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Synoptic weather types that have caused heavy precipitation in Estonia in the period 1961–2005

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Abstract. The subjects of the study are heavy precipitation and weather types, caused by it, in Estonia in the period 1961–2005. Precipitation is labeled "heavy rainfall" when its 24-hour accumulated sum is at least 50 mm. The work was concentrated on manual analysis and classification of synoptic situations as well as on the definition of tracks of cyclones, fronts and troughs in order to better understand the circumstances leading to the heavy rainfalls. Most of heavy rainfalls have been caused by the passage of different depressions and frontal systems. The role played by convective precipitation is less significant. Most frequently, heavy rainfall is brought to Estonia by the southern cyclones, born in the region of the Black Sea or the Mediterranean Sea.

Key words: heavy rainfall, synoptic weather types, cyclone tracks, manual analysis, Estonia.

1. INTRODUCTION

History and present experience show that heavy precipitation can cause flash flooding and major damage in Estonia. The most recent two remarkable rain events took place in towns: on August 5–6, 2003, 131 mm during 24 hours in Jõhvi, and on July 28–29, 2004, 145 mm during 48 hours in Tallinn. Both events caused flash flooding and local infrastructure damages and attracted a lot of attention in media. Such increased attention has raised the question of whether extreme precipitation in Estonia is truly becoming more frequent or if it is because enhanced media attention has triggered more research on heavy precipitation related events in Estonia in the recent years [1,2]. In [2] it has been found that the annual number of the sum of extreme wet and dry days indicates the rising trend of extremes in the precipitation regime (extremely dry periods are precipitation extremes as well) of Estonia in 1957–2006. In [1] no remarkable trend in heavy precipitation events, recorded in Estonian stations in 1961–2005, was found. One reason for different conclusions lies in the differing definitions of extremely wet days. Thus, 50 mm for daily precipitation is a very high threshold for Estonian climate and does not provide a sufficient number of cases for proper statistical investigation; however, it does offer a reasonable number of cases for manual analysis.

There exists a set of studies, used to determine the change in the probability of heavy precipitation all over the world, which take into account all available daily data. However, these results about extreme precipitation trends from measured station data in Northern Europe and the former Soviet Union are contradictory: [3] does not establish a major change neither in daily precipitation extreme values nor in their occurrence, while [4] finds a widespread increase in the frequency of very heavy precipitation during the past 50 to 100 years. The same uncertainty concerns future climate [5] in that precipitation is projected to increase in the Baltic Sea area, especially during winter. During summer (when extreme rainfall occurs) the increased precipitation amounts in the north is contrasted with a decrease in the south of this region.

Investigations of the spatio-temporal distribution of precipitation amounts and intensities constitute important information for planning engineers. This information helps in the design of drainage systems. The floods in Estonian towns in recent years indicate that the capacity of rainwater management systems has been exceeded or that the drainage infrastructure is missing or outdated. Our work offers some initial data for planning purposes. However, it is clear that upgrading drainage systems will be costly and for that much more data is needed. Some of the data have very short time series (intensities of precipitation per hour or shorter time, for instance).

Heavy precipitation generally originates from deep convective clouds (*Cumulonimbus*). These are the only clouds that can produce thunder, lightning, hail, tornado and torrential rain. At mid-latitudes the development of severe convective systems is mostly associated with synoptic forcing and with convective potential instability. The purpose of the work is to perform a preliminary study of synoptic situations associated with heavy precipitation in Estonia in the period of 1961–2005. The aim is to understand better the synoptic forcing, leading to heavy rainfalls, and assess their uniqueness. This paves the way for automatic synoptic typing, relying solely on the fields provided by global meteorological models and thus applicable also to the output of global climate simulation models. The work concentrates on the analysis and classification of synoptic situations that bring heavy rainfall and not on the proper trend analysis of these rare weather hazards as the existing precipitation database is insufficient for this.

2. DATA AND METHOD

The precipitation data originate from 27 meteorological, 64 hydrological and 16 precipitation stations in Estonia. Only 26 of these have performed measurements without any gaps during 1961–2005. In these 107 stations, precipitation is measured at least through 30% of days. The data originate from the Estonian Meteorological and Hydrological Institute. All months available have been investigated.

