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Climatology of cyclones with a southern origin, and their influence on air temperature and precipitation in Estonia

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Cyclones with a southern origin that passed over Estonia between 1948 and 2004 were analysed in terms of their frequency, duration, and sea-level pressure. Long-term changes in these characteristics, and the influence of these cyclones on surface air temperature and precipitation, were analysed. For the purposes of this study, "southern cyclones" were defined to be the ones that formed south of 47°N and east of the 0° meridian, and entered a circle of 1000-km radius centred in Estonia. These events, which were obtained from a database of cyclones, were considered to have had an effect on weather conditions in Estonia. Although few trends were statistically significant, southern cyclones were in general found to weaken over the period studied. The number and duration of southern cyclones decreased over the period, and sea-level pressure increased. Southern cyclones induced an increase in temperature if they pass over Estonia from the west, and a decrease in temperature if they pass over Estonia from the east. On average 10% of annual precipitation in Estonia was related to cyclones with a southern origin.

Introduction

Local climate and its variability are highly dependent on atmospheric circulation. Usually, an intense zonal circulation over northern and central Europe causes higher temperatures in winter and lower temperatures in summer (Kożuchowski 1993, Hurrell 1995, Jacobeit *et al*. 2001). The opposite is true in the case of meridional circulation formed by a blocking anticyclone over central or eastern Europe (Kożuchowski and Marciniak 1988, Keevallik *et al*. 1999, Post *et al*. 2002, Sepp and Jaagus 2002, Cahynová and Huth 2009, Jones and Lister 2009).

Intense cyclonic activity induces active mixing of air masses with different origins, and is a very typical element of atmospheric circulation in the temperate zone. The majority of extratropical cyclones that affect Europe form over the North Atlantic. The climatology of cyclones in the northern hemisphere has undergone thorough analysis (Gulev *et al*. 2001, McCabe *et al*. 2001, Chang and Fu 2002, Raible *et al*. 2008), including numerous studies of changes in cyclonic activity in the Arctic Basin (e.g. Zhang *et al*. 2004, Serreze and Barrett 2008, Sorteberg and Walsh 2008, Sepp and Jaagus 2011). Several authors also analysed changes in cyclonic activity over Europe (e.g. Alexandersson *et al*. 1998, Sepp *et al*. 2005, Bartholy *et al*. 2006, Sepp 2009). Most of these authors reported a considerable increase in cyclonic activity over the North Atlantic and European regions, especially over northern Europe, during the second half of the 20th century.

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Recent climate warming in both temperate and polar regions is closely related to changes in cyclonic activity and cyclone tracks. Higher winter temperatures are related to the change in cyclone trajectories that have shifted towards higher latitudes (Sepp *et al*. 2005). Wang *et al*. (2006) stated that the mean winter storm track over the North Atlantic has moved northwards by about 180 km during the last half-century. This migration has led to the advection of a greater amount of relatively warm maritime air into northern Europe.

In addition to the influence of the western cyclones, weather conditions in northern Europe are also affected by cyclones formed in the Mediterranean, Black Sea, and Caspian Sea regions that generally move northwards. In this study, these cyclones (1) with a southern origin, and (2) that move significantly northwards, are defined as "southern cyclones". Van Bebber (1891) classified this kind of cyclone trajectory as Vb. They cause an advection of tropical air into the higher latitudes and of arctic air into the lower latitudes. As a result, southern cyclones induce sharp contrasts in air temperature between the warm and cold air masses that can reach up to 15 °C. They cause severe weather events, such as heavy rainfall, flash floods, gusts of wind, thunderstorms, hail, and tornadoes.

Southern cyclones affect both local weather conditions (Bukantis and Bartkeviciene 2005, Jaagus *et al*. 2010), and also the generation of local extreme weather events (Mätlik and Post 2008, Isayev and Sherstyukov 2008). For example, the heaviest rainfall events in southern Poland are caused by southern cyclones (Twardosz and Niedźwiedź 2001, Niedźwiedź 2003). Southern cyclones have also been mentioned within the context of atmospheric chemistry (Uranova 1980, Surkova *et al*. 2010).

The climatologies of the Mediterranean and Black Sea cyclones have been well studied (e.g. Alpert *et al*. 1990, Trigo *et a*l. 1999, Maheras *et al*. 2001, Trigo *et a*l. 2002). Given that the number of cyclones that move as far north as the Baltic Sea region is small in comparison with the total number of Mediterranean cyclones, they have not been studied in detail.

Estonia is located in a climatic transition zone characterised by very high cyclonic activity. Alternation of air masses that results, makes the weather conditions very variable. Climatological studies of southern cyclones are of great importance in view of the fact that those cyclones bring the most unfavorable and dangerous weather conditions during summer (Merilain and Tooming 2003).

The first detailed investigation of southern cyclones was based on the analysis of five-year (1952–1956) synoptic maps, and showed that these cyclones comprise about 10% of all the cyclones that affect Estonia (Kannes *et al*. 1957). These authors report that the majority of northwards-moving southern cyclones are formed over the Lombardy Lowland and Genoa Bay, and that cyclones of this type are rather more frequent in spring and autumn. This finding is supported by the data provided by Belskaya (1949) that showed the highest frequencies of southern cyclones at the end of winter and beginning of spring. This is explained by the fact that it is during this period that the most remarkable contrasts in temperature are observed over southern Europe, the Mediterranean Sea, and the Black Sea. In contrast, Linno (1982) argued that southern cyclones are most common in summer. In the first half of summer, the study found that 26% of the cyclones that affect the weather in Estonia are southern cyclones, compared to only about 6% of those that occurred in winter.

