.

Although the correlations presented here are based on the 7-year smoothed averages of TD and CWT frequencies, it should be added that they are also evident in case of annual data. 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 during the period from May to August. In 1976, when the annual number of TDs was the lowest, there were 23 such days. We can say that these sharp interannual variations in the TD frequency clearly reflect differences in the prevailing atmospheric circulations in northern Europe in different summers.

Conclusions

Long-term changes in the thunderstorm climate of the Baltic countries and their relationships with changes in regional atmospheric circulation in northern Europe were analyzed during the period of 1950–2004. The following conclusions can be drawn:

1. The mean annual TD number calculated for all the 40 stations included in the study together decreased significantly at a rate of 0.9 TDs per decade which is 4.4% of the annual average number of TDs (20.2) in the study area. Downward trends were stronger at the stations located in the southern part of the study area.
2. The highest number of thunderstorm days was observed during 1953–1963 whereas the lowest activity was in 1990–1994. A remarkably large inter-annual variability and abrupt changes in the thunderstorm activity were obvious.
3. Winter thunderstorms were rare in the Baltic countries throughout the study period with usually less than five reports per 40 stations annually. Although their frequency was clearly higher during the 1990s, no statistically significant long-term trend was found.
4. There were no statistically significant changes in the beginning and end dates of the thunderstorm season, based on the dates of the 10th and 90th percentile of the thunderstorm season.
5. Thunderstorms were most frequent during the warm easterly or southerly flow circula-

tion types and the cyclonic weather type. The probability of thunderstorms was the lowest during the weather types with cool northerly airflow, as well as with strong anticyclonic vorticity.

6. Long-term changes in the TD frequency in the Baltic countries are generally in line with changes in the frequency of circulation weather types. Long-term decrease in the TD frequency was accompanied by the increased frequency of weather types unfavorable to thunderstorms and the decreased frequency of types favorable to thunderstorm formation.

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References

Adzhiev A.K. & Adzhieva A.A. 2009. Spatial and temporal variations of thunderstorm activity in the Northern Caucasus. *Russ. Meteorol. Hydrol.* 34: 789–793.

Bielec Z. 2001. Long-term variability of thunderstorms and thunderstorm precipitation occurrence in Cracow, Poland, in the period 1896–1995. *Atmos. Res.* 56: 161–170.

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

Changnon S.A. 1985. Secular variations in thunder-day frequencies in the twentieth century. *J. Geophys. Res.* 90: 6181–6194.

Changnon S.A. 1988. Climatography of thunder events in the conterminous United States. Part I: temporal aspects. *J. Climate* 1: 389–398.

Changnon S.A. 1993. Relationships between thunderstorms and cloud-to-ground lightning in the United States. *J. Appl. Meteorol.* 32: 88–104.

Changnon S.A. 2001. Assessment of the quality of thunderstorm data at first-order stations. *J. Appl. Meteorol.* 40: 783–794.

Changnon S.A. & Changnon D. 2001. Long-term fluctuations in the thunderstorm activity in the United States. *Climatic Change* 50: 489–503.

Davis S. & Walsh K.J.E. 2008. Southeast Australian thunderstorms: are they increasing in frequency? *Aust. Meteorol. Mag.* 57: 1–11.

Demuzere M., Werner M., Van Lipzig N.P.M. & Roeckner E. 2009. An analysis of present and future ECHAM5 pressure fields using a classification of circulation patterns. *Int. J. Climatol.* 29: 1796–1810.

Easterling D.R & Peterson T.C. 1995. A new method for detecting undocumented discontinuities in climatological time series. *Int. J. Climatol.* 15: 369–377.

Enno S.E. 2010. Spatio-temporal changes in thunderstorm frequency in Estonia. In: *Proceedings of the 6-th Study Conference on BALTEX,* June 14–18, 2010, Miedzyzdroje, Poland, pp. 140–141.

Enno S.E. 2011. A Climatology of cloud-to-ground lightning over Estonia, 2005–2009. *Atmos. Res.* 100: 310–317.

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

Fleagle R.G. 1949. The audibility of thunder. *J. Acoust. Soc. Am.* 21: 411–412.

Gorbatenko V. & Dulzon A. 2001. Variations of thunderstorm. In: *Science and Technology, KORUS '01, Proceedings of the Fifth Russian-Korean International Symposium on Science and Technology*, *26 Jun–3 Jul 2001*, vol. 2, pp. 62–66. [doi:10.1109/KORUS.2001.975178]

Jaagus J. 2006. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. *Theor. Appl. Climatol.* 83: 77–88.

Jaagus J., Briede A., Rimkus E. & Remm K. 2013. Spatial variability and trends in daily minimum and maximum temperatures and in the diurnal temperature range in Lithuania, Latvia and Estonia. *Theor. Appl. Climatol.* doi: 10.1007/s00704-013-1041-7.

Jenkinson A.F. & Collison F.P. 1977. *An initial climatology of gales over the North Sea*. Synoptic Climatology Branch Memorandum 62, Meteorological Office, Bracknell.

