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KAUPO MÄNDLA

Southern cyclones in northern Europe and their influence on climate variability

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Southern cyclones in northern Europe and their influence on climate variability

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PRESS

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Author's contribution

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

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

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

IV The author has performed an analysis of characteristics of cyclones influencing northern Europe, composed frequency maps and has written a part of the results and discussion of the manuscript.

LIST OF ABBREVIATIONS

1–K circle	–	1000 km–radius circle, with its centre located in the center of Estonia
CSS	–	cyclone of southern sea
ECMWF	–	European Centre of Medium–Range Forecasts
ERA40	–	ECMWF reanalysis of the global atmosphere and surface conditions for 45 years, from 1957 to 2002
ESC	–	eastern southern cyclone (southern cyclone, whose centre moves east of Estonia)
GCM	–	general circulation model
MK	–	Mann–Kendall test statistic
NAO	–	North Atlantic Oscillation
NCAR	–	National Center for Atmospheric Research
NCEP	–	National Centers for Environmental Prediction
NORDLIS	–	Nordic Lightning Information System
SC	–	southern cyclone
SCTD	–	southern cyclone–related thunder day
SLP	–	sea level pressure
TD	–	thunder day
WSC	–	western southern cyclone (southern cyclone, whose centre moves west of Estonia)

ABSTRACT

The present work concentrates on cyclones, which have formed over the Mediterranean, the Black Sea or the Caspian Sea (southern cyclones) and have influenced weather conditions in northern Europe, particularly in Estonia. Southern cyclones are rather rare in northern Europe but by carrying warm and moist subtropical air northwards, they have a lot of potential to significantly design weather conditions in affected areas and to cause severe weather events. Their properties and movement is very different from those of their counterparts, which stayed to southern Europe, and their manifestations in local weather could be more severe than in other low pressure systems.

Cyclonic activity over northern Europe and Estonia was described and analysed using several available datasets. Particular attention was concentrated on southern cyclones and their climatological analysis by using the database of the Northern Hemisphere cyclones including the period 1948–2010. Impact of southern cyclones on local temperature and precipitation in Estonia was analysed at ten meteorological stations. Relationships between southern cyclones and thunderstorms were studied by using the data of human observers at weather stations in 1950–2010. An analysis of southern cyclones was carried out in relation to lightning data, which were provided by the Nordic Lightning Information System (NORDLIS) for the time period 2005–2010, containing automatically registered lightning data for Estonia.

Weather conditions in Estonia are mainly determined by low pressure systems formed over Iceland, the North Sea and the Norwegian Sea regions and over the eastern slopes of the Scandinavian Mountains; cyclones from southern Europe sometimes also move to northern Europe. Southern cyclones constitute approximately 10% of all cyclones that affect weather conditions in Estonia. Much more southern cyclones appear in the warm half–year than in the cold one. In average, nine southern cyclones out of approximately 30 southern cyclones that annually move to northern Europe influenced Estonia. Results showed that southern cyclones affecting weather conditions in northern Europe have mainly formed over northern Italy, the Gulf of Genoa and surrounding areas, as well as north of Black Sea. Southern cyclones are much longer–lasting and deeper than the cyclones originating from the same areas over southern Europe, but not moving to northern Europe. The strongest southern cyclones usually moved to the eastern part of northern Europe including the Baltic countries.

About two thirds of the southern cyclones influencing Estonia passed the country from the eastern side, mostly causing a cooling. The rest of southern cyclones, passing Estonia from the western side, usually raised air temperature in Estonia. In the average, 10% of annual precipitation in Estonia was associated to southern cyclones. The highest precipitation amounts were observed in summer. The maximum rainfall caused by southern cyclones was observed in southeastern and the lowest one in western Estonia. Precipitation

amounts and spatial distribution are clearly related to the distance between the cyclone centre and the meteorological station.

A significant intensification of southern cyclones was detected in the eastern part of northern Europe where their mean and mean minimum air pressure has decreased in 1948–2010. On the contrary, in Estonia there has been a slight weakening of southern cyclones in their mean SLP. However, in the whole area of the Baltic countries there was still no change.

Thunderstorms mostly appear and are related to southern cyclones from April to October, when 99% of such thunder events were observed. In the summer months, up to 80% of southern cyclones were associated to thunderstorms in Estonia. The total annual duration of thunder events caused by southern cyclones at different stations constitutes about 10% of the yearly duration of all thunder events. Sometimes, southern cyclones are capable of generating very long–lasting thunder events. It was found that in approximately 2/3 of the thunderstorms which were related to southern cyclones, the centres of the cyclones passed closer than 500 km from the meteorological station where thunder was observed. However, 2/3 of southern cyclones passed farther than 500 km and did not cause thunderstorms in Estonia. Their spatial extent was probably smaller and their cloud systems did not affect Estonia. Some regional differences occurred, and two stations clearly differed from the others. In the hilly south eastern part of Estonia (Võru station) there was detected the highest number of thunder days, as well the highest count of thunder days related to southern cyclones. On the contrary, in Vilsandi, which represents well open sea conditions, there was observed the lowest number of thunder days related to southern cyclones but the longest duration of thunder events, especially in August.

The analysis of daily counts of cloud–to–ground lightning strikes showed that in most of the years, southern cyclones had caused a much higher number of lightning strikes per day than other events and therefore it can be concluded that the southern cyclones–induced thunderstorms are more intense than others. However, it should be noticed, that the overall lightning statistics is significantly affected by some individual intense storms.

1. INTRODUCTION

Global climate has large variations on temporal and spatial scale and the processes affecting climate can exhibit a considerable natural variability as well. Even in the lack of external influence, periodic and irregular variations on a great range of spatial and temporal scales are observed (IPCC 2013). Several sectors of human activity like tourism, transportation, construction, energy production, agriculture, forest management, fishery and many others are strongly affected by climatic variations. Hence, the understanding of climate variability on different spatial and temporal scales has a large social and economic importance, especially on the background of recent climatic changes (UNFCCC 1992; Hulme et al 1999, IPCC 2013). Therefore, different researches consistently examine the past, current and modelled future climatic changes and their features on global, continental and regional scales (Giorgi and Francisco 2000; Nakicenovic and Swart 2000; Murphy et al. 2004 etc.). Investigations of changing averages and extremes of climate variables (e.g., temperature, precipitation, wind and sea level pressure) are particularly important.

Extensive public interest in climate and in the issues of climate change has been one of the main factors forcing climatological studies in recent times. Weather–related extremes and disasters are often reflected by media channels. Numerous papers and discussions have also treated the influence of greenhouse gases (e.g. CO_2, CH_4, N_2O, CFCs) as the main cause of climate warming (Wigley 1998; Shine et al. 2005; Hansen et al 2012; IPCC 2013). Public at large is concerned about rapid climate changes which can induce risks to people's health, property and threaten public prosperity. All of these have led to a necessity to perform more detailed, diverse and more complex climatological studies.

Recent climate warming is observable especially in North America and Europe, including the Baltic Sea region (Räisänen 2001; Pryor and Barthelmie 2003; BACC 2008) and Estonia (Tooming and Kadaja 1999; Jaagus 2006, 2008). Climate in northern Europe depends on atmospheric circulation, on the energy that is transported to northern Europe from outside. Weather in this region is greatly determined by high cyclonic activity and the domination of westerlies. A humid and relatively warm air mass moving eastwards from the northern Atlantic brings much higher winter temperatures to northern Europe comparing with other regions of the world at the same latitudes. On the contrary, this circulation causes cooler and humid weather conditions in summer (BACC 2008). Additionally, continental or arctic air frequently prevails in winter bringing cold weather. Considering the aforementioned aspects it is possible to deduce that climate changes are caused by changes in atmospheric circulation.

One of the main factors controlling the transport of air masses with different qualities is cyclonic activity. Low pressure systems play an important role in the transport of energy and moisture across these latitudes. Cyclones carry cold arctic and polar air towards the equator and warm tropical air pole wards. Therefore, weather in the middle latitudes is largely dominated by cyclonic systems. While most of the cyclones produce relatively favourable day–to–day weather conditions, a very small fraction of them is capable to intensify to the extent of causing extreme weather conditions like strong winds, high precipitation amounts, storm–induced floodings, widespread damages and, possibly, losses in human lives. The strongest cyclones are the most damaging. More of available energy leads to the appearance of stronger cyclones. Higher amount of energy comes from warmer seas.

Cyclones that have formed over southern Europe and move to northern Europe are usually considered as more powerful and thus dangerous. Several papers (Kannes et al. 1957; Mätlik & Post 2008; Bielec–Bakowska 2003; Bocheva et al. 2007; Post and Link 2007; Jaagus et al. 2010; Maslova 2010) have reported the importance of southern cyclones manifesting their ability to cause extreme weather events like blizzards, storm winds, and heavy snowfall in winter and heavy rainfall, floods, thunderstorms, squalls, hail and even destructive tornadoes in summer.

Sometimes, mainly in summer, tropical and humid air is carried far into northern latitudes. Tropical air inflow is often related to low pressure systems, which have originated from southern Europe. Containing plenty of moist and warm air, these cyclones are very important in generating hazardous weather conditions. Tropical air inflow to northern Europe usually takes place when a southern cyclone moves to northern latitudes in Europe. For Europe, southern cyclones are generally the low pressure systems which form over the Mediterranean, the Black Sea and the Caspian Sea regions and move significantly northwards, carrying properties of the original air mass along their trajectories to further north. The frequency and movement of these cyclones have been under attention in several papers (van Bebber 1891; Belskaya 1949; Kannes et al. 1957; Kudryan 1981; Linno 1982; Jaagus et al. 2010; Kaznacheeva and Shuvalov 2012; Degirmendžić 2013). A more detailed overview of papers related to southern cyclones is presented in chapter 2.3.

Climate changes that were reported in northern Europe and in Estonia during the last decades and discussed in the studies mentioned in Chapter 2.3 rise two general hypotheses on which relies the present Thesis. At first, southern cyclones are partly responsible for the current climate warming. To examine this, different parameters of southern cyclones (Publications I, II, III, IV) and the relationships between southern cyclones and weather parameters in Estonia (Publications I, II) were investigated. The second hypothesis states that southern cyclones are more severe than other cyclones. In order to find an answer, SCs are compared to other cyclones affecting weather in northern Europe (Publications III, IV) and to the studied southern cyclones–related thunder events (Publication II).

2. BACKGROUND OF SOUTHERN CYCLONES IN EUROPE

2.1. Formation of southern cyclones

Initially, the term “cyclone” was used in a very general meaning for all circular or greatly curved wind systems (e.g. tornadoes, twisters, waterspouts). Because cyclonic rotation and relatively low atmospheric pressure usually exist together, the terms cyclone and low are equally used in general. In meteorology, a cyclone is generally understood as an area of closed isobars, which has circular rotation clockwise in Southern Hemisphere and anticlockwise in Northern Hemisphere because of the Coriolis force (Moran 1989).

Frontal zones are located between the air masses. In these zones the changes in meteorological elements are faster and sharper than inside the air mass. Along these zones winds are blowing at fairly high velocities, which produce a sharp change in wind speed – a strong wind speed shear. This generates a kind of instability in the flow (Ahrens 1994). It can be said that low pressure systems generated over open water usually form close to oceanic frontal zones, which are the regions with strong sea surface temperature gradients (Sinclair 1995). In particular circumstances, in frontal zone, the warm air invades further into the cold air and a wave appears. If the wave development continues, the formation of a cyclone starts. Northward moving warm air and southward moving cold air are forced around each other, forming a bend in the temperature gradient. The generation of a cyclone has a number of stages. In the wave stadium, there forms one closed isobar and the cyclone is visible in the lower atmosphere (below 3 km). Next is the stadium of a young cyclone where a warm sector forms in the cyclone. Air pressure in the centre of the cyclone decreases and a distinct pattern of closed isobars appears on the weather map. The cyclone grows to reach to higher layers of the atmosphere and expands over a wider area covered by clouds and rain as well. In the stage of maximum development of a cyclone, SLP in the center of the cyclone reaches its minimum value. At the same time a decrease in SLP in the front of the cyclone is going to equal with an increase in SLP in the rear of the cyclone. The warm sector becomes narrower and in the centre of the cyclone the cold air catches the warm air. That means the occlusion of the cyclone where the warm air will be raised to the higher altitude by the cold air. After that the cyclone starts to weaken.

Another important factor in the formation of cyclones is the orography of mountainous areas. It is known that the airflow over mountains is much more disturbed than a flow over a flat terrain. Mountains are obstacles for air masses. The initial generation of these cyclones takes place with the movement of airflows over the mountains. The lee cyclones usually start under the leading edge of a mountainous cross–barrier. Vertical motion of the air induced by the orography affects the evolution of vorticity in mid–troposphere, which is superimposed on an area of low–level convergence and orographic descent

(Chung et al. 1976; Buzzi and Tribaldi 1978). It has been argued that instead of a thermal anomaly, a low–level potential vorticity anomaly created by the deformation of airflow on an obstacle also has a significant influence on the initiation and localization of the cyclones generated by orography (Tafferner 1990; Aebischer and Schär 1998; Horvath et al. 2006) where the air starts to move around mountains.

Both descriptions of the formation of cyclones are simpflications and real formation is much more complicated. According to the experiences that were acquired during the writing process of the articles it can be stated that cyclones are equally capable to form over both the land and the sea areas.

Southern cyclones which develop over relatively warm seas in the Mediterranean region are also mid–latitude cyclones which form similarly to other cyclones in same latitudes. In the Mediterranean region, their generation is more influenced by orography than the areas over the northern Atlantic Ocean. Regarding southern Europe and the Mediterranean region, most of the cyclones form inside the region and cover relatively short distances during their lifetime.

In Europe, extratropical cyclones are the low pressure systems that mainly affect local weather conditions. These systems may also be described as mid–latitude cyclones because of their area of formation and motion. Together with cold–core Polar cyclones they are the largest low–pressure systems on the synoptic scale. The typical diameter of mid–latitude cyclones reaches up to 2000 km and their average lifetime is 2–6 days (Ahrens 2001).

In middle latitudes cyclones are generally driven on their trajectory by prevailing winds, in extratropical regions by westerly winds from the west to the east across both the Northern and Southern hemispheres. This is the same direction as the rotation of the Earth and it is the optimal moving direction of cyclones. Anticyclones act as obstacles for cyclones and push them to change the cyclone's preferred trajectory and move along the edge of a high pressure area. When the zonal flow regime is precluded by anticyclones, the airflow generally occurs more northwards and southwards, and the cyclones take the same direction (Ahrens 1994). Therefore, a cyclone moving from the south to the north is a rather rare event.

2.2. Cyclone tracking

Cyclones form an integral part of the atmospheric climate system. They undergo a life cycle during which they move along more or less well–defined paths which are called cyclone tracks. Cyclone tracks indicate the movement of cyclone centres. Changes in the tracks, triggered by anthropogenic causes or by long–term natural variability, have a strong effect on regional climate.

Thus, one of the major tasks of cyclone analyses is the tracking of cyclones. The earliest identifications of storm tracks, which also analyse cyclones in the European region, were based on the manual tracking of low pressure systems by interpreting synoptic maps visually and recording the parameters like the location and central pressure of each individual cyclone (e.g. Mohn et al. 1870; van Bebber 1891; Hosler and Gamage 1956; Streten and Troup 1973; Colucci 1976; Hayden 1981; Whittaker and Horn 1984; Akyildiz 1985; Reed et al. 1986; Agee 1991; Shrinke 1993). It should be mentioned that the manual reanalysis of cyclone trajectories, based on weather maps reconstructed using all available data would provide the best tracks. Thus, the manual tracking of cyclones is usually much more accurate compared with automated numerical algorithms. Experienced manpower can better evaluate difficult and complex synoptical situations which appear in time. However, given to the lack of data in some regions and the complexity of cyclone development, such activities inevitably involve some subjective choices being made by the analyst (Neu et al. 2013) that are eliminated in automated programs. There is no accepted single "truth" regarding specific cyclone tracks. The manual tracking procedures are also susceptible to random mistakes in identification of low pressure systems and to misprints during the digitalizing process, but these potential errors do not have major influence on the tracking outcome. Furthermore, manual tracking procedures need a lot of time and labour for quantifying the behaviour of all cyclones over many decades. This is the main reason why much faster but potentially less precise automated tracking methods are widely used and preferred at present.

