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Long–range alternation of extreme high day and night temperatures in Lithuania

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Abstract Extreme temperatures seriously impact all aspects of human life. In the 20th century, in Lithuania, the number of extremely hot events tended to increase. The aim of this study was to analyze the frequency of extremely hot day and night events and synoptic conditions during 1961–2010. Data of maximal and minimal temperatures of the warm period (May–September), obtained from 18 meteorological stations were used. Hot weather events were determined using the 95 percentile. Spatial (clustering) and temporal (regression coefficients, Mann–Kendall test) analyse were made. Also, the atmospheric circulation was analyzed using the COST733 action applications. The results have shown that the recurrence time of the highest temperature in the territory is mostly asynchronous. The daily values of extremes have a distribution similar to climatic regions, and for the night–time they become more latitudinal. The number of hot days and nights significantly increased in the second part of the period under analysis, especially during 1998–2010. Circulation analysis has shown that the most persistent types responsible for the development and persistence of hot weather conditions represent anti–cyclonic patterns. However, different circulation types depend on classification methods (GrossWetterType/ Litynsky), domain (D00/D05) and event time (day/night), chosen from the COST733 database.

Keywords *Air temperature • Extremely hot days • Extremely hot nights • Atmospheric circulation • GrossWetter Type • Litynsky classification • Lithuania*

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INTRODUCTION

High air temperatures are not a frequent but yearly recurring event in Lithuania. In this study, all days and nights with a temperature above the 95 percentile level were described as extreme. Temperatures exceeding 25°C were recorded 12.6 (in the coastal part) and 25.6 (in continental part) times per year, and their frequency showed an increasing trend in the 20th century (Bukantis *et al.* 2000; Bukantis, Valiuškevičienė 2005). Extreme temperature periods (above 30 °C) lasting for a few days were very rare (Alosevičienė 2001) and were recognized as a natural meteorological disaster. Extreme temperatures have a serious impact on the social, economical and ecological aspects of life (Easterling *et al.* 1997; Karl, Easterling 1999; Horton *et al.* 2001; Frich *et al.* 2002; Hughes 2003; Klein Tank *et al.* 2009) both on the local and on the global scales. Most vulnerable sectors are agriculture, forestry, public health and transportation (IPCC 2007; Adapting to... 2009).

It is obvious, that extreme heat events have become more frequent in most parts of the world, and extreme weather conditions have been analyzed very widely (Brázdil *et al.* 1996; Luterbacher *et al.* 2004; Liu *et al.* 2006; El Kenawy *et al.* 2009) over the last 20 years. Usually, various indicator complexes are used for the characterization of extreme conditions (Easterling *et al.* 2000; Frich *et al.* 2002; Klein Tank *et al.* 2002; Klein Tank, Können 2003; Tebaldi *et al.* 2006). Most often examined extreme indexes are *warm days* (*nights*) (percentage of time when the daily maximum (minimum) temperature exceeds the 90th percentile), *summer* (*hot*) *days* (annual count when the daily maximum temperature >25 °C (>30 °C) (Kyselý 2002; Domonkos *et al.* 2003; Meehl, Tebaldi 2004; Khaliq *et al.* 2005; Alexander *et al.* 2007; Kürbis *et al.* 2009) and others. Also *Extreme Value Theory (EVT)* and distribution of *Generalized Extreme Value (GEV)* (Kyselý 2002; Parey 2008) are usually employed when determining extreme conditions. *GEV s*howed very reliable results for extreme values, but it is not quite proper for determining the duration of extreme events. The duration of extreme temperature periods is successfully determined from the regression functions of available data series. Large scale circulation (Domonkos *et al.* 2003; van den Besselaar *et al.* 2010) and synoptic condition (Garcia *et al.* 2002; Luterbacher *et al.* 2004; Garcia-Herrera *et al.* 2005) patterns are often accounted for in research.

In the Baltic Sea region, extreme heat events have been analyzed in the framework of the European Climate Assessment (ECA) project (Klein Tank *et al.* 2002; Klein Tank, Können 2003) and special assessment report of the HELCOM (BACC 2007). The application of regional models (Tebaldi *et al.* 2006; Dankers, Hiederer 2008; Fischer, Schär 2009) revealed the general peculiarities of extreme changes in the Baltic region. An increase of climate extremity was detected in studies in the neighbouring countries (Wibig, Głowicki 2002; Climate change... 2007; Avotniece *et al.* 2010; Briede, Lizuma 2010; Tammets 2010).

In Lithuania, the investigation of temperature extremes was initiated by K. Kaušyla (1964) and was continued by his students at Vilnius University and at the Department of Geography of the Academy of Sciences (from 1990 – Institute of Geography). The frequency and spatial distribution of drought periods have been analyzed since the end of the 19th century (Bukantis 1996). Drought periods were determined as a function of soil wetness and the hydrothermal coefficient (HTK). The results showed a significant correlation with air temperature anomalies (above 30 °C) (Buitkuvienė 1998). Also, synoptic conditions of extreme droughts were described (Bukantis 1994; Bukantis *et al.* 2001). In Lithuania, *hot days* are recognized when the maximum daily temperature exceeds 25 °C three and more days; and *extremely hot days* (aka *sultriness*) when the temperature reaches 30 °C (≥5 days) (Bukantis *et al.* 2000; Alosevičienė 2001). Spatial and temporal variations of temperature extremes were analyzed by A. Bukantis, L. Rimkutė (1998), A. Bukantis *et al.* (2001), A. Bukantis, L. Valiuškevičienė (2005). Along with the chronological analysis synoptic conditions that favour hot days (Bukantis, Valiuškevičienė 2005; Liukaitytė, Rimkus 2008) and a large–scale circulation during positive temperature anomalies (Buz, Pechiuriene 1988; Bukantis *et al.* 2001) were analyzed. The research included sea level and 500 hPa pressure field studies (Stankūnavičius, Bartkevičienė 2003) favourable for the formation of such anomalies. The NAO influence on summer positive temperature anomalies (Stankūnavičius 2009) is not significant because of the lag effect.

