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CLIMATOLOGY

Temperature extremes and detection of heat and cold waves at three sites in Estonia

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Abstract. Daily maximum and minimum temperatures are analysed from long time series for three Estonian sites: Tallinn on the southern coast of the Gulf of Finland (1920–2013), Tartu in inland Estonia (1894–2013), and Pärnu on the northern coast of the Gulf of Riga (1878–2013). The probabilities of extreme temperatures (defined in the meteorological practice in Estonia as lower than −30 °C in winter and higher than 30 °C in summer) and their successions (incl. cold and heat waves) are evaluated for the three sites. It is suggested that the thresholds based on upper or lower percentiles of the distributions of daily maxima/minima recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) are more suitable for the detection of cold and heat waves in Estonian climatic conditions than the current practice.

Key words: temperature extremes, heat wave, cold wave, probability of occurrence, Estonia.

1. INTRODUCTION

The climate of a certain region is characterized not only by the average (long-term, annual, seasonal, monthly, daily) values of the meteorological parameters, but also by their variability. To describe the variability of air temperature, several characteristics can be used on long-term, annual, seasonal, monthly, or daily basis: standard deviation, average maxima and minima, absolute maxima and minima. The main objective of the present paper is to describe the statistics of the maximum and minimum temperatures at three sites characteristic of different regions of Estonia.

In many aspects, however, various types of severe events such as temperature extremes and heat and cold waves are of great importance. There are no universal definitions of heat wave and cold wave as both depend on the background climatic conditions of the region under consideration (Robinson, 2001; Meehl and Tebaldi, 2004). One purpose of our paper is to better justify the determination of heat and cold waves in Estonian climatic conditions.

As daily temperature maxima in summer are connected with heat waves and minima in winter with cold waves, analysis of temperature extremes permits one to estimate the occurrence probability of various severe events. In this context, extreme values of meteorological parameters need precise definitions (e.g. Wong et al., 2011).

Analysis of daily temperature extremes is usually directed towards detection of climate change. For this purpose, different indices have been constructed. The simplest indices – monthly mean maximum and minimum temperatures – are used by Jaagus et al. (2014) together with the diurnal temperature range to calculate trends in the Baltic States during 1951–2010. They chose that time interval to involve as many stations with homogeneous time series as possible. Homogeneity of the time series was granted by means of using similar measurement devices and routines and leaving out stations that had been relocated. Statistically significant increasing trends in maximum and minimum temperatures (which were coherent with changes in the

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mean temperature) were detected for the annual averages and several months. No trend in the annual values of the diurnal temperature range was detected.

Regarding temperature, the following indicators are suggested for mid-latitude climates (Frich et al., 2002):

- total number of frost days during a year (minimum below 0 °C);
- intra-annual extreme temperature range;
- growing season length;
- heat wave duration index: maximum period for the year of at least 5 consecutive days with T_{max} at least 5 °C above the 1961–1990 daily T_{max} normal;
- per cent of time T_{min} exceeding 90th percentile of daily climatological distribution of minimum temperature – a measure of the number of warm nights.

These indicators have been used to clarify whether the frequency and/or severity of temperature extremes changed during the second half of the 20th century on a global scale. The changes demonstrated considerable coherence showing an increase in the number of warm summer nights, a decrease in the number of frost days, and a decrease in the intra-annual extreme temperature range. The most popular indices of extremes to detect climate change (e.g. Wong et al., 2011; García-Cueto et al., 2014) are given by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Klein Tank et al., 2009). These indices can be used also for establishing suitable thresholds for heat and cold waves at any site (Unkaševič and Tošič, 2015) and are used in this study.

2. MATERIAL AND METHODS

For the calculation of the probabilities of rare events the time series must be as long as possible (Van den Brink et al., 2005). As homogeneity is not of vital importance in this context, we use data from three Estonian meteorological stations with the longest data sets: Tallinn on the southern coast of the Gulf of Finland, Tartu representing inland Estonia, and Pärnu on the northern coast of the Gulf of Riga (Fig. 1).

