Thunderstorms caused by southern cyclones in Estonia

Kaupo Mändla, Sven-Erik Enno and Mait Sepp

Department of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia; kaupo.mandla@ut.ee

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Abstract. The relationships between the frequency and duration of thunderstorms, lightning and southern cyclones over Estonia are presented for the period 1950–2010. A total of 545 southern cyclones and 2106 thunderstorm days were detected, whereas 11.3% of the observed thunder days were associated with southern cyclones. At the same time, 29.2% of all southern cyclones were accompanied by thunderstorms. In the thunder season, however, this percentage was much higher, reaching up to 80% in summer months. The number of thunder days was largest when the centres of southern cyclones passed a measuring station at a distance less than 500 km. The number of cloud-to-ground lightning strikes related to southern cyclones was larger than that of any other thunder events. The results of our study demonstrate that the intensity of thunderstorms related to southern cyclones is higher than that of other thunderstorms. Correlation analysis revealed statistically significant relationships between the frequency of thunder days related to southern cyclones and the frequency of southern cyclones, also between the frequency of thunder days related to southern cyclones and days of other thunder events.

Key words: southern cyclone, thunderstorm, cyclone frequency, duration of thunderstorm, Estonia.

INTRODUCTION

Climate in Estonia is largely determined by intense cyclonic activity. Alternation of air masses makes weather conditions very changeable (Jaagus 2006). Most of the low pressure systems influencing Estonia are formed over the Atlantic Ocean. In addition to the so-called western cyclones, weather in northern Europe is also affected by southern cyclones (hereafter SC) that form over the Mediterranean, Black Sea and Caspian Sea regions, and move northwards. Southern cyclones constitute 9–13% of all cyclones that affect weather conditions in Estonia (Kannes et al. 1957; Linno 1982; Sepp et al. 2005).

The advection of subtropical air to higher latitudes takes place on the eastern edge of an SC, while the advection of cold air from higher latitudes occurs in the western part of the cyclone. As a result, an SC often generates distinct differences in air temperature and may cause dangerous weather phenomena, such as powerful thunderstorms, squalls, heavy precipitation, hail, flash floods and even destructive tornadoes (Kannes et al. 1957; Bielec-Bakowska 2003; Bukantis & Bartkeviciene 2005; Sepp et al. 2005; Bocheva et al. 2007; Apostol 2008; Jaagus et al. 2010).

Southern cyclones are rather infrequent in Estonia, on average about nine cases a year (Mändla et al. 2012). At the same time, SCs play an important role in the formation of extreme and dangerous weather events (Merilain & Tooming 2003). For example, a significant part of extreme precipitation events in Estonia is related to SCs (Mätlik & Post 2008). On 15 July 2000, an SC-related tornado killed one person and damaged several buildings in Rakvere. On 12 August 2005, a tornado appeared in Maardu, uprooting trees and destroying roofs and windows (Kallis 2012). On 23 November 2008, an SC brought a powerful snowstorm all over Estonia. The maximum snow depth was more than 50 cm and many roads were blocked by heavy snowfall. A very low sea level pressure, 953.1 hPa, was registered in Mustvee (Kamenik 2008).

Thunderstorms and lightning are the most common SC-related weather phenomena, which may cause losses in human lives and property. Usually they are most severe along the fronts, where the humidity and temperature contrasts and rising air facilitate the emergence of powerful convection. In this regard SCs provide particularly good conditions for the emergence of powerful thunderstorms. Several examples can be found in history, where SC-related thunderstorms lasted for a considerably long time. The duration of SC-related thunderstorms registered at the Pärnu and Võru stations in summer 1972 was more than 7 h. Similar thunderstorms, lasting more than 9 h, occurred on Vilsandi Island in 1970 and 1972.

The presented material leads to a question whether the thunderstorms associated to SCs are in general more severe than others, and can any long-term changes in thunder activity be examined on the background of climate change. During previous decades, different tendencies have been noticed in the frequency of SCs and thunderstorms. On the one hand, the frequency of SCs has not changed significantly (Mändla et al. 2012), but the number of severe thunderstorms over Europe has increased in the last decade (e.g. Dotzek et al. 2009). On the other hand, the number of thunders over the eastern Baltic region has decreased during the last half of the 20th century (Enno 2011; Enno et al. 2013). Several studies have reported severe thunderstorms and lightnings accompanied by SC-related advection of warm and humid tropical air (Kolendowicz 1998, 2006, 2012; Bielec-Bakowska 2003; Tuomi & Mäkelä 2008) or by cold fronts (Horvath et al. 2008), but no frequency analyses and associated comparisons have yet been performed.

The objectives of this study are

(a) to analyse the frequency and duration of the thunderstorms caused by SCs in comparison with the frequency and duration of thunderstorms not related to SCs;
(b) to analyse long-term changes in the characteristics of SC-related thunderstorms and changes in the proportion of SC-related thunderstorms to other thunderstorms during 1950–2010;
(c) to compare the lightning intensity of SC-related thunderstorms with the lightning intensity of thunderstorms not related to SCs.