A rainfall event is defined as heavy if the accumulated sum of precipitation from 18 UTC of the previous day to 18 UTC of the measurement day is at least 50 mm. Rainfall is defined as extreme if the same 24 h accumulated sum is at least 100 mm. A day in which at least one of the stations registered this amount of precipitation, was considered to be a day with heavy rainfall. As our aim is to investigate the synoptic situations that bring heavy precipitation, we need the maximum amount of the events. Therefore, data from all stations have been taken into account, despite the number of missing days at the station. This makes the time-series of the heavy rainfall days per year non-homogeneous, as the number of registering stations has been the largest in 1970–1987 (when more than 100 stations were measuring) and the smallest since 2001 (less than 60 stations). During the whole period and at all stations the measurements have been carried out with the Tretyakov type rain gauge. It should be pointed out that the measured precipitation amount is always a bit less than the actual one. Some of the water is lost on watering the rain gauge, during evaporation and splashing in the wind. Since 1966, the wetting correction has been added to the initial data already at the stations. Although this does not make the time series homogeneous, the daily extreme precipitation sums are slightly affected.

In order to determine the origin and trajectory of cyclones, waves, troughs and fronts, the synoptic maps of Europe (charts printed in Obninsk World Data Centre for Meteorology with the time interval of 12 h) have been manually explored by an experienced meteorologist for the period 1961–1989. For later years, the operational charts with computer plotted synoptic data and manually added frontal zones were used. These charts exist with a 6-h time step for the period 1990–2005. The track of some cyclones has been found with the help of 6-hourly sea level pressure data from the National Centres for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis [6]. From this data, the 2–5 day period before each day with heavy rainfall was investigated.

The situation in the upper-level atmosphere was studied using 500 hPa charts. At this level the broad-scale flow and the jet streams, but also some intricate details of low-level storm systems can be followed. Analogically to the synoptic maps of Europe as a whole, these maps were printed in Obninsk World Data Centre for Meteorology with the time interval of 12 h in the period of 1961–1989. For later years (1992–2005), the charts of the operational analysis with the time interval of 12 h were employed.

The satellite images from the archive of NERC Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk) have been used to illustrate the cloud patterns during different types of heavy rainfall events. The features of atmospheric circulation are described by the trajectories of cyclones, fronts and troughs that affect the character of weather in Estonia [7].

3. SPATIAL-TEMPORAL DISTRIBUTION OF HEAVY RAINFALLS

In total, 509 heavy precipitation events were registered in Estonia during the period 1961–2005 and they occurred over 199 days. The 50 mm precipitation threshold was exceeded in all hydrological and precipitation stations (where the entire 45-year period was measured) and in all meteorological stations, except the one in Pärnu. All events occurred in the warm season from May to October, whereby 87% of these days belonged to the three summer months. This means that in all cases there was liquid precipitation. Over these the months, heavy rainfall events were distributed as follows: 66 days in July, 65 days in August, 42 days in June, 14 days in September, 9 days in May and 3 days in October. Of the heavy precipitation events, 62% were observed only in one station. During the remaining 38% of the days, it rained heavily simultaneously in two or more stations. There were 11 days with extreme rainfall in the period mentioned (Table 1).

Many events are not registered in the database due to their locality. The precipitation measurements network with less than 100 stations is not dense enough to detect all variable meteorological events such as rainfall. There are usually large local precipitation gradients in heavy rainfall events. A good example is the heavy rain in Tallinn on July 18, 1964, that was measured only in some parts of the city. It rained 61 mm over 2 h [7]. Many warehouses in the harbour were damaged, but only 15 mm of precipitation was registered at the Tallinn-Kose meteorological station and the event was not registered in the database as heavy precipitation.

Another reason for missing events is related to the definition of the beginning of the day. An extreme 24-h rainfall may be split into two parts by this regular observing hour. For example, the heaviest rain of this century occurred in Jõhvi on August 6, 2003. According to our database, it rained 90.0 mm over 24 h. In the Jõhvi weather journal, since 11 am on August 5 until 11 am on August 6, 131 mm of precipitation is recorded [1]. The selected beginning time at 18 UTC

Table 1. Data about extreme (≥100 mm/24 h) rainfall days in the period 1961–2005

Date	Station	24 h rainfall sum, mm	Weather type, trajectory
4.07.1972	Metsküla	148	B, southern
9.07.1978	Polli	112	B, southern
26.05.1983	Konnuvere	115	B, southern
29.06.1985	Ulila	137	A, local
21.08.1985	Kloostrimetsa	120	D, local
28.07.1987	Oore (Oreküla)	120	A, western
8.08.1987	Sänna	100	A, southern
3.07.1988	Võru	131	F
21.07.1991	Rohuküla	121	C, local
2.08.1994	Jõgeva	100	F
12.06.1998	Kääpa	136	B, southern

is related to the measurement times in the hydrological and precipitation stations, otherwise we could not use the data together with the data from the meteorological stations.