The instrumental observations in Tallinn date back to the end of the 18th century (Tarand, 2003), but the time series of daily minimum and maximum temperatures starts in January 1920. Recordings of daily minimum and maximum temperatures in Tartu are available since 1 January 1894 and in Pärnu from 1 January 1878.

For different reasons, there are gaps in the time series of daily extreme temperatures. These gaps are shown in Table 1 where WWI and WWII denote the hectic times of the two world wars.

Even though the employed time series contain several (minor) inhomogeneities (Keevallik and Vint,

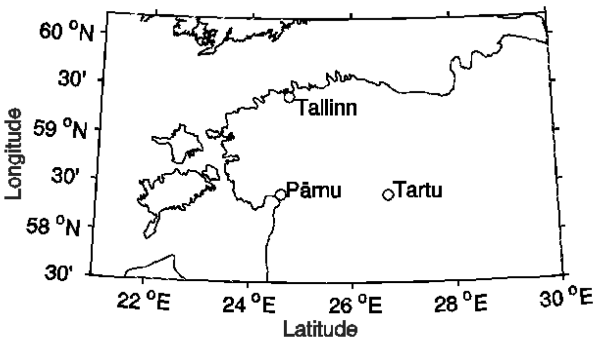

Fig. 1. Location of the meteorological stations under consideration.

2012), they are not crucial from the viewpoint of our study. Several changes (relocation, new instruments, different observation times) have indeed affected the data sets at these stations. For instance, the relocation of Tallinn meteorological station in 1980 and Pärnu meteorological station in 1990 caused an increase in the daily averages in the data sets from 1931–2010 and 1901–2010, respectively. Such an increase was also detected for Tartu in 1966 (in the context of the data set for 1881–2010) when the observation routine of 4 times a day was replaced by 8 times a day (Keevallik and Vint, 2012).

The absolute maximum temperature in Estonia (35.6 °C) was recorded on 11 August 1992 and the absolute minimum of –43.5 °C on 17 January 1940. According to the homepage of the Estonian Weather Service, the situation is labelled as (very) dangerous when the daily maximal temperature is above 30 °C during at least (three) two consecutive days or the daily minimal temperature is below –30 °C during at least (three) two consecutive days. The choice of these thresholds is not documented, but it seems to be related to the comfort temperature of the human beings in this climate zone. We use the same thresholds below in this study to identify the extreme events. In Estonia, daily maxima above 30 °C may only occur from May to September, and daily minima below –30 °C from December to February. Notice that as the temperatures are given in the data files with the accuracy to the first decimal place, actually the thresholds ±29.5 ºC were used.

A simple estimate of the return period of an extreme event within a relatively long time series is calculated as the ratio of the number of years in the time series to the number of recorded occurrences during this time period. A more complicated method to calculate values for large return periods from short records is described by Van den Brink and Können (2011). The inverse value of the return period is the probability of the occurrence p of the event in any one year. The probability P of the