DATA AND METHODS

The database of cyclones (Gulev et al. 2001) contains the cyclone-tracking output from the NCEP/NCAR reanalysis (Kalnay et al. 1996) of sea level pressure fields with six-hourly temporal and 2.5° × 2.5° spatial resolution. The database was composed for the period 1950–2010 using the software developed by Grigoriev et al. (2000). Cyclones are described by their geographical coordinates (with an accuracy of 0.1°) and sea level pressure in their centres. The database includes cyclones with the duration of at least 24 h.

From the viewpoint of Estonia, an SC is defined as a low which has formed south of 47°N, east of the 0° meridian, west of 60°E, and has entered into the circle with a radius of 1000 km (hereafter circle-1K) centred at 58.75° and 25.5°E (Fig. 1; Mändla et al. 2012). These cyclones are formed in the Mediterranean, Black and Caspian Sea regions. The 0° meridian was used to eliminate western cyclones formed over the Atlantic. The SCs are divided into two classes depending on their trajectories. The western class (WSC) includes the cyclones passing Estonia (25°E) from the west. The eastern class (ESC) contains the cyclones passing 25°E from the east (Mändla et al. 2012). The WSCs are supposed to bring warmer air and the ESCs to cause colder air advection in Estonia. The reliability of the data and cyclone counting methods were discussed in detail by Mändla et al. (2012).

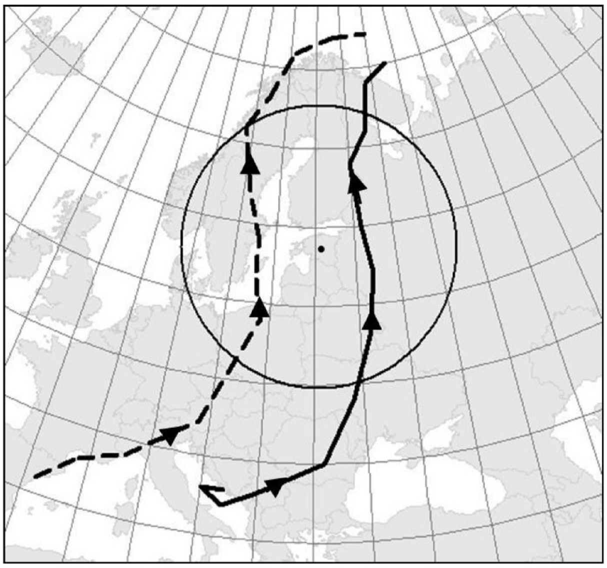

Fig. 1. Map of Europe showing the circle of 1000 km radius with its centre in Estonia at 58.75°N and 25.5°E, and the example trajectories of the two classes of southern cyclones: from south to northwest of Estonia (19–20 August 1948, dashed line) and from south to northeast of Estonia (28 January–1 February 2004, solid line).

Visual observations of thunderstorms were carried out at five Estonian meteorological stations during 1950–2010. The stations (Fig. 2) are located in different climatic conditions: maritime (Vilsandi), coastal (Tallinn, Pärnu) and continental (Tartu, Võru). The used time series of thunderstorms are the longest in Estonia (Enno et al. 2013).

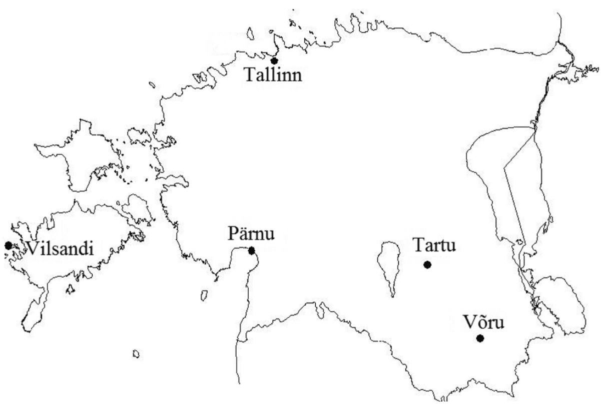

Fig. 2. Location of the five meteorological stations discussed in the text.

The thunderstorm data were obtained from the Estonian Meteorological and Hydrological Institute (EMHI). Visual data records contain the starting and ending times of all registered thunderstorms. The start of a thunderstorm is registered when the observer hears the first sound of thunder. The end of a thunderstorm (thunder event) is recorded 15 min after the last clap of thunder is heard by the observer. The quality of visual thunderstorm observations was discussed by Reap & Orville (1990) and Enno et al. (2013).

For a more detailed analysis, a 500 km-radius circle was generated around each meteorological station. The SCs were additionally divided into groups depending on the minimum distance (0–500 km and 500–1000 km) of their centres from the particular station. For each SC in these groups it was established whether it passed the station from the western or eastern side.