With the arrival of high–speed computers, scientists started to develop and use automated methods for tracking different climatological indicators. The earliest application of automated tracking in meteorology was cloud tracking by using satellite data to assess cloud movements in time and space (Endlich et al. 1971; Leese and Novak 1971). One of the first automated assessment and tracking methods for cyclones was created by Williamson (1981); this worked particularly well for the extratropical areas where cyclonic activity can be related with strong variations in the pressure field. The usage of digital data from several reanalysis projects or from available observations opened up the path to numerous studies that developed and used automated or semi–automated numerical algorithms for application in climatological archives or data modelling to identify and track cyclones (Lambert 1988; Alpert et al. 1990a; Le Treut and Kalnay 1990; Murray and Simmonds 1991; König et al. 1993; Jones and Simmonds 1993; Hodges 1994; Serreze et al. 1993, 1997; Lefevre and Nielsen–Gammon 1995; Haak and Ubricht 1996; Blender et al. 1997; Serreze et al. 1997; Trigo et al. 1999; 2000; Sickmöller et al. 2000; Gulev et al. 2001; Hoskins and Hodges 2002; Hodges et al. 2003; Hanson et al. 2004; Kleppek et al. 2008; Raible et al. 2008; Satake et al. 2013). All of these papers used the pressure field to assess the occurrence and position of cyclones. Specific algorithms find the cyclone centres and relate these with sequential data sets, which allow tracking by the movement and life cycle of low pressure systems. Today, the reanalysis databases (ERA–40, NCEP/NCAR) and automatic algorithms that find the center of a cyclone in time and space are widely used in the Mediterranean region and bordering areas, as well as elsewhere. However, automated algorithms are also the main cause for internal uncertainties in cyclone tracking. In some synoptic situations it is hard to determine the exact position of a cyclone in time or to distinguish between various low pressure systems. The most problematic issues are the existence of multi–centre lows or a situation when a rapid–wave cyclone overruns stationary depressions (Gulev et al. 2001). In limited areas, (e.g. the Black Sea, the Mediterranean Sea, the Caspian Sea, studied in detail by Radinovic 1987; Alpert et al. 1990a, b; Trigo et al. 1999, 2000; Maheras et al. 2001; Spanos et al. 2003; Bartholy et al. 2009; Nissen et al. 2013; Mändla et al. 2014a), the accuracy of cyclone tracking increases, but there are biases in the number of cyclones, which are formed or decayed outside of the study region.

Generally, semi–automated algorithms prove to be a good approach in cyclone tracking. They are not as strict as fully automated schemes, which might cause problems in complex synoptic situations. Fully automated schemes are fast, but a specific operator still has its own role to make the final decision about location of centre of the cyclone. Operator's eye is more accurate than any automated scheme. Therefore, semi–automated algorithms unite the best qualities of cyclone tracking – the speed of the computer and the precision of human eye.

2.3. Southern cyclones and weather in Europe

The number of cyclones formed over southern Europe is not as high as that of over the Northern Atlantic, but it has a significant effect on weather conditions over southern Europe (Kutiel and Kay 1992; Cullen and de Menocal 2000). Most of the low pressure systems in the Mediterranean region (Mediterranean Sea and surrounding areas), especially over the Mediterranean Sea, form inside the region and over the sea. There are many areas of high cyclonic activity where numerous cyclones form over the Gulf of Genoa, over the areas near southern Italy and over Cyprus (Maheras et al. 2002), and there are also less active formation areas south of the Pyrenees, south of the Iberian Peninsula, over the Alboran Sea (Picornell et al. 2001; Bartholy et al. 2009), over Turkey and the Black Sea (Trigo 1999, 2002; Spanos. et al. 2003). These cyclones generally move on their trajectories from the west to the east and mostly prefer tracks along the northern coast of the Mediterranean Sea (Trigo et al. 1999; 2000; 2002; Bartholy et al. 2009), where the highest frequencies of cyclone tracks in the region have been detected.

Every year, a number of low pressure systems that form over the Mediterranean region, pick different trajectories. Compared to the total number of cyclones formed over these areas, only a small number of cyclones move further north and affect weather in central and northern Europe (Mändla et al. 2014a). These southern cyclones reach to northern latitudes generally in terms of meridional circulation when a westerly flow is blocked by major anticyclones located over eastern or central Europe. These conditions cause the flow of warm and moist tropical air into northern latitudes, which brings higher temperatures to the areas influenced (Sepp and Jaagus 2002; Jones and Lister 2009), and at the same time, cause an advection of arctic air to lower latitudes. That reflects sharp air temperature contrasts between the warm and cold air masses up to 15˚C or even more (Kannes et al. 1957).

It should be clearly recognized in the interpretation of connections between SCs and local climate that SCs are defined differently in different studies. For example, Sepp (2005) classified a low pressure system as a SC if it had crossed 52°N from the south to the north within 5–50°E. This interval was divided into three sectors (I— 5–20°E, II— 20–35°E, III— 35–50°E). According to Kaznacheeva and Shuvalov (2012), the formation area of SCs corresponds to the territory between 24.75°N and 50.65°N and 15.5°W and 45° E. By Degirmendžić (2013), a low pressure system was considered as SC when at any stage of its development the low pressure system was situated within the Mediterranean or Black Sea basins and at a later stage of development the cyclone was located not further than 350 km from the Polish border. There were no specific latitude and longitude borders to define the formation area of SCs.

Moreover, it should be noticed that the term "southern cyclone" was not used only in Europe. In Turkmenistan, these low pressure systems are related to the maximum frequency of dust storms, predominantly in winter, leading to great contrasts in air temperature between local and Iranian air masses (Orlovsky et al. 2005). On the Kamchatka Peninsula, in Far East, southern cyclones make up 70% of all cyclones observed over the Bering Sea and 52% of the cyclones over the Sea of Okhotsk (Kuznetsov et al. 2007). The same type of cyclones, which typically form over the Yellow Sea, the Japan Sea and Central China affect weather conditions over the southern part of the Russian Far East. In these areas, four out of five cases of snowfalls were caused by southern cyclones; it was also suggested that southern cyclones can bring acid precipitation to the Russian southern Far East (Kondrat'ev et al 2007).

In Europe, southern cyclones are generally called the low pressure systems which move to farther north mainly from the Mediterranean and the Black Sea areas. The term "southern cyclone" is still rarely used, because in western Europe the cyclones from the Black Sea and the Caspian Sea are nearly non–existent. Due to this fact, in Europe usually the expression "Mediterranean cyclone" or, sometimes, "cyclone Vb" according to van Bebber (1891) is used to identify these cyclones. Many studies of these cyclones have been performed in the past decade. A common feature of these papers is the description of extreme weather events that accompany with these cyclones.

For example, severe weather events caused by southern cyclones included heavy precipitation over Ukraine in February 2006 and in the Caucasus in the autumn of 2010 (Kaznacheeva and Shuvalov 2012). In May 2014, similar very high precipitation amounts were recorded in Serbia and Bosnia and

Herzegovina. They were also caused by southern cyclones. Media have reported that heavy and long–lasting precipitation events were accompanied by historical floods and landslides in same region. In the past, intense precipitation and wind storms related to southern cyclones have also been detected in Bulgaria (Simeonov and Georgiev 2003; Bocheva et al. 2007). In Hungary, there have been reports about heavy snowfalls that were caused by cyclones which had been originated from the Mediterranean Sea (Bednorz et al. 2013). Many detailed analyses have also been performed on specific extreme cases of Mediterranean cyclones over southern Europe (Pytharoulis et al. 1999; Jansa et al. 2001; Homar et al. 2002; Arreola et al. 2003; Homar and Stensrud 2004; Moscatello et al. 2008; Laviola et al. 2011).

One of the first studies on these low pressure systems was performed by van Bebber (1891). On his map, the trajectory of these cyclones is classified as Vb, which is one of the most important southern cyclone (SC) trajectories originating from the Adriatic Sea and causing long–lasting extreme precipitation episodes in the Alps and the Carpathian Mountains, as well as disastrous floodings in central Europe (Morawska–Horawska 1971; Kundzewicz 1999, 2005; Spreitzhofer 1999b, 2000; Ulbrich et al 2003; Mudelsee et al 2004; Kundzewicz et al 2005; Kysely and Picek 2011; Twardosz 2007; 2009; Bednorz 2008; 2011; Müller et al. 2009; Niedzwiedz et al. 2014). Several severe flooding events occurred in the last two decades (in years 1997, 2002 and 2013) in the Oder/Odra and the Elbe/Labe River basins and in their tributaries.

In addition, some studies reported severe thunderstorm and lightning events accompanied by the advection of warm and humid tropical air related to southern cyclones, for example in Poland (Kolendowicz 1998, 2006, 2012; Bielec–Bakowska 2003) and in Finland (Tuomi and Mäkelä 2008). In Poland, the summer maximum daily air temperature has sometimes been related to southeasterly cyclonic airflow (Ustrnul et al. 2010). In Sweden, Hellstrom (2005) found that extreme rainfall events tended to be favoured by southerly winds, and weaker rainfall by westerly winds. Similar deduction was made by Gustaffson et al. (2010). Severe snowfalls caused by SCs were reported in Sweden (Bednorz et al. 2013). In Lithuania, the most extreme rainfall events were registered in relation with southern cyclones (Rimkus et al. 2011). In addition to severe weather, SCs are sometimes responsible for the transportation of Saharan dust to Europe (Isakov and Tikhonov 2010) and the inflow of warmer air which leads to more rapid melting of snow and ice in winter over the Azov Sea and the Strait of Kerch (Borovskaya and Lomakin 2008).

There are several studies that deal directly or partially with the trajectories and frequency of SCs over the eastern and northern parts of Europe (Belskaya 1949; Kannes et al. 1957; Kudryan 1981; Linno 1982; Pärn 1986; Bukantis and Bartkeviciene 2005; Sepp 2005; Post and Link 2007; Maslova 2010; Kaznacheeva and Shuvalov 2012).One of the first more detailed investigations of southern cyclones encompassing Estonia and northwestern Russia was carried out by Belskaya (1949), discovering that the highest numbers of SCs appeared at the end of winter and at the beginning of spring. The first detailed study of southern cyclones, made in Estonia and concentrated only on Estonian climate, was carried out by Kannes et al. (1957). Their work was based on the analysis of synoptic maps using five years' time period (1952–1956) and it discovered that southern cyclones comprise approximately 10% of all the cyclones affecting weather conditions in Estonia. They also mentioned that these cyclones mostly form over northern Italy and the Gulf of Genoa and are most frequent in spring. The high number of SCs in spring is caused by a remarkable contrast in temperature over southern Europe and the Mediterranean region. Contrary to that, Linno (1982) reported that more SCs appear in summer, and 26% of all cyclones emerge in the first half of summer. Linno (1982) also compiled the first map of cyclone trajectories which affect Estonia (Fig.1). Southern cyclone tracks are depicted as 5a, 5b and 5c; according to Linno (1982) and Pärn (1986), they comprise about 13% of annual total number of cyclones. By the same authors, approximately 80% of all cyclones affecting weather conditions in Estonia are western cyclones that originate from the Atlantic Ocean. Aforementioned studies about statistics of SCs in the context of Estonia are characterized by a very short time period (5–10 years). Link and Post (2007) have studied cyclones in the Baltic Sea region during 1948–2000 and found that approximately 10–15% of cyclones affecting local weather conditions move to the region from the southern side.

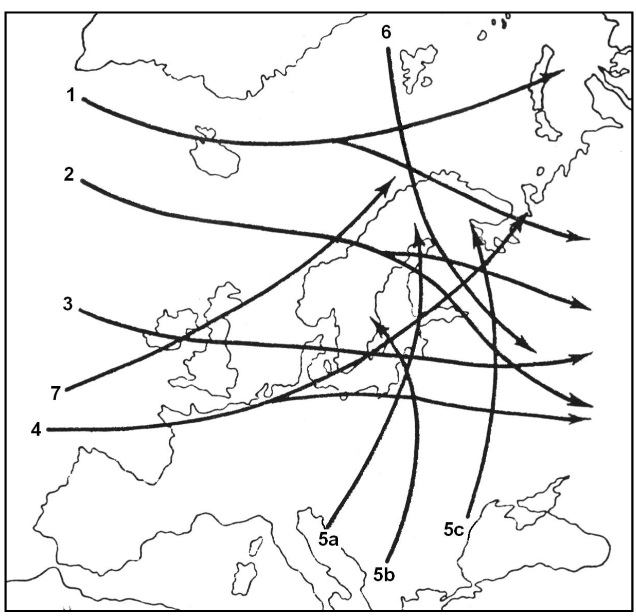

Figure 1. Main tracks of cyclones having an effect on weather conditions in Estonia (Linno 1982).

As in central and eastern Europe, SCs are frequently responsible for the most intense precipitation events in Estonia and according to Mätlik and Post. (2008), three highest daily rainfall amounts in Estonia have been caused by SCs.

In a general literature–based conclusion we can say that SCs, which are rather rare visitors in northern Europe, carry moist subtropical air northwards and thus have a great potential to induce severe weather events.

3. DATA AND METHODS

The climatologies of cyclones have often been performed using one of the two reanalysis projects – NCEP/NCAR (Kalnay et al. 1996) or ERA40 (Uppala et al. 2005) – to assess the observed changes in extra–tropical storm tracks and cyclone activity (Blender et al. 1997; Trigo et al. 1999, 2000; Simmonds and Keay 2000; Gulev et al. 2001; Chang and Fu 2002; Hoskins and Hodges 2002; Pinto et al. 2005; Wang et al. 2006). Some authors have compared different reanalysis databases (e.g., Hanson et al. 2004; Trigo 2006; Wang et al. 2006; Bromwich et al. 2007; Raible et al. 2008; Hodges et al. 2011; Tilinina et al. 2013) to detect similarities and to understand when one or the other should be preferred. Comparisons have found a higher number of cyclones in ERA–40 than in NCEP/NCAR, especially in summer, as well as a stronger deepening of cyclones in case of ERA–40 (Tilinina et al. 2013). According to Trigo (2006), interannual trends during 1958– 2002 were found to be consistent in the Euro–Atlantic sector in ERA–40 and in NCEP/NCAR. For data analysis in the current thesis, the database of cyclones, compiled and described in detail by Gulev et al. (2001) was used. The database consists of cyclone tracking output from six–hourly NCEP/NCAR reanalysis (Kalnay et al. 1996) of SLP fields with a 2.5°×2.5° spatial resolution for the Northern Hemisphere. The technique of the cyclone trajectory identification was developed by Grigoriev et al. (2000) at the Laboratory of the Ocean–Atmosphere Interaction and Monitoring of Climatic Environmental Changes of the Shirshov Institute of Oceanology of the Russian Academy of Sciences. It is based on computer animations of the SLP fields and, based on the animation, the operator determines the actual position of the centre of the cyclone. This semi–automated approach makes the procedure faster than manual tracking methods but still less dependent on the subjective view and mistakes of an operator. In the animation, the centre of a cyclone is identified using eight neighbouring grid points, described by the geographical coordinates of their centre and the sea–level pressure (SLP) at these points. This is superior to the identification of a minimum with respect to, for example, four grid points (Lambert 1996) or using the mean SLP over nine grid points minus a prescribed value, (usually 2 hPa, Serreze et al 1995). The semiautomatic procedure allows making the final decision by a human operator and detecting cyclone centres with an accuracy of 0.1°. All low–pressure systems with durations of less than 24 hours were originally excluded from the database (Gulev et al. 2001). It is necessary to emphasize that all four publications which constitute the core of this thesis, are based on the same database of cyclones. The definition of SCs varies depending on the area influenced. For the analysis of southern cyclones affecting weather conditions in Estonia, all cyclones which were formed south of 47˚N, east of 0˚ meridian, west of 60˚E and moved on their trajectory into the 1000 km radius circle (1–K circle) centred at 58.75°N and 25.5°E (Fig. 2, Publication I and II) were found in the database. The circle of 1000 km radius was used because, generally, the diameter of mid–latitude cyclones is 2000 km

(Ahrens 1994; Sumner 2006), as mentioned before, and while the centres of these pressure systems move on the edge of this circle, then the edge of the cyclone reaches to the areas in the central point of the circle and affects weather conditions over these areas. Although the centre of the 1–K circle is located in the central point of Estonia and most of deductions are valid for Estonia, this circle encompasses a large part of northern and central Europe and, therefore, the results are applicable for a much wider area than Estonia.