Table 1. Missing values in the series of daily maximum and minimum temperatures

Station	Missing maxima	Missing minima
Tallinn	1–2 Aug 1938 1 Jun–30 Sep 1941 (WWII) 1–30 Sep 1944 (WWII) 1–31 Mar 1946, 11 Apr 1946, 18 Apr 1946, 30 Apr 1946, 17 May 1946, 21 May 1946, 24–26 May 1946, 28–31 Jul 1946 1 Sep 2003 26 Oct 2005, 27 Oct 2005	1 Jun–30 Sep 1941 (WWII) 1–30 Sep 1944 (WWII) 17 Sep 1945 1 Feb–31 Jul 1946 1 Sep 2003 26–27 Oct 2005
Tartu	1 Mar 1894, 15 Mar 1894, 28 Jan 1895, 5 Feb 1895 8–10 Feb 1895, 13–14 Feb 1895, 17 Feb 1895, 23 Feb 1895 1 Aug–30 Sep 1944 (WWII) 1–31 May 1951 1 Sep 2003, 11 Oct 2003, 17 Oct 2003	1 Aug–31 Sep 1944 (WWII) 1–31 May 1951 11–29 Feb 1952 1 Sep 2003, 11 Oct 2003, 17 Oct 2003
Pärnu	1 Jan 1878–31 Dec 1914 20 Aug–31 Oct 1915 (WWI) 1 Jun 1917–31 Dec 1919 (WWI) 5–10 Feb 1924 1–31 Jan 1942 (WWII) 1 Sep–31 Dec 1944 (WWII) 1 Mar–31 May 1945 (WWII) 1–31 Jul 1945	1–19 Aug 1878 31 Aug 1880 31 May 1882 1 Jan 1883–31 Dec 1886 1 Jul–23 Aug 1893 1–30 Jun 1903 20 Aug–31 Oct 1915 (WWI) 1 Jun 1917–31 Dec 1919 (WWI) 1 Mar–31 May 1945 (WWII) 1–31 Jul 1945

occurrence of this event k times in n successive years is presented by the binomial distribution:

$$P = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}. \quad (1)$$

3. PROBABILITIES OF EXTREME TEMPERATURES

The probability that daily maximum temperature exceeds 30 °C is the highest in July (Table 2). In Tartu such temperatures occur nearly every year and in Tallinn every third year. The probability that the daily minimum is below –30 °C is the highest in January, being 31% for Tartu and only 7% for Tallinn. This is consistent with the well-known difference between weather conditions at the seaside and in the inland of Estonia (Jaagus et al., 2014). The climate of Tartu is evidently more continental than that of Tallinn. The conditions in Pärnu are not as mild as in Tallinn and not as contrasting as in Tartu.

Table 2. Probability of the occurrence p (%) of daily maxima above 30 °C in summer and daily minima below –30 °C in winter

Month	Summer, $t > 30$ °C			Month	Winter, $t < -30$ °C		
	Tallinn	Tartu	Pärnu		Tallinn	Tartu	Pärnu
June	4.3	28.9	17.5	December	1.0	5.0	1.6
July	33.3	86.0	43.7	January	7.4	31.4	10.7
August	6.4	32.5	13.4	February	4.2	20.0	7.6

These probabilities can be used as a benchmark to estimate the skill of forecasts of various kinds, for example to check how much a certain complicated forecast is better than the climatological one (Hamill and Juras, 2006; Keevallik et al., 2014).

A more detailed description of temperature extremes can be given, for instance, as

- the probability that a specific extreme event takes place at least once in n successive years;
- the probability that a specific extreme event takes place exactly k times in n successive years.

We analyse these probabilities for the test time interval on decadal scale (n = 10 years) using Eq. (1).

The probabilities of the occurrence of extreme temperatures (Tables 3 and 4) indicate, not unexpectedly, that the temperature contrasts are the largest in Tartu, which is situated inland. Here in July the temperature exceeds 30 °C nine times during ten successive years with the probability of 36%. In each ten-year period this temperature is reached at least five times. In Tallinn, where the maritime conditions prevail, the probability that the temperature rises above 30 °C at least once during ten successive years is practically similar to that in Tartu, but the difference is in the most probable number of events: in Tartu the probability is the highest that it happens nine times, in Tallinn three times. In January, the temperature in Tartu falls below –30 °C

Table 3. Probability (%) that daily maximum temperature is above 30 °C in 10 successive years according to Table 2 and Eq. (1)

	Once	2 times	3 times	4 times	5 times	6 times	7 times	8 times	9 times	10 times	At least once
Tallinn											
June	29	6	1								36
July	9	20	26	22	13	5	2				98
August	35	11	2								48
Tartu											
May	8										8
June	13	25	27	19	9	3	1				97
July					1	3	12	26	36	22	100
August	9	20	26	22	13	5	1				98
September	8										8
Pärnu											
May	32	8	1								41
June	31	30	17	6	2						85
July	2	9	18	24	23	15	7	2			100
August	37	26	11	3	1						76