To determine the relationships between thunderstorms and SCs, a list of the dates of SCs in the circle-1K was compared with the thunderstorm data from the five stations. If a thunderstorm was observed at least at one station on a given day, this day was considered as a thunderstorm day (TD). If an SC was detected in the circle-1K on a TD, it was considered that the thunderstorm had been induced by the SC (from now on SCTD). One SC may cause TDs in several subsequent days because an SC can stay in the circle for more than one day (on average, for 44 h; Mändla et al. 2012). The SCs that were associated with thunder are defined as thunder-related SCs.

All these events were analysed on an annual and monthly basis. Special attention was paid to the so-called thunder season from April to October when approximately 99% of all thunderstorms in Estonia have been observed (Enno 2011). The frequency of SCTDs and the duration of all thunderstorms were calculated separately for each station.

In order to analyse long-term trends in thunderstorms induced by SCs, it was first checked whether the distribution of a particular variable can be approximated with a normal distribution. A reasonable match with a normal distribution was assumed when the test value W of the Shapiro–Wilk test (Shapiro et al. 1968) was higher than 0.05. In such cases a linear regression analysis with Student's t-test was used. Trends were considered statistically significant if $p \leq 0.05$. The Mann–Kendall test was used in case of non-normal distribution (Mann 1945; Kendall 1975). A trend was regarded as statistically significant when the Mann–Kendall statistic $MK \geq 1.96$. In case of non-normal distribution, the slope was calculated using Sen's method (Sen 1968). Changes in the trend were found by multiplying the slopes with the number of years (61). The non-parametric Mann–Whitney U test (Mann & Whitney 1947) was used to evaluate the significance of the difference between the parameters of the SC-related thunder events and the parameters of other thunder events. When the test value was <0.05, the difference was considered as statistically significant.

Correlation analysis was performed to understand better the processes and relationships between the time series of SC-related thunderstorms and other thunder events. The automatically registered lightning database that originates from the NORDLIS lightning detection network was obtained from the EMHI (Enno 2011). It contains a total of 361 688 cloud-to-ground flashes registered during 2005–2010.

The dates of SCs located within the circle-1K were compared with the data of lightning strikes in Estonia. If a lightning was observed by the NORDLIS network in Estonia on the same day when an SC was in this circle, this event was noted as a lightning caused by the SC. For comparison, we calculated daily mean counts and percentiles of cloud-to-ground lightning strikes for SCTD and for other thunder events during 2005–2010.

FREQUENCY OF SOUTHERN CYCLONES RELATED TO THUNDERSTORMS

A total of 545 SCs were detected within the circle-1K during 1950–2010. It was found that 159 of them (29.2%) had induced a thunderstorm in Estonia. This number represents cases when an SC was detected in the circle-1K and a thunderstorm was observed at least at one station in Estonia on the same day.

All together 2106 TDs occurred during the study period, 239 of which (11.3%) were SCTDs. On 107 days, SC-related thunder was observed at only one station. On 13 days, thunder appeared at all five stations. The mean annual number of SCTDs was 3.9. A well-defined peak is visible in 1972 (Fig. 3), mainly reflecting a high number of SC-related thunder events that were registered in Võru.

The mean number of TDs without SCs was 30.6 per year, when thunder was detected at least at one station. At single stations, this number was significantly lower. The lowest mean annual numbers of TDs without SCs of the study period were recorded at the coastal station of Tallinn (14.0) and at the maritime station of Vilsandi (14.5). The highest average annual numbers were observed at the continental stations of Tartu (20.3) and Võru (19.6).

The numbers of SCTDs were largest at the Tartu and Võru stations, 116 and 153, respectively. The number of SCTDs during the whole study period, averaged by five stations, was 108.2 (Table 1), comprising 9.4% of the mean of all TDs registered during 1950–2010. This proportion was highest in Võru (11.3%) where the probability of thunderstorm appearance was relatively

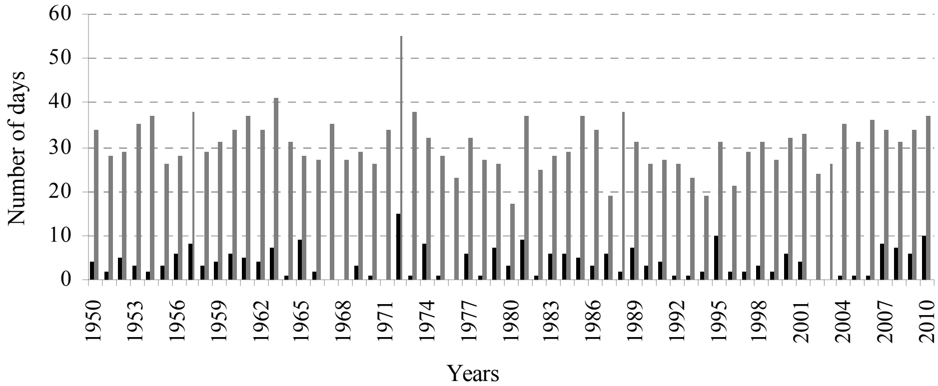

Fig. 3. Number of days with a southern cyclone (black) and other events (grey) in the circle-1K around Estonia, which were associated with thunderstorms in 1950–2010.