The most severe extreme precipitation events in Estonia have concurred with the incidence of southern cyclones (Mätlik and Post 2008). Therefore, southern cyclones often have an important role in generating extreme weather phenomena in Estonia.

Changes in the frequency of southern cyclones were analysed by Sepp (2005) which he defined to be lows that crossed 52°N latitude from south to north, between 5°E and 50°E. The analysis showed a statistically significant decreasing trend in the annual frequency of southern cyclones that crossed over Ukraine between 1948 and 2000. This finding supports a decreasing trend in the frequency of cyclones with a western origin over Hungary and Ukraine (Domonkos 2003, Sepp 2005).

During the second half of the 20th century, the climate of the whole of northern Europe (including Estonia) warmed up significantly

(BACC Author Team 2008). This change was largely influenced by the strengthening of westerly airflow in winter (Jaagus 2006). While changes occurred in the general circulation and cyclonic activity of this region, it may also be presumed that there were changes in the regime of southern cyclones.

The aim of our study was to analyse:

- frequency and duration of southern cyclones of different types,
- mean sea-level pressure in the centre of southern cyclones,
- long-term changes in the characteristics of southern cyclones,
- influence of southern cyclones on the surface air temperature in Estonia,
- total precipitation in Estonia related to southern cyclones.

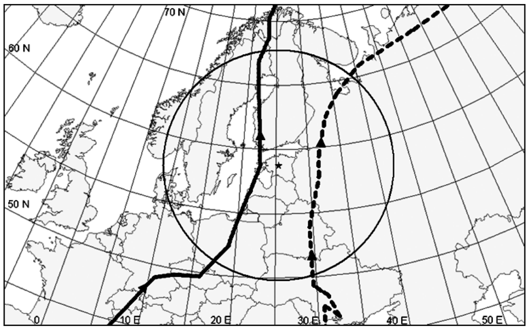

Fig. 1. Map of Europe showing the circle of 1000 km radius with its centre in Estonia at 58.75°N and 25.5°E, and example trajectories of the two classes of southern cyclones: from the south to the northwest of Estonia (19–20 August 1948, solid line), and from the south to the northeast of Estonia (15–16 August 1951, dashed line).

Data and methods

For the present study, we used the database of cyclones described by Gulev *et al*. (2001). The database consists of cyclone tracking output from six-hourly NCEP/NCAR reanalysis (Kalnay *et al*. 1996) of sea-level pressure fields with a 2.5° × 2.5° spatial resolution using software developed by Grigoriev *et al*. (2000). Cyclones are described using geographical coordinates of their centres (with an accuracy of 0.1°) and the sea-level pressure (SLP) at these points. All low pressure formations with durations of less than 24 hours were excluded from the database.

We identified all southern cyclones in the cyclone database that might have had an effect on weather conditions in Estonia during the years 1948–2004. We defined southern cyclones as lows, determined by Gulev *et al*. (2001), which had formed south of 47°N and east of the 0° meridian. The northern limit was chosen so that the region of formation of the southern cyclones lay over the Mediterranean, Black Sea, and Caspian Sea regions. The 0° meridian was used as a limit in order to eliminate all cyclones that formed over the Atlantic Ocean.

Southern cyclones were defined to be the ones that formed south of 47°N and east of the 0° meridian, and entered a circle of 1000 km radius centred in Estonia at 58.75°N and 25.5°E (Fig. 1).

Several suggestions have been made concerning the size of the circle required for statistical studies of cyclones. For example, Zolina and Gulev (2002) obtained their averages using circular cells with a radius of 555 km, as recommended by Sinclair (1994). At low latitudes, this corresponds to boxes of approximately 10° × 10°. Rudeva and Gulev (2007) analysed changes in a cyclone radius during the lifetime of a cyclone. They found that the effective average radius of cyclones in the northern hemisphere ranged from 300–400 km over the continents to more than 900 km over the oceans. Similar results were obtained by Schneidereit *et al*. (2010). Simmonds and Keay (2000) found that the mean radius of cyclones moving over 50°–70° latitude in the southern hemisphere could reach up to 6.5° during their lifetimes. Most of these studies were based on the concept of the effective radius of the cyclone (Rudeva and Gulev 2007), which is defined as the radius between the centre of a cyclone and the last closed isobar line coinciding with the maxima of kinetic energy (Schneidereit *et al*. 2010). Here, we used a classical distance of 1000 km for the detection of southern cyclones under the assumption that cyclonic activity affects weather over a large area, and has an influence on weather conditions in Estonia.

In order to describe intra-annual variability, the cyclones were divided by season into winter (DJF), spring (MAM), summer (JJA) and

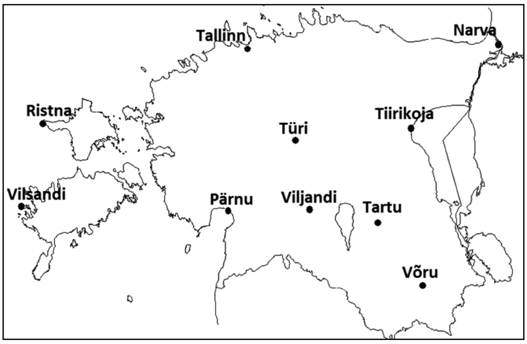

Fig. 2. Locations of the 10 meteorological stations in Estonia from which data were obtained.

autumn (SON). If cyclones occurred over two months they were included in the month of their formation. The minimum accepted duration of a cyclone in the circle with the radius of 1000 km was four six-hour observations (one day). We, therefore, considered that weather conditions in Estonia were affected when a cyclone was located in the circle for at least 24 hours.