To assess the influence of SCs on the whole of northern Europe, SCs are defined as low pressure systems that had formed south of 50°N, east of the 0° meridian and west of 60°E (Fig. 2, Publication III). The border 50°N was chosen because in this case, the region of formation of southern cyclones covers the Mediterranean, the Black Sea and the Caspian Sea regions. This latitude generally runs along the mountainous areas of central Europe (the Carpathian Mountains, the Sudetes, the Harz). The 0° meridian was used as the western border to eliminate cyclones, which have formed over the Atlantic Ocean. The eastern border of the generation area of southern cyclones – 60°E runs along the Ural Mountains forming also the eastern border of the European continent and is acting as a natural obstacle for cyclones. To classify low pressure system as SC, in addition to the defined formation area, this cyclone should cross the latitude 55°N, which also runs approximately along the southern coast of the Baltic Sea. This could generally be estimated as the southern border of northern Europe. To describe the trajectories of SCs in more detail in northern Europe, the area north of 55°N was divided into six sectors with 10 degree longitude intervals (Publication III). The first sector was 0°–10°E and the last one 50°–60°E (Fig. 2). To understand the specificity of SCs, they were compared with all cyclones that had formed over the Mediterranean, the Black and Caspian Sea regions east of the 0° meridian, west of 60°E, south of 50°N and did not cross 55°N. These low pressure systems are called the cyclones of southern seas (CSS, Publication III). In both of these groups, the cyclones were analysed by frequency, duration and SLP.

Additional attention was paid to low pressure systems (not only SCs), which formed outside the 1–K circle and moved into that circle with mean SLP below 1000 hPa and which were defined as relatively strong cyclones. The 1000 km radius circle was used to detect all distant cyclones for northern Europe. Strong cyclones often affect the results of trend analysis. SLP of these cyclones differ significantly from others. The cyclones with mean SLP below 981.1 hPa were analysed separately and defined as strong ones. These low pressure systems comprise 10% percentile of mean SLP of all cyclones (Publication IV).

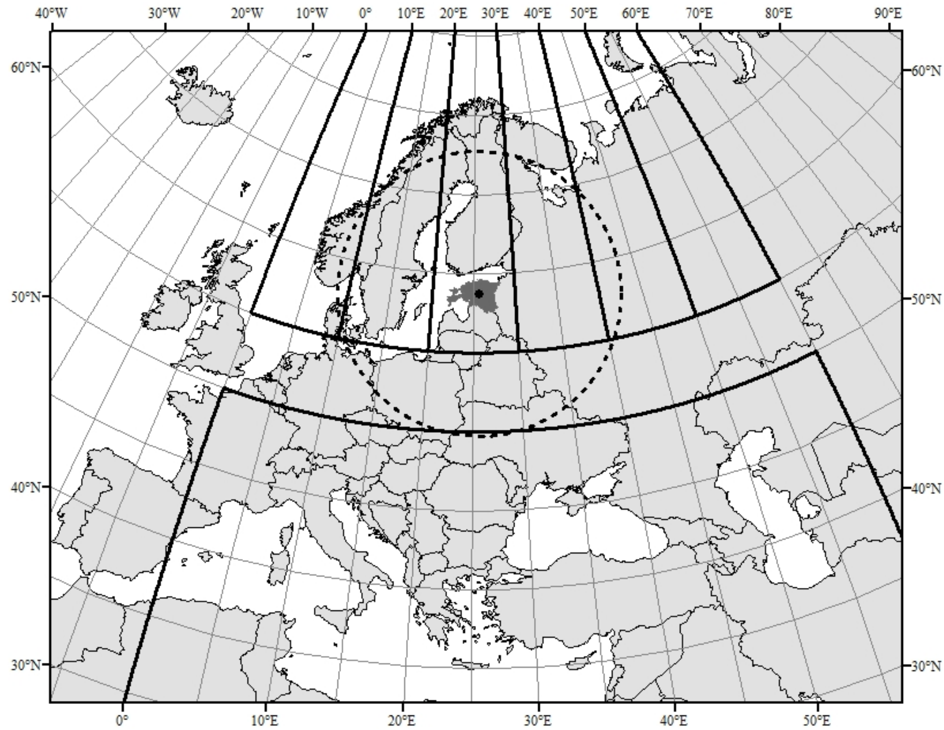

Figure 2. Estonia, 1–K circle centred in Estonia with its centre point at 58.75°N and 25.5°E, the formation area and study area of southern cyclones for six sectors between 0°–60°E north of 55°N.

The main cyclogenetic areas were detected for cyclones with mean SLP below 1000 hPa. The parameters of cyclones under analysis were their frequency, duration, mean and minimum SLP in the center of the cyclones. The areas of origin of all low pressure systems moving to northern Europe were analysed during 1948–2010. The analysis was performed for three 21–year time periods (1948–1968, 1969–1989 and 1990–2010), in the cold half–year (October–March) and in the warm half–year (April–September) in 100 x 100 km grid boxes (Publication IV). Two equal–length half–years were defined to compare the total number of cyclones in the warm and cold time period of the year. Another possibility to divide months into half–years is from November to March (cold) and from April to October (warm). This approach is justified when precipitation is under analysis and this distribution would describe snow and sleet in the cold half–year, and rain in the warm half–year. It should be noticed, that half–years are defined a bit differently in Publication IV because we did not analyse precipitation in this section, so the equal–length half–years were chosen. In order to describe seasonal variability, the cyclones were divided into winter (DJF), spring (MAM), summer (JJA) and autumn (SON). If a cyclone emerged at the turn of two months, the month of its formation was used.

Spatial distribution of the origin areas of cyclones heading into 1–K circle was studied by using k–means cluster analysis (Publication IV). According to this method it is essential to define the number of clusters. This is a critical point in further analysis. The algorithm applies to the number of clusters and divides all locations of origin of cyclones into a defined number of clusters. Many tests were compiled to evaluate the number of clusters (Steinley 2006), but the final decision still remains subjective and it is determined by the needs and purposes of a certain study (Jain 2010). After several tests by using macro XLSTATPro, twelve classes were chosen as the appropriate amount and the locations of these clusters partly or mostly lay in the more intense formation areas of cyclones. It is known that near the pole meridians converge. Distributing formation points of cyclones into clusters by k–means method, the distance of every point from the neighbouring point is essential. To get the right distances between the origin points of cyclones near the polar region, Bonne pseudo–conic projection was applied. This clustering is in more detail described in Publication IV.

Performing the analysis of the temperature and precipitation that SCs might bring along into Estonia, SCs were divided into two classes according to their trajectories (Publication I). The first class included the cyclones that moved from the south to the north, passing Estonia of the west, and crossing the Baltic Sea and/or the Scandinavian Peninsula. Low pressure systems that moved from the south to the north and passed by the eastern side of Estonia (moved over Russian areas) were in the second class. The border between these classes was chosen to be 25°E. This longitude approximately bisects the Estonian territory. It was assumed that SCs, which are in the first class, bring warmer air to Estonia from the south, and cyclones belonging to the second class are related to the advection of colder air from the north.

Daily mean air temperature and daily precipitation data from 10 meteorological stations were used to analyse the influence of southern cyclones on weather conditions in Estonia (Fig 2 in Publication I). The used stations are located in different parts of Estonia and all of them had continuous series of measurements available. It was assumed that the meteorological data were reliable and homogeneous for the period under observation. The stations were chosen in the way that they would cover more or less evenly the whole territory of Estonia, and cover all the main regions where local climate variations are important. The choice and distribution of stations should be representative in order to describe air temperature and precipitation all over Estonia.

As reported by Paciorek et al. (2002), it is hard to assess the extent to which the passing cyclones have an effect on the monthly or seasonal mean air temperature because differences between individual cyclones are pretty large. Analysis of the influence of SCs on air temperature in Estonia was also rather complicated. At first, mean daily temperature of the day when a SC was at its nearest point to Estonia was found. Secondly, the mean temperature of the two previous days from the date when a SC was observed at its nearest location to

Estonia was calculated. The temperature change induced by SC was calculated at every station as the difference between the temperature of the day when SC was at its nearest point and the mean temperature of the two previous days. Finally, the calculated temperature anomalies were averaged over the 10 stations and 54 years (1951–2004), because this was the longest available time series of cyclones in the database (Publication I).

In precipitation analysis, daily data for every day when a SC was located inside the 1–K circle during the period 1948–2004 were taken into account (Publication I). The mean annual and seasonal rainfall associated to SCs was calculated for each station. Also the maximum 24–hour rainfall was found for each station. Sometimes two SCs were located within the 1–K circle at the same time and in this case it was not possible to determine, which of them had caused rainfall in Estonia. In such cases the same daily precipitation was taken into account for both low pressure systems. As a result, there were minor variations in the total values of precipitation, depending on whether the values were found by cyclones or by days with precipitation per month. Low pressure systems which had brought daily precipitation above 10, 5, 2, and 0 mm, and those without any precipitation were counted. Calculations were made for all SCs, and separately for cyclones of both classes depending on whether the cyclone passed either west or east of Estonia.

While SCs are one of the major sources of severe weather events, another objective of the analysis was to determine the relationships between SCs and thunderstorms in Estonia (Publication II). For that purpose there were used visual observations of thunderstorms at five Estonian meteorological stations to examine thunderstorms during 1950–2010. The stations are located at different climatic conditions: maritime (Vilsandi), coastal (Tallinn, Pärnu) and continental (Tartu, Võru). The used time series of thunderstorms are the longest in Estonia. The data about thunderstorm observations originated from the Estonian Weather Service. Records of visual datasets consist of the starting and ending times of all registered thunderstorms. The beginning of a thunderstorm is registered when the first clap of thunder is heard by the observer. The end of a thunderstorm (thunder event) is recorded 15 minutes after the last sound of thunder heard by the observer. The quality of visual thunderstorm observations has been discussed in detail by Reap and Orville (1990) and Enno et al. (2013).

For a more detailed analysis, in addition to 1–K circle, 500 km–radius circles were generated around each meteorological station. The SCs were additionally divided into groups depending on the minimum distance (0–500 km and 500–1000 km) from their centres to each station. For each SC in those groups it was identified whether they passed the station from the western or eastern side. To detect the relationships between thunderstorms and SCs, the dates of SCs in the 1–K circle were compared with the thunderstorm data from five stations (Publication II). If a thunderstorm was observed at least at one station on the same day, this event was registered as a thunderstorm day (TD). If a SC was determined in the 1–K circle on a TD, then that day was considered to be related to the SC (SCTD). One SC may often cause TDs on several subsequent days because a SC can stay in the 1–K circle for more than one day. SCs which were associated to thunder were defined as thunder–related SCs. All these thunder events were analysed on the annual, seasonal and monthly basis. Special attention was paid to the thunder season from April to October when about 99 per cent 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.

Analysis of the relationships between SCs and the appearance of lightning in Estonia was performed (Publication II). The automatically registered lightning database originates from the NORDLIS lightning detection network and was obtained from the Estonian Weather Service (Enno 2011). The used time period is 2005–2010 and the database contains the total of 361 688 registered cloud–to–ground flashes. The lightning detector started to work on the Estonian territory in 2005. During the data analysis the dates of SCs located within the 1–K circle were compared with the data of lightning strikes in Estonia. When lightning was observed by the NORDLIS network in Estonia on the same day when a SC was in the 1–K circle, this event was taken into account as a lightning caused by the SC. For comparison, we calculated the daily mean counts and percentiles of cloud–to–ground lightning strikes for SCTD and for other thunder events during 2005–2010.

In order to analyse long–term trends in the parameters of SCs, CSSs, temperature, precipitation, thunder and lightning, it was first checked whether the distribution of a particular variable can be approximated with a normal distribution by using the Shapiro–Wilk test (Shapiro et al. 1968). If the test value W was higher than 0.05, the time series was considered as normally distributed. In case of a normal distribution, linear regression analysis with the Student's t–test (Eisenhart 1979) was used for the trend analysis. Trends were considered statistically significant at the 95% level ($p \leq 0.05$). The Mann–Kendall test was used in case of a non–normal distribution (Mann 1945; Kendall 1975). A trend was regarded as statistically significant when the Mann–Kendall statistic (MK) was ≥1.96. In case of non–normal distribution, the slope was calculated using the Sen's method (Sen 1968). Changes by trend were found by multiplying slopes with the number of years. In case of analysing relationships between SCs and thunderstorms in Estonia the non–parametric Mann–Whitney U test (Mann and Whitney 1947) was used for the evaluation of significance of the difference between the parameters of the SCs–related thunder events and the parameters of other thunder events. When the test value was below 0.05, the difference was considered as statistically significant. Additionally, correlation analysis (Rodgers and Nicewander 1988) was performed between the different characteristics of SCs and CSSs, between thunderstorms related to SCs and other thunder events. The correlation was considered to be material if significance exceeded 95% level. Usually correlation coefficients with a value ≥ 0.25 had this significance.

4. RESULTS

4.1. Climatology of southern cyclones

Results of Publication III showed that during 1948–2010, altogether 19412 CSSs were formed. Therefore, over southern Europe, the average of 308.1 CSSs were observed per year. During the same time period, 1926 SCs formed in same region, but moved significantly northwards, crossing 55°N, and reached to the northern part of Europe. Thus there were 30.6 SCs per year, which means that 9.9% of all low pressure systems formed over the southern seas moved to farther north in their trajectory (Fig. 2 in Publication III). The correlation coefficient between SCs and CSSs shows a significant relationship (r = 0.35) on the 99% level.

In the time period 1948–2004, 8.9 SCs per year entered the 1–K circle. Much more SCs passed east of Estonia (ESCs, approximately 2/3) than west of Estonia (WSCs). On the average, a SC spent about 1/3 of their lifetime within the 1–K circle.

The highest number of SCs has formed over the northern areas of the Mediterranean and Black Sea regions (Fig. 3 in Publication III). In the Caspian Sea region, the SC formation areas are showing more or less uniform distribution. The highest amounts of SCs have formed over northern Italy and its neighbouring areas. It is visible that SCs tend to form closer to 50°N, the northern border used for defining lows as SCs. In rare cases, cyclones were originated from the southern part on the Mediterranean Sea.

A rather similar area of origin of the cyclones that have formed over southern Europe and moved into the 1–K circle is visible in clusters 11 and 12 (Figure 2 in Publication IV). These clusters together are somewhat larger in their spatial extent than the origin area of SCs in Publications I, II and III. The total number of stronger cyclones with mean SLP below 1000hPa in these clusters was 451 or 7.2 per year during 1948–2010, which comprises 20.6% of all the studied cyclones with mean SLP below 1000 hPa entering the 1–K circle.