Table 1. Numbers of thunder days grouped by stations and by trajectories: cyclones moving from south to north and passing Estonia from the west (W) and east (E) in distance intervals 0–500 km and 500–1000 km during 1950–2010. SCTD – thunder days related to southern cyclones

Station	Other thunder days	SCTD	500–1000 km W	0–500 km W	0–500 km E	500–1000 km E
Pärnu	1023	97	11	30	46	10
Tallinn	853	93	17	35	29	12
Tartu	1237	116	22	51	34	9
Võru	1195	153	26	73	48	6
Vilsandi	887	82	10	26	34	12
Mean	1039	108.2	17.2	43	38.2	9.8

high and the number of detected SCTDs was also higher than at other stations. The proportion of SCTDs (8.4%) was lowest in Vilsandi where the probability of thunderstorm appearance was relatively low and the number of detected SCTDs was the lowest. During the 61-year period, no significant changes were detected in the proportion between SCTDs and other TDs.

In more than 2/3 of the SCTDs cases, the centres of SCs were closer to the stations than 500 km. The number of WSCs among these SCs was slightly larger than that of ESCs. Most of the thunderstorm-inducing SCs that stayed at a distance of 500–1000 km passed Estonia from the west (Table 1). The total number of SCs closer to the stations than 500 km was 185, and the number of SCs within a distance of 500–1000 km was 360.

During the thunder season from April to October, 40.6% of SCs were related to thunder. As expected, the monthly distribution of SCTDs (Fig. 4) demonstrates a sharp maximum in summer. The highest counts (61 SCTDs per 61 years) were recorded in July. Similarly high numbers of SCTDs were detected in other summer months as well – 60 in August and 54 in June. It means that in summer months, more than 2/3 (70.3%), in August even 82.5%, of all the SCs induced thunder. Outside the thunder season, SCTDs appeared only on three days.

A significant decrease in the frequency of SCTDs ($p < 0.05$) by 0.9 days occurred in August during 1950–2010. Increasing trends for the ESCs approaching nearer than 500 km to the station were recorded in Tartu and Võru (Table 2).

Correlation analysis showed statistically significant ($p < 0.01$) relationships between the frequencies of SCTDs and other TDs over the stations ($r = 0.47$). As expected, there is also a high correlation ($p < 0.01$) between the total number of SCs and the number of thunder-related SCs ($r = 0.53$), the total number of SCs and SCTDs ($r = 0.44$) and, of course, between SCTDs and the number of thunder-related SCs ($r = 0.82$).

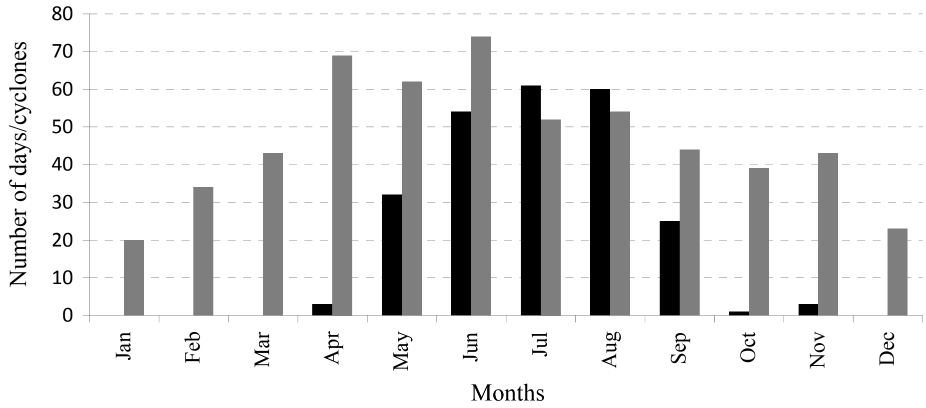

Fig. 4. Monthly numbers of thunder days associated with southern cyclones (black) having caused a thunder at least at one station and the number of southern cyclones (grey) in 1950–2010.

Table 2. Total number and annual total duration (hours) of thunderstorms related to SCs grouped by stations and by cyclone trajectories: passing Estonia from the west (W) and east (E) in distance intervals 0–500 km and 500–1000 km, and their changes by trend during 1950–2010. Statistically significant trends are marked in boldface

Station	Cyclone passing distance and direction from the station	Total number	Change by trend, No.	Annual total duration	Change by trend, h
Pärnu	500–1000 km W	9	−0.3	2.1	−0.4
	0–500 km W	30	0.2	3.3	0.7
	500–1000 km E	6	−0.1	1.2	−0.5
	0–500 km E	38	0.1	3.8	−0.7
Tallinn	500–1000 km W	11	−0.3	1.3	**1.7**
	0–500 km W	25	0.2	3.8	1.1
	500–1000 km E	9	0.0	1.3	−0.1
	0–500 km E	28	0.1	3.9	−0.4
Tartu	500–1000 km W	13	−0.1	4.1	−1.5
	0–500 km W	33	−0.2	2.7	0.6
	500–1000 km E	4	0.2	1.3	−0.7
	0–500 km E	23	**0.6**	3.1	−0.3
Võru	500–1000 km W	17	−0.4	3.1	−0.7
	0–500 km W	42	−0.1	3.3	0.5
	500–1000 km E	4	0.1	0.9	−0.8
	0–500 km E	29	**0.8**	4.0	0.7
Vilsandi	500–1000 km W	8	−0.2	2.3	−0.5
	0–500 km W	19	0.1	3.4	0.2
	500–1000 km E	11	−0.2	2.6	−0.9
	0–500 km E	29	0.4	4.5	−0.1
Mean	500–1000 km W	11.6	−0.2	2.6	−0.3
	0–500 km W	29.8	0.1	3.3	0.6
	500–1000 km E	6.8	0.0	1.5	−0.6
	0–500 km E	29.4	0.3	3.9	−0.2