Southern cyclones were divided into two classes according to their trajectory (Fig. 1). Class A included the cyclones that moved from south to north, passing Estonia to the west, and crossing the Baltic Sea and/or Scandinavia. Class B consisted of the cyclones that moved from south to north and passed by the eastern side of Estonia, i.e., those that moved over Russia. The border between these classes was chosen to be 25°E. We assumed that southern cyclones belonging to class A bring warmer air to Estonia from the south, and cyclones belonging to class B are associated with the advection of colder air from further north.

The main characteristics that describe southern cyclones in this study are (1) frequency and duration of the cyclones, (2) average SLP in the cyclone centre when it is located inside the 1000 km circle, and (3) SLP of a cyclone at the tracking point nearest to Estonia, i.e., nearest to the centre of the 1000 km circle. The distances between the centre of the circle and the cyclone tracking points were calculated and the tracking point with the minimum distance was determined to be the nearest point.

All the data were checked for normality using Shapiro-Wilk's test (Shapiro *et al.* 1968). As nearly all the studied time series were non-normally distributed, a Mann-Kendall test was used for the trend analysis. A trend was considered statistically significant (at $p \leq 0.05$) when the Mann-Kendall (MK) statistics was either ≥ 1.96 or ≤ -1.96 (Mann 1945, Kendall 1975). Trend slopes were calculated using Sen's method (Sen 1968). Changes were calculated by multiplying slopes by the duration of the study period (57 years).

Daily precipitation and daily mean air temperature data from 10 meteorological stations were used to study the effect of southern cyclones on weather conditions in Estonia (Fig. 2). The stations are situated in different parts of Estonia and a continuous series of measurements is available from them. We assumed that the meteorological data (air temperature and precipitation) were reliable and homogeneous for the periods analysed. The sites were chosen so that they more or less uniformly covered the territory of Estonia, and covered all the main regions where local climate variations were important.

Daily precipitation data were obtained for each day when a southern cyclone was located inside the 1000 km circle during the period 1948–2004. The average annual and seasonal precipitation related to southern cyclones was calculated for each station. The maximum 24-hour rainfall was found for each cyclone. In some cases, two southern cyclones were located within the 1000-km circle at the same time, in which case it was not possible to detect which of them had brought precipitation to Estonia, and the same daily precipitation was considered for both cyclones. As a result, there was some variation in the total values of precipitation, depending on whether the values were determined by cyclone number or by month. We counted cyclones that had caused daily precipitation above 10, 5, 2, and 0 mm, and those without any precipitation. These characteristics were calculated for all southern cyclones, and separately for cyclones of class A and B.

Analysis of the effect of southern cyclones on air temperature was rather more complicated. First, we calculated daily mean temperatures averaged over the 10 stations and 54 years (1951–2004). Next, we obtained the temperature anomalies between every day and the two previous days that a southern cyclone was observed at the tracking point nearest to Estonia. We calculated the temperature change due to a southern cyclone to be the difference between the temperature at the nearest point and the mean temperature at that point on the two previous days. Long-term variations in mean annual temperature caused by southern cyclones during 1951–2004 were analysed using the Mann-Kendall test.

Results

Seasonal regime of southern cyclones

In total, 506 lows were considered to be southern cyclones that affected the weather in Estonia between 1948 and 2004, which yielded a mean frequency of 8.9 cyclones per year. The highest frequency of southern cyclones occurred in spring and summer, with 156 and 151 cyclones respectively (Table 1). There were fewer southern cyclones in autumn, and especially in winter. The number of cyclones with a class B trajectory was about twice that of cyclones of class A. The frequency of class B cyclones was higher than that of cyclones of class A in every season, with a maximum in spring (109 cyclones). Class A cyclones occurred most frequently in summer (Fig. 3).

Standard deviation of the number of southern cyclones, which describes their inter-annual variability, was highest for class B, and in spring; and lowest for class A, and in winter (Table 1). The maximum number of southern cyclones was observed in the years 1952, 1960, 1974 and 1991. Southern cyclones were scarce in 1948, 1963, 1968, 1993, 1999 and 2002.

On average, southern cyclones spent about one third (35.4%) of their lifetimes within the 1000-km circle. The mean duration within the circle was 44.0 hours (Table 1). Class A cyclones stayed inside the 1000-km circle for longer than class B cyclones. The longest durations within the circle occurred in summer and the shortest in winter. Inter-annual variability in the mean duration of southern cyclones within the 1000-km circle was highest in summer and autumn, and for class A cyclones.

The most severe southern cyclones (i.e., those with the lowest SLP) were observed during winter, although they were less frequent in

Table 1. Southern cyclones from 1948 to 2004 according to total number, duration in the 1000-km circle, SLP at the tracking point nearest to Estonia, and mean SLP in the 1000-km circle. The change in these characteristics is presented in terms of a linear trend (57-year time series) for each class and season. Mann-Kendall (MK) test results are given for statistically significant trends only.