It is difficult to obtain an accurate estimate of long-term tendency of the spatial and temporal distribution of heavy precipitation events because they may be very local and heterogeneous in duration. The data of the 20 main meteorological stations of Estonia that have functioned without gaps during 1961–2005, have been taken for a brief assessment of some spatial-temporal tendencies. These stations registered 99 heavy rainfall events that occurred over 72 days. Figure 1 presents the spatial distribution of these heavy rainfalls. Relying on such a sparse network, it is not possible to highlight any favourable area for heavy rainfalls. This can mean that the contribution of the geographical position and orography are insignificant for formation of heavy precipitation and only synoptic factors and environmental conditions such as temperature, humidity and stability characteristics of the air masses play a vital role.

The temporal variability of heavy rainfalls is also ambiguous (Fig. 2). There is no evidence about the growth or decrease in the number of the days with heavy rainfalls in Estonia during the last 45 years. The maximum number of the days falls to the period 1985–1988.

Fig. 1. Occurrence of heavy precipitations (the number of days) at 20 main meteorological stations of Estonia in the period 1961–2005; x – locations of the stations that recorded extreme rainfall (≥100 mm/24 h) in the same period.

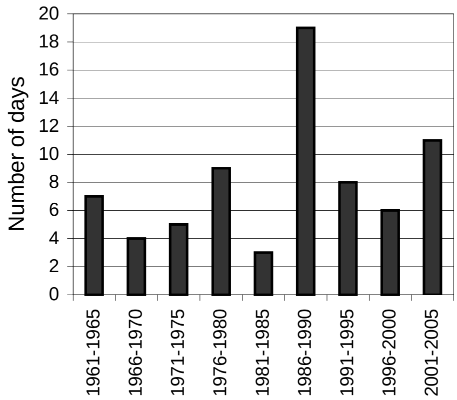

Fig. 2. The number of days with heavy precipitation events within five-year periods, recorded by 20 main meteorological stations of Estonia in 1961–2005.

4. TYPICAL TRAJECTORIES OF CYCLONES THAT INFLUENCE THE WEATHER

The Baltic Sea area is a region of intensive cyclonic activity. Synoptic scale atmospheric circulation in Estonia is described in greater detail in [7], where the classification of the trajectories of the cyclones that influence weather in Estonia can be found. Based on this classification, all cyclones and anticyclones in the years 1965–1974 have been counted from the synoptic maps by Ene Linno. According to [7], on average 132 cyclones affect the character of weather in Estonia during a year. The number of the cyclones passing over Estonia in the warm half-year (53) is much less than the number of cyclones in the cold season (79).

In order to find out the main features of the atmospheric circulation in the Baltic Sea area for the days with extreme rainfall, the origin and the moving trajectories of baric systems have been taken into account. By using typical trajectories of cyclones [7] that influence the weather in Estonia, six main trajectories (out of 8 [7]) were highlighted. These can be roughly named as northern, northwestern, western, southwestern, southern and local cyclones. Figure 3 illustrates the typical tracks of these cyclones.

The northern (N) or the so-called "diving" cyclones occur mostly in winter. During the warm season (May 5–Oct 15) they are insignificant, forming only 4% of the cyclones of the season.

The most frequent trajectory is northwestern (NW). Nearly one fourth (24%) of all cyclones come to Estonia from the northwest, from a region south of Iceland. Often, crossing the Scandinavian mountains, a new centre of low forms and it moves further to the east or southeast. The highest frequency of north-western depressions occurs in early winter (31% in Oct 16–Dec 24). In the warm season (when all heavy precipitation events have occurred), the frequency is the same as in the entire year (24%–25%).