DURATION OF THUNDERSTORMS ASSOCIATED WITH SOUTHERN CYCLONES

The total duration of thunder events in 1950–2010, averaged by the five stations, was 2088.6 h, while the average duration of thunderstorms related to SCs was 195.0 h (9.3% of the summary duration). This percentage was in the range of 8–12% for coastal and inland stations but only 3% for the maritime Vilsandi station. The annual mean durations of SC-related and other thunder events averaged by the five stations were 3.2 and 31.1 h, respectively (Fig. 5). The highest mean duration of SC-related thunder events was in 1972. At the same time, there were many years with no thunder-related SCs.

The mean durations of SC-related thunder events are generally higher than those of other thunder events at all stations, with the exception of Võru (Table 3). It is remarkable that the mean duration of thunderstorms in Vilsandi is clearly longer than at other stations. According to the Mann–Whitney U test, the difference in durations of SC-related and other thunder events was not significant at all stations.

As a rule, thunderstorms lasted longer when the central point of an SC passed Estonia at a distance less than 500 km. In the case of ESCs at a distance closer than 500 km of a station, the duration of thunderstorms was mostly longer than with WSCs. On the other hand, thunderstorms associated with WSCs tend to be more persistent in case of SCs that occur farther than 500 km from a station. The mean duration of thunderstorms did not vary much among the stations. The longest mean annual sum of durations, 4.5 h, was obtained for the Vilsandi station for the ESCs in the distance interval 0–500 km (Table 2). The longest SC-related thunderstorms were observed in Vilsandi on 1 July 1970 (9 h 12 min,

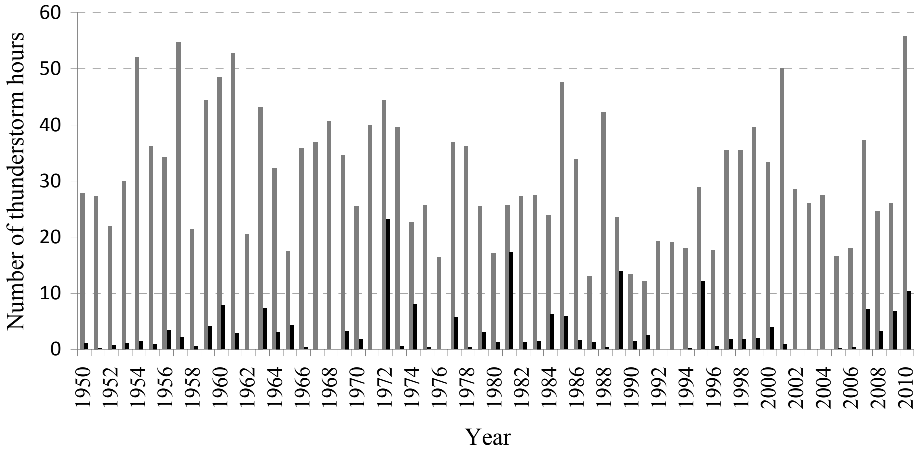

Fig. 5. Five-station mean duration of thunderstorms related to (black line) and not related to (grey line) southern cyclones in Estonia in 1950–2010.

Table 3. Average duration and change by trend of other thunder events and southern cyclones-associated thunderstorms at five meteorological stations in Estonia during 1950–2010. Significant changes are marked in boldface

Station	Mean duration of other thunder events, h	Change by trend, h	Mean duration associated with SCs, h	Change by trend, h
Pärnu	2.0	**−0.98**	2.1	−0.86
Tallinn	1.8	**0.53**	2.0	0.42
Tartu	1.9	**−0.47**	2.1	−0.85
Võru	2.1	**−0.64**	2.0	0.21
Vilsandi	2.4	**0.81**	2.5	0.28
Mean	2.0	−0.15	2.1	−0.16

WSC) and on 27 August 1972 (9 h 6 min, ESC). A very long thunderstorm occurred in Pärnu on 25 July 1960 (7 h 54 min, WSC). Long thunderstorms (>7 h) were also detected in Pärnu and Võru in summer 1972.