The climate change has already disrupted the steady situation of hot day recurrence, and there will be even more changes at the end of the 21st century. According to the HELCOM assessment, hot days will become more frequent and severe in the south–eastern part of the Baltic Sea region (BACC 2007). Moreover, previous works on hot events were more focused on statistical analysis of the events, whereas the recent studies of Klein Tank *et al.* (2002) and the COST733 action (2010) offer new opportunities to analyze hot events in more complex and precise ways. The aim of this study was to analyze the frequency of the extremely hot day and night events and the synoptic conditions between 1961 and 2010 in Lithuania.

DATA AND METHODS

The maximal and minimal temperatures of the warm period (May–September) at 18 meteorological stations were analyzed in this research (Fig. 1). The analysis covered a 50-year period from 1961 to 2010 (the measurements at the Dūkštas meteorological station started in 1972). At some stations, the observations had single gaps (<1%) which were filled using the difference method. Data from a supplementary meteorological station with closest correlation links were used for the reconstruction. Extremely high temperatures of the warm period were determined in this study. All days and nights with a temperature above the 95 percentile level were described as hot. The 95 percentile levels were calculated for every day and night of the May–September period for all 18 meteorological stations. Afterwards the obtained time series were smoothed by the moving averages method.

At the next stage of the study periods of hot days and nights were distinguished. Such periods comprised three days or more when the air temperature exceeded the 95 percentile level in more than one-third of Lithuania's territory. In total, 68 periods of hot days and 66 periods of hot nights were distinguished. Cluster analysis was used for the regionalization of Lithuania's territory. Regions with a specific reoccurrence regime of extremely high temperatures were determined. The joining (tree clustering) method was used and complete linkage (Euclidean distance) was chosen for distance metrics.

The annual number of extremely hot days and nights was calculated and the statistical meaning of changes was determined at all meteorological stations. The sign and magnitude of changes were determined by the regression analysis. The statistical significance ($\alpha < 0.05$) of the tendencies was determined using the Mann–Kendall test. It is a non-parametric test for detecting a trend in a time series. The Mann–Kendall test is widely used in environmental studies, because it is simple, robust and can cope with missing values and values below a detection limit. Calculations were made using MULTMK / PARTMK software (Libiseller 2002). All the Mann–Kendall test values above 1.96 and below –1.959 were described as statistically significant ($\alpha < 0.05$). For the analysis of changes in different months of the warm period four meteorological stations (Klaipėda, Laukuva, Kaunas and Vilnius), representing different Lithuanian climatic regions, were chosen. The statistical significance of changes was also evaluated.

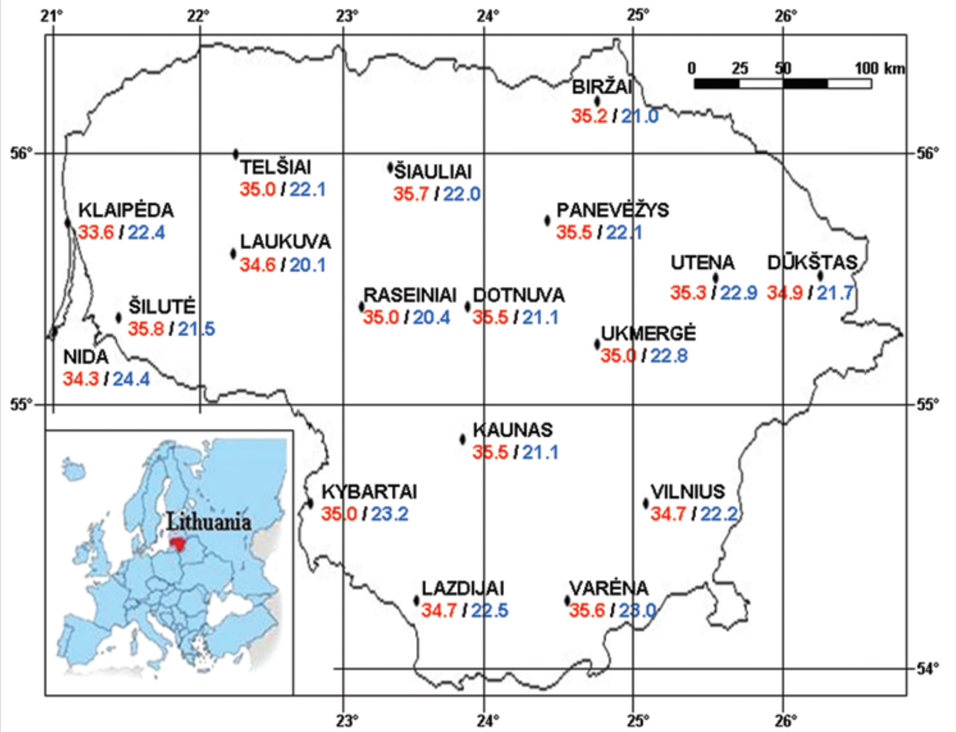

Fig. 1 Location map of Lithuania (bottom left) and meteorological stations whose data were used in the study. The highest day (red) and night (blue) temperatures during the study period are presented for each station. Compiled by J. Kažys, 2011.