In clusters 11 and 12, generally representing SCs, the total amount of cyclones and their mean SLP are relatively higher and the duration somewhat lower than in cyclones which formed in other clusters over the Atlantic Ocean (Table 2 in Publication IV). If to consider not only stronger SCs with mean SLP below 1000 hPa but all SCs, the proportion of SCs entering to 1–K circle is approximately 10% of all cyclones. On seasonal basis, the largest annual mean number of SCs heading to northern Europe and crossing 55˚N in 1948–2010 was observed in spring (9.6) and a slightly smaller number in summer (8.9). In autumn and winter, the total number of SCs was much lower. Monthly distribution shows the uniformly highest counts of SCs in April, May and June. More than 10% of the total number of SCs was detected during each of these three months. Similar intra–annual distribution of SCs appeared in the 1–K circle. Monthly distribution in the percentage of the total number of SCs and CSSs achieved the highest value in April and decreased month by month after that.

Analysing SCs by sectors in northern Europe, it is clear that their number and duration increases, and their mean SLP decreases from the west to the east (Table 1 in Publication III). The number of the SCs having crossed 55°N to the west of the 0° meridian was marginal compared to the total number of SCs. In every next sector, a much larger number of cyclones was detected, reaching the highest counts in the easternmost sector >60°E. The second largest number of SCs was detected in the sector 20°–30° corresponding to the Baltic Sea region. It can be said that approximately 25% of all SCs crossed 55°N far in the east, on the other side of the Ural Mountains.

The mean lifetime of SCs has been 130.6 hours (Table 1). Comparing with the duration of CSSs (65.1 hours) in southern Europe, this is much longer. The difference in the duration between SCs and CSSs is approximately twofold, in many years even more (Fig. 5 in Publication III). This makes sense because SCs are usually distinctively stronger than other CCS (Publication III) and therefore can follow a much longer trajectory. In their later life cycle, these cyclones will probably be part of westerly flow, while it is easier for them to move towards the east, which may in some sense prolong their life span. In southern Europe, most of the cyclones do not travel long distances. Generally, they decay over the same region where they have formed. In case of SCs, the inter–annual fluctuations in duration are much higher and clearly distinguishable comparing with the CSSs. In some cases, SCs last for an extremely long time. For example, on 25th July 1996, a SC formed with the longest registered lifetime of 23.5 days.

Table 1. The mean number, duration and SLP of SCs crossing 55˚N during 1948–2010 and SCs entering the 1–K circle during 1948–2004. For the latter, their duration in the 1–K circle is presented. Significant changes (95% level) are marked in boldface. Annual mean duration and SLP are based on daily data and differ from the mean over seasons.

	Mean number	**Mean duration (h)**	**Change (h)**	**Mean SLP**	**Change (hPa)**
SCs	30.6	130.6	–5.3	1001.2	0.4
Winter	5.4	113.5	1.2	1000.7	–0.9
Spring	9.6	130.8	–8.3	1001.5	0.2
Summer	8.7	145.1	**–31.2**	1001.4	1.2
Autumn	6.7	124.5	1.3	1001.4	–0.4
SCs in 1–K circle	8.9	44	–3.7	1000.8	**3.6**
Winter	1.4	36.7	–5.1	998.5	**6.6**
Spring	2.7	42.9	–0.7	1001.3	–1.6
Summer	2.6	46.8	–4.4	1001.9	**3.8**
Autumn	2.1	42.2	–4.6	999.9	4.4

The highest seasonal duration of SCs was observed in summer when their average lifetime was 145.1 hours. The lowest duration of SCs was detected in winter (113.5 hours). Similarly, the highest monthly duration values were detected in May, July and August. This means that SCs last longer in the warmer part of the year. In the 1–K circle, there was detected a similar intra–annual duration distribution of SCs, which directly affect weather conditions in Estonia.

The frequency of the duration of SCs in percentage shows that more than 1/3 (36%) of cyclones is lasting 90–138 hours (Fig. 6 in Publication III); 31 cyclones had lasted even more than 312 hours (13 days). On the contrary, more than half of CSSs had the duration of up to two days and approximately 75% of them up to three days. The life span of CSSs only rarely extends to the length that is average for SCs.

If we examine the SCs in northern Europe by sectors, then the mean annual duration of SCs crossing 55N west of 0 meridian was relatively low (108 hours). Moving from the west to the east, the average annual duration of SCs increases sector by sector and reaches the maximum mean duration of 144.2 hours in the SCs moving east of 60° E (Table 1 in Publication III).

The mean annual air pressure in the central point of SCs was 1001.2 hPa during the period 1948–2010. In CSSs, it was much higher – 1006.4 hPa. No correlation was detected in mean and minimum SLP between SCs and CSSs. Mean SLP of the majority of SCs was between 995 and 1000 hPa, while the highest frequency of CSSs had an average air pressure between 1005–1010 hPa (Fig. 8 in Publication III). The largest overlap between SCs and CSSs was in the 1000–1005 hPa range, but in SCs, it was in the shallower part of the cyclones, while in the case of CSSs, it was in the deeper part.

The value of average minimum air pressure of SCs in same time period was much lower– 993.8 hPa – than in mean SLP. In CSSs, it was significantly higher – 1002.9 hPa. It can also be pointed out that in 50 of the 63 study years the minimum air pressure of the deepest cyclones was lower in case of SCs compared to CSSs. Percentage distribution is given in Fig. 10 in Publication III. The most remarkable difference indicates that 72% of CSSs had a minimum SLP above 1000 hPa, while 75.9% of SCs had a minimum SLP below 1000 hPa.

Seasonally, the deepest SCs were detected in winter, when the mean annual SLP of SCs was 1000.7 hPa. In other seasons, this value was uniformly higher. The lowest monthly mean air pressure of SCs was observed in December, while the highest value was observed in May and September. Similarly, the most severe SCs with the lowest SLP were found among the SCs which entered the 1–K circle during winter. In CSSs the intra–annual distribution of mean SLP is opposite; the deepest cyclones appeared in summer months and the weakest at the end of autumn and in winter (Fig. 3).

Most of SCs have minimum SLP near to their formation areas or slightly after formation (Figure 11, Publication III). Moving away from the formation areas, the frequency of the deepest points of the SCs is decreasing. The highest total numbers of SCs that have had a minimum SLP can be found over the eastern part of the Alps, the Carpathian Mountains, Central and Eastern Ukraine, and over the northern part of the Caspian Sea region.

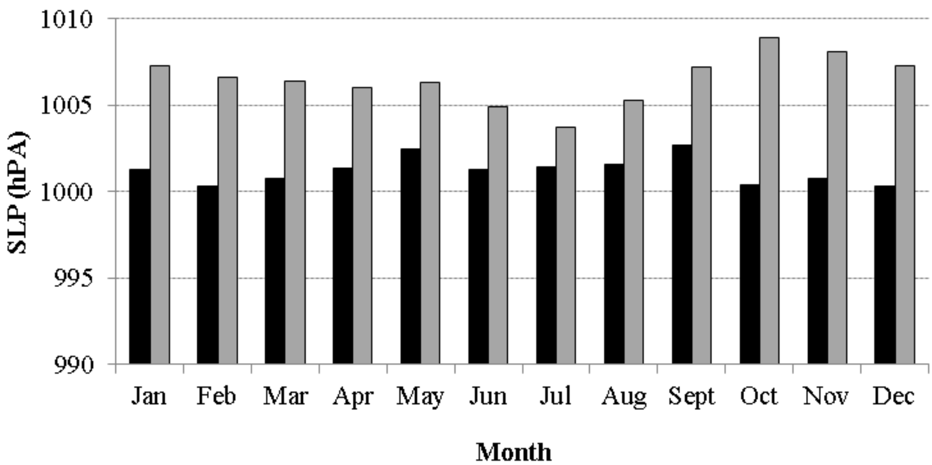

Figure 3. Mean monthly SLP of SCs (black) and CSSs (grey) during 1948–2010.

In northern Europe, the annual mean SLP of SCs was higher in the western sectors (Table 1 in Publication III) and lower in the eastern sectors (east of 30°E) of the study region. There is a large difference in mean annual SLP between the westernmost and easternmost sectors. The lowest average annual SLP was in the sector 50–60° E, which basically lies directly on the western side of the Ural Mountains. The annual mean minimum SLP decreases gradually by sectors from the west to the east, reaching a minimum mean value in the sector east of 60°E, which indicates that SCs are more intense in the eastern part of the study region.

4.2. Formation regions of cyclones

On the background of SCs, most of low pressure systems, which design weather conditions in northern Europe, approach from the west. Considering all the cyclones, during 1948–2010, the total of 7702 cyclones entered the 1–K circle (with cyclones formed inside the 1–K circle). About 3600 of them had mean SLP higher than 1000 hPa. Almost half of them had formed inside the circle, mainly over the central part of Sweden, on the eastern slopes of the Scandinavian mountains and over the Gulf of Bothnia (Fig. 4). The maximum density of cyclone formation was more than 100 cyclones in 100×100 km grid boxes per whole period analysed. After removing low pressure systems which had formed inside the 1–K circle (mean SLP was higher than 1000 hPa), 2185 relatively strong cyclones remained that had been formed farther off and entered the 1–K circle. The mean annual number of cyclones that had formed outside and then entered to the 1–K circle was 34.7 The analysis shows that a large part of low pressure systems moving to the Baltic Sea form directly on the border of the 1–K circle. Such aggregation is inevitable if a fixed area is used, because cyclones which form near to the border have a much higher probability to move into the circle (Sepp and Jaagus 2011). According to this fact, the largest number of low pressure systems was formed over the North Sea, the total reaching up to 55 in the same grid boxes during the study period. Other slightly less active major cyclogenetic areas were located near Iceland, over the Norwegian Sea and over the northern part of Italy with the Gulf of Genoa and the Adriatic Sea (Figure not shown; pattern is similar as in cold half–year in Fig. 5).

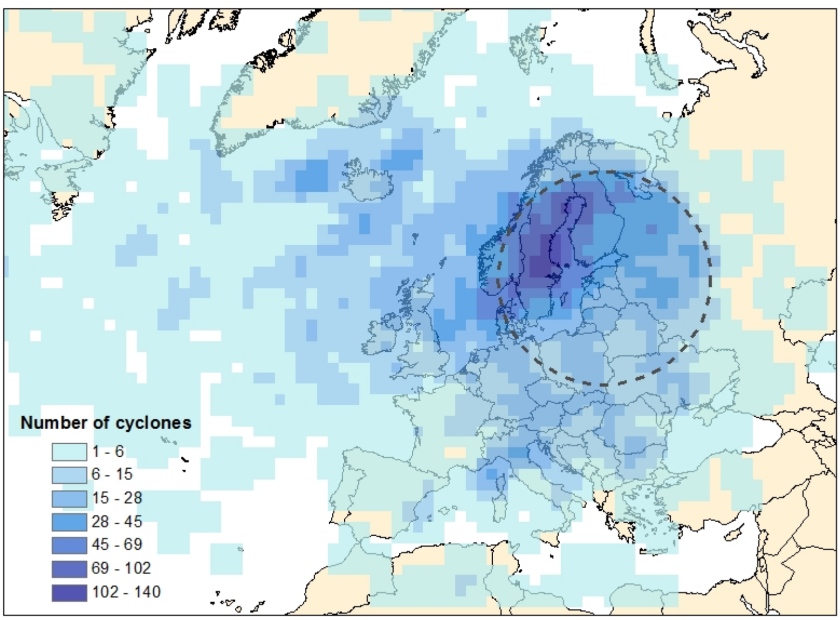

Figure 4. Formation areas and frequencies of cyclones entering to the 1–K circle and also forming inside the circle during 1948–2010.

In the cold half–year, the main formation areas of cyclones are located over the Atlantic Ocean (Fig. 5). Generally, the distribution is similar as in the whole year, but frequencies are different. Active cyclogenetic areas are located over the North Sea, near Iceland and those with a slightly lower number of cyclones over the Norwegian Sea. At the same time, the formation of a much smaller number of cyclones was detected in southern Europe with the only notable activity over the northern part of the Adriatic Sea. In the warm half–year, however, the cyclogenetic areas are mostly concentrated to southern Europe.

The most active and wide generation area of cyclones is located near northern Italy, also encompassing the surrounding areas. The only remarkable formation region of cyclones in northern Europe is located over the Norwegian Sea. In the cold half–year from October to March, 21.8 cyclones per year formed outside the 1–K circle and in the warm half–year, the annual number of cyclones, which entered the circle was about two times lower. Different areas of cyclogenesis dominate in different 21–year periods (Figure 2 in Publication IV).

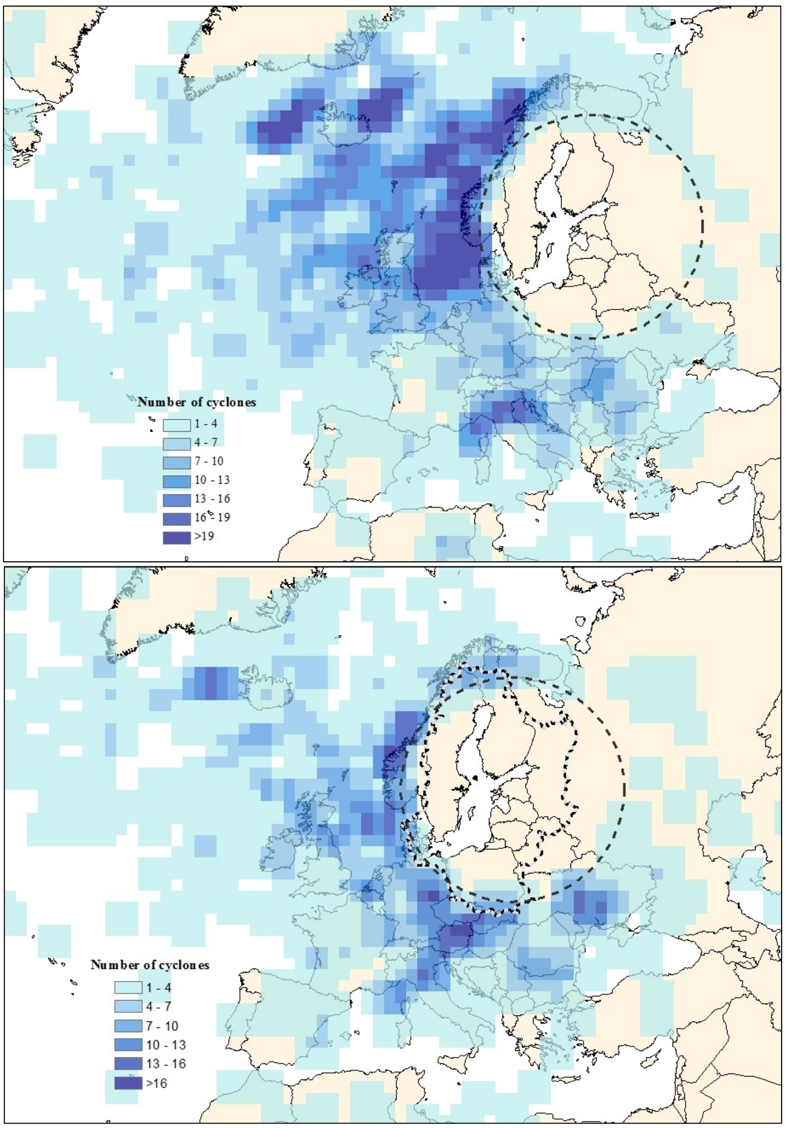

Figure 5. Main formation areas and frequencies of cyclones entering the 1–K circle in the cold half–year (above) and the warm half–year (below) during 1948–2010.

The annual average lifetime of these cyclones was been 129.5 hours. The longest–living cyclones originated from west of North America, from its eastern coast and from the southwestern and central parts of the North Atlantic (Figure 2, Publication IV). The number of cyclones, the duration, mean and mean minimum SLP of all low pressure systems entering the 1–K circle show notable differences in different seasons and during the 21–year time periods (Table 2).