Table 4. Probability (%) that daily minimum temperature is below –30 °C in 10 successive years according to Table 2 and Eq. (1)

	Once	2 times	3 times	4 times	5 times	6 times	7 times	At least once
Tallinn								
December	10							10
January	37	13	3					53
February	29	6	1					35
Tartu								
December	31	7	1					40
January	11	22	27	21	12	4	1	98
February	27	30	20	9	3	1		89
Pärnu								
December	13	1						14
January	39	21	7	1				68
February	37	14	3					55

during ten successive years three times with the probability of 27%. In Tallinn, this probability is only 3%.

The cases of very dangerous heat (three consecutive days with daily maximum above 30 °C) are generally rare (Table 5). Only four such events and only in July–August took place in Tallinn during 92 years and 13 (in June–July) in Pärnu during 96 years. In contrast, in Tartu as many as 13 such events took place before the year 1920 and 19 after that year. Mostly such hot periods occurred in July and August, but sometimes also in June and in 1906 even in May. Heat is extremely dangerous when the night between hot days is too warm. The occurrence of such events is reflected as the number of tropical nights (daily minimum higher than 20 °C) during dangerous hot periods (Table 5).

Interestingly, dangerous heat conditions usually did not occur simultaneously at all measurement sites. The most serious heat periods were at the end of July 2003 when a heat period was recorded at all three measurement sites. In Pärnu the dangerous situation lasted for five days separated by five tropical nights. At that time (until the end of 2004) the measurement site in Pärnu was in the middle of the town, but in July of 2010 when very hot periods were detected in all three sites again, the measurements in Pärnu were performed already at the airport.

Very dangerous cold, when the daily minimum temperature falls below –30 °C during at least three consecutive days, never occurred in Tallinn and was recorded only once in Pärnu (9–12 January 1987). However, in Tartu nine cases were detected, the longest lasted for nine days: from 5 January to 13 January 1987.

Table 5. Periods of dangerous heat (at least three consecutive days with daily maximum above 30 °C). The number of tropical nights during these periods is shown in brackets. For better comparison the data for Tartu are presented separately before and after 1920

Tallinn	Tartu before 1920	Tartu since 1920	Pärnu
	6–10 Jun 1896	3–5 Jul 1920 (1)	
	1–3 Aug 1896 (1)	25–28 Jul 1925	
	22–25 Aug 1900		17–19 Jul 1927 (1)
	13–18 Jul 1901	25–27 Jul 1932	
	26–31 Jul 1901	9–12 Jul 1933	
	26–28 Jun 1905	24–26 Jul 1935	
	17–19 May 1906		17–19 Jun 1939
	19–21 Jul 1908	14–16 Aug 1939	
	8–10 Aug 1912	24–26 Jun 1940	
	8–13 Jul 1914	10–15 Jul 1941 (4)	
	20–24 Jul 1914		8–10 Jun 1956 (1)
	19–22 Jun 1917 (2)		25–27 Jul 1959
	3–5 Jul 1918	24–26 Jul 1963	
			27–30 Jun 1972
		5–7 Jul 1973	5–7 Jul 1973
			12–14 Jun 1977 (1)
			9–11 Jul 1983
		13–16 Jul 1994	
28–30 Jul 1994		28–30 Jul 1994	
26–28 Aug 1997			30 Jun–2 Jul 1997 (2)
		13–15 Jul 1999 (1)	
		15–18 Jul 2001	
		30 Jul–1 Aug 2002	30 Jul–1 Aug 2002
			15–17 Jul 2003 (1)
28–31 Jul 2003 (3)		28–30 Jul 2003 (1)	28 Jul–1 Aug 2003 (5)
		7–10 Jul 2006	
12–15 Jul 2010 (2)		11–16 Jul 2010 (3)	12–15 Jul 2010 (1)
		25–28 Jul 2010 (3)	