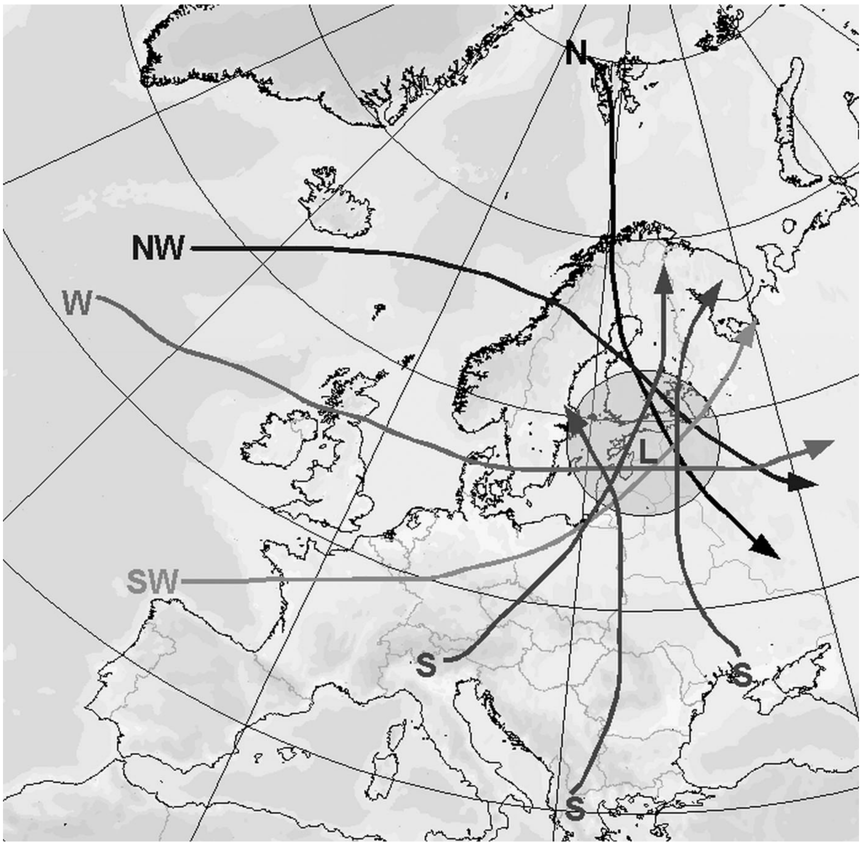

Fig. 3. Typical trajectories of cyclones that caused heavy precipitation in Estonia during the period from 1961 to 2005.

The western trajectory lows (W) move from the west to the east over Northern Great Britain and Southern Scandinavia to the Baltic States. The so-called Skagerrack's cyclones with the shorter track also belong to this group. On average, 12% of this warm season cyclones pass over Estonia by the western trajectory.

The southwestern cyclones (SW) often form near the Bay of Biscay and move northeastwards. The frequency of these cyclones in a warm season is slightly higher than over the whole year: 14% against 12%.

The southern cyclones (S) may originate from the area of the Black Sea, the Balkans or the Mediterranean and move along the meridian to the north. In spring the frequency of these cyclones increases up to 15% and reaches a maximum (26%) in the first part of the summer and in the second part of the summer it is 20%. For the warm season, it totals 19% and for the whole year the percentage is 13%.

The area of formation of local cyclones that have short lifetime, is marked by the circle L in Fig. 3 (within the radius of 500 km from the Estonian geographical centre). In [7] the annual mean number of local cyclones is insignificant, including the warm half-year (for both only 4%).

5. CLASSIFICATION OF THE SYNOPTIC SITUATIONS BRINGING HEAVY RAIN

An experienced weather forecaster analysed the synoptic situations of all days with heavy rainfall in order to identify similarities between them and to classify them. The main criterion of classification was based on the formation and movement of baric systems at sea level. Six basic synoptic situations with three main baric systems, appropriate for 198 days with heavy rainfall, have been distinguished and only 1 day remained unclassified (Table 2).

The majority of heavy precipitation events is associated with cyclones. There are two dominant weather types – A (deep extensive low) and B (minor low level cyclone). Atmospheric fronts, accompanying the clash of air masses with different thermal and humidity characteristics, also play an important role in the creation of the conditions for the formation of heavy rainfalls (types C – frontal wave, D – trough with rapid front and E – slow front). The final group consists of convective precipitation, which is largely caused by convection and instability effects (weather type F).

Type A is associated with deep depression (visible both on the surface and in the upper air pressure field), the centre of which crosses over or near Estonia. These deep depressions produce not only widespread and continuous precipitation, but also strong gusty winds over a large area. In most cases, heavy precipitation was registered in more than one station and sometimes for 2–3 consecutive days. The most dramatic example is the southern cyclone that brought heavy rainfall to Estonia on August 7 to 8, 1987 when 47 heavy rainfall events were recorded. In southeastern Estonia the amount of precipitation reached 139–158 mm/48 h. About 80% of crop was damaged and the town Võru was flooded. The satellite image in Fig. 4 shows the spiral structure of the cyclonic cloud system, covering a large territory. Three days with extreme rainfall belong to this type of weather (Table 1).