The longest thunderstorm events both caused and not caused by SCs were detected in June and July. From May to August, the mean duration of the SC-related thunder events was higher than that of other thunder events, but it was slightly lower in September and much lower in April (Fig. 6). Few very short thunder events occurred in October, but the longer thunderstorm duration in November associated with SCs was caused by the appearance of two thunder events in Vilsandi on 19 November 1977. Relatively longer SC-related thunderstorms have been observed in Vilsandi in August in

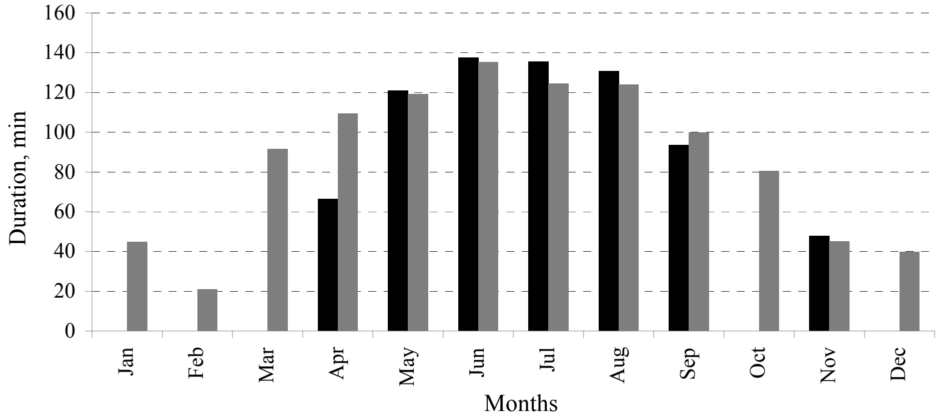

Fig. 6. Mean monthly duration of thunder events in case of southern cyclones (black) and in other thunder events (grey) in 1950–2010.

comparison with the other stations in the same month. The duration of thunderstorms in August constitutes 31.9% of the annual duration in Vilsandi, while at the other stations, this is only 21.2–26.2%. By months, the ratio of total durations between the SC-related thunder events and other thunder events was the highest from May to August. The peak was in May (10.6%) and June (11.1%) and after that, the ratio of monthly thunderstorm duration started to decrease from month to month.

There were no statistically significant changes in the mean annual as well as in the monthly durations of thunderstorms caused by SCs during 1950–2010 (Fig. 5). A significant increasing trend by 1.7 h in the duration of SC-related thunderstorms was registered in Tallinn in case of WSCs at the distance interval 500–1000 km. For other thunder events not related to SCs, a decreasing trend in mean duration was detected at the Pärnu, Tartu and Võru stations, and an increasing trend in Tallinn and Vilsandi (Table 3). For the duration of SC-induced thunderstorms, some maximum years were revealed. During the years 1972, 1974, 1981, 1989 and 1995 approximately 30–40% of the annual duration of thunderstorms was associated with SCs (Fig. 5). However, in many years (around 1960, in the mid-1980s and around 2000) the annual number of thunderstorm hours was high but they were not related to SCs. No statistically significant correlation has been found between the time series of mean duration of SC-related thunder events and mean duration of other thunder events.

RELATIONSHIPS BETWEEN SOUTHERN CYCLONES AND LIGHTNING

Comparing the data from the NORDLIS lightning detection network (686 days) with the occurrence of SCs (62 days) in the 1000 km circle during 2005–2010, we found that much higher lightning counts were registered on SC-related TDs than on TDs not related to SCs. The average count of SC-related lightning strikes was 1481 per TD. Regarding other thunder events, it was only 433 cloud-to-ground lightning strikes per day. Therefore, thunderstorms associated with SCs caused about three times higher lightning counts than other thunder events. The frequency of lightning strikes was very variable during the six study years. The numbers of cloud-to-ground lightning strikes caused by SCs were much higher in 2007, 2009 and 2010. In 2009, the number of SC-induced lightning strikes was almost ten times higher than that of the lightning strikes initiated by other thunder events (Fig. 7).

The Mann–Whitney U test showed that the difference in the number of lightning strikes in thunder events under the influence of SCs and other thunder events is statistically significant ($p < 0.05$). Percentiles of lightning strikes induced by SCs are much higher (Table 4),

Table 4. Percentiles of lightning strikes induced by southern cyclones and by other thunder events during 2005–2010

Percentile	Lightning strikes by SCs	Lightning strikes by other thunder events
10	1	1
20	2	2
30	5.3	4
40	29.6	8
50	91.5	22
60	200.6	57
70	510.5	130.4
80	1 872.4	312.6
90	6 273.3	939.6
95	7 912.2	1 959.8
99	11 702.0	7 449.3