Table 2. Number of relatively stronger cyclones, mean duration, mean SLP, mean minimum SLP per year in cyclones headed into the 1K–circle in northern Europe in the time period 1948–2010.

	Nr of cyclones	Mean duration (h)	Mean SLP (hPa)	Mean min SLP (hPa)
All cyclones	34.7	129.5	991.6	980.9
Warm half-year	12.8	147.7	995.3	986.2
Cold half-year	21.8	118.3	989.3	977.8
Winter	11.1	109.5	988.8	976.9
Spring	8.1	134.0	993.4	983.1
Summer	5.8	158.4	996.3	988.0
Autumn	9.7	134.7	990.8	979.8
1948-1968	34.8	134.9	992.7	982.6
1969-1989	34.3	124.0	991.3	980.7
1990-2010	35.0	129.5	990.6	979.6

Generally SCs constitute 10% of cyclones, which form over southern Europe and also 10% of cyclones entering the 1–K circle in northern Europe. SCs are more durable and more powerful than CSSs. Seasonally they are more intense in winter, while CSSs are having lowest mean SLP in summer.

4.3. Influence of southern cyclones on weather in Estonia

It is possible to assume that WSCs cause an increase in air temperature in Estonia. This might happen due to the advection of warm and potentially tropical air, which is located in the eastern part of the cyclones, where southerly winds prevail. At the same time it can be assumed that ESCs cause a cooling due to the advection of cold arctic air. This appears because Estonia is situated at the western part of these cyclones characterized by northerly flow of air. Different trajectories cause opposite effects of SCs on temperature, therefore thermal effects caused by SCs were detected separately for both of these cyclone classes (Table 3).

Table 3. Mean temperature change and precipitation brought by WSCs and ESCs during 1948–2004.

	Mean temperature change (˚C)	Change by trend	Mean precipitation (mm)	Change by trend
WSCs	0.3	0.2	23.4	–2.4
Winter	0.3	–2.1	2.2	–1.4
Spring	0.4	–0.5	4.6	4.3
Summer	0.8	2.2	9.8	–1.6
Autumn	0.3	0.4	6.7	1.9
ESCs	–0.4	–0.3	45.8	–8.6
Winter	0.1	–2.0	3.8	1.3
Spring	–0.5	–1.5	9	4.6
Summer	–0.3	–0.1	20	–1.5
Autumn	–0.6	0.9	11.9	1.7

As it was expected, WSCs were associated with the temperature increase in Estonia. The largest mean warming was in summer and the smallest in autumn and in winter. It should be pointed out that the observed temperature changes were highly variable. 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 ESCs was about 0.5 °C, but it varied also considerably for particular cyclones. The highest temperature increase (9°C) due to ESCs was observed on 27 February 1958, and the highest decrease (5.6 °C) detected on 17 December 1965. The seasonal analysis did not show trends in mean temperature caused by SCs. In general, SCs influence on air temperature depending on their direction of passing Estonia is not as clear as expected.

In earlier studies it was indicated that SCs are related to the incidence of heavy precipitation events. Using the data from the 10 meteorological stations it was found that the mean annual amount of precipitation measured on days when a SC was located within the 1–K circle around Estonia was 69.2 mm. Therefore SCs have caused 11.1% of the long–term mean annual precipitation at these stations.

As the number of ESCs was almost two times higher than the total count of WSCs, the detected total precipitation amount differs in same magnitude (Table 3 in Publication I). The highest mean precipitation per year that was related to SCs was detected at Võru (77.6 mm). In general, higher precipitation amounts were in southeastern Estonia, and lower precipitation occurred in the western Estonian archipelago (Fig. 7 in Publication I). The mean annual precipitation related to SCs was extremely variable at all these stations.

The mean daily precipitation related to a SC was 2.6 mm. The maximum daily rainfall caused by SCs was recorded at Ristna on the west coast of

Hiiumaa (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 SCs were the highest in summer and the lowest in winter. This difference is manifold and corresponds to the seasonal distribution of precipitation in Estonia (Table 3 in Publication I).

On 84% of the days when a SC was located within the 1–K circle, there was some precipitation in Estonia. On average, light daily precipitation of ≥2 mm was recorded in 59.2% of SCs, moderate precipitation ≥5 mm in 39.5% of SCs, and very strong precipitation ≥10 mm in 18.7% of cyclones. Precipitation related to SCs was significantly higher in continental Estonia (Tiirikoja, Tartu, Võru, Viljandi, Türi) and lower at the coastal stations (Vilsandi, Tallinn, Ristna, Pärnu).

In the time period 1950–2010, the total of 545 SCs was detected in the 1K–circle; 159 SCs (29.2%) of them had induced a thunderstorm in Estonia. This represents cases when a SC was detected in the 1–K circle and a thunderstorm was observed at least at one station in Estonia on the same day.

In total there were 2106 TDs during the study period, 239 of which (11.3%) were thunder days related to SCs (SCTDs). While on 107 days the SC–related thunder was observed at only one station, then on 13 days thunder appeared at all five stations. The mean annual number of SCTDs was 3.9. The mean number of TDs without SCs, when thunder was detected at least at one station was 30.6 per year. At single stations, this number was significantly lower. The largest total numbers of SCTDs were recorded 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 in Publication II), comprising 9.4% of the mean of all TDs registered during the study period. This proportion was the highest in Võru (11.3%) and the lowest in Vilsandi (8.4%).

In more than 2/3 of the SCTDs cases, the centres of SCs were closer to the stations than 500 km. Most of the thunder–related SCs that stayed farther, i.e. at a distance of 500–1000 km, passed Estonia from the west. The total number of SCs closer to the stations than 500 km was 185, and the number of SCs within the 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 in Publication II) demonstrates a sharp maximum in summer. The highest counts were recorded in July. Similarly high numbers of SCTDs were detected in other summer months as well. 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.

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

The total duration of SC–related thunder events in 1950–2010 comprises 9.3% of the summary duration of all thunder events. 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 of other thunder events averaged by the five stations were 3.2 and 31.1 h, respectively. Interestingly, the mean durations of SC–related thunder events were generally higher than those of other thunder events at all stations, with the exception of Võru (Table 3 in Publication II). It is remarkable that the mean duration of thunderstorms in Vilsandi is clearly longer than at other stations.

As a rule, thunderstorms lasted longer when the central point of a SC passed Estonia at a distance less than 500 km. In ESCs at a distance closer than 500 km of a station, the duration of thunderstorms was mostly longer than with WSCs. The mean duration of thunderstorms did not vary much among the stations. The longest mean annual sum of durations, 4.5 hours, was obtained for the Vilsandi station in the ESCs at the distance interval of 0–500 km (Table 2 in Publication II). The longest SC–related thunderstorms were observed in Vilsandi on 1 July 1970 (9 h 12 min, WSC).

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 in Publication II). Relatively longer SC–related thunderstorms have been observed in Vilsandi in August in 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%.

Comparing the data from the NORDLIS lightning detection network (686 days) with the appearance of SCs (62 days) in the 1–K circle, during 2005–2010 much higher lightning counts were found on SCTDs than on TDs not related to SCs. The average count of SC–related lightning strikes was 1481 per TD. In case of 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 related to SCs were much higher in many years. In 2009, the number of SC–induced lightning strikes was almost ten times higher than that of the lightning strikes caused by other thunder events (Fig. 7 in Publication II). The highest count of lightning strikes per day was also registered for a SC on 13 June 2009, reaching to the value 14056.

The Mann–Whitney U test showed that the difference between the number of lightning strikes induced by SCs and other thunder events is statistically significant ($p < 0.05$). Percentiles of lightning strikes caused by SCs are much higher (Table 4, Publication II), especially the highest percentiles (90th, 95th and 99th) of SC–induced thunderstorms, which are more than 4 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.

4.4. Long–term changes

There have been many changes in SCs entering the 1–K circle and crossing 55°N in northern Europe. In sector >60°, the number of SCs was increased by 2.6 (MK=1.97; Fig. 6). Still there were no trends in the frequency of SCs over the Baltic and Scandinavian areas. In summer, the mean duration of SCs, which had formed over southern Europe and moved north of 55˚N, was decreased by 31.2 hours ($p<0.05$). There was a decrease in mean annual duration of SCs in northern Europe east of Estonia in the sector 30–40°E, by 30.2 hours (MK = 2.55) and in the sector 40–50°E, by 41.1 hours (MK = 1.98).

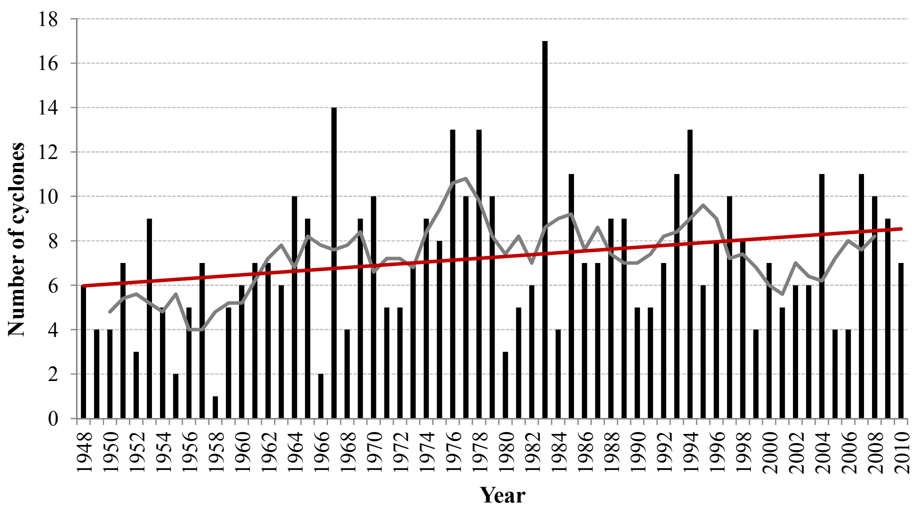

Figure 6. Annual number of SCs and its five–year moving average in the sector >60°E with its linear trend ($p<0.05$) in 1948–2010.

Generally, on the background of SCs, a significant deepening was found in all cyclones that were formed at a distance and entered the 1–K circle during 1948–2010. In whole study period, the mean SLP and mean annual minimum SLP had decreased by 2.9hPa ($p<0.001$) and by 4 hPa ($p<0.001$) correspondingly in the center of these cyclones (Figure 4 in Publication IV). Intensification of cyclones of the same magnitude has occurred in the cold half–year and even cyclones in the warm half–year have become more powerful in time. Both strong (10th percentile) and relatively strong cyclones (mean SLP <1000 hPa) have decreasing trends in mean and minimum SLP. Of all the cyclones, the low pressure systems in cluster 12, which generally represents SCs formed over the eastern Mediterranean, the Black Sea and the Caspian Sea and entered the 1–K circle, have become more intense also. Their mean and minimum SLP have decreased respectively by 2.7 hPa ($p<0.05$) and 4.9 hPa ($p<0.05$).The SCs moving to farther east of the Ural Mountains in the sector >60°E have specifically intensified. The mean annual minimum SLP of these cyclones shows the highest decrease by 6.7 hPa ($p<0.05$) (Fig. 14 in Publication III). Similarly, a statistically significant decrease in minimum annual SLP of the deepest SCs was 7.4 hPa (MK=2.39; Fig. 7). Hence, the deepest SCs and those in the easternmost class have started to become more powerful. However, it should be noticed that inside the 1K–circle, the SLP at the tracking point nearest to Estonia and the mean SLP of SCs have increased by 3.6 hPa (MK=2.6), which indicates a weakening of SCs near Estonia and in the Baltic Sea area. A similar weakening of SCs was found west of Estonia in the sector 10°–20°E, where the mean SLP increased by 4.0 hPa (MK=2.81). In addition to that, mean annual SLP shows an increasing trend by 2.2 hPa ($p<0.05$) in the sector 30°–40°E, which lies directly east of Estonia.

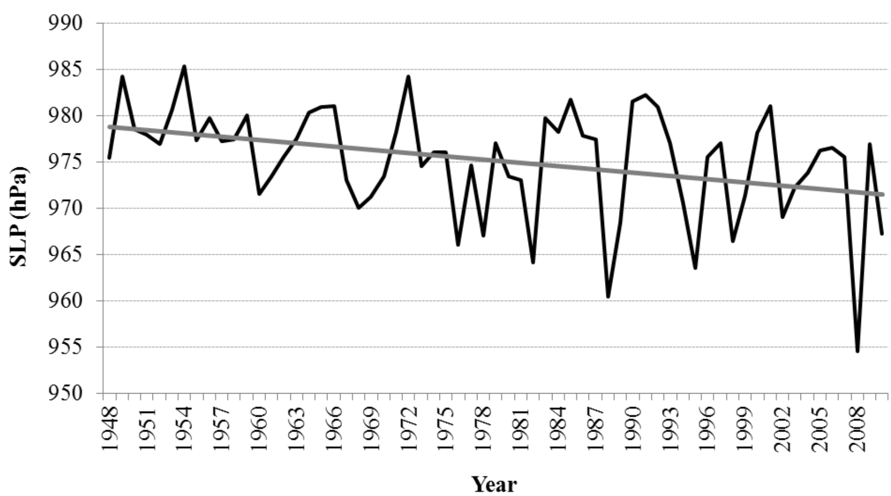

Figure 7. Minimum SLP of the deepest SCs with their linear trend in 1948–2010.

Several significant trends were detected in precipitation totals related to SCs at individual stations. The most significant decrease in total precipitation was found in summer. This trend was statistically significant at three coastal stations (Tallinn: –22 mm, MK = 2.6; Ristna: –27 mm, MK = 2.6; Vilsandi: –19.8 mm, MK = 2.4), and comparing with WSCs, the decreasing trend was much stronger in ESCs. Annual mean precipitation related to SCs had decreased in Vilsandi by 0.8 mm (MK=2.02). Significant increasing trends in mean yearly precipitation were found in Pärnu by 1.8 mm (MK = 2.1; Fig. 8) and in Viljandi by 2.0 mm (MK = 2.1) in WSCs.

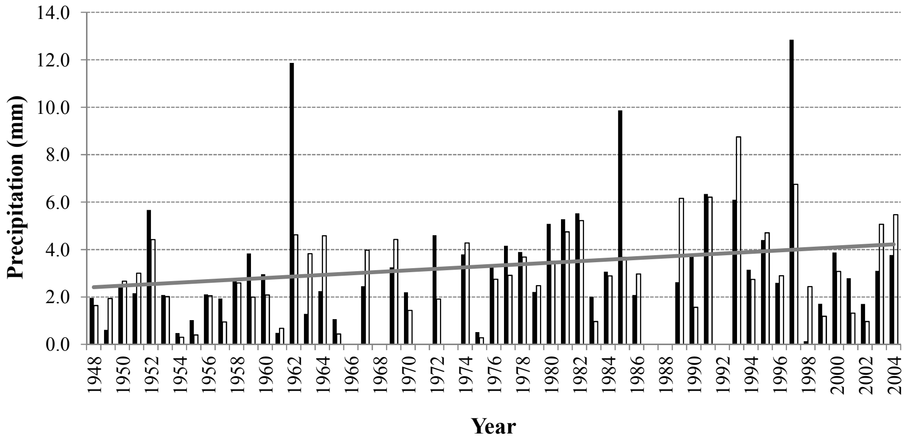

Figure 8. Mean annual precipitation amounts in Pärnu (black) with a linear trend and in Viljandi (white) caused by WSCs during 1948–2004.