The atmospheric circulation features of all extreme periods were investigated. The leading weather types responsible for the initiation and / or maintaining hot days and hot nights in Lithuania were extracted from the action COST733 web-based application. This application is designed for plotting centric maps of different circulation types and associated statistics and is accessed at *http://cost733.met.no/*.

Two of all available classifications were used in this study, both belonging to the same method group – threshold–based (THR) and to the group called "modified": GrossWetterTypes (GWT) and Litynsky (LIT). Also, both classifications use sea level pressure data as the input. The threshold–based method means distinguishing among different flow regimes according the threshold values of the indices representing flow intensity, direction and / or vortex parameters. Only one standard option—18 types of each classification—was used and only for two domains: the European (D00) and the Baltic Sea (D05) which extends between 53N and 68N and between 8E and 34E. The description of the GWT classification is available in Beck *et al.* (2007), while information about the original LIT classification may be found in Lityński's (1969) research, although the main difference between the "modified" LIT classification and the original is the input data and the automated algorithm. Therefore, 18 available weather types (WT) of two different classifications for two different spatial domains were applied in the study to identify the circulation regimes most favourable for the formation of hot days and nights in Lithuania.

All hot weather cases were divided into three standard stages: the hot weather body (HWB) – weather patterns (days) maintaining extra high temperatures (equal to or longer than three days), the hot weather developing period (DP) – three days prior to HWB and the hot weather relaxation period (RP) – one to three days after HWB. Not all cases ideally match such standard periods: some cases seem to be physically related to earlier and / or later cases, however, separated by the so-called intermediate period (IP) – one to four days that don't match the HWB criteria. HWB days also were analysed determining: a) most favourable weather types initiating or maintaining hot weather and b) weather type persistence during DP and HWB stages.

RESULTS

Spatial distribution of hot weather events

The warm period air temperature extremity significantly increased in the second part of the study period. Almost all highest temperature records were determined in the last two decades. The highest maximum air temperature record in the study period was registered at the Šilutė meteorological station on 10 August 1992 (35.8 °C). Highest temperatures on the same day were registered at 12 from the 18 meteorological stations. At four meteorological stations the highest temperatures were recorded in July 1994.

The all time warmest night (the highest minimum air temperature) record (24.4 °C) was noted at the coastal Nida meteorological station on 8 July 2006. Due its specific location between the Baltic Sea and the Curonian Lagoon, the minimum night temperature average of warm the period in Nida is approximately by 2 °C higher than in the rest of the country. Such difference is especially high in the second part of the warm period when water temperature reaches its maximal values and prevents night air cooling. The most pronounced spatial unevenness of highest night temperatures records in Lithuania is shown (see Fig. 1).

The territorial distribution of the 95 percentile level values during the warm period was also analyzed (Fig. 2). It shows differences of such values at the Vilnius and Klaipėda meteorological stations which represent the most continental and the most marine climate, respectively. Due to the cooling effect of the Baltic Sea the 95 percentile maximal day temperature values are lower in the coastal region during the whole warm period. At the same time, the 95 percentile minimal night temperatures are very similar in the first part of the warm period, whereas in the second part in Klaipėda these values are by 2–3 °C higher. It is most likely that extremely hot days and nights at the same time will be observed in a small part of Lithuania's territory. In 40–50% of cases such events covered only one fifth of the country (Fig. 3). Meanwhile, hot days and nights covered the whole Lithuania only in 10–20% of cases (mostly in July and August). Hot days cover the whole territory more often than nights.

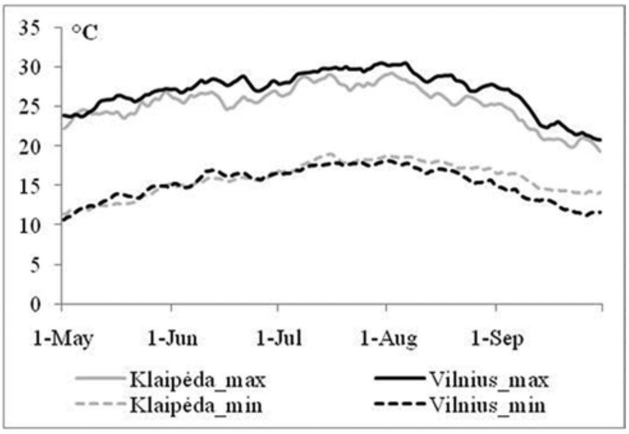

Fig. 2 Smoothed curves of 95 percentile level of day (max) and night (min) air temperature in Vilnius and Klaipėda in 1961–2010. Compiled by E. Rimkus, 2011.

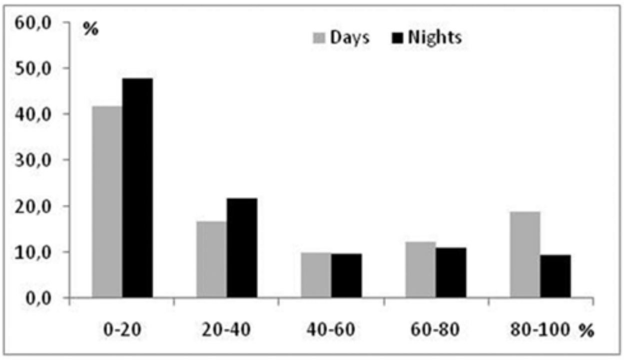

Fig. 3 Recurrence (%) of hot days and nights in Lithuania. On the horizontal axis represented is the number of stations (percent from total number) when extreme temperatures were measured at the same time. Compiled by E. Rimkus, 2011.