Type B is associated with the lower level small depression that usually forms near the frontal wave or at the point of occlusion crossing over Estonia. These minor lows are invisible in the upper pressure field and usually move according to the main mid-level flow. They usually tend to merge with more extensive low pressure systems. Four days with extreme rainfall, including an absolute Estonian

Table 2. The division of weather types, bringing heavy rainfall, for different baric systems in Estonia in 1961–2005. Relative frequencies of the heavy rain bringing events are shown. There was one unclassified day that is not included in the table as it makes up less than 1% of all heavy rainfall cases

Baric system (relative frequency, %)	Cyclone 54			Atmospheric front 34		Convection 12
	A	B	C	D	E	F
Weather type (relative frequency, %)	Deep low 25	Minor low 29	Wave 10	Trough with front 16	Slow front 8	Convective 12

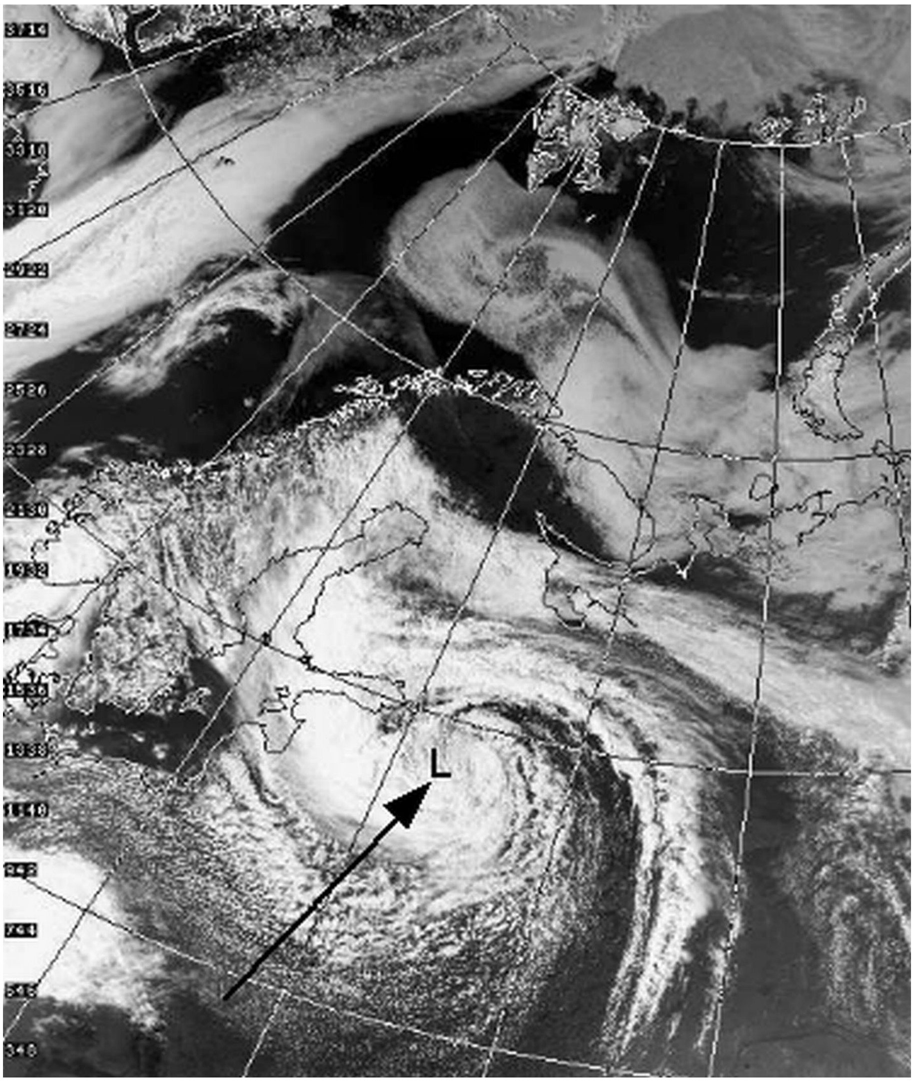

Fig. 4. NOAA-9 AVHRR channel 1 (visible) image on August 7, 1987 at 12 08 UTC. → L – the track and the location of the centre of depression. The picture is from the archive of NERC Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk).

record of 24-h precipitation – 148 mm at Metsküla – are associated with this dominant weather type (Table 1). The weather map in Fig. 5 shows a typical situation of this weather type. The minor low of the local formation caused the last flash flooding in Tallinn, when 148 mm/48 h rained on July 28–29 in 2004.