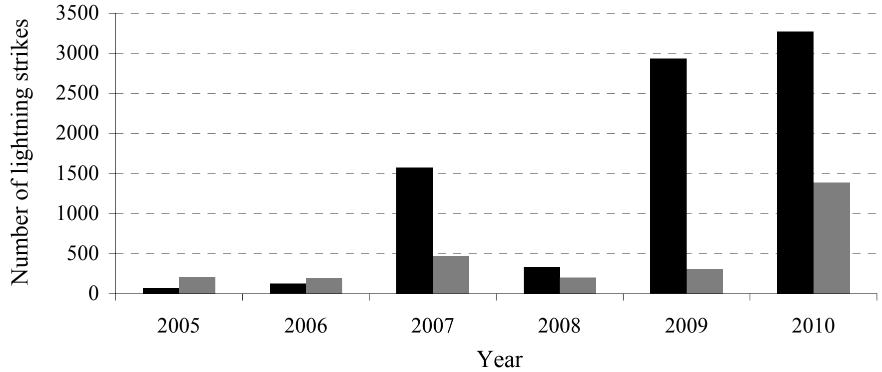

Fig. 7. Mean number of lightning strikes per day in southern cyclones (black) and in other thunder events (grey) in 2005–2010.

especially the 80th, 90th and 95th percentiles of SC-induced thunderstorms, which are 4–6 times higher compared to the other types of thunder events. The NORDLIS data revealed that the maximum number of lightning strikes per day is also higher in case of thunderstorms caused by SCs.

DISCUSSION

We assumed that a proportionally large part of thunderstorms is associated with SCs. According to previous studies, SCs constitute 9–13% of all cyclones that have affected weather conditions in Estonia (Kannes et al. 1957; Linno 1982; Sepp et al. 2005; Link & Post 2007). Our analysis revealed that SCs have caused about 9–10% of all thunder events over Estonia. It is approximately the same proportion that SCs constitute in the total number of cyclones affecting Estonia. Similar proportions were observed in case of SCTDs when thunder was registered at least at one station. However, it must be noticed that in case of the other TDs, we cannot determine which of them are caused by cyclones and which are the so-called air-mass thunderstorms. In principle, if we eliminate the part of air-mass thunders, which are certainly not related to cyclones, the proportion of SC-related thunder events will be much higher than the above-mentioned 10%.

In general, no significant changes occur in the SCTD frequency time series. This result is in line with the frequency of SCs (Mändla et al. 2012), but contradicts the essential decreasing trend of thunder events (Enno et al. 2013).

Correlation analysis revealed statistically significant relationships between the frequencies of SCs and SCTDs, as well as between the frequencies of TDs related to SCs and other TDs. Warm weather in summer is directly related to the influence of SCs that carry the tropical air to high latitudes. This causes unstable air stratification that is favourable for the intense convection, for the formation of cumulonimbus clouds and thunderstorms.

The highest thunderstorm activity in Estonia was detected in summer months (Enno 2011) when also the number of SCs was largest (Mändla et al. 2012). As expected, the highest number of days with SC-caused thunderstorms occurred in summer, especially in August, when about 4/5 of all SCs caused thunderstorms. The only statistically significant trend of SCTDs was detected in August. Its decrease may be related to the decrease in the number of TDs during the second half of the 20th century (Enno et al. 2013). No respective changes were recorded either in the number of SCs (Kaznacheeva & Shuvalov 2012; Mändla et al. 2012) or in the cyclonic activity over the Mediterranean (Trigo et al. 1999; Kaznacheeva & Shuvalov 2012).

Two thirds of SC-induced thunderstorms were observed when an SC moved at a distance up to 500 km from the station. However, it should be noticed that the majority of SCs pass Estonia at a greater distance than 500 km. A large part of cyclones which move farther than 500 km do not induce thunder in Estonia, probably because the frontal zones of these cyclones are located too far away. At a distance up to 500 km, there were more SCTDs in case of WSCs than in case of ESCs. For ESCs, the mean duration of thunderstorms was longer in the distance interval 0–500 km from the station, while for WSCs, it was longer in the distance interval 500–1000 km. In case of a WSC, Estonia is affected by the warm sector of the cyclone containing much convective energy that causes stronger and longer thunderstorms.

The mean annual duration of SC-related thunder events at different stations was around 3 h, which constitutes only about 10% of the yearly duration of all thunder events. However, SCs are capable of generating very long-lasting thunder events. The maximum total duration of SC-related thunder events was registered in July. As these thunder events were very rare (on average, 2–4 events per year), the monthly total durations were strongly affected by solitary cases when a thunderstorm lasted for several hours. Still, we can state that thunder events caused by SCs tend to last longer in July than, for example, in August when there is the maximum of SCTDs.

No essential differences occur in the variables of thunderstorms between the Pärnu, Tallinn and Tartu stations, while Võru and Vilsandi stand out among other stations. The highest annual number of TDs, as well as of SCTDs, and their highest annual duration were registered at the Võru station, situated in southeastern Estonia in a primeval valley between the Haanja and Otepää uplands. The lowest numbers of SCTDs, but the longest thunder events, especially in August, were found at the Vilsandi station, located on the western coast of the West Estonian Archipelago. In general, the stations with more thunder also record more SCTDs. The results of this study are in line with those presented by Enno et al. (2013) where the highest number of TDs was detected at the continental stations in July and at the coastal and maritime stations in August.