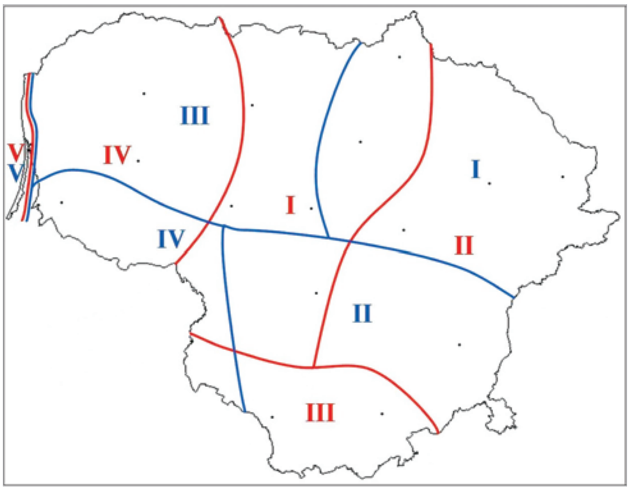

Fig. 4 Results of the cluster analysis, showing regions with synchronous recurrence of extremely hot day (red) and night (blue) temperatures. Compiled by J. Kažys, 2011.

The Lithuanian territory was divided into regions in which extreme temperatures were usually measured at the same time using cluster analysis (Fig. 4). Five regions were divided according to day and night temperature extremes. In both cases, the largest part of the Lithuanian territory is covered by four clusters, but the location of regions is slightly different. Day clusters almost fully correspond to the climatic regions of Lithuania which are distributed longitudinally. Climatic regions were distinguished taking into account the distance from the sea, relief and soil type (Kaušyla 1964). On the other hand, the distribution of night clusters shows latitudinal features.

Temporal distribution of hot weather events

The longest period (12 days) of hot days was observed on 26 July – 6 August 1994. Meanwhile, the longest period (12 nights) of extremely warm nights was observed twice: on 25 August – 5 September 1968 and 12–23 June 1999. Analysis shows a positive tendency of changes in the annual number of hot days and nights in the study period (1961–2010) (Fig. 5). An especially high recurrence of extremely warm nights was recorded in 2010 when the territorial mean value reached 34 nights (maximum at the Dukštas meteorological station 43). The maximum number of such events was noted in 2002 when the spatial average reached 31 days (maximum at Kaunas meteorological station 37).

Positive tendencies of changes in the recurrence of extremely hot days and nights were noted in all meteorological stations of Lithuania (Table 1). According to the Mann–Kendall test results, a statistically significant

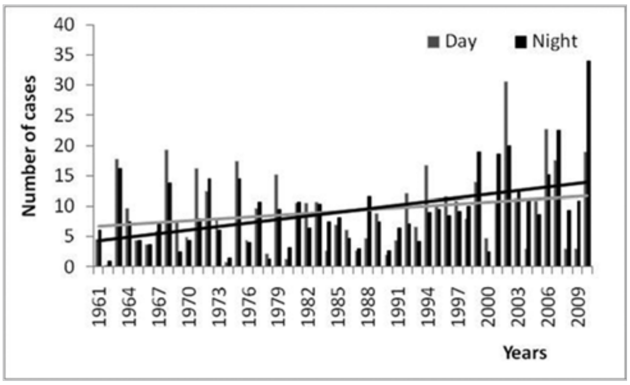

Fig. 5 Mean number of cases per warm season (May–September) with extremely high day and night temperature in 1961–2010. Mean numbers were calculated according to data from 18 meteorological stations. Compiled by E. Rimkus, 2011.

increase of extremely warm nights was determined in almost all meteorological stations, whereas the number of hot days significantly increased only in Panevėžys.

rather insignificant negative changes prevail. Only in Klaipėda the negative change of hot–day number in June was statistically significant.

Prevailing weather types during hot weather events

It should be noted that not always a large number of hot days and nights was observed in the same year. For example, the values of both indices were very high in 2002, whereas the number of hot days exceeded the number of hot nights twice in 1971 and 1994, and the number of hot nights was almost two times higher than the number of hot days in 2010. Such inadequacy can be explained by atmospheric circulation features. If the whole boundary layer is involved into anticyclone circulation, even hot days the surface can cool down significantly during the night. In contrast, if in a warm air mass a cloud cover is formed due to air turbulence near the surface the daily air temperature maximum doesn't reach extreme values, meanwhile the night

Table 1 Changes in recurrence of hot days and nights in Lithuania in 1961–2010. In the table presented linear regression coefficients. Bolded values are statistically significant ($\alpha < 0.05$) according to Mann–Kendall test. Compiled by E. Rimkus, 2011.

	Biržai	Dotnuva	Dūkštas	Kaunas	Kybartai	Klaipėda	Laukuva	Lazdijai	Nida	Panevėžys	Raseiniai	Šiauliai	Šilutė	Telšiai	Ukmergė	Utena	Varėna	Vilnius
Day	0.15	0.07	0.19	0.07	0.08	0.06	0.06	0.08	0.14	**0.17**	0.12	0.13	0.07	0.12	0.08	0.08	0.09	0.07
Night	**0.21**	**0.33**	0.23	**0.18**	**0.18**	**0.19**	0.12	**0.17**	**0.23**	**0.17**	**0.13**	**0.18**	**0.18**	**0.22**	**0.23**	**0.19**	**0.22**	**0.22**

The most significant increase in the number of hot days and nights was observed in July and August (Fig. 6). Statistically significant changes of the number of hot nights according to the Mann–Kendall test were determined in August at all the stations. Positive tendencies were observed in other months as well. The greatest changes of the number of extremely hot days were determined in July. The calculated changes in Vilnius and Klaipėda are statistically significant. However, in the first part of the warm period as well as in September, cooling is relatively slight and air temperature values can remain above the extreme level.