Type C is associated with the frontal wave. The majority of the wave disturbance forms on the slow moving cold front and produces widespread and occasional heavy precipitation. The local wave that slowly moved from Southern Finland over Estonia southwards caused 10 events of heavy rain on July 27 in

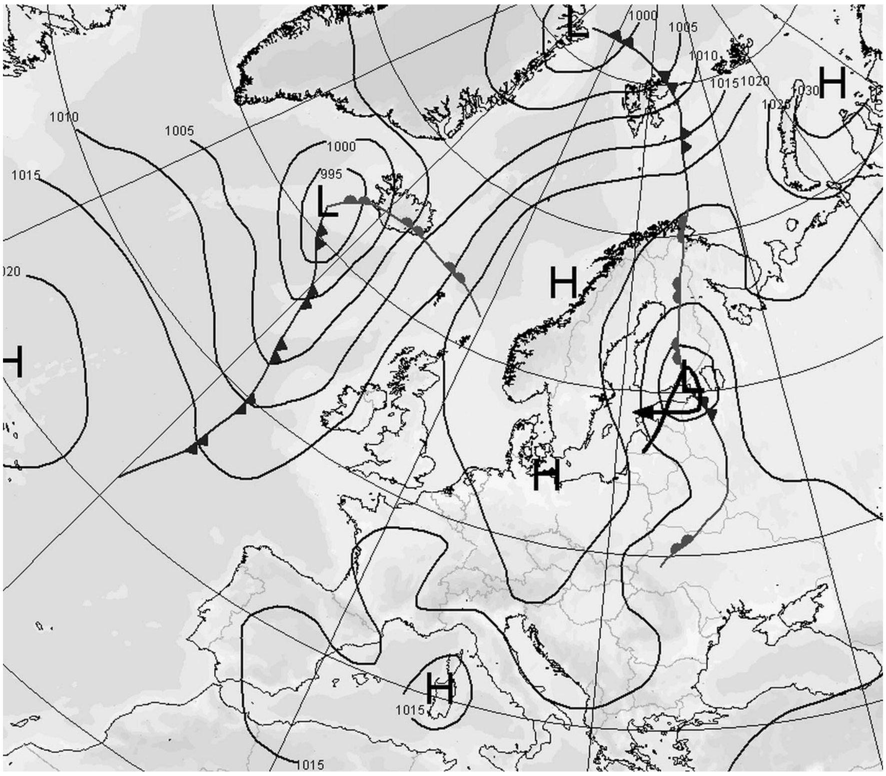

Fig. 5. Surface analysis chart for 00 UTC July 24, 2004. Surface pressure is plotted with solid lines after every 5 hPa. Atmospheric fronts, the location of the centres of high (H) and low (L) pressure systems are also presented. An arrow shows the trajectory of the minor (heavy rain bringing) low close to Estonia.

1990. The maximum of 24-h accumulated sum of precipitation exceeded 81 mm at Tõrva.

Type D is associated with the fast running cold or occluded front within well-marked trough. Here are dominant Scandinavian troughs that are often visible also in the upper pressure field. Scattered showers in the rear of such troughs often complement the frontal rainfalls. In all cases, heavy precipitation was observed only in one station, except on August 11, 1991, when the Scandinavian trough with a cold front passed over Estonia and heavy rainfalls were registered in 4 stations with the maximum amount of precipitation 92 mm/24 h at Jõgeva.

Type E is associated with slowly moving cold or occluded front within a surface slack area of low pressure. Heavy precipitation, related to this type of weather, may be characterized as isolated rain showers, but may also be significant. Sometimes heavy rain can occur a long distance from the frontal line in the warm air mass where heating is at a maximum. The maximum amount of precipitation for this type of weather was registered on June 25, 1991 at Räpina – 79 mm.

Type F is associated with the weak surface pressure field and convective precipitation. For this weather type, the synoptic factors are insignificant and the vital ingredients for causing heavy rainfalls are local atmospheric conditions: thermal, humidity and stability characteristics. The most common feature for this situation is isolated rain showers, which were observed only in one station, except on August 2, 1994, when 4 stations in Eastern Estonia registered heavy precipitation simultaneously. The quantity of precipitation at Jõgeva exceeded 100 mm/24 h. The best example of a deep convection is the torrential rain and flash flooding in Võru on July 3, 1988, when 130.8 mm of rain came down from 3 pm until 9 pm. In the infrared satellite image from NOAA-9 (Fig. 6) we can see a bright white cloud over the SE part of Estonia. This means that the temperature