	Number					Duration (h)			SLP (hPa)								
	Total	Average per year	SD	Max. per year	Min. per year	Mean	SD	Max	At nearest point	SD	Min	Change*	MK	Mean	SD	Change*	MK
All	506	8.9	3.7	24	2	44.0	11.2	150.0	1001.1	3.3	968.5	3.6	2.2	1000.8	3.0	3.6	2.6
Class A	170	3.0	2.1	9	0	44.4	13.0	120.0	1001.3	5.4	968.5	–	0.9	1001.2	4.6	–	1.6
Class B	336	5.9	2.9	15	1	43.3	10.3	150.0	1000.7	4.1	976.6	4.1	2.3	1000.4	3.6	3.9	2.3
Winter	77	1.4	1.5	8	0	36.7	10.6	102.0	999.8	8.9	968.5	7.2	2	998.5	7.1	6.6	2.13
Spring	156	2.7	2.2	10	0	42.9	11.9	108.0	1002.0	5.3	980.9	–	0.97	1001.3	4.1	–	0.61
Summer	151	2.6	2.0	9	0	46.8	14.6	120.0	1001.7	5.0	980.8	–	1.76	1001.9	4.3	3.8	1.96
Autumn	122	2.1	2.0	11	0	42.2	14.5	150.0	1000.3	6.4	976.6	–	1.88	999.9	6.1	–	1.75

* Change as indicated by the trend.

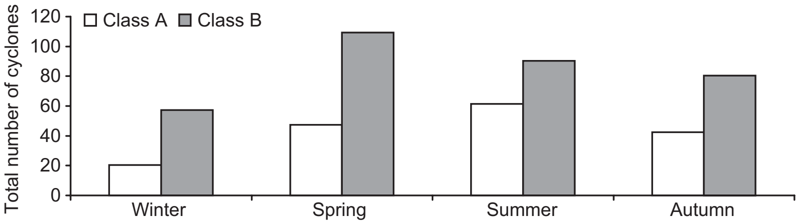

Fig. 3. Total number of southern cyclones for the two trajectory classes in different seasons during 1948–2004.

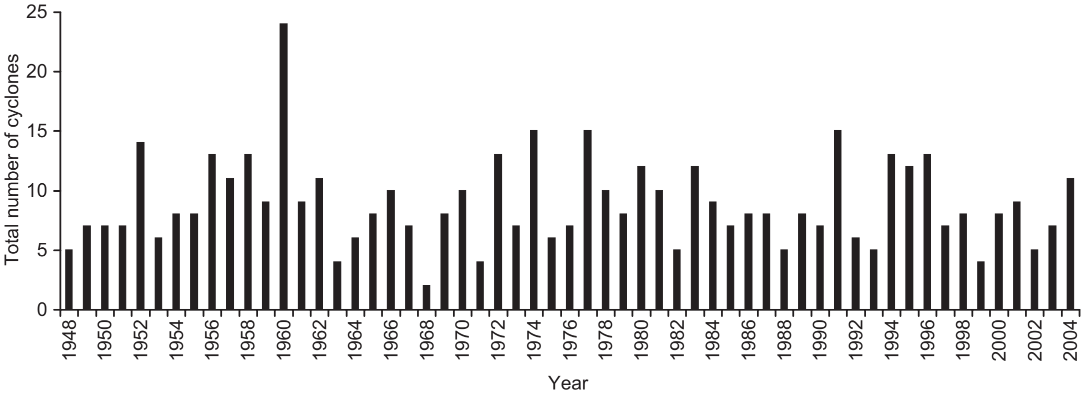

Fig. 4. Time series of the total number of southern cyclones located within the 1000-km radius circle over Estonia during 1948–2004.

winter than in the other seasons. Lower SLP was more typical for class B southern cyclones. The lowest measured air pressure, at 968.5 hPa, was observed on 4 December 1976.

Long-term changes in the variables of southern cyclones

The annual number of southern cyclones influencing weather conditions in Estonia did not changed markedly during 1948–2004 (Fig. 4). Although there were no significant trends in the time series of number and duration of the southern cyclones for particular seasons, a weak decrease is noticeable in winter and summer, and a weak increase in spring.

We found statistically significant trends in the SLP time series of the southern cyclones, both for SLP at the tracking point nearest to Estonia as well as for mean SLP of the cyclones located within the 1000-km circle (Fig. 5 and Table 1). All these trends were positive that indicates weakening of southern cyclones.

The largest increase in SLP of the southern cyclones (by about 7 hPa in 57 years) was found for winter. An increase in mean SLP of the cyclones was detected in summer. There were no trends in SLP of the southern cyclones in spring and autumn. It is important to notice that the increasing trends in SLP were found exclusively for the cyclones of class B (Table 1).

Influence of southern cyclones on air temperature in Estonia

We assumed that class A southern cyclones cause an increase in air temperature in Estonia. This is due to advection of warm, and potentially tropical summer air, that is located in the eastern periphery of the cyclones, where southerly winds prevail. At the same time, we assumed that class B southern cyclones cause cooling due to the advection of cold arctic air. This is because Estonia is situated at the western periphery of class B cyclones, and is characterised by a northerly flow of air. Due to the opposite effects of

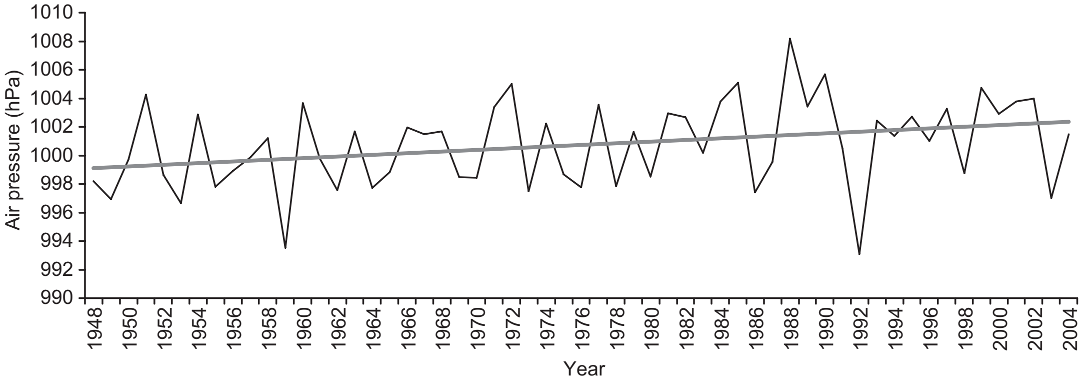

Fig. 5. Time series and linear trend (significant: Mann-Kendall statistics = 2.57) of the mean SLP of southern cyclones located within the 1000-km circle over Estonia, 1948–2004 (net change 3.3 hPa).

southern cyclones with different trajectories on temperature, we analysed the thermal effect of southern cyclones separately for classes A and B (Table 2).