An earlier study has shown that the long-term persistence of circulation types in the GWT and the LIT classifications made for the D00 (large Europe) domains are 1.4 and 1.7 days, respectively. For a smaller domain, e. g. D02 (Western Scandinavia), the difference in persistency between these classifications decreases towards zero (Cahynová, Huth 2009). The percentage of the average length of the event repre-

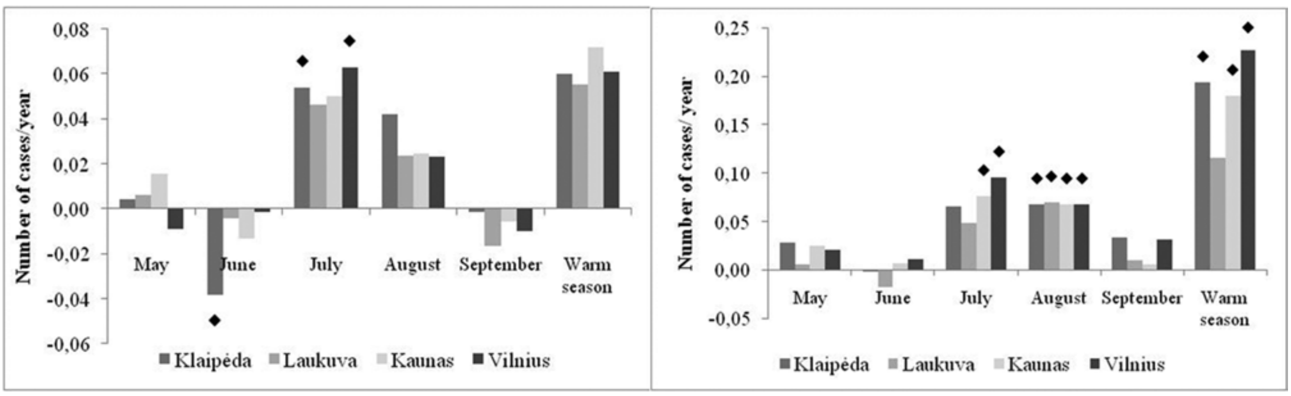

Fig. 6 Rate of changes (number of cases per year) of monthly number of days with extremely (above 95th percentile) high day (left) and night (right) temperatures during the warm period of a year in 1961–2010. Marked columns represent statistically significant changes ($\alpha < 0.05$) according to Mann–Kendall test. Compiled by E. Rimkus, 2011.

sented by these two individual classifications differs by about 15% – as the LIT classification is designed to represent shorter events than does the GWT. The same study also notes that there is no statistically significant correlation in the persistence of circulation types between the LIT and the GWT, and they show no significant trend in the mean seasonal persistence of synoptic types for the warm half of the year. The results of another study concerning regional hydrological drought development, using COST733 weather types show the GWT to demonstrate a much better performance than does the LIT classification (Fleig *et al.* 2010).

Exceptionally anticyclone patterns appear to be the most favourable weather types for HWB days regardless of the classification method and domain; however, circulation differences between the extracted types are better represented for the GWT D00 and LIT D05 classifications. HBW types favourable for the nights also represent anticyclone circulation; however, some types depend to cyclonic or intermediate circulation patterns (Table 2). Most of the extracted favourable types are directly or indirectly related to the Eastern European or Central European blocking patterns. A smaller domain (D05) allows distinguishing the leading favourable type, and this feature is more pronounced in the LIT classification method.

Most persistent types responsible for developing and maintaining HWB represent anticyclonic patterns with their central part within Lithuania and / or Southern Baltic or over the European part of Russia. That is true for the GWT D00 classification, while for the D05 there are prevailing weather types representing the southern or south–western flank of persistent anticyclone northward or north–eastern from Lithuania (Table 3). Similar findings are presented in a paper of Ustrnul *et al.* (2010) which deals with the synoptic conditions (the prevailing south–western airflow) of extreme air temperature patterns in Poland; however, large scale southerly and south–eastern airflow over Lithuania, as well as over Latvia, appears to be of the same importance in hot weather events as the south–westerly airflow (Avotniece *et al.* 2010). The weather types determined by the LIT classification method represent a large–scale troposphere wave with a trough over Western or Central Europe and the ridge over Eastern Europe (D00), and the southern or south–western periphery of the blocking anticyclone over Fennoscandia or Northern Russia (D05). Such conditions refer to the negative sign of the North Atlantic oscillation index and partially match the results of Jaagus' (2006) study. A warmer and wetter flank (periphery) of the anticyclone and / or a quasi-stationary low system (the western side of the anticyclone and the eastern or north–eastern side of the cyclone) appear to be more characteristic of the night, but not of the day types.

Table 2 Most favourable weather types initiating or maintaining hot weather during HWB events according different classification methods, domains and day time. Compiled by G. Stankūnavičius, 2011.