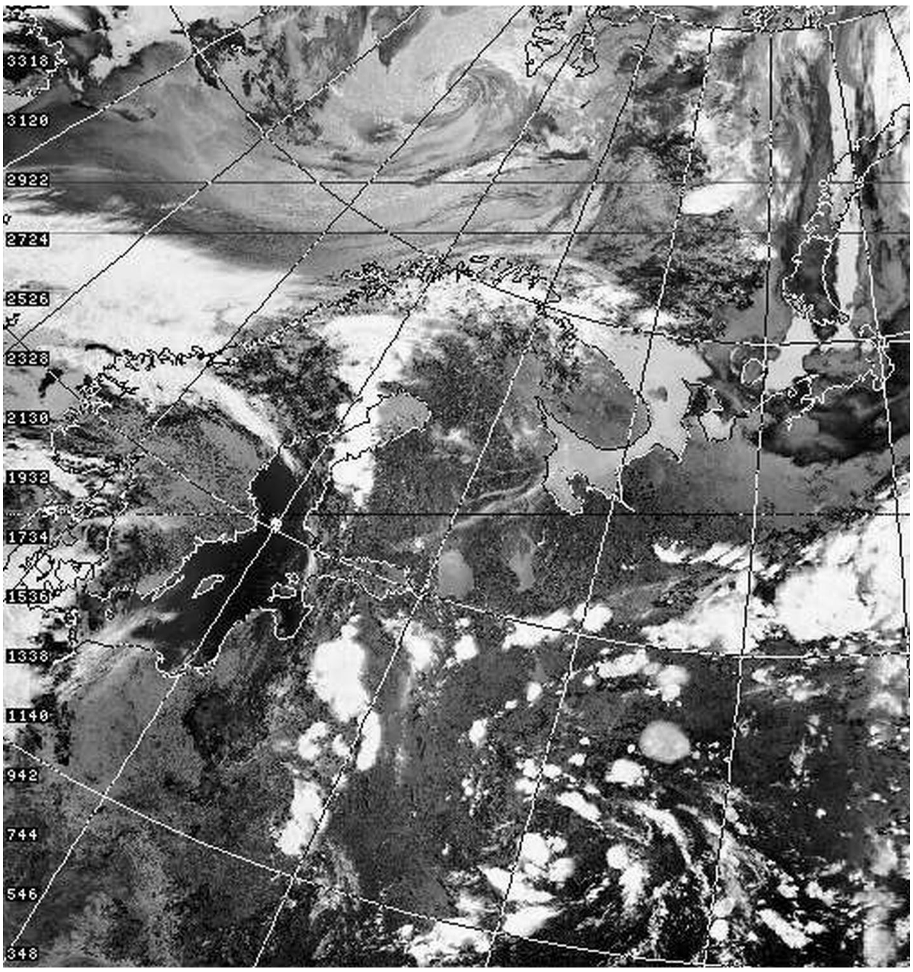

Fig. 6. NOAA-9 AVHRR channel 3 (short wave infra-red) image on July 3, 1988 at 12 43 UTC. The picture is from the archive of NERC Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk).

of the cloud top is very low and the vertical size of this convective cloud is extremely high.

The unclassified day is associated with a quasi-stationary occluded front over Latvia that did not cross Estonia, but its cloud system covered the southern part of the country and caused heavy rain on August 18, 1962 in Elva.

6. CLASSIFICATION OF SYNOPTIC SITUATIONS FOR DAYS WITH HEAVY PRECIPITATION

In addition to the division of heavy precipitation days into six synoptic situations, the origin and the propagation trajectory of all baric systems have been examined. All tracks of the deep and minor cyclones (weather types A and B), the frontal waves (type C) and the troughs with front (type D) were divided between five aforementioned typical trajectories of cyclones (Fig. 3) and the baric system of local origin.

The results of the classification of synoptic situations for days with heavy precipitation are presented in Table 3. Most frequently, in 53 cases out of 199, the baric systems that bring heavy rainfall come to Estonia by the southern track. This track is mostly chosen by minor or deep lows. The local formation of low-pressure systems occurs in 35 cases out of 199. The occurrence frequency of this type depends on the definition of the area of formation. This time we have chosen a 500 km circle around Estonian geographical centre. In [7], these cyclones are also called the Baltic Sea cyclones and their amount was much lower (4%) for all seasons. For frontal situations, the most popular track is the western or the northwestern one. Heavy rains mainly do not come from the north (only 2 cases).