Jones P.D., Harpham C. & Briffa K.R. 2013. Lamb weather types derived from reanalysis products. *Int. J. Climatol.* 33: 1129–1139.

Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Leetmaa A., Reynolds R., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K.C., Ropelewski C., Wang J., Jenne R. & Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.* 77: 437–471.

Kendall M.G. 1975. *Rank correlation methods*, 4th ed. Charles Griffin, London.

Kolendowicz L. 2006. The influence of synoptic situations on the occurrence of days with thunderstorms during a year in the territory of Poland. *Int. J. Climatol.* 26: 1803–1820.

Kunz M., Sander J. & Kottmeier C. 2009. Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. *Int. J. Climatol.* 29: 2283–2297.

Lamb H.H. 1972. *British Isles Weather types and a register of daily sequence of circulation patterns, 1861–1971*. Geophys. Mem. 116, Meteorol. Office, London.

Libiseller C. 2002. *MULTMK/PARTMK — a program for the computation of multivariate and partial Mann-Kendall test*. Available at http://www.slu.se/PageFiles/70727/Manual.pdf.

Linderson M.L. 2001. Objective classification of atmospheric circulation over Southern Scandinavia. *Int. J. Climatol.* 21: 155–169.

Mann H.B. 1945. Non-parametric tests against trend. *Econometrica* 13: 245–259.

Marcinoniene I. 2003. Tornadoes in Lithuania in the period of 1950–2002 including analysis of the strongest tornado of 29 May 1981. *Atmos. Res.* 67–68: 475–484.

Merilain M. & Tooming H. 2003. Dramatic days in Estonia. *Weather* 58: 119–125.

Munzara J. & Franc, M. 2003. Winter thunderstorms in central Europe in the past and the present. *Atmos. Res.* 67–68: 501–515.

Päädam K. & Post P. 2011. Temporal variability of precipitation extremes in Estonia 1961–2008. *Oceanologia* 53: 245–257.

Pinto O., Pinto I.R.C.A. & Ferro M.A.S. 2013. A study of the long-term variability of thunderstorm days in Southeast Brazil. *J. Geophys. Res.* 118: 5231–5246.

Post P., Truija V. & Tuulik J. 2002. Circulation weather types and their influence on temperature and precipitation in Estonia. *Boreal Env. Res.* 7: 281–289.

Price C. 2009. Thunderstorms, lightning and climate change. In: Betz H.D., Schumann U. & Laroche P. (eds.), *Lightning: principles, instruments and applications*, Springer, New York, pp. 521–535.

Price C. & Asfur M. 2006. Inferred long term trends in lightning activity over Africa. *Earth Planets Space* 58: 1197–1201.

Racko S., Simon A. & Sokol A. 2002. Some of the causes of thunderstorm occurrence during winter season. *Meteorologické zprávy* 55(3): 69–81. [In Slovak with English summary].

Ramos A.M., Ramos R., Sousa P., Trigo R.M., Janeira M. & Prior V. 2011. Cloud to ground lightning activity over Portugal and its association with circulation weather types. *Atmos. Res.* 101: 84–101.

Rimkus E., Kazys J., Bukantis A. & Krotovas A. 2011. Temporal variation of extreme precipitation events in Lithuania. *Oceanologia* 53: 259–277.

Salmi T., Määttä A., Anttila P., Ruoho-Airola T. & Amnell T. 2002. *Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates-the Excel template application MAKESENS*. Available at http://www.ilmanlaatu.fi/ilmansaasteet/julkaisu/pdf/MAKESENS-Manual_2002.pdf.

Sen P.K. 1968. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* 63: 1379–1389.

Simeonov P., Bocheva L. & Marinova T. 2009. Severe convective storms phenomena occurrence during the warm half of the year in Bulgaria (1961–2006). *Atmos. Res.* 93: 498–505.

Sonnadara U., Cooray V. & Götschl T. 2006. Characteristics of cloud-to-ground lightning flashes over Sweden. *Phys. Scripta* 74: 541–548.

Štěpánek P. 2008. *AnClim — software for time series analysis*. Deptartment of Geography, Faculty of Natural Sciences, MU, Brno.

Tomás C., Pablo F. & Soriano L.R. 2004. Circulation weather types and cloud-to-ground flash density over Iberian Peninsula. *Int. J. Climatol.* 24: 109–123.

Trigo R.M. & DaCamara, C.C. 2000. Circulation weather types and their influence on the precipitation regime in Portugal. *Int. J. Climatol.* 20: 1559–1581.

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

Wei J., Liu M., Zhang B. & Yu J. 2011. Analysis of the trends of thunderstorms in 1951–2007 in Jiangsu province. *J. Trop. Meteorol.* 17: 58–63.

Williams E. 2005. Lightning and climate: a review. *Atmos. Res.* 76: 272–287.

Zhang X. & Pei H. 2011. The characteristics and variation trends of temporal and spatial distribution of thunderstorms in the area of Linyi. In: *Proceedings of the International Conference on Information Science and Technology,* March 26–28, 2011, Nanjing, Jiangsu, China, pp. 652–656.