As it was supposed, the cyclones of class A were related to a temperature increase in Estonia. The greatest warming occurred in summer (on average 0.8 °C), and the smallest in autumn and winter. An increase, however statistically insignificant, was detected in air temperatures related to the occurrence of southern cyclones in summer (Fig. 6).

It should be emphasised that the observed temperature changes were highly variable (*see* standard deviations (SD) in Table 2). These daily changes ranged from highly positive (6 °C on 14 February 1956) to highly negative (–4 °C on 17 September 1976).

The mean decrease in air temperature caused by class B cyclones was about 0.5 °C, but this varied considerably for particular cyclonic events. In general, the standard deviation of temperature changes was smaller than that for class A cyclones, except in winter. The highest temperature increase due to a class B southern cyclone (9 °C) was observed on 27 February 1958, and the highest decrease (5.6 °C) occurred on 17 December 1965.

The analysis of the trends in mean temperature in the seasons (Table 2) demonstrated a weak decrease in winter and spring, and a weak increase in summer and autumn. However, none of these changes was statistically significant (Mann-Kendall statistics < 1.96 in all cases).

Influence of southern cyclones on precipitation in Estonia

Our findings also indicate that southern cyclones are related to the incidence of heavy precipitation events, as also described by Mätlik and Post (2008). Using the data from the 10 meteorological stations we found that the mean annual precipitation, measured on days when a southern cyclone was located within the 1000-km circle around Estonia, was 69.2 mm. This means that southern cyclones induced 11.1% of the long-term mean annual precipitation at these stations.

In the analysed data set, the number of class B cyclones was almost double the number of class A cyclones (Table 3). The mean precipitation per cyclone was similar for both classes (7.3 and 7.2 mm for class A and B, respec-

Table 2. Mean temperature change in Estonia for the period 1951–2004 caused by different types of southern cyclones.

	Mean temperature change (°C)	SD (°C)
Class A	0.3	1.3
Spring	0.4	2.1
Summer	0.8	1.7
Autumn	0.3	2.1
Winter	0.3	2.6
Class B	–0.4	0.8
Spring	–0.5	1.5
Summer	–0.3	1.1
Autumn	–0.6	1.2
Winter	0.1	3.0

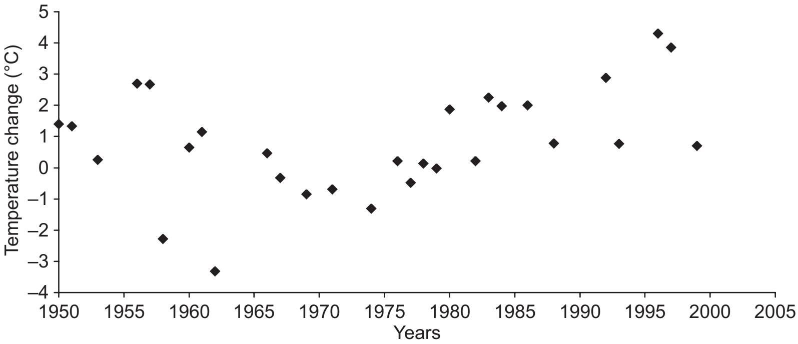

Fig. 6. Annual mean temperature change caused by class A southern cyclones in summer from 1951–2004 (trend not significant MK = 1.84).

tively). The highest annual mean precipitation that was related to southern cyclones occurred at Võru (77.6 mm). In general, higher precipitation occurred in southeastern Estonia, and lower precipitation occurred in the western Estonian archipelago (Fig. 7).

The mean daily precipitation resulting from a southern cyclone was 2.6 mm (Table 3). The highest mean value was detected at Tiirikoja (3.0 mm) in eastern Estonia, and the lowest at the westernmost station Vilsandi (2.0 mm). The maximum daily rainfall related to southern cyclones was recorded at Ristna (69.6 mm on 4 July 1972). The average maximum 24-hour precipitation at the 10 stations was 56 mm.

The mean seasonal values of precipitation related to southern cyclones were highest in summer (29.8 mm) and lowest in winter (6.0 mm). This difference corresponds to the seasonal distribution of precipitation. The mean precipitation related to southern cyclones was higher in autumn than in spring.

The mean daily precipitation related to class A southern cyclones was higher (2.9 mm) than that related to class B cyclones (2.6 mm) (*see* Table 3). Typically, the maximum values of daily precipitation for class A cyclones were recorded in western Estonia (3.3 mm at Ristna) and the minimum values in eastern Estonia (2.4 mm in Narva). At the same time, the maximum daily precipitation for class B cyclones was measured in eastern Estonia (3.2 mm at Tiirikoja) and the minimum precipitation in western Estonia (1.7 mm at Vilsandi). This result is not unexpected and indicates that higher precipitation was recorded in regions closer to the centres of the cyclones.