Classification method	Domain	Time	Weather type number	% of the total frequency	Description of weather type
GWT	00	Day	8	10.8	Anticyclone over Northern Russia
			14	9.7	Scandinavian anticyclone
			5	9.3	Blocking over Central Europe
			15	8.5	Ext. anticyclone in Northern Europe
		Night	5	9.3	Blocking over Central Europe
			15	8.6	Ext. anticyclone in Northern Europe
			8	8.1	Anticyclone over Northern Russia
	05	Day	15	12.2	SW periphery of the high in NW Russia
			16	10.9	SW periphery of the high in NW Russia or NE periphery of the low in Germany
			14	9.8	Southern periphery of a Scandinavian high
		Night	7	9.8	NE periphery of the low in SW Baltic
			15	9.4	SW periphery of the high in NW Russia
			14	8	Southern periphery of a Scandinavian high
LIT	00	Day	13	7.0	High over Russia, trough over C. Europe
			15	6.7	High over S. Russia, trough over C. Europe
			1	6.3	Low over Germany
			7	6.2	Ext. low over NW and Central Europe
		Night	13	7.0	High over Russia, trough over C. Europe
			15	6.4	High over S. Russia, trough over C. Europe
			1	6.3	Low over Northwestern Europe
	05	Day	8	12.5	SW periphery of the high in NW Russia
			6	10.0	Southern periphery of a Scandinavian high
			10	9.6	Western part of Russian anticyclone
		Night	8	11.2	SW periphery of the high in NW Russia
			7	6.9	NE periphery of the low in SW Baltic
			6	6.7	Southern periphery of a Scandinavian high

Table 3 The persistence of weather types during DP and HWB stages according to different classification methods, domains and day time. Compiled by G. Stankūnavičius, 2011.

Classification method	Domain	Time	Weather type number	Number of cases	Description of weather type
GWT	00	Day	18	26	High extending across Baltic Sea
			17	15	Low over British Isles
			5	14	Blocking over Central Europe
			9	11	High over Central and Eastern Europe
		Night	17	18	Low over British Isles
			5	15	Blocking over Central Europe
			18	15	High extending across Baltic Sea
			3	13	Low over North Sea
			9	11	High over Central and Eastern Europe
	05	Day	15	17	SW periphery of the high in NW Russia
			14	14	Southern periphery of Scandinavian high
			9	9	High over Lithuania
		Night	14	13	Southern periphery of Scandinavian high
			15	10	SW periphery of the high in NW Russia
LIT	00	Day	5	10	Low over Netherlands and North Sea
			1	9	Low over Northwestern Europe
			3	8	Low over Great Britain and North Sea
		Night	15	9	High over S. Russia, trough over C Europe
			1	8	Low over Northwestern Europe
			3	7	Low over Great Britain and North Sea
	05	Day	8	17	SW periphery of the high in NW Russia
			6	14	Southern periphery of Scandinavian high
		Night	8	19	SW periphery of the high in NW Russia
			6	17	Southern periphery of Scandinavian high

Development and decay stages of hot weather events

Most frequent weather types during DP stage in the GWT D00 are anticyclone circulation extending from Southern Scandinavia to the Eastern Baltic and a warm troposphere ridge over Northern and Eastern Europe (low over the British Isles). The second type is most frequent for HWB night events. For GWT D05, there prevail the western part of the Russian anticyclone and the central part of anticyclone (high over Lithuania) types and only for HWB day events. HWB night events in the same classification have no leading types (not shown). The LIT D00 classification for DP stage days suggests the north–eastern flank (mostly dry) of the Central European anticyclone and the north–eastern flank of the low over Denmark and the south–western part of the Baltic Sea, while for DP nights it exposes types 1; 5; and 3 (see Table 3). The LIT D05 classification for DP days represents several types related to the south–western, western or central parts of a large–scale anticyclone circulation, while for the night only one leading type – the south–western periphery of the high over North–western Russia.

In contrast to the DP, stage the RP stage can not always be identified using three consecutive weather types. Sometimes the first day after HWB is critical, and the passage of the atmospheric front (for instance) with a cloud system and cold advection behind it rapidly brakes all the favouring conditions that prevailed before. Therefore, the statistics of RP weather types is not consistent with that of DP. Most frequent types for RP in the GWT D00 classification are the south–western flow of Southern Scandinavian (low over Lithuania), the eastern periphery of the Faeroe-Scotland anticyclone (westward retreating blocking high) or a typical zone flow over the Southern Baltic. These types are characteristic of RP day events, while the night HWB periods could be interrupted without changes in the circulation conditions; because changes in the cloud cover or a drier air advection aloft are able to lower considerably the night–time temperatures. The GWT D05 classification has no one leading type responsible for RP at both days and nights. The LIT D00 represents one leading type (however, statistically insignificant) for RP – the eastern part of the Central European ridge, while the LIT D05 offers several types representing the eastern or north–eastern periphery of the Central European anticyclone (not shown).

Finally, IP periods not always appear within HWB events. They are more frequent in hot summers, when HWB tend to resume after a short break under the same favouring circulation conditions. In the GWT D00 classification, the prevailing weather types of IP are 18 and 17 (see Table 3); in the GWT D05 there prevail – weather types representing the south–western periphery of Northern or Central Russia anticyclones; in the LIT D00 dominates the representing the north–eastern periphery of Central European anticyclone; and in the LIT D05 the type representing the north–western part of the extended high over Russia (not shown).

A case study of hot weather events

The relation of particular weather types to the sea level pressure or geopotential height configuration is much better pronounced during cold seasons (James 2007). This study also shows that the large–scale ridges and troughs of atmospheric waves are better seen during early (May – the first part of June) and late (September) events, while midsummer hot weather events include less vivid pressure patterns.

To reveal the contrast between the consecutive weather types, two different hot weather events were selected at the beginning (1–9 May 2002) and the end (24 September – 1 October 1981) of the warm season. Both events are analysed for the DP and HWB periods; however, one of them consists of homogeneous weather types (one to four depending on the classification), while the other comprises multiple types (5 to 9 depending on the classification). The duration of the events as well as their DP and HWB is almost the same (8 and 9 days).

