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ORIGINAL PAPER

Variability and trends in daily minimum and maximum temperatures and in the diurnal temperature range in Lithuania, Latvia and Estonia in 1951–2010

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Abstract Spatial distribution and trends in mean and absolute maximum and minimum temperatures and in the diurnal temperature range were analysed at 47 stations in the eastern Baltic region (Lithuania, Latvia and Estonia) during 1951–2010. Dependence of the studied variables on geographical factors (latitude, the Baltic Sea, land elevation) is discussed. Statistically significant increasing trends in maximum and minimum temperatures were detected for March, April, July, August and annual values. At the majority of stations, the increase was detected also in February and May in case of maximum temperature and in January and May in case of minimum temperature. Warming was slightly higher in the northern part of the study area, i.e. in Estonia. Trends in the diurnal temperature range differ seasonally. The highest increasing trend revealed in April and, at some stations, also in May, July and August. Negative and mostly insignificant changes have occurred in January, February, March and June. The annual temperature range has not changed.

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1 Introduction

A significant climate warming has been observed in the Baltic Sea region in the last half century. During a long period (1871–2004), annual mean air temperature has increased by 0.10 K/decade in the northern part of the region and by 0.07 K/decade in its southern part (BACC Author Team 2008). These numbers are much higher for the second half of the twentieth century and for the beginning of the twenty-first century (Casty et al. 2007; Lehmann et al. 2011), which are in line with the global temperature changes (IPCC 2007). The increase in mean air temperature has been detected in all three Baltic countries Lithuania (Bukantis and Rimkus 2005; Kriaučiunienė et al. 2012), Latvia (Lizuma et al. 2007; Klavins and Rodinov 2010) and Estonia (Jaagus 2006; Kont et al. 2007; 2011; Russak 2009), as well as in their neighbouring regions—in Poland (Degirmendžić et al. 2004), Sweden (Alexandersson 2002), Finland (Tuomenvirta et al. 2004; Tietäväinen et al. 2009) and Russia (Anisimov et al. 2007, 2011).

For practical purposes and for the humans' everyday life, daily mean temperature is not as important as daily maximum and minimum temperatures. It is natural that daily extreme temperatures have similar trends as the daily mean temperature, but there are certain peculiarities. In many studies, daily minimum temperature, maximum temperature and the daily temperature range are analysed as separate variables. Globally, it has been found that minimum temperature has increased mostly faster than maximum temperature during the period of the intense climate warming after 1950 (Karl et al. 1993; Easterling et al. 1997; Stone and Weaver 2002; Vose et al. 2005; Alexander et al. 2006). Consequently, the diurnal temperature range (DTR) has decreased in the major part of continental areas. DTR has a slightly negative trend also in the Baltic Sea region during 1950–1993 (Easterling et al. 1997).

A later analysis demonstrated that the decrease in the DTR was only evident from 1950 to 1980 (Vose et al. 2005).

Similar changes in maximum and minimum temperature and in DTR were obtained in many regions of Europe (Brázdil et al. 1996; Heino et al. 1999). Some studies have analysed temperature extremes using a number of extreme indices (Frich et al. 2002; Klein Tank and Können 2003; Moberg and Jones 2005; Moberg et al. 2006; Shmakin and Popova 2006; Platova 2008), finding an increase in warm extremes and a decrease in cold extremes during the second half of twentieth century.

When the temperature increase in higher latitudes has taken place in winter and spring, then in subtropical regions, it has in the highest magnitude which occurred in summer (del Río et al. 2012; Brunetti et al. 2006; Ben-Gai et al. 1999; Tabari and Hosseinzadeh Talaee 2011; Nastos et al. 2011). Statistically significant decreasing trend in DTR was detected in Fennoscandia (Tuomenvirta et al 2000) and in Poland (Wibig and Glowicki 2002; Miętus and Filipak 2004). Negative trends in DTR in autumn and positive trends in spring were detected in the Czech Republic (Brázdil et al. 2009)

Some respective studies have been realised in the Baltic countries. In Rīga, the mean minimum temperature has increased by 0.20 K/decade during 1913–2006, while the mean maximum temperature has increased by 0.18 K/decade (Lizuma et al. 2007). Mean maximum temperature has increased more rapidly in April and May, but minimum temperature has increased much in winter. Consequently, the daily temperature range has decreased. Annual mean daily minimum and maximum temperatures have significantly increased at the five studied stations in Latvia (Avotniece et al. 2010). A significant decrease in DTR was determined only at two stations in eastern Latvia.