On 84% of days when a southern cyclone was located within the 1000-km circle, some precipitation (> 0 mm) occurred (Table 4). On average, daily precipitation of 2 mm and above was recorded for 59.2% of southern cyclones, of 5 mm and higher for 39.5%, and of 10 mm and higher for 18.7% of cyclones. Precipitation related to southern cyclones was significantly higher in continental Estonia (Tiirikoja, Tartu, Võru, Viljandi, Türi) and lower at the coastal stations (Vilsandi, Tallinn, Ristna, Pärnu).

The mean annual precipitation related to the southern cyclones was extremely variable at all the stations (Fig. 8). In the mean time series, a weak insignificant decrease could be noticed. However, several statistically significant trends in total precipitation related to the southern cyclones were detected at individual stations. The most significant decrease was found to have occurred in summer. The decrease in mean precipitation across all 10 stations, related to southern cyclones in summer over 53 years, was 18.9 mm. This trend was statistically significant at the three coastal stations (Tallinn: Mann-Kendall statistics = 2.6, Ristna: Mann-Kendall

Table 3. Mean precipitation (mm) related to southern cyclones.

Precipitation	All cyclones	Class A	Class B
Mean annual	69.2	23.4	45.8
Mean daily	2.6	2.9	2.6
Max. 24-hour	69.6	69.6	59.7
Mean spring	13.6	4.6	9.0
Mean summer	29.8	9.8	20.0
Mean autumn	18.5	6.7	11.9
Mean winter	6.0	2.2	3.8

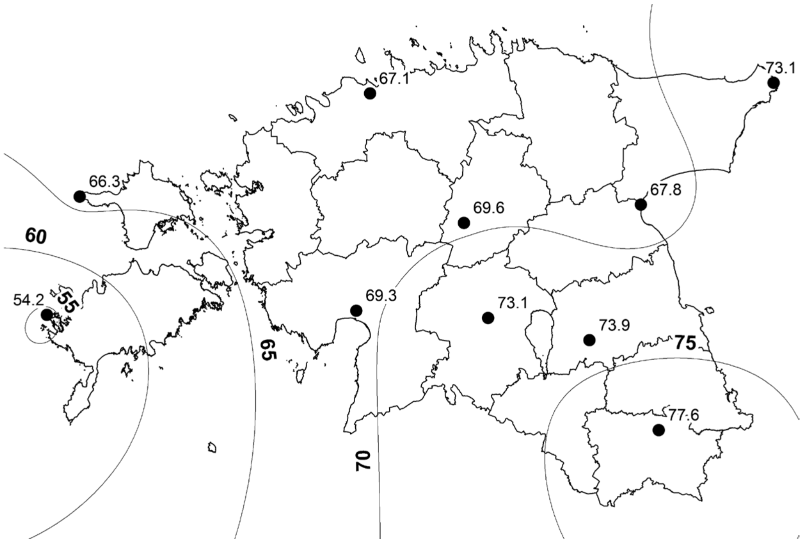

Fig. 7. Mean annual precipitation (mm per year) related to southern cyclones at 10 meteorological stations in Estonia, 1948–2004.

statistics = 2.6, Vilsandi Mann-Kendall statistics = 2.4), and was much stronger for class B cyclones. Significant increasing trends in annual precipitation were found at Pärnu (Mann-Kendall statistics = 2.1) and Viljandi (Mann-Kendall statistics = 2.1) for class A cyclones. A small insignificant increase in precipitation related to all southern cyclones was found only in spring.

Discussion

There are a number of important issues that may affect the results of our study. The foremost of these is the reliability of the analysed data. Numerous databases of cyclones were created during the last decade (e.g. Serreze *et al*. 2000, Zhang *et al*. 2004, Pinto *et al*. 2005, Raible *et al*. 2008, Hewson and Titley 2010). In most cases, they were created using algorithms that can be described as mathematical functions that calculate the exact position of the centre of a cyclone using data from surrounding grid points (Serreze *et al*. 2000). However, a critical weakness of such fully automated methods is the use of spatial resolutions that are too high, which erroneously estimate the real positions of lows. Thus, the number of fast-moving cyclones may be underestimated (Zolina and Gulev 2002).

In the cyclone database used here, the potential error related to fully automated methods of identification was avoided through the use of a semi-automated approach. Trajectories of lows were generated visually, using the animation of SLP fields described by Grigoriev *et al*. (2000). Given that the human eye is able to extrapolate dynamical processes despite a lack of data, the output of this subjective approach is arguably more reliable than that provided by a fully automated method (Zolina and Gulev 2002). The same cyclone database was used, for example, to study shifts of the NAO (Jung *et al*. 2003), the synoptic variability of air–sea turbulent

Table 4. Percentages of days when a southern cyclone was located within a 1000-km circle and precipitation occurred: data for the period 1948–2004.

	Precipitaion			
	> 10 mm	> 5 mm	> 2 mm	> 0 mm
Narva	19.9	41.0	57.7	82.8
Pärnu	20.6	38.1	58.9	83.2
Ristna	17.8	40.3	59.5	82.6
Tallinn	18.2	38.3	56.1	81.6
Tartu	20.8	42.9	62.3	86.6
Tiirikoja	16.2	39.1	58.5	88.0
Türi	19.2	39.3	60.1	84.2
Viljandi	19.8	41.3	60.6	85.4
Vilsandi	12.9	32.9	55.4	80.1
Võru	21.6	42.1	62.7	86.2
Average	18.7	39.5	59.2	84.0