In case of thunder events a significant decrease in the frequency of SCTDs by 0.9 days ($p < 0.05$) was in August during 1950–2010. Increasing trends in SCTDs for the ESCs approaching closer than 500 km to the station were recorded in Tartu and Võru (Table 2, Publication II). A significant increasing trend by 0.9 h in the duration of SC–related thunderstorms was registered in Tallinn in case of WSCs at the distance interval 500–1000 km. During the particular years 1972, 1974, 1981, 1989 and 1995, approximately 30–40% of the annual duration of thunderstorms was associated with SCs. 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.

5. DISCUSSION

5.1. Data quality

In every data analysis there is an issue about data quality and uncertainty. Uncertainties in the characteristics of cyclone activity derive from the application of cyclone detection and tracking methods and the use of different data (Sinclair and Watterson 1999; Simmonds and Keay 2000; Hodges et al. 2003; Rudeva and Gulev 2007). This was extensively expressed in the intercomparison of mid–latitude storm diagnostics project (Neu et al. 2013), where the results of applying fifteen different cyclone detection and tracking methods to a single reanalysis were analysed. Consistency across the methods is generally higher for deep cyclones and the largest difference was found between methods in the detection of short–living, weak and slowly moving cyclones, and the capturing of the earliest and the latest stages of the cyclone life cycle, detection of which is more sensitive to the choice of scheme. Differences in the distributions are generally larger in the Northern Hemisphere than in the Southern Hemisphere and are larger over parts of continents, which are the regions of high interest because of high impacts of storm (Neu et al. 2013). According to Hodges et al. (2003), a number of small–scale weak cyclones were not detected among the reanalyses. They are distributed throughout the storm tracks, particularly in the regions known for small–scale activity, such as secondary development regions and the Mediterranean. In this case, the critical aspect is the time step of cyclones in the database. Due to a larger time step, weaker and short–living cyclones will be not detected because they form and decay between the detection times.

Another source of uncertainty is associated with the use of reanalyses that differ in model settings, resolution, and data assimilation methods (Hodges et al. 2003, 2011; Pinto et al. 2005; Wernli and Schweirz 2006; Raible et al. 2008) as they may influence the ability of the whole reanalysis project to correctly simulate the atmospheric circulation conditions related to extratropical cyclones. Explorations into the impact of spatial and temporal resolution were performed by Blender and Schubert (2000) and Pinto et al. (2005). It was found that a decrease in resolution causes the missing of the tracks and cyclones. For example, using a time step of 24h, only 45% of cyclone tracks were identified, in a fine resolution (1.125° × 1.125°, 2 h) nearly all of the tracks and cyclones were detected (Pinto et al. 2005). Decreasing the spatial and temporal resolution of the input data decreases the cyclone track density and cyclone counts. Reducing the temporal resolution alone contributes to a decline in the number of fast moving systems, which is relevant for the cyclone track density. Lowering spatial resolution alone mainly reduces the number of weak cyclones (Pinto et al. 2005). Blender and Schubert (2000) also found that a coarser temporal resolution may result in 10%–50% biases in cyclone counts when the resolution decreases from 2 hours to 24 hours.

Past comparisons of cyclone activity in reanalyses were mostly focused on the NCEP–NCAR (Kalnay et al. 1996) and 40–yr ECMWF Re–Analysis (ERA–40; Uppala et al. 2005), as well as on a stronger deepening of cyclones in ERA–40. These comparisons generally demonstrated that ERA–40 systematically represents more cyclones, and therefore, a higher cyclone centre density, than the NCEP–NCAR reanalysis dataset (Raible et al. 2008). Geostrophically adjusted geopotential height gradients around cyclone centres, a measure of cyclone intensity, are enhanced in ERA–40 compared with the NCEP–NCAR reanalysis dataset (Raible et al. 2008). The strongest difference appears in summer. These differences can be explained by the different horizontal resolution of the models which are used to create the reanalysis datasets.

One of the latest papers (Tilinina et al. 2013) performed the intercomparison of cyclone activity in five different reanalyses (NCEP–DOE, JRA–25, ERA–Interim, NCEP–CFSR, and NASA–MERRA) and applied a single numerical tracking algorithm for cyclone tracking. All of the mentioned reanalyses cover the same period from 1979 to 2010 but differ in their spatial and spectral resolution as well as in model configuration and assimilation methods. This is similar to earlier analyses by Blender and Schubert (2000). The total number of cyclones increases with the increasing resolution of the particular reanalysis. Differences among the reanalyses are almost entirely caused by moderate and shallow cyclones, which constitute more than 90% of the total count. However, for reanalyses, the model formulation and data assimilation algorithms are also likely responsible for significantly higher numbers of cyclones and their higher intensity relative to the other products. The smallest variances in cyclone counts are observed over the oceanic storm tracks, and the largest number of cyclones in different datasets is identified over the continents, particularly over the Mediterranean storm track in the summer. Only NASA–MERRA shows a significantly higher number of very deep cyclones. In summer, a higher appearance of short–lived cyclones was found in the NASA–MERRA reanalysis and a higher appearance of long–lived systems in the ERA–Interim and NCEP–CFSR.

The above–mentioned analysis shows that the usage of different data and different tracking methods provide results, which are often hardly comparable. In current thesis, only one database (Gulev et al. 2001) was used and cyclones were chosen based on same principle. Therefore, deductions made in Publications I–IV should be comparable. The question is, to what extent are the results of these publications comparable to those of other similar papers, where other databases of cyclones are used. However, considering that the current thesis analyses relatively stronger cyclones, where the potential errors are smaller, we can suppose that at least the statistics of stronger cyclones is comparable to other papers.

The NCEP/NCAR reanalysis data (Kalnay et al. 1996) has been widely used. The NCEP/NCAR Reanalysis Projects use a fixed and consistent global data assimilation and filtering system, a database as complete as possible from the radiosonde, aeroplane, satellite and meteorological station data. The advantages of using this data are its possible independence of local influences like vegetation or all kinds of obstacles, the filtering of the data and its consistent availability (Jimenez et al. 2012). Many outputs of reanalysis data have been criticized, mainly concerning the time period before the pre–satellite age earlier than 1979 in Polar Regions (Basist and Chelliah 1997, Santer et al 1999, Sturaro 2003). The regions analysed in the current thesis encompass more southerly areas away from the Polar Region, and therefore it can be assumed that the used air pressure data are reliable. The NCEP/NCAR reanalysis data are considered to have instantaneous values at the reference time (Gulev et al. 2001).

In the database of cyclones based on the NCEP/NCAR reanalysis (Gulev et al. 2001), the locations of cyclones are registered in every 6 hours. Considering the formation point of a cyclone, it is important to take into account that a low pressure system might have been formed up to 6 hours before its first registration time in the database. During that time the cyclone might move significantly away from its location of origin (Nesterov 2011; Vyazilova 2012; Post and Kõuts 2013). It can be assumed that the difference between the actual and fixed location of the formation point do not affect results in a substantial manner and it is not very likely that the major part of cyclones form in one place and will be registered much farther off at other locations. Like it was mentioned before, the best results for cyclones and their tracks come from semi–automated schemes, which combine the strongest sides of subjective and automated methods. Therefore, the semi–automated database (Gulev et al. 2001) used in the thesis is of quite a good quality and allows detecting cyclones in an accuracy of 0.1˚. This is relevant considering the small size of Estonia. Such and accuracy is provided by very few databases.

In the higher latitudes, mapping becomes very sensitive to the cell size. In the midlatitudes the actual configuration of cells of the grids becomes very different from that for the high latitudes and may not necessarily provide an effective catchment of cyclones (Zolina and Gulev 2002). To account for the varying density of the cyclone tracks of different directions, one possibility is to use circular cells, first recommended by Kelsey (1925), and used for mapping cyclone frequencies by Sinclair (1994). Circular cells are very effective in detection of cyclones for their consideration of regional climatologies. Still, on a global scale they may result in variable spatial smoothing at different latitudes (Zolina and Gulev 2002).

Several suggestions have been made in the past regarding the proper size of the circle for statistical analyses of low pressure systems. For example, in their analysis, Zolina and Gulev (2002) used circles with a radius of 555 km, which had suitably been assessed by Sinclair (1994). Rudeva and Gulev (2007) found that the effective average radius of cyclones in the Northern Hemisphere is 300–400 km over the continents and it could even be more than 900 km over the oceans, which was confirmed by Schneidereit et al. (2010). Simmonds and Keay (2000) reported that the mean radius of low pressure systems moving over higher latitudes of 50º–70º in the Southern Hemisphere could be up to 6.5º in grid. Most of the mentioned papers were based on the concept of the effective radius of the cyclone, which is defined as the radius between the centre of a low pressure area and the last closed isobar coinciding with the maxima of kinetic energy (Grotjahn and Castello 2000; Schneidereit et al. 2010). In the current analysis, the classical distance of 1000 km was used for the detection of SCs based on the assumption that cyclonic activity is having an effect on weather over a large area, and it has been affecting weather conditions in Estonia. In fact, the cyclone intensity is closely related to the cyclone size (Campins et al. 2011).

When determining the number of cyclones, it is relevant to take into account the systematic underestimation of cyclones in the database used. The error depends on the time interval used, the grid size, and also the geometry of the grid where cyclones have been detected. The most problematic for detection are fast–moving cyclones that cross the grid faster than the time interval of the database. No grid (rectangular, circular or other) can fully account for fast–moving cyclones that pass one or more grid cells during one time step. A larger error appears when a larger time interval and a larger grid size are used. These biases tend to underestimate storm counts (Zolina and Gulev 2002). For example, in the time intervals of 6 and 12 hours in a 5° × 5° grid, the typical underestimation of cyclones has been estimated to be 10–20% (Zolina and Gulev 2002). This error is larger in areas with intense cyclonic activity, particularly near the Icelandic low and in the Mediterranean region. Higher temporal resolution minimizes the bias. In Publications I, II and IV, a circle was used instead of a grid. The use of the circle reduces the uncertainty, which is related to counting cyclones, and decreases the error in their trajectories by a 1.5–3 times as compared with square grid cells (Zolina and Gulev 2002). Therefore, estimating of the frequency of cyclones by using circular geometry was considered more convenient.

Another important issue was the location of the circle used in the analysis. The dependence of the frequency of low pressure systems on the location of the circle used was studied in detail by Link and Post (2007). They counted cyclones over the Baltic Sea and found that the location of the central point of the circle is a critical factor in detecting parameters of local cyclone activity. In Publications I, II and IV, the defined location of the circle was most suitable for determining cyclones and their influence on Estonia and closer surrounding areas. Radius of the circle where cyclones were counted and analysed was no less important. In many studies, the mean effective radius of the cyclone was analysed (Sinclair 1994; Simmonds and Keay 2000; Zolina and Gulev 2002; Rudeva and Gulev 2007; Schneidereit et al. 2010) and it was generally found to be 300–900 km. However, Hanson et al. (2004) reported that in the NCEP reanalysis database, approximately 27% of mid–latitude cyclones have a mean radius of 500–1000 km and 45% of these cyclones, of 1000–1500 km. The 1–K circle was used in Publications I, II and IV, because generally, the radius of mid–latitude cyclones is 1000 km and while the center of these pressure systems moves on the edge of the circle, they also affect weather conditions over the areas in the centre of the circle. Cyclones were analysed under the assumption that cyclonic activity affects weather over a large area, and has an influence on weather conditions in Estonia.

The 1–K circle was appropriate for statistical analysis of SCs, but in evaluation of thunderstorms related to SCs this circle was too large. A large number of SCs passed Estonia at a long distance near the edge of 1–K circle and did not cause thunderstorms in Estonia. Therefore, considering particular weather phenomena, it is reasonable to analyse cyclones, which move in a smaller circle with the radius of 500 km or at the same time in two circles with radii of 500 and 1000 km.

5.2. Climatology of southern cyclones

Some earlier papers (Belskaya 1949; Kannes et al. 1957) have stated that SCs constitute about 10% of all cyclones influencing weather conditions in Estonia. In the database used, 417 SCs were the same in every publication during 1948–2004. It is more than 70% of all the SCs described and analysed in every paper. Therefore, all four papers describe similar climatological processes but look at them from different perspectives. During the same time period, 3856 cyclones which entered to the 1–K circle were formed outside the circle. This means that SCs constitute 10.8% of all cyclones influencing weather in Estonia. This is the same ratio as mentioned in earlier papers. Still the ratio between stronger SCs and all strong cyclones which move to northern Europe is different. If we remove shallow cyclones with mean SLP >1000 hPa, then the total of 2185 cyclones (SCs within) and 451 SCs appeared during 1948–2004. Therefore, stronger SCs constitute 20.6% of all stronger cyclones. This means that SCs are proportionally deeper with their mean SLP and stronger than those cyclones, which mainly form over the northern Atlantic. This is a novel result. Among the latter, the number of cyclones with mean SLP >1000 hPa is proportionally larger than among SCs.

As expected, the majority of mid–latitude cyclones entering to the 1–K circle are generated over the North Atlantic. Publication IV clearly indicates this pattern. However, it became apparent that almost a half of low pressure systems influencing weather conditions in Estonia form within the northern European region, especially in the central part of Sweden and in the eastern slopes of the Scandinavian mountains. This finding is in line with the results provided by Sepp et al. (2005) who reported the formation of a large number of cyclones in the area between 5E and 20E, for example over the eastern part of the North Sea and the western side of the Baltic Sea, showing rather similar counts of cyclones. Similarly it was found that the largest numbers of cyclones formed inside the Baltic Sea region near Oslo (Sepp 2009). It was found that 40% of the cyclones that showed up in the region had formed inside the Baltic Sea region (Link and Post 2007; Post and Link 2007). According to Publication 4, this amount of cyclones is almost 50%. It is possible to conclude that the weather in northern Europe is highly influenced by cyclones of local origin and the Baltic Sea region itself is a relatively active cyclogenesis region. However, the data used in the above–mentioned studies do not allow answering the question whether these local cyclones are independent pressure systems or whether they are secondary parts of larger cyclones.

The other half of cyclones that have an effect on the weather in the 1–K circle were formed outside the region, mainly over the North Sea, the Norwegian Sea, near Iceland and over northern Italy. Similar formation areas over the North Atlantic during 1948–2000 were found by Link and Post (2007) and for 1958–2000, by Trigo (2006). In the studied time period 1948–2010, locations of the areas of origin of low pressure systems varied in the shorter time sections. Each 21–year period shows a different distribution of cyclogenetic areas of cyclones moving to northern Europe. A noticeable and persistent cyclone activity centre was also found over southern Europe (Fig. 5). This represents SCs influencing weather conditions in northern Europe.

The most intense formation of SCs was principally located over northern Italy and neighbouring areas (Kaznacheeva and Shuvalov 2012; Publication I, III, IV). Still, they analysed only the Mediterranean Sea. The current thesis also analyses another important formation areas of SCs – the Black Sea and the Caspian Sea. This area is one of the most active cyclogenetic centres in the Mediterranean region (Trigo et al. 1999). Another relatively active area of SCs origin near Cyprus in the Eastern Mediterranean was detected by Kaznacheeva and Shuvalov (2012). Pretty similar patterns of formation areas of the Mediterranean cyclones, with the highest rates of cyclone formation over northern Italy and the Gulf of Genoa, were reported by several authors (Trigo et al. 1999; Maheras et al. 2001; Lionello et al. 2006; Romem et al. 2007; Campins et al. 2011). In addition, Alpert et al. (1990) detected high cyclonic activity over the central and southern parts of the Caspian Sea and over the eastern part of the Black Sea. A formation area of cyclones over the eastern part of the Black Sea was also determined by Trigo et al. (1999). Publication III shows that not many SCs were formed over the eastern Mediterranean, but the largest number of this type of low pressure systems originated from northern Italy and the Gulf of Genoa region. Cyclones evolving over the Cyprus area are not likely to move so far north as to classify them as SCs. It is necessary to stress that a large number of SCs form near 50° N, which is the northernmost border of the SC formation area used in this study. Therefore, the results also depend on the methodology used. It is obvious that cyclones forming near the border can cross it more easily.