Table 3. Occurrence (in the number of days) of the heavy rainfall bringing synoptic weather types and their division between propagation tracks in the period 1961–2005

Trajectory	A Deep low	B Minor low	C Wave	D Trough with front	E Slow front	F Convective	Unclassified	Sum
NW	2	5	–	11	–	–	–	18
W	8	2	–	14	–	–	–	24
SW	9	7	6	4	–	–	–	26
S	22	25	5	1	–	–	–	53
N	–	2	–	–	–	–	–	2
Local	8	16	9	2	–	–	–	35
Total	49	57	20	32	16	24	1	199

7. CONCLUSIONS AND FUTURE PERSPECTIVES

Heavy precipitation, exceeding 50 mm/24 h is found in Estonia only in the warm season, from May to October. In the network of 107 stations (that have functioned during at least 30% of the investigated period), 199 days with heavy rainfall were recorded in 1961–2005. The brief assessment of the spatio-temporal distribution of heavy rainfall did not reveal any significant long-term trend in this period. Also, the geographical distribution of heavy rainfall cases from 20 Estonian meteorological stations during the period under investigation was extremely variable, without any favourable sub-regions for heavy precipitation.

Of all heavy precipitation events in Estonia during 1961–2005, 88% were produced by the passage of different depressions and frontal systems, 12% were caused by convection and instability effects. The dominant heavy rain bringing weather type is B, which is associated with lower level small depression. It has caused 29% of heavy rainfalls during the investigated period. From the trajectories of lows or troughs, the southern is a dominant (53 days) cause of heavy rain. The local formation of low-pressure systems has also made a significant contribution at 35 days.

The most frequent synoptic situation that brings heavy rainfall to Estonia is connected to southern cyclones born in the region of the Black Sea or the Mediterranean Sea. During the warm season, the southern cyclones form on average 19% of all cyclones [7], but at the time of heavy rainfalls they cause about half of the cyclonic cases and 25% of the total cases. This refers to the great role the southern cyclones play in bringing heavy rain to Estonia.

The 50 mm threshold for heavy precipitation gave a reasonable number of synoptic cases feasible for manual investigation. With lower fixed thresholds (e.g. 10 mm) or percent thresholds we shall get an amount of synoptic cases that could be treated only by automatic methods in the future. The development of an automated weather type classification, that accurately describes the precipitation extremes of synoptic situations, can be based on both sides of our manual classification. The results discussed in this article will then offer a database for comparison. One possibility is to exploit the software from [6] and the Northern Hemispheric cyclone database and classify cyclone trajectories using clustering methods. Other prospects are related to the COST action 733 weather type classifications database, where more than 20 classifications are available for 11 different domains in Europe, including the Baltic Sea area. From there it is possible to find the classification that best distinguishes the favourable circulation conditions for heavy rainfall in Estonia. Unfortunately, it offers only identification of "frozen" situations that govern the Baltic Sea region atmospheric circulation, compared to storm tracks that give also information about the source regions and transformation history of air masses.

Estonian precipitation regime extremes have been so rarely investigated that from the engineering viewpoint, the calculation of return periods of heavy precipitation for different thresholds in all stations will be one step ahead. Another interesting research direction will be minute or hour scale rainfall intensities for which the first five-year long time series from automatic weather stations will soon be available.

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Sünoptilised ilmatüübid, mis põhjustasid ekstreemsademeid Eestis aastatel 1961–2005

Olga Mätlik ja Piia Post

Ekstreemsademetega päevad Eestis on jagatud kuueks sünoptiliseks ilmatüübiks, analüüsides käsitsi sünoptilisi kaarte. Ekstreemsademe päevaks on loetud päev, mil vähemalt ühes Eestis sademeid registreerinud jaamas on ööpäevasumma olnud vähemalt 50 mm. Selliseid päevi on 199, need esinevad vaid soojal aastaajal maist oktoobrini. Kuna eesmärgiks on saada võimalikult palju eri ekstreemsademetega sünoptilisi situatsioone, siis on kasutatud andmeid 107 jaamast, kus ajavahemikul 1961–2005 sademeid mõõdeti (vaid 42 jaama mõõtsid sel perioodil pidevalt). Kuus baarilist süsteemi, mis toovad endaga kaasa ekstreemsademeid, on: ulatuslik kõrge tsüklon, väike madal tsüklon, laine frondil, kiire frondiga lohk, aeglane front ja konvektiivsed sademed. Kõige enam põhjustasid ektreemsademeid madal tsüklon (57 juhtu) ja kõrge tsüklon (49 juhtu). Seega oli üle poole ekstreemsadudest võimalik seostada konkreetse tsükloniga. Ekstreemsadusid põhjustavate tsüklonite ja lohkude trajektooridest osutusid olulisimateks lõunatrajektoorid. Sellised baarilised süsteemid olid sagedasti moodustunud Musta mere ja Vahemere piirkonnas.