Analysis of daily extreme temperatures in Lithuania in 1950–2003 shows that the average annual maximum and minimum air temperature has increased. In most of Lithuania, changes were statistically significant ($p<0.05$) and fluctuated from 0.2 to 0.3 K/decade. Positive changes were not statistically significant only in the eastern part of Lithuania (Bukantis and Valiuškevičienė 2005). Another study determined an increase in the number of warm days and nights in 1961–2010. Analysis of air temperature data from 18 meteorological stations showed that the number of warm nights during the warm period of a year increased significantly over almost the whole territory of Lithuania, while statistically significant shift in the number of warm days was observed only at a few meteorological stations. The largest positive changes were determined in July and August (Kažys et al. 2011). There are no studies on extreme temperatures in Estonia.

The spatial pattern of daily minimum and maximum temperature and DTR in the Baltic countries depends on large-scale as well as on local landscape factors. The main large-scale factors are latitude and the Baltic Sea. Among local landscape factors, we have used the elevation of stations, distance to the sea coast, land cover mode, share of forests, landscaped areas and inland water bodies around the stations within 1 and 20 km at different sectors. One task of this study was to analyse how different factors form the mean pattern of the studied variables. The relationship between the elevation of meteorological stations and diurnal temperature range is analysed as daily warming and nocturnal cooling which are more intense in low-lying locations.

The main objective of this article is to analyse variability and trends in the time series of daily minimum and maximum temperature and DTR in the three Baltic countries during 1951–2010. We have especially analysed seasonal differences in the trends. Thereby, we assume that maximum as well as minimum temperatures have significantly increased and minimum temperature has increased much more than maximum temperature. Consequently, we hypothesize that the daily temperature range has decreased.

2 Data and methods

Daily minimum and maximum temperatures measured at meteorological stations were used for the analysis in this study. The diurnal temperature range DTR (amplitude) was

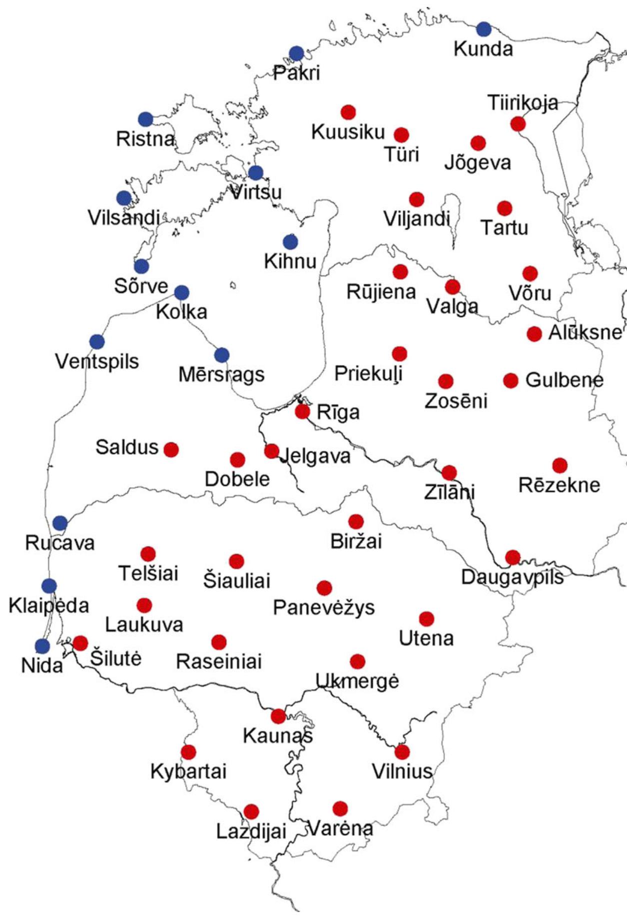

Fig. 1 Location of maritime (*blue*) and continental (*red*) stations

Table 1 Monthly and annual mean maximum temperatures spatially averaged by countries and by locations into maritime and continental stations