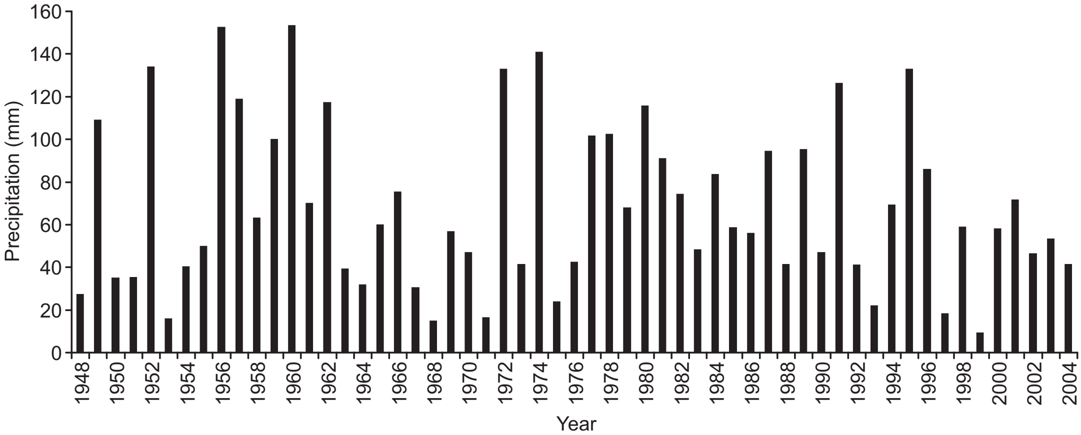

Fig. 8. Time series of annual precipitation related to southern cyclones calculated using mean daily precipitation at 10 meteorological stations in Estonia, 1948-2004.

fluxes (Zolina and Gulev 2003), the sensitivity to horizontal resolution of the European Centre for Medium-Range Weather Forecasts model in simulating extratropical cyclones (Jung *et al.* 2006), and the life cycles of cyclones (Rudeva and Gulev 2007, Rudeva 2008).

In detecting the frequency of cyclones, it is essential to consider the systematic underestimation of cyclones in the database. The error depends on the time lag used, the grid size, and also the geometry of the grid in which cyclones are counted. Fast moving cyclones that cross the grid faster than the time lag of the database pose problems. A larger error results from a larger time lag and a larger grid size. For the time lags of 6 and 12 hours in a 5° × 5° grid, the average underestimation has been assessed to be 10%–20% (Zolina and Gulev 2002). This error is greater for areas with intense cyclonic activity, especially near the Icelandic low and in the Mediterranean region. In the present study, we used a circle rather than a grid. The use of circular geometry reduces the uncertainty associated with counting cyclones, and lowers the error in their trajectories by a factor of 1.5 as compared with rectangular or square grids (Zolina and Gulev 2002). In general, we therefore considered the cyclone data used here to be realistic.

The next important consideration was the location of the circle used for the analysis. The dependence of the number of cyclones on the location of the circle used was discussed in detail by Link and Post (2007). They analysed the possible sources of error in the counting of cyclones observed over the Baltic Proper. Link and Post (2007) argued that the location of the central point of the circle is a critical factor in statistics of regional cyclone activity. In the present study, we defined the location of the circle that was most appropriate for Estonia.

In our analysis, we detected an average of 8.9 southern cyclones per year. Using the cyclone counting method described by Link and Post (2007), we estimate that the percentage of southern cyclones is about 9%–11% of all cyclones within the 1000-km circle. This finding is in line with those of previous studies, which reported that southern cyclones were related to about 10%–13% of all cyclones that affected weather conditions in Estonia (Kannes *et al.* 1957, Linno 1982).

A number of authors have concluded that there was a general decrease in the frequency of cyclones in the mid-latitudes (30°–60°N) during the second half of the 20th century (Held 1993, Lambert 1996, Serreze *et al.* 1997, Sickmöller *et al.* 2000, Gulev *et al.* 2001, McCabe *et al.* 2001). Sepp (2005) reported a decreasing tendency in the frequency of southern cyclones over central Europe. However, in this study we found no statistically significant trend in the frequency of southern cyclones. We, therefore, conclude that the significant trends in cyclone frequency reported elsewhere are caused not by southern cyclones, but by western ones. This can be explained by the differing definitions of southern cyclones used in different studies. The relatively strict definition of southern cyclones used herein eliminates all cyclones that formed over the Atlantic Ocean and moved to the Baltic Sea region via the Mediterranean or central Europe. Sepp (2005), for example, did not use such rigid boundaries and therefore does not excluded cyclones that formed over the Atlantic or the Bay of Biscay.

The largest number of southern cyclones was observed in spring (156 cyclones for 1948–2004). Almost the same number of cyclones occurred in the summer months, but in autumn and winter, the number of southern cyclones was much lower. In general, this finding was concurrent with the seasonal distribution of cyclogenesis over the Mediterranean basin (Trigo *et al*. 1999). Belskaja (1949) reported different results, with more southern cyclones being formed at the end of winter and the beginning of spring. Linno (1982) detected fewer southern cyclones in winter (6%–9% of all cyclones) and a maximum number in summer. These differences in the number of southern cyclones may be explained by the different periods studied, and the different methods used to define and detect southern cyclones.

The mean duration of southern cyclones within the circle was almost two days. The longest durations occurred in summer, and the shortest in winter. In general, this seasonal distribution agrees with the mean duration of Mediterranean cyclones described elsewhere (Trigo *et al*. 1999).