4. PERCENTILE THRESHOLDS TO DETERMINE WARM AND COLD WAVES IN ESTONIA

As the events to which the Estonian Weather Service refers as very dangerous situations are very rare, we make an attempt to find a more suitable definition of the heat and cold waves. According to the practice recommended by the ETCCDI, we applied more flexible thresholds to determine (extremely) cold nights, warm days, and heat and cold waves (Klein Tank et al., 2009):

- cold night: temperature lower than 10th percentile of daily minimal temperatures calculated for a 5-day window centred on each calendar day in 1961–1990;
- warm day: temperature higher than 90th percentile of daily maximal temperatures calculated for a 5-day window centred on each calendar day in 1961–1990;
- cold wave: six consecutive cold nights;
- heat wave: six consecutive warm days;
- tropical night: daily minimum higher than 20 °C.

For Tallinn (Fig. 2) as well as for the other two sites (not shown) these thresholds for the detection of warm days and cold nights do not appear to be well suited for practical detection of the warm and cold waves, especially for the cold wave in winter when day-to-day variability of the threshold is remarkable. It may happen that the same minimal temperature during several days of a certain year is labelled differently for two consecutive days. For instance, –21.5 °C is below the threshold on 10 February (cold) and above it on 11 February (not cold enough).

To avoid such shortcomings, these percentile thresholds were approximated by means of Fourier series

$$\theta = p_0 + p_1 \sin\frac{2\pi t}{366} + p_2 \cos\frac{2\pi t}{366} + p_3 \sin\frac{2\pi t}{183} + p_4 \cos\frac{2\pi t}{183} + p_5 \sin\frac{2\pi t}{91.5} + p_6 \cos\frac{2\pi t}{91.5}, \quad (2)$$

where θ is threshold temperature and t is the Julian day of the year (incl. 29 February). The Fourier coefficients are shown in Table 6.

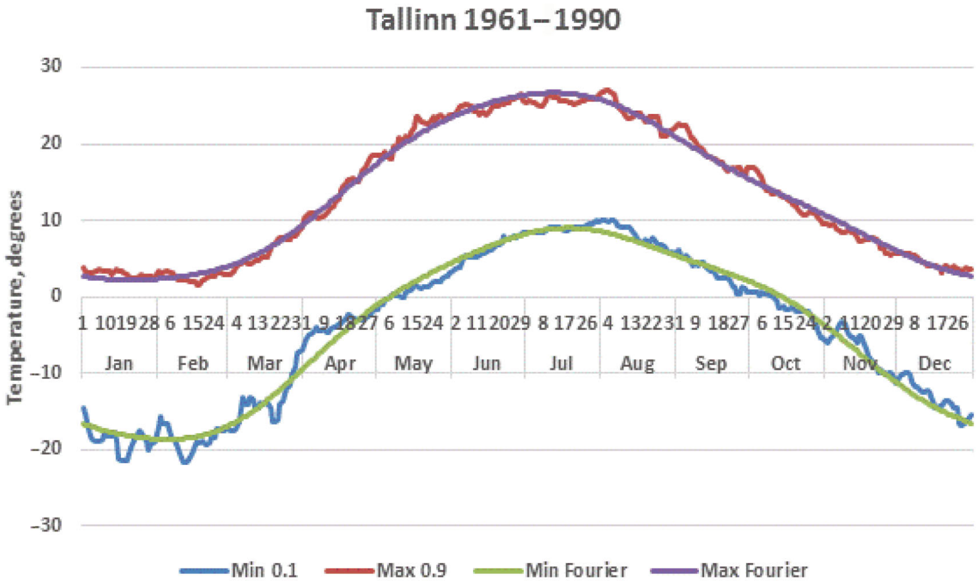

Fig. 2. Calculated thresholds for estimating warm and cold waves for Tallinn and an approximation of the annual course of the thresholds by means of Fourier series: Min 0.1 – 10th percentile of daily minimal temperature; Max 0.9 – 90th percentile of daily maximal temperature.