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Estonia—maritime	−0.7	−1.7	1.2	6.6	12.7	17.4	20.1	19.5	15.0	9.9	4.7	1.4	8.9
Estonia—continental	−3.0	−2.9	1.8	9.3	16.3	20.4	22.2	20.8	15.3	9.0	2.6	−1.1	9.3
Latvia—maritime	0.1	−0.4	2.8	8.4	14.2	18.4	20.7	20.4	16.1	10.8	5.2	1.8	9.9
Latvia—continental	−2.7	−2.3	2.4	10.1	16.9	20.5	22.3	21.2	15.7	9.5	3.0	−0.9	9.7
Lithuania—maritime	0.2	0.1	3.3	9.3	15.1	18.8	21.0	21.0	16.7	11.4	5.8	2.3	10.5
Lithuania—continental	−1.9	−1.3	3.3	11.0	17.6	21.0	22.7	22.0	16.7	10.6	4.0	−0.1	10.5

calculated as a difference between daily maximum and minimum temperatures. The main period of 1951–2010 was used. This is the longest continuous temperature series for which data from a number of stations are available. The total number of the used stations was 47, while 16 stations were from Lithuania and Latvia each and 15 from Estonia. The data were obtained from the Estonian Meteorological and Hydrological Institute (EMHI), the Latvian Environment, Geology and Meteorology Centre and the Lithuanian Hydrometeorological Service. The stations were located more or less evenly over the study area (Fig. 1).

We took into account that the properties of maximum and minimum air temperatures as well as of the DTR are clearly different in the coastal zone and in the hinterland. We grouped and analysed maritime and continental stations separately. The criterion for maritime stations was the distance up to 5 km from the coastline. The number of maritime stations in Estonia was seven, in Latvia four and in Lithuania two. The problem of data homogeneity is crucial in trend analyses. We selected only such stations for the analysis where no inhomogeneities had been detected in time series. A number of stations with long time series were omitted due to relocations. But unfortunately, not all changes were documented (e.g. very small relocations inside the station territory) or can be evaluated (related with slow building activity). Statistical significance of documented changes was investigated using the Student's t test.

On the other hand, there were no significant changes in daily maximum and minimum temperature measurements, methodology and instruments during the investigation period. The height of thermometers, shield and thermometer type did not change at all almost until the end of the investigated period. Automatic weather stations were established in Latvia since May 2001, in Estonia since September 2003 and in Lithuania only in 2010. Parallel measurements with classical thermometers and automatic weather stations made in the EMHI revealed no differences.

We assume that our time series are homogeneous, i.e. they do not contain artificial breaks. Nevertheless, there might be some factors, for example, large trees in the neighbourhood of a meteorological station that can influence the local thermal conditions and thereby the homogeneity of temperature series.

We used the time series of four monthly variables: mean maximum temperature, the highest maximum, mean minimum and the lowest minimum temperature. Their mean values and standard deviations were calculated for all the stations. The relationship between the absolute height of stations and DTR was studied using linear regression analysis.

Maximum and minimum temperatures are not always normally distributed. A clear negative asymmetry is typical for winter temperatures, while a slight positive asymmetry is observed in daily maximum temperature for summer and late spring. Therefore, the trend analysis was conducted using the non-parametric Mann–Kendall (MK) test. Trends are considered statistically significant on $p<0.05$ if the MK statistic is 1.96 or higher. The trend slopes were calculated using the Sen method. These methods were described in detail, for example, by Tabari and Hosseinzade Talaee (2011).

We calculated trends for every station as well as for the groups of maritime and continental stations separately at the three countries. In case of average trends, their statistical

Table 2 Monthly and annual mean minimum temperatures spatially averaged by countries and by locations into maritime and continental stations

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Estonia—maritime	−5.2	−6.5	−4.2	0.7	5.7	10.7	13.8	13.6	9.8	5.5	0.9	−2.6	3.6
Estonia—continental	−8.8	−9.7	−6.3	−0.2	4.8	9.2	11.5	10.8	6.7	2.7	−2.0	−6.2	1.1
Latvia—maritime	−4.9	−5.8	−3.5	0.9	5.5	9.9	12.6	12.5	8.9	5.0	0.9	−2.7	3.3
Latvia—continental	−8.0	−8.4	−5.1	0.9	5.9	9.9	12.0	11.4	7.3	3.2	−1.4	−5.6	1.9
Lithuania—maritime	−4.6	−4.9	−2.3	2.5	7.3	11.6	14.5	14.5	10.8	6.5	1.7	−2.1	4.7
Lithuania—continental	−7.0	−7.2	−4.0	1.7	6.5	10.2	12.3	11.7	7.8	3.8	−0.4	−4.7	2.6

Table 3 Monthly and annual mean daily temperature ranges spatially averaged by countries and by locations into maritime and continental stations

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Estonia—maritime	4.4	4.7	5.3	5.9	7.0	6.6	6.2	5.9	5.3	4.3	3.8	4.0	5.3
Estonia—continental	5.8	6.6	8.2	9.4	11.5	11.2	10.7	10.1	8.7	6.3	4.5	5.1	8.2
Latvia—maritime	4.9	5.4	6.3	7.5	8.8	8.5	8.1	7.9	7.2	5.8	4.3	4.5	6.6
Latvia—continental	5.3	6.1	7.4	9.2	11.0	10.6	10.3	9.8	8.5	6.3	4.4	4.7	7.8
Lithuania—maritime	4.8	4.8	5.6	6.7	7.8	7.2	6.5	6.4	5.9	4.9	4.1	4.4	5.8
Lithuania—continental	5.2	5.8	7.3	9.4	11.1	10.8	10.4	10.3	8.9	6.7	4.4	4.6	7.9

significance was found with the use of the multivariate Mann–Kendall test (Lettenmaier 1988) that groups data from measuring sites and calculates the combined MK statistic and p value using time series from all grouped stations.