It was assumed that the thunderstorms associated with SCs are more intense than other thunderstorms in Estonia. The data from the NORDLIS lightning detection network confirm this hypothesis. Our analysis showed that despite very short time series, thunderstorms related to SCs clearly have much more lightning strikes than the other thunder events. The mean number of SC-related lightning strikes per TD was about 3–4 times higher. The SC-related lightning counts per TD were much higher in most of the analysed years. In 2009, this difference was even more than ten times in favour of SCs. The percentiles of lightning strikes caused by SCs were many times higher than those of other thunder events, especially in case of higher values. The maximum count of lightning strikes per day was also produced by an SC. Some other studies have also reported about severe thunderstorms and lightnings accompanied by SC-related advection of warm and humid tropical air (Kolendowicz 1998, 2006, 2012; Bielec-Bakowska 2003; Tuomi & Mäkelä 2008).

CONCLUSIONS

We assumed that (i) SCs bring relatively more thunder, (ii) these thunderstorms are more persistent and (iii) they produce a higher number of lightning strikes. We were also interested in any changes in the time series of thunder events related to SCs. In addition, a correlation analysis was performed to understand basic relationships between the different parameters of thunder activity and SCs.

Our analysis shows that, in general, the frequency of thunderstorms caused by SCs is approximately the same as the appearance of SCs compared to all cyclones (ca 10%). However, as the data of thunder events contain also air-mass thunderstorms, we can argue that SCs are responsible for relatively more thunder than cyclones approaching Estonia from other directions. The thunderstorms related to SCs tend to last somewhat longer than other thunder events. However, it should be noticed that as SC-related thunderstorms occur relatively infrequently, the statistics of their duration are heavily affected by some extremely long (>7 h) events. Despite the short time series of the NORDLIS lightning detection network, we can conclude that SC-related thunder events are indeed more severe than others. This means that the thunderstorms associated with SCs cause about three times (up to ten times in 2009) higher lightning counts than other thunder events.

Virtually no changes were recorded in the time series of SC-related and other thunderstorms. The only substantial trend occurred in the frequency of SCTDs in August. This decreasing trend can be associated with a general decreasing tendency in the number of TDs during the second half of the 20th century.

Our analysis revealed some regional variations in the thunder data at five meteorological stations that were used in the study. A distinct difference occurred between the Võru (located in a valley between the uplands in southeastern Estonia) and Vilsandi (maritime station) data. The correlation analysis shows that SC-related thunderstorms not only depend on the frequency of SCs, but are also positively correlated with the frequency of other thunder events. This result suggests that the climatology of thunderstorms is quite complex and versatile.

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Seosed lõunatsüklonite ja äikese vahel Eestis

Kaupo Mändla, Sven-Erik Enno ja Mait Sepp

On käsitletud lõunatsüklonite ja äikese esinemissagedust, kestust, välkude esinemist ning nende parameetrite omavahelisi seoseid Eestis perioodil 1950–2010. Äikese andmestik on pärit Eesti Meteoroloogia ja Hüdroloogia Instituudi viiest meteoroloogiajaamast. Lõunatsüklonid filtreeriti välja põhjapoolkera tsüklonite andmebaasist. Lõunatsükloniks nimetame madalrõhkkonda, mis tekkis lõuna pool 47° põhjalaiust, nullmeridiaanist ida pool ja lääne pool 60° idapikkust ning sisenes oma teekonnal 1000 km raadiusega ringi, mille kese asub Eestis. Arvestati, et kõik need madalrõhkkonnad mõjutasid Eesti ilmastikku.

Vaatlusalusel perioodil esines 545 lõunatsüklonit ja keskmiselt 2106 äikesepäeva, millest lõunatsüklonitega oli seotud 239 (11,3%). Samas olid 29,2% lõunatsüklonitest seotud äikesega Eesti territooriumil, kusjuures 40,6% lõunatsüklonitest põhjustasid äikest nn äikesehooajal aprillist oktoobrini. Kõrgeimat äikese aktiivsust täheldati suvekuudel, kui 60–80% lõunatsüklonitest tõid endaga äikest kaasa. Vaid 3 päeva kõigist lõunatsüklonite põhjustatud äikesepäevadest esines väljaspool äikesehooaega.

Aasta keskmine lõunatsüklonitega seotud äikeste arv on suurenenud Tartus ja Võrus lõunatsüklonite puhul, mis möödusid Eestist idast lähemal kui 500 km. Muutus oli vastavalt 0,6 ja 0,8 tsüklonit uuritava perioodi kohta. Lõunatsüklonite korral, mis möödusid Tallinna vaatlusjaamast lääne poolt kaugemal kui 500 km, suurenes äikese kestus 1,7 tunni võrra. Võrreldes äikestega, mis möödusid jaamast kaugemalt kui 500 km, esines tunduvalt suurem arv äikesepäevi olukorras, kus lõunatsüklon möödus jaamast lähemalt kui 500 km. Lõunatsüklonitega kaasnes keskmiselt üle kolme korra rohkem pilv-maa-välkusid kui teistel juhtudel. Enamikul uuritavatest aastatest põhjustasid lõunatsüklonid äikesepäeval enam välku kui ülejäänud äikesejuhtumid.