The pressure patterns of HWB of both events indicate a pronounced upper level ridge (500 hPa) oriented from the south (Fig. 7, top left) and southeast (Fig. 7, top right) to north–western Russia and surrounded with deep troughs upstream and downstream from the ridge axis. The upper frontal zone is closer to the Lithuanian area in the September pattern, while the local upper level centre dominates in the May pattern. The absolute values of geopotential height in the ridge axis are higher in the September than in May pattern; however, such difference could be explained by climatic reasons.

The standard deviation of the geopotential height over the Southeast Baltic in the May pattern (consisting of contrasting weather types) differs only marginally from the September pattern (consisting of homogeneous weather types); however, the standard deviation over the surrounding areas, particularly over the Northeast Atlantic, is larger by 60–100 meters (Fig. 7, bottom). This fact indicates that events consisting of both multiple and homogeneous types represent similar patterns of low-frequency atmospheric variability (e. g. blocking) over the same area, the main difference between these events being the form of interaction between high-frequency synoptic eddies and low-frequency large–scale waves.

DISCUSSION

Spatial differences in highest temperature records in the Lithuanian territory are insignificant and just exceed 2 °C (see Fig. 1). The first reason is that the territory is almost flat, its elevations reaching between 0 and 300 meters above sea level. The second reason is that there are no large water bodies such as oceans and open seas; the Baltic Sea is a rather small, shallow, inner land basin. The Lithuanian land seacoast is approx. 100 km long, and the cooling effect of the Baltic Sea is felt only on the Curonian Spit and in a narrow zone (up to 10 km) on the land seacoast. It should be mentioned that temperature regime in the coastal region is quite different. A very important

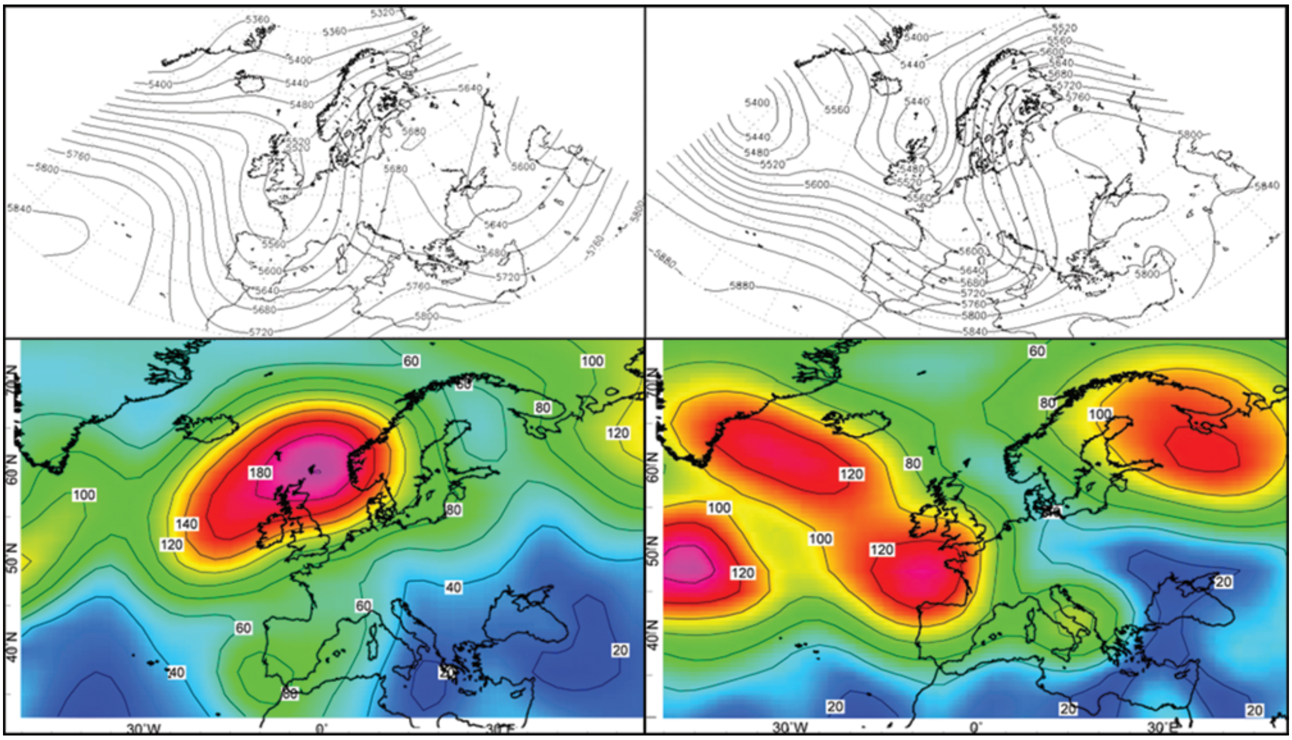

Fig. 7 Mean geopotential height (m) at the 500 hPa level (top) and the standard deviation of geopotential height (m) at the same level (bottom). Top panels indicate only HWB periods, while bottom panels show both DP and HWB periods. HWB periods last from 4 to 9 May 2002 (top left) and from 27 of September to 1 October (top right), while in bottom panels the periods are by three days longer. Isolines are every 40 m (top) and 20 m (bottom). Plots were made and data processed using subdaily ERA-40 data and GrADS software. Compiled by G. Stankūnavičius, 2011.

factor which influences the air temperature regime is water temperature. Water temperature near the coast strongly depends on the prevailing wind direction and speed and can fluctuate a lot even if weather conditions in the other part of Lithuania almost do not change (Fig. 2). The larger differences in highest night temperatures (Figs 1, 3) could also be explained by a more considerable influence of the local environment (topography, type of soil, distance from major water bodies, etc.) on the night air cooling rate. Night weather conditions are strongly influenced by local factors, and extreme temperatures are more localized (Fig. 4), whereas daily air temperatures more strongly depend on atmospheric macro–circulation patterns. The similar results obtained by A. Bukantis (1994) and A. Galvonaitė *et al.* (2007) have shown that the number of extremes doubles with moving from the coastal to the continental part, and the maximum was found in the southern part of Lithuania.