The local landscape variables used as explanatory variables for mapping of temperature parameters were the same as used in Jaagus et al. (2010) and Remm et al. (2011). These were the Cartesian coordinates of the location; 26 variables to characterize land cover diversity and the dominant land cover class; ten variables of the land surface elevation; seven variables to describe the distance from the sea coast and the share of water bodies; and six to describe the share of forested area.

Two data layers were used to derive the landscape features (excluding the coordinates): the Coordination of Information on the Environment land cover 2000 database (European Commission) and the global Shuttle Radar Topography Mission surface elevation model (U.S. National Aeronautics and Space Administration). Both data layers follow a constant methodology, cover all the study area and have a suitable amount of details for mapping at a regional scale.

The spatial indices calculated from the data layers included the number of categories, the index of dominance, the share of a particular category, the modal category and the reverse distance-weighted modal category in the case of land cover. The mean value, aspect and the quotient of variation were derived from the elevation model.

Coordinates in SN and WE directions enable to describe spatial trends in the west–east and south–north directions. The spatially closer data points are more similar regarding the predictors SN and WE and therefore have more impact on the estimated value.

The software system Constud (Remm and Remm 2008) was used for finding the combinations of feature weights and creating maps of estimated values for temperature minimum and maximum values and amplitudes. Constud includes iterative fitting of weights for calculating similarity-based estimations.

Table 4 Explanatory variables selected by machine learning in Constud used for calculating maps—variables are in descending order according to their weight (w)

Jan_min	w	Jan_max	w	Jul_min	w	Jul_max	w	Jul_DTR	w	Ann_DTR	w
WE	1.681	elev_1	1.746	forest_10	1.448	mode_20	1.591	water_10sw	1.792	mode_10sw	1.381
elev_20	0.693	WE	1.610	mode_10sw	1.209	WE	1.525	mode_1sw	1.464	water_20	1.322
forest_10	0.626	SN	0.378	aspect_20	1.103	d_coast	1.444	d_coast	1.226	forest_10	1.079
		forest_20	0.265	artif_20	1.012	SN	1.373	water_1	1.117	water_1sw	1.006
				d_coast	0.996	elev_1	1.027	elev	1.082	mode_20sw	0.823
				mode_20	0.659	water_1	0.848	water_20	0.942	forest_1sw	0.736
				mode_1	0.574	water_20sw	0.834	water_1sw	0.736	WE	0.653
						dom_20	0.748	mode_10	0.556		
						water_20	0.697	mode_20sw	0.086		
						dw_mode_20	0.567				
						dw_mode_20sw	0.346				

d_coast distance to sea coast, *elev_1* mean elevation within 1 km, *WE* west–east Cartesian coordinate, *SN* south–north Cartesian coordinate, *mode_1* land cover mode within 1 km, *mode_20* land cover mode within 20 km, *mode_10sw* land cover mode within 10 km in the SW sector, *mode_20sw* land cover mode within 20 km in the SW sector, *dw-mode_20sw* reverse distance-weighted land cover mode within 20 km in the SW sector, *dw-mode_20sw* reverse distance-weighted land cover mode within 20 km in the SW sector, *dom_20* index of dominance within 20 km, *forest_1* share of forest within 1 km, *forest_10* share of forest within 10 km, *forest_20* share of forest within 20 km, *artif_20* share of artificial areas within 20 km, *water_1* share of water bodies within 1 km, *water_1sw* share of water bodies within 1 km in SW sector, *water_20* share of water bodies within 20 km, *water_20sw* share of water bodies within 20 km in SW sector, *aspect_20* surface aspect generalized in 20 km radius

The details of similarity and machine learning algorithms used in Constud are given in Remm and Kelviste (2011), Remm et al. (2011) and in the Constud webpage: http://www.geo.ut.ee/CONSTUD. Default machine learning parameters were used in Constud. The estimated values for the output maps were created using 1-km grid density.