Intra–annual distribution of cyclogenetic areas influencing northern Europe shows major seasonal differences. In the warm half–year, major cyclogenetic regions are located in more southerly regions – over northern Italy and surrounding areas, also over central Europe and Ukraine (Publication IV), representing the generation of a larger number of cyclones over southern Europe in summer. Contrary to that, in the cold half–year, the areas of origin of cyclones entering the 1–K circle are concentrated to the northern Atlantic and the cyclogenetic area over southern Europe is weakened. Similar results were found by Alexandersson et al. (1998), Trigo et al. (2002) and by Wang et al. (2008), where much higher storminess was detected, especially over the North Sea and other parts of the Atlantic Ocean, during the wintertime than in summer.

In Publication I, a yearly average of about 9 SCs was detected, which accounts for about 9–11% of all cyclones in the 1–K circle. This finding is in agreement with those of the previous studies, which reported that SCs were related to about 10–13% of all cyclones that affected weather conditions in Estonia (Kannes et al. 1957; Linno 1982). Bielec–Bacowska (2010) also assessed that approximately 10–11% of cyclones, which originate from the Mediterranean, travel towards northern and north–eastern Europe. For the period 1948–2004, Kaznacheeva and Shuvalov (2012) found that 14 SCs per year moved to the European part of northern Russia and to Scandinavia from the Mediterranean region. A similar annual frequency of cyclones was found by Belskaya (1949), analysing a shorter time period. In Publication III, the mean annual number of SCs was about 31. This is a much higher count than in the earlier studies, but the area where the SCs have formed is also much larger, encompassing the Black Sea and the Caspian Sea regions in addition to the Mediterranean region. Generally, the SCs comprise approximately 10% of all low–pressure systems which were originated from the seas in southern Europe (Belskaya 1949; Kaznacheeva and Shuvalov 2012; Publication I). There was also a statistically significant positive correlation in the frequency between SCs and CSSs. Considering the above–mentioned findings, on the one hand, we can deduce that the proportion of SCs in northern Europe is relatively stable – about 10%. On the other hand, correlation shows that the number of SCs is clearly related to processes in the Mediterranean region – more cyclones form over the Mediterranean region, more SCs move to the Baltic Sea.

Much more SCs heading to northern Europe were observed in the warmer part of the year, in spring and summer, than in autumn and winter. This finding is in agreement with the deduction – more cyclones form over the Mediterranean region, more SCs move to northern Europe and the seasonal distribution of SCs is similar to the general seasonal distribution of cyclogenesis over the Mediterranean basin (Trigo et al 1999, 2000, 2002; Bartholy 2009; Campins et al. 2011), as well as over the Black Sea and the Caspian Sea regions (Alpert et al 1990). Similarly, Linno (1982) found fewer SCs in winter and a maximum number in summer. Contrary to that, Belskaja (1949) found that more SCs were formed at the end of winter and the beginning of spring. These differences in the number of SCs may be explained by the different periods analysed, and the different methods used for defining and detecting SCs.

Findings from Publication III revealed an interesting result that about one–fourth of the SCs, which have moved to northern Europe and European areas of the northern part of Russia, move on the other side of the Ural Mountains, east of 60° E. In other sectors defined, a general increase was found in the number of SCs moving by sectors from the west to the east. The sector 20–30° E, which generally corresponds to the region of the Baltic countries where a relatively higher number of SCs moved northwards, stands out among other sectors. Publication I confirmed these findings about SCs influencing Estonia and its closer neighbouring areas, where about 2/3 of SCs passed east of Estonia. Similar results were exhibited by Kaznacheeva and Shuvalov (2012), showing that the highest numbers of SCs mainly move to the European part of Russia and a smaller amount of SCs head towards western Europe and the Scandinavian area. One exception is the sector encompassing the area of the Baltic countries, where a higher number of SCs was detected (Publication III). Very similar deductions were made by Alpert et al. (1990) and by Degirmendžic (2013), who reported that the majority of SCs from the Mediterranean, Black and Caspian Seas followed northeastern trajectories and also headed to the northwestern territory of Russia. It can also be deduced that if a cyclone is moved northwards, it starts to move eastwards and in farther north becomes part of westerly flow. Another assumption states that if the number and intensity of cyclones moving to the sector > 60° E has risen, it may lead to significant climate changes in northwestern Siberia, because the number of cyclones over this area is very low.

Mean duration of SCs was about 130 hours. In comparison, it has been found that more than 60% of cyclones in the Atlantic exist for 2–6 days with the mean lifetime of about four days (Gulev et al 2001). Rudeva and Gulev (2010) reported that the typical lifetime of the North Atlantic cyclones was 4–5.5 days. Therefore, SCs last as long as cyclones which form over the northern Atlantic, but are much more durable than the CSSs which form over southern Europe but do not move to northern Europe.

The annual pattern of mean duration of SCs was similar for all cyclones moving to northern Europe. Longer lasting SCs appeared in summer and shorter ones in winter. In general, this seasonal distribution is in a good agreement with the mean duration of pressure systems in the Mediterranean region (Trigo et al. 1999), where the formation areas of SCs are located. Generally, the Mediterranean cyclones have shorter life cycles and a smaller spatial extent than the mid–latitude cyclones which form over the Atlantic Ocean (Lionello et al. 2006). According to Campins et al. (2011), the annual mean duration of the Mediterranean cyclones is 14.2 h. This lifetime is longer in winter and shorter in summer. It has been mentioned that over 60 % of all the detected low pressure systems in the Mediterranean last for less than 12 h (Trigo et al. 1999) and are, in general, very short–living formations. The highest mean yearly durations of cyclones over the Gulf of Genoa (25.2 h) and in eastern Sahara (26.4 h) was found by Campins et al. (2011). Similar areas with a longer duration were reported by Trigo et al. (1999) also. Trigo et al. (1999) and Lionello et al. (2006) found that if the shortest–living cyclones whose duration is less than 12 h are excluded, the mean lifetime of low pressure systems in the Mediterranean region is about 28 h. In Publication III, the mean lifetime of CSSs is much higher, but all much longer–living SCs are included to these analyses. In the used database, the shortest cyclones were 24 hours, which causes longer mean duration of cyclones than it is found in other studies. If to consider that the mean yearly lifetime of SCs found in Publication III has been more than 130 h, then it is possible to deduce that the SCs that form in the same region but move significantly northwards last considerably longer and follow much longer trajectories than CSSs.

It was found in Publication III that the mean yearly SLP of SCs was much lower than in CSSs and therefore, it is possible to deduce that SCs are much more intense than the CSSs that form in same region but do not move significantly northwards. In northern Europe, the deepest SCs were situated east of the Ural Mountains. According to Publications I and III, the SCs with the lowest SLP were determined in winter and shallowest in summer. This is in a good agreement with the findings in several studies showing that the total number of weak cyclones is relatively high in summer, while deeper cyclones exist in the Mediterranean region in winter (Trigo et al. 1999; Campins et al. 2003; 2011). Although more intense cyclones have been observed over the Gulf of Genoa than in other areas in the Mediterranean (Campins et al. 2011), most of the cyclones which develop over the Mediterranean region are shallow (Trigo 2006). Obviously cyclones transport their properties along their trajectories, and while deeper pressure systems form in the Mediterranean region during the wintertime than in other seasons, the SCs will also be more intense in that time of the year.

5.3. Effect of southern cyclones on weather in Estonia

It was supposed that WSCs bring warmer air into Estonia, and ESCs cause colder air advection. Almost two thirds of all SCs pass to the east of Estonia, on average, reducing air temperature, while WSCs increased air temperature (Table 2 in Publication I). The warming effect of SCs was the greatest in summer, and the cooling effect of ESCs was the greatest in autumn. In general, the effect of SCs on changes in air temperature in Estonia was not as large as expected. There are several reasons. Cyclones of smaller spatial extent and weaker pressure systems might remain too far from Estonia to have a great effect on local air temperature. In addition, in some cases WSCs do not cause warming due to the advection of tropical air masses, but rather have a cooling effect because of the appearance of thick cloud cover, which prevents an increase in air temperature in the warm season. The effect of ESCs on air temperature may be much more complicated. Estonia is located at the western periphery of ESCs and, therefore, is mostly influenced by northerly winds. Our understanding that a cyclone is bipolar formation, where colder air always moves on the western edge of cyclone, is a great simplification (Table 3) – the real situation is much more complicated. If an ESC has not moved as far north as the latitudes of Estonia, then at its northwestern edge, northeasterly winds might bring even warmer air from northern Russia in the summer. Some individual WSCs have still indicated a significant warming effect and ESCs a notable cooling.

SCs were found to produce a total precipitation of slightly more than 10% of the annual amount. This 10% is the same proportion as the percentage of SCs to all cyclones having an effect on weather in Estonia. A similar result was reported by Kannes et al. (1957). The highest summary precipitation per year was observed in southeastern Estonia, and the lowest in the western Estonian archipelago. This result is in agreement with the mean distribution of yearly precipitation in Estonia (Jaagus et al. 2010). Hence, in case of SCs we cannot see any specific precipitation pattern in Estonia. Seasonally, the highest precipitation totals related to SCs were detected in summer, and the lowest in winter. This is due to the different frequencies of SCs in different seasons. This seasonal distribution of the whole precipitation is similar to the findings by Jaagus and Tarand (1988), Heino et al. (2008) and Jaagus et al. (2010).

Sometimes SCs produce heavy rainfall. Almost one fifth of the SCs induced extreme precipitation of over 10 mm in 24 hours. This result emerged expectedly as many papers reported that the daily maximum and extreme precipitation is highly dependent on the development and movement of cyclones, which originated from the Mediterranean region (e.g. Mätlik and Post 2008). For example, in the Dinaric Alps (Radinovic 1987), in Bulgaria (Bocheva et al. 2007), in the Alps and the Carpathian mountains and in Germany they have caused devastating floods (Spreitzhofer 2000; Ulbrich et al. 2003; Mudelsee et al. 2004; Bednorz 2011; Twardosz 2007, 2009). It has also been found that the shorter–lived cyclones from the Mediterranean provide little precipitation, while during the wet season (winter) the more intense and longer–lived cyclones carry large precipitation (Bartholy et al. 2009).

Another important feature that deserves to be pointed out is the pattern where precipitation in the cyclones clearly increases with the cyclone intensity quantified through the radial SLP difference. Such findings were reported by Bauer and Del Genio (2006), Chang and Song (2006), and Field and Wood (2007), who all agree that the cyclone intensity drives cyclone moisture characteristics. When to consider that SCs are clearly deeper than CSSs, then it is possible to deduce that SCs carry much more precipitation than the pressure systems, which form in the same areas but do not move to northern Europe. Therefore, deeper SCs are also much more probable to bring large precipitation amounts, which may cause floodings in the areas influenced.

It can be said that the importance of SCs manifests in a high probability of causing severe weather events (Kannes et al.1957; Linno 1982; Pärn 1986; Publication I). Therefore, it was presumed that a proportionally large part of thunderstorms in Estonia is also related with SCs. For example in Poland, Bielec–Bacowska (2003) found that the largest probability of the occurrence of a day with a thunderstorm takes place during the southeastern and southern air advection connected with cyclonic systems. This might often be related to SCs. Based on earlier studies, SCs constitute 9–13% of all cyclones that have had an effect on weather conditions in Estonia (Kannes et al.1957; Linno 1982; Link and Post 2007). Outcome of Publication II showed that SCs have caused about 10% of all thunder events over Estonia, which is approximately the same proportion that SCs constitute in the total number of cyclones affecting weather conditions in Estonia. Similar proportions were found in case of SCTDs when thunder was registered at least at one station. Still, it must be pointed out that in other TDs, it is not possible to detect which of them are caused by low pressure systems and which are the air–mass thunderstorms. Generally, if the part of air–mass thunders, which is certainly not associated to cyclones will be eliminated, the proportion of SC–related thunder events will be much higher than the reported 10%.

Many reliable correlations were determined. Statistically significant relationships were found between the frequencies of SCs and SCTDs, as well as between the SC–related TDs and other TDs. This was an expected result because the warm weather in summer, when most of thunderstorms appear, is directly associated to the influence of SCs that carry the moist and humid tropical air to higher latitudes. This causes unstable air stratification which is a precondition for intense convection and for the formation of thunder clouds.

The most active thunderstorm–inducing months in Estonia were in summer (Enno 2011) when the number of SCs was the largest as well (Publication I, III). As expected, the highest number of days with SC–related thunderstorms was in summer, especially in August, when about 80% of all SCs were caused by thunderstorms (Publication II).

The total yearly duration of SC–related thunder events at different stations constitutes only about 10% of the annual duration of all thunder events. Nevertheless, SCs are able to generate very long–lasting thunder events. As these thunder events were very rare, the monthly total durations were strongly affected by single cases when a thunderstorm lasted for several hours. Still, it is possible to deduce that thunder events caused by SCs tend to last longer in July than, for example, in August when there was the maximum of SCTDs.

About 2/3 of SC–related thunderstorms were determined when a SC moved at a distance up to 500 km from the meteorological station (Publication II). Still, it should be noticed that the majority of SCs pass Estonia at a farther distance than 500 km but a large part of them do not cause thunder in Estonia. Probably, the frontal zones of these cyclones are located too far away. At a distance farther than 500 km from a station, the mean duration of thunderstorms in WSCs was longer than in ESCs. In case of WSCs, Estonia is affected by the warm sector of the low pressure system which contains much convective energy and causes stronger and longer thunderstorms.

The continental station Võru and the maritime station Vilsandi stand out among other meteorological stations. The highest number of TDs per year, as well as of SCTDs, and their highest annual lifetime were detected at the Võru station. The lowest numbers of SCTDs, but the longest thunder events, especially in August, were found at the Vilsandi station. In general, the stations with more thunder also record more SCTDs. The results of this study are in agreement with those reported by Enno et al. (2013) where the highest counts of TDs were determined at the continental stations in July and at the coastal and maritime stations in August.

On the basis of the data from the NORDLIS lightning detection network it is possible to state that the thunderstorms associated with SCs are more intense than other thunderstorms in Estonia. Despite the very short time series available, thunderstorms associated to SCs clearly have much more lightning strikes per day than other thunder events. The mean number of SC–related lightning strikes per TD was more than three times higher. In most of the analysed years the SC–related lightning counts per TD were much higher. Most of the percentiles of lightning strikes caused by SCs were many times higher than those of other thunder events (Publication II). Generally, SCs in relation to thunderstorms, found in Publication II were in line with findings in other studies (Kolendowicz 2006, 2012; Bielec–Bakowska 2003; Tuomi and Mäkelä 2008), which also reported about severe thunderstorms and lightning accompanied by SC–related advection of warm and humid tropical air. It has been found even in Estonia that thunderstorms are most common in southerly or southeasterly airflow conditions, which generally represent the influence of SCs (Enno et al. 2014). The relationship was the highest in summer.

5.4. Changes in southern cyclones

There is no statistically significant trend in the frequency of SCs despite the fact that the Mediterranean region has been considered as one of the areas that will surely be affected by climate change (Giorgi 2006). Strong cyclones play an important role in this region and neighbouring areas. They might induce high–impact weather events, which may cause windstorms, storm surges, landslides and floodings (De Zolt et al. 2006; Lionello et al. 2006, 2010; Nissen et al. 2010). Therefore, changes in cyclone appearance and characteristics are implied to play a main role in the past, present and future changes in the climate in the Mediterranean and all over the areas influenced by SCs.

In CSSs, a decrease in the annual total number of low pressure systems in the Western Mediterranean was found by Maheras et al. (2001). A similar decreasing trend in the Mediterranean was also reported by Bartholy et al. (2009) in winter and in spring. However, the overall average cyclone frequency in the Mediterranean region remains fairly constant throughout the year (Trigo et al. 1999), which explains the absence of long–term changes in the frequency of SCs.