Mean SLP of cyclones located at the tracking point nearest to Estonia was 1001.1 hPa. This value increased significantly over time, showing that southern cyclones weakened during the 57-year period studied here. The most severe southern cyclones, i.e., those with the lowest SLP (average below 1000 hPa), were observed during winter. SLP of these lows showed a significant increase in winter. This finding is in agreement with the general conclusion of Zhang *et al*. (2004), who reported that an increase in SLP was apparent in the mid-latitudes, with winter maxima in the North Atlantic and Eurasia, and summer maxima in Eurasia. On the other hand, an analysis of cyclones that formed over the Baltic Sea catchment area indicated a general decrease in SLP at cyclone centres (Sepp 2009).

Here, it was assumed that the southern cyclones that pass to the west of Estonia (class A) bring warmer air into Estonia, and those that pass to the east of Estonia (class B) cause cooling. Almost two thirds of all southern cyclones pass to the east of Estonia. Our results indicate that, on average, class B cyclones reduced the air temperature by 0.4 °C, while class A cyclones increased it by 0.3 °C. The warming effect of southern cyclones was greatest in summer, and the cooling effect of class B cyclones was greatest in autumn. In general, the effect of southern cyclones on changes in air temperature in Estonia was not as great as expected. There are many reasons for this. Firstly, as mentioned above, smaller and weaker cyclones might remain too far from Estonia to have much effect on local air temperature. In addition, in some cases class A cyclones do not cause warming through the advection of tropical air masses, but rather have a cooling effect because of the introduction of thick cloud cover that prevents warming in the warm season.

The effect of class B southern cyclones on temperature may be much more complicated. Estonia is located at the western periphery of class B cyclones, and is influenced by northerly winds. Northerly winds do not usually cause a lower temperature in winter (Table 2). If a class B southern cyclone has not moved as far north as the latitudes of Estonia, then at its northwestern periphery, northeasterly winds might introduce even warmer air from northern Russia in the summer season.

There were, however, clear temperature changes in individual cases. For example, on 25–27 February 1958, a class A southern cyclone caused a mean temperature increase in Estonia of 9.0 °C, while between 29 June and 1 July, 1981, a class B southern cyclone caused a cooling of 6.3 °C. However, during the analysis it became clear that the trends in temperature change during the period 1951–2004 were not statistically significant.

Southern cyclones were found to produce mean precipitation of 69.2 mm per year at the 10 stations in Estonia. This is slightly more than

10% of the annual precipitation. A similar result was also reported by Kannes *et al*. (1957). The highest annual mean precipitation was observed in southeastern Estonia, and the lowest in the western Estonian archipelago. This result is in line with the mean distribution of annual precipitation in Estonia (Jaagus *et al*. 2010). The mean summer precipitation related to southern cyclones decreased during the period studied, a trend that was found to be statistically significant at the three coastal stations. This change is at odds with the general increasing trend in precipitation in Estonia during the second half of the 20th century, especially in winter and spring (Jaagus 2006). We, therefore, conclude that the precipitation in Estonia caused by southern cyclones decreased over the last few decades.

In this study, the highest precipitation related to southern cyclones was detected in summer, and the lowest in winter. This is due to the different frequencies of southern cyclones in different seasons. Almost one fifth of the southern cyclones caused extreme precipitation of over 10 mm in 24 hours, about one third of southern cyclones induced heavy daily rainfall of over 5 mm, and more than half of the cyclones in the current study brought strong precipitation in excess of 2 mm in 24 hours.

Conclusions

On average, 8.9 southern cyclones per year were detected in the 1000-km circle around Estonia during the period 1948–2004. The majority of southern cyclones were observed in spring and summer, and the minority in winter. The number of cyclones with a class B trajectory (passing to the east of Estonia) was about twice the number of class A cyclones (passing to the west of Estonia). On average, southern cyclones spent about one third of their lifetime in the 1000-km circle. The mean duration of their stay within the circle was 44.0 hours. The highest durations occurred in summer and the lowest in winter. The most severe southern cyclones, i.e., those with the lowest sea level pressure (SLP), were observed during the winter season. Statistically significant positive trends were detected for the time series of SLP of all southern cyclones, and also all class B cyclones. Statistically significant positive trends were also detected in winter for SLP at the tracking point nearest to Estonia, as well as for the mean SLP of cyclones located within the 1000-km circle. We therefore observed a general weakening of the southern cyclones observed in our 57-year time series.

As expected, the incidence of class A cyclones was related to a temperature increase in Estonia, with the greatest warming detected in summer. Class B southern cyclones were related to a temperature decrease in Estonia, except in winter. The mean cooling of air temperature related to class B cyclones was about 0.5 °C, but this varied considerably for individual cyclones.

The mean annual precipitation measured for days when a southern cyclone was located within the 1000-km circle around Estonia was 69.2 mm. The mean precipitation per cyclone was similar for both trajectories, namely 7.3 mm for class A and 7.2 mm for class B. Higher precipitation was observed in southeastern Estonia and lower precipitation was observed in the western Estonian archipelago. The mean daily precipitation related to a southern cyclone was 2.6 mm. The precipitation related to southern cyclones was highest in summer and lowest in winter. The mean daily precipitation related to class A southern cyclones was slightly higher than that of class B cyclones. Typically, the maximum daily precipitation values for class A cyclones were observed for western Estonia, and the minimum values were observed for eastern Estonia. The opposite was true for class B cyclones. Of all southern cyclones, 39.5% were related to an average maximum daily precipitation of 5 mm or more. This value decreased to 18.7% for a daily precipitation of 10 mm or more. The mean precipitation related to southern cyclones in summer, recorded at 10 stations across Estonia, decreased by 18.9 mm during the 57 years studied. This trend was statistically significant at the three coastal stations (Tallinn, Ristna, and Vilsandi). There were also statistically significant positive trends in the annual precipitation associated with class A cyclones at Pärnu and Viljandi.

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