The largest number of temperature extremes was observed in the first decade of the 21st century, whereas the 1980s can be characterized as a period with a small number of such events (Fig. 5). The number of hot days increased also after 1992. The number of hot nights increased especially significantly. Ten or more hot nights per warm period were observed only ten times in 1961–1997, whereas in the last thirteen years such threshold was exceeded almost every year. These findings correspond to data of other researches that showed an increase of number of hot days in the 30s and a decrease in 80s of the 20th century. Since the beginning of the 90s increasing the trends of temperature extremes were obvious (Bukantis, Rimkutė 1998; Bukantis *et al.* 2001; Bukantis, Valiuškevičienė 2005).

It is possible to find more extreme temperatures in medieval ages in the Baltic Sea region (Dippner, Voss 2004). Although from the beginning of instrumental measurements the recent summer conditions are most extreme (higher temperatures, less precipitation) as a result of the global warming (IPCC 2007). Especially significantly the number of extremes rose in mid-summer months (Fig. 6) and this is in agreement with the previous findings (Bukantis 2000; Galvonaitė *et al.* 2007). Changes in the frequency and severity of extremely hot events (especially in mid-summer) could be ascribed to the effect of climate change in The Baltic Sea region (BACC 2007). Results of the present research could contribute to the next BACC assessment. Moreover, the complexity of the results could help the modelling the highest temperature extremes and atmospheric circulation conditions in the 21st century.

Quite similar changes in temperature extremes were determined in the neighbouring counties. The methods and periods were different, but the results showed the same tendencies. In Poland, the number of highest daily maximum temperatures and the frequency of days with the temperature above 20 °C increased in July–August and deceased in June in 1951–1998 (Wibig, Głowicki 2002). Another study showed that circulation types with an anticyclone ridge were most important for extremely hot days in summer in Poland (1951–2006) according to different atmospheric circulation classifications (Ustrnul *et al.* 2010). A comprehensive study of draughts (1957–2006) revealed an increasing of inter-annual variability of the average number of dry days in Estonia. Also, the growing trend of the annual total number of extremely dry days was statistically significant (Tammets 2010). Much more hot summer days occurred in the 1930s and in the beginning of the 21st century, using data from 10 meteorological stations for the period 1925–2009 in Latvia. Over the whole observation period, a statistically significant increase in the number of warm days and nights has been noted (Avotniece *et al.* 2010; Briede, Lizuma 2010).

According to the GrossWetterTypes (GWT) and Litynsky (LIT) classifications in the COST733 database, most frequently the hot weather events are initiated and maintained by anticyclone circulation patterns. The smaller domain (D05) allows distinguishing the prevailing favourable type, particularly for hot (tropical) nights, and the LIT classification method appears to be most suitable for this task. Tropical nights could be initiated by the same large–scale airflow as hot days; however, there are some necessary additional conditions such as the presence of a trough in the sea level pressure field or warm sector, vicinity of a slowly moving front, humidity advection, the cloudy sky, etc.

Concerning the classified weather types as the main actors transporting and / or transforming warm air masses of tropical origin one can deal only with the large domain and GWT classification. The study shows that a persistent large–scale southerly or south–westerly airflow over the Southern Baltic can explain more than two thirds of all analysed hot weather cases; similar results are available for the Poland area (Ustrnul *et al.* 2010); however, one third of cases represent south–easterly airflow over the East European plane and is more typical of northern areas – Latvia (Avotniece *et al.* 2010) and Estonia (Jaagus 2006).

Summertime airflow and pressure patterns almost always are less pronounced than their counterparts in the cold season or even in early autumn or late spring. That's why hot weather formation in the latter two seasons is better represented by pressure patterns and airflow anomalies; however, the persistency of hot weather in these seasons is very sensitive to mesoscale and boundary layer processes such as frontal cloudiness, high wind speed, fog, etc. Therefore, the weather types responsible for hot weather formation at the beginning and at the end of the warm season have to be very anomalous not only in a particular area such as Lithuania, but also across the whole Europe.

CONCLUSIONS

The maximum temperature recurrence time in the territory almost corresponds to the climatic regions of Lithuania. Daily temperature maximum (95 percentile) values from May to September are lower in coastal regions due to the cooling effect of the sea, while the night-time maximum (95 percentile) temperatures are quite similar in all parts of Lithuania in the beginning of the warm season, and in the second part they becomes 2–3 °C higher in the coastal zone. Moreover, the recurrence of highest minimum temperatures has more latitudinal pattern with a very special regime in the coastal zone.

The Mann–Kendall test showed positive trends in the recurrence of the number of highest maximum and minimum temperatures in the study period (1961–2010) in Lithuania. The highest number of hot events falls on the 1st decade of the 21st century: 37 cases of hot days were recorded in 2002, while the record of hot nights (43 cases) was set in 2010. The number of hot days and nights increased mostly in July and August.

Most persistent types responsible for the development and persistence of consecutive hot days in a particular area (Lithuanian territory) represent anti–cyclonic patterns with the central part over Lithuania and / or the Southern Baltic or over the European part of Russia. This is true for the GWT D00 (bigger domain) classification, while for D05 there prevail the weather types representing the southern or south–western flank of a persistent anticyclone northward or north–eastward from Lithuania. However, a smaller domain (D05) in the GWT classification allows determining a few prevailing types instead of the range of weather types of similar frequency.

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