Parameters of cyclones and their trajectories have not always been similar from year to year. Statistically significant negative trends in the number of cyclones affecting the Mediterranean region have been detected in the recent decades and the second half of the 20th century (Flocas et al. 2010; Maheras et al. 2001; Nissen et al. 2010; Trigo et al. 2000). On the other hand, according to Kouroutzoglou et al. (2011), the number of rapidly intensifying Mediterranean cyclones has possibly decreased, but this reduction is not statistically significant. Low pressure systems which move from the Mediterranean region to northern latitudes are also affected by changes in cyclonicity over southern Europe. A considerable increase has been found in the prevalence of cyclones on the North Atlantic and over northern Europe during the second half of the 20th century (Alexandersson et al. 1998; McCabe et al. 2001; Sepp et al. 2005, 2009; Bartholy et al. 2006; Wang et al 2006). Although the majority of climate changes in northern Europe are related to changes in cyclonicity (BACC 2008), there are no signs that these changes would be related to SCs.

On the background of past changes in cyclonicity over the Mediterranean region, these changes tend to be continuing also in the future. Many studies, based on global climate model simulations investigating the Mediterranean cyclone activity under changing greenhouse gas conditions, have reported, in addition to the Atlantic Ocean, also a strong decline in winter cyclone activity for the Mediterranean region (i.e. Lionello et al. 2002; Geng and Sugi 2003; Pinto et al. 2006, 2007; Raible et al. 2010), which directly affects the activity of SCs as well. Still, the projected changes in cyclone intensity in the Mediterranean region are not clearly one–directional because of different capacities of general circulation models (Anagnostopoulou et al. 2006).

In Publications I and III, no significant long term trend was found in the frequency of SCs. However, Sepp (2005) analysed SCs and found a change in their frequency. A statistically significant decreasing trend in the annual number of these low pressure systems was found over Ukraine during 1948–2000. This finding resembles a decreasing trend in the frequency of western cyclones over Ukraine and Hungary (Domonkos 2003). In the time period 1948–2004, a similar decreasing trend in the cyclones moving significantly northwards from the Mediterranean region was also found by Kaznacheeva and Shuvalov (2012). It is possible to deduce that the significant trends in cyclone frequency reported in other papers are caused not by SCs, but by western cyclones (cyclone, which is formed over the Atlantic Ocean, but due to specificity of its trajectory, move northwards from the Mediterranean region). This can also be explained by the different definitions of SCs used in various studies. The relatively rigid definition of SCs used in Publications I, II and IV eliminates all cyclones that formed over the Atlantic Ocean and moved to the Baltic Sea region through the Mediterranean region or central Europe. For example, Sepp (2005) did not use such strict limits and thus the cyclones that formed over the Atlantic were also included.

Findings in Publication IV revealed that even the areas of origin of cyclones are not persistent in time and space. No significant northwards shift was detected in the cyclogenetic areas of low pressure systems heading to northern Europe, but several movements were detected in the shorter 21–year time periods. No notable shifts in the cyclogenetic areas of SCs were found. A significant increase by 10% in the number of powerful cyclones that entered the Baltic Sea was detected in the time period 1948–2002 (Sorteberg et al. 2005). Similar results were reported by Sepp et al. (2005) who also detected an upwards trend in the frequency of all cyclones over northern Europe during 1948–2000.

The most persistent and significant trends in the time series of SCs were in SLP. In all the SCs heading to northern Europe the mean annual SLP has decreased in the deepest lows. According to k–means clustering, the annual mean and mean minimum SLP of cyclones in clusters 11 and 12, generally representing SCs, decreased as well. In some sectors in northern Europe, the mean and minimum SLP of SCs has decreased and these low pressure systems have become more powerful in time. Earlier studies did not describe any long–term changes in the SLP of cyclones in the Mediterranean region. However, it is known that their intensity is lower in the summer months and higher in winter (Maheras et al 2001; Bartholy et al 2009). The reason might be the usage of relatively strong cyclones in clusters 11 and 12, which have become stronger. Including weaker cyclones into the analysis of SCs, we did not reveal so clear trends in SLP. According to Publication III, in all SCs there was a decreasing trend in SLP in the deepest cyclones, but no change in mean SLP. That means that stronger SCs have started to become more intense, but not all SCs show the changes. Generally, SCs are much stronger than CSSs. Still, the further shallower cyclones should be analysed separately because their statistics differ significantly from that of the stronger ones (Maheras et al. 2001; Sepp 2009; Sepp and Jaagus 2011).

Mean SLP of SCs at the tracking point nearest to Estonia increased significantly over time, which means a weakening of SCs in the closest locations to the country during the study period. This increase in mean SLP of SCs is also evident in sectors 10–20˚E and 30–40˚E (Publication III). In the nearest locations to Estonia the SLP of these low pressure systems showed a significant increase in winter as well. This result is in accordance with the findings of Zhang et al. (2004) who reported that an increase in SLP was explicit in the mid–latitudes, with winter maxima in the North Atlantic and Eurasia. On the other hand, an analysis of cyclones that formed over the Baltic Sea region indicated a general decrease in SLP at cyclone centres (Sepp 2009), but the study analysed all the cyclones. Still farther off, east of 50˚E, the minimum SLP of SCs has decreased in the period analysed. Therefore, it seems that SCs tend to behave differently in different parts of northern Europe.

The mean summer precipitation related to SCs has showed a decline during the period analysed, a significant downward trend was found at the three coastal stations of Tallinn, Ristna and Vilsandi (Table 4 in Publication I). Annual mean precipitation related to SCs was decreased in Vilsandi. This change contradicts with the general increasing trend in precipitation in Estonia during the second half of the 20th century, especially in winter and spring (Jaagus 2006). Therefore, it must be concluded that the precipitation changes in Estonia caused by SCs show a different behaviour than the whole precipitation pattern in Estonia.

There were no significant changes in the frequency of SCTD. This finding is in agreement with the frequency of SCs (Publication I), but differs from the decreasing trend in thunder events (Enno et al. 2013). A statistically significant decreasing trend in SCTDs was detected in August. It may be associated with the decrease in the number of TDs during the second half of the 20th century (Enno et al. 2013). No respective changes in August were recorded neither in the number of SCs (Publication I; Kaznacheeva & Shuvalov 2012) nor in the activity of cyclones over the Mediterranean (Trigo et al. 1999). This change has to be related to changes in local processes in the Baltic Sea region.

It can be deduced that due to the absence of trends in the frequency of SCs climate warming in Estonia and northern Europe is not related to SCs, but is associated to an increase in the frequency of western cyclones and their intensity over the Baltic Sea region (Heyen et al. 1996; Alexandersson et al. 1998; Sepp 2009; Jaagus and Suursaar 2013).

6. CONCLUSIONS

This thesis investigates the climate of SCs moving over northern Europe and Estonia, with a specific focus on the climatology of SCs, their influence on local climate variability and long term trends in SCs. Present thesis is driven by two major hypotheses: (1) climate warming in northern Europe and Estonia is related to SCs. (2) SCs are more severe than other cyclones.

Analyses performed to control the first hypothesis show following results:

1) In this thesis, the database of cyclones in the Northern Hemisphere was used and in a clearly distinguishable pattern it was revealed that SCs constitute approximately 10% of all cyclones affecting weather conditions in northern Europe. This proportion has not changed as well as there have been no major changes in the number and duration of SCs that were identified in northern Europe. At the tracking point nearest to Estonia and in the corresponding sector, SCs have become weaker in time.

2) SCs passing west of Estonia bring warmer air, and those that pass east of Estonia are related to colder air advection in Estonia, but in general the influence of different low pressure systems originating from the south on local air temperature might be very different. There were no significant SCs–related changes in the temperature of the in–brought air. Therefore it was revealed that climate warming in northern Europe and Estonia is directly not related to SCs.

3) The mean annual precipitation amount of SCs forms about 10% of annual total rainfall in Estonia. This proportion has not changed in time. Higher precipitation rate was detected in south–eastern Estonia and lower rate was observed in the western Estonian archipelago. Occasionally, these low pressure systems may cause severe precipitation events and approximately 20% of southern cyclones have induced rainfall of more than 10 mm per 24 hours.

According to previous results the first hypothesis did not find support. As a general conclusion, SCs are not behind the recent climate changes in northern Europe and in Estonia.

Second hypothesis controlled by analysis show following results:

4) SCs are relatively rare phenomena. SCs are more durable and deeper formations than the pressure systems originated from same areas over southern Europe but stayed in the Mediterranean, Black Sea and Caspian Sea regions. SCs comprise about 10% of all cyclones entering to northern Europe, but in case of stronger cyclones with mean SLP <1000 hPa, the proportion of SCs is 20%. Hence, these low pressure systems are generally stronger than other cyclones moving to northern Europe.

5) The frequency of thunderstorms in Estonia caused by SCs is approximately the same as the frequency of SCs compared to all cyclones. If to

exclude air mass thunderstorms, this proportion rises and SCs cause potentially more thunderstorms than other cyclones. The thunderstorms related to SCs tend to last somewhat longer than other thunder events also. Thunderstorms are most frequently related to SCs in August. Based on the NORDLIS lightning detection network, the SC–related thunder events are more severe than others, the difference in lightning counts is more than three times in favour of SCs.

Based on these results the second hypothesis is confirmed. SCs and extreme weather events (lightning, heavy precipitation) related to SCs tend to be more severe than others.

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SUMMARY IN ESTONIAN

Lõunatsüklonid Põhja–Euroopas ja nende mõju kliima varieeruvusele

Põhja–Euroopa ilma kujundab aktiivne tsüklonaalne tegevus. Valdav enamus madalrõhkkondi, mis piirkonda mõjutavad, tekivad Atlandi ookeani põhjaosas ja liiguvad oma teekonnal idasuunas. Nende kõrval esineb igal aastal teatav hulk madalrõhkkondasid, mis tekivad kaugemal Lõuna-Euroopa kohal ja liiguvad oma teekonnal oluliselt põhja poole mõjutades ka Eesti ilma. Kandes kuuma ja niisket troopilist õhku põhja poole, on neil suur potentsiaal kujundada olulisel määral ilma aladel, mida lõunatsüklonid oma teekonnal ületavad. Sageli kaasnevad nendega järsud temperatuuri muutused, tugevad sajud, rahe, tormituuled ja äike, vahel toovad nad endaga kaasa ka üleujutusi ja keeristorme. Seega on need tsüklonid Eesti jaoks olulised ekstreemsete ilmanähtuste põhjustajad, millega on omakorda seotud majanduslikud kahjud. Globaalsete kliimamuutuste taustal on oluliseks aspektiks saanud muutused ekstreemsete ilmanähtuste sageduses ja intensiivsuses. Varasemalt on koostatud mõningaid vähemal või rohkemal määral lõunatsükloneid käsitlevaid uurimusi, kuid vaadeldud aegread on olnud väga lühikesed ja ei ole analüüsitud põhjalikku mõju Eesti ilmastikule.

Käesoleva väitekirja eesmärgiks on uurida lõunatsüklonite klimatoloogiat Põhja–Euroopas, selle pikaajalisi muutusi ja lõunatsüklonite mõju Eesti ilmastikule. Täpsemad uurimisülesanded olid järgnevad:

1) Kas lõunatsüklonid on kaasa aidanud põhja–Euroopas aset leidnud kliima soojenemisele;
2) Lõunatsüklonite trajektooride kindlaks tegemine Põhja–Euroopas;
3) Lõunatsüklonite esinemissageduse, kestuse ja õhurõhu analüüs üldisemalt ja eraldi nende madalrõhkkondades puhul, mis mõjutasid Eesti ilma;
4) Lõunatsüklonite mõju hindamine Eesti ilmastikule sademete, temperatuurimuutuste ja äikese esinemise kaudu;
5) Pikaajaliste muutuste kindlaks tegemine lõunatsüklonite parameetrites ja nende poolt toodud sademetes, temperatuurimuutustes ning äikese esinemissageduses;
6) Lõunatsüklonite ja nende poolt põhjustatud ilmanähtuste võrdlemine teiste sarnaste uuringutega Eestis, naaberaladel ja põhja–Euroopas.

Tulemustest selgus, et lõunatsüklonid erinevad oluliselt madalrõhkkondadest, mis tekivad samas piirkonnas lõuna–Euroopas, aga ei liigu oma teekonnal põhja poole. Lõunatsüklonite eluiga on palju pikem ja nad on palju tugevemad. Eesti ilma mõjutas keskmiselt 9 lõunatsüklonit aastas. Samal ajal liikus kogu põhja–Euroopasse aasta jooksul keskmiselt 30 lõunatsüklonit, mis moodustavad ligikaudu 10% kõigist lõuna–Euroopas tekkinud tsüklonitest. Kõige tugevamad ja pikaealisemad lõunatsüklonid liiguvad põhja–Euroopa idaossa ja Baltimaade piirkonda. Mõningates piirkondades on lõunatsüklonid muutunud tugevamaks, näiteks põhja–Euroopas idapoolsetes sektorites on lõunatsüklonite keskmine ja minimaalne õhurõhk vähenenud. Seevastu Baltimaade piirkonnas on täheldatav teatav lõunatsüklonite nõrgenemine.

Kõigist lõunatsüklonitest on ligikaudu 2/3 möödunud Eestist idapoolt. Need madalrõhkkonnad põhjustavad temperatuuri langust Eesti aladel. Ülejäänud lõunatsüklonid möödusid Eestist läänepoolt tuues endaga kaasa soojema õhu sissevoolu. Ligikaudu 10% Eesti aastasest sajuhulgast on seotud lõunatsüklonitega. Suurimad sajuhulgad esinesid suvel. Enim sademeid on lõunatsüklonid toonud kagu–Eestisse ja kõige vähem lääne–Eestisse. Selgus, et sajuhulgad ja sademete ruumiline jaotus on selgelt seotud lõunatsükloni keskme kaugusega meteoroloogiajaamast.

Lõunatsüklonid toovad endaga kaasa äikest peamiselt nn. „äikesehooajal" aprillist oktoobrini. Sel ajavahemikul vaadeldi 99% kõigist äikestest. Suvel põhjustavad Eestis äikest kuni 80% lõunatsüklonitest. Kogu Eesti aastasest äikeste kestusest moodustab lõunatsüklonitega seotud äikeste kestus umbes 10%. Vahel põhjustavad lõunatsüklonid väga pikaealisi äikeseid. Ligikaudu 2/3 lõunatsüklonitega seotud äikestest paiknes tsükloni kese äikest registreerinud meteoroloogia jaamale lähemal kui 500km. Umbes 2/3 lõunatsüklonitest, mis ei toonud endaga kaasa äikest, möödusid jaamast kaugemalt kui 500km. Ilmselt nende madalrõhkkondade ruumiline ulatus oli väiksem ja nende pilvesüsteemid ei mõjutanud Eestit. Kaks meteoroloogiajaama eristusid teistest selgelt: Võru jaamas oli suurim lõunatsüklonitega seotud äikesepäevade arv, seevastu Vilsandi meteoroloogiajaamas registreeriti väikseim lõunatsüklonitega seotud äikesepäevade arv, aga kõige kestvamad äikesed, eriti augustis.

Võrreldes teiste äikese juhtudega on ööpäevas registreeritud välgulöökide arv olnud lõunatsüklonite korral mitu korda kõrgem. Siiski üksikud väga tugevad äikesetormid on põhjustanud olulise osa aastasest välgulöökide koguarvust ja suuremal määral mõjutanud kogu välkude statistikat. Enamikel aastatel on lõunatsüklonid põhjustanud suuremaid välgulöökide ööpäevaseid sagedusi, kui teised juhtumid. Võib väita, et lõunatsüklonite poolt põhjustatud äikesed on tugevamad kui teised.

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