Table 6. Fourier coefficients of the threshold temperatures

	Threshold for heat wave			Threshold for cold wave		
	Tallinn	Tartu	Pärnu	Tallinn	Tartu	Pärnu
p_0	13.764	14.493	13.553	–4.036	–6.118	–3.606
p_1	–3.012	–2.811	–2.972	–5.756	–5.782	–5.954
p_2	–11.828	–12.909	–12.479	–12.373	–13.634	–13.225
p_3	–0.670	–0.715	–0.883	–1.447	–1.828	–1.492
p_4	1.057	0.518	1.239	–0.234	–0.945	–0.412
p_5	0.262	0.479	0.261	0.507	0.521	0.562
p_6	–0.24	–0.380	–0.451	0.126	–0.047	–0.071

Approximation (2) was used to detect heat waves in summer (June, July, and August) and cold waves in winter (December, January, and February) according to the ETCCDI practice.

The use of the current practice (the fixed threshold of ±30 °C in three consecutive days) is clearly problematic in Estonia as the data in Table 7 suggest.

Table 7. Number of heat waves and cold waves according to the method of the ETCCDI approximated by means of Fourier series and the number of cases (in brackets) when the fixed thresholds of ±30 °C were used

Site	Heat waves	Cold waves
Tallinn	20 (4)	21 (0)
Tartu before 1920	12 (12)	1 (0)
since 1920	30 (19)	17 (9)
Pärnu before 1920	0	10 (0)
since 1920	37 (13)	19 (1)

It is sensible to use a site-specific ETCCDI method that is much more flexible and, most importantly, is adaptable in the sense that it is able to detect also periods throughout the year that are warmer and/or colder than normal.

5. CONCLUSIONS

The probability that the daily minimum temperature is below –30 °C is the highest in January. Such low temperatures occur almost surely at least once (and most probably three times) during ten successive years in Tartu and with the probability of 53% in Tallinn. The probability that the daily maximum is above 30 °C is the highest in July when such temperatures almost surely occur at least once during each ten successive years at all three stations. In Tallinn the probability that such maxima occur exactly three times during ten successive years is 26%, but in Tartu they normally occur at least five times during any ten successive years. This knowledge could be regarded as a climatological prediction and could be used as a benchmark to estimate the skill of various forecasts.

The current standard description of very dangerous warm and cold situations in Estonia is associated with daily maximum temperatures above 30 °C or daily minimum temperatures below –30 °C during at least three consecutive days. Such events are rare, especially in Tallinn. An extremely dangerous cold event took place in January 1987 when the temperature was –30 °C or lower during a 14-day period in Tartu and a 3-day period in Pärnu. An extremely dangerous heat was recorded in July 2003 and in July 2010 at all three stations. Then the daily maxima exceeded 30 °C and the days were separated by some warm nights when the temperature did not fall below 20 °C.

The ETCCDI method is eventually more practical to establish site-specific and more flexible thresholds and to detect heat and cold waves. In particular, the ETCCDI thresholds approximated by means of Fourier series seem to be more suitable for practical application, as the large day-to-day differences are removed.

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Ekstreemsete temperatuuride esinemistõenäosused ning kuuma- ja külmalainete määratlemine Eestis

Sirje Keevallik ja Kairi Vint

On analüüsitud õhutemperatuuri päevaste maksimumide ja öiste miinimumide pikki aegridu Tallinnas (1920–2013), Tartus (1894–2013) ning Pärnus (1878–2013). On leitud empiirilised tõenäosused, mitu korda esinevad ekstreemsed temperatuurid (talvel –30 °C või alla selle ja suvel üle 30 °C) kümne järjestikuse aasta jooksul. On näidatud, et nende läveväärtuste alusel on kuuma- ja külmalainete identifitseerimine Eesti tingimustes probleemne. Märksa sobivam on nende määratlemiseks kasutada kliimamuutuste tuvastamise ja indeksite ekspertkomisjoni (ETCCDI) soovitatud metoodikat, mis tugineb ööpäeva maksimumide ja miinimumide ülemiste ning alumiste detsiilide analüüsile.