To evaluate the impact of the absolute height (elevation of the stations) on air temperature, the data from 32 continental meteorological stations were analysed. The heights vary from 5 m (Jelgava) to 188 m (Zosēni). Values of linear regression between air temperature and altitude in different months and statistical significance of the relationship were determined.

3 Spatial and temporal variability

Daily maximum and minimum temperatures as well as DTRs in the Baltic countries are influenced by two main

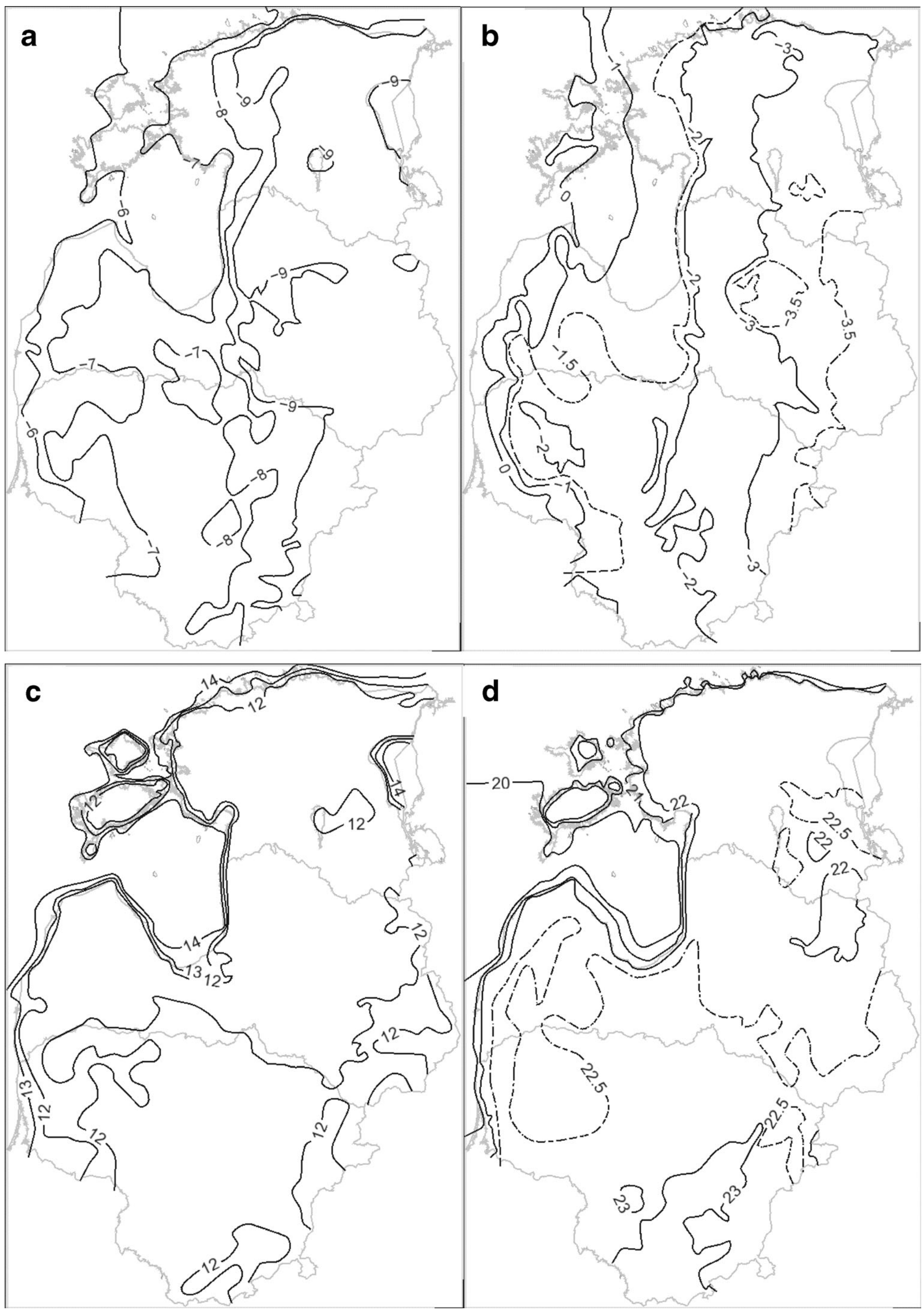

Fig. 2 Maps of temperature parameters in Lithuania, Latvia and Estonia during 1951–2010. **a** Monthly mean minimum in January. **b** Monthly mean maximum in January. **c** Monthly mean minimum in July. **d** Monthly mean maximum in July. Values on isolines are orientated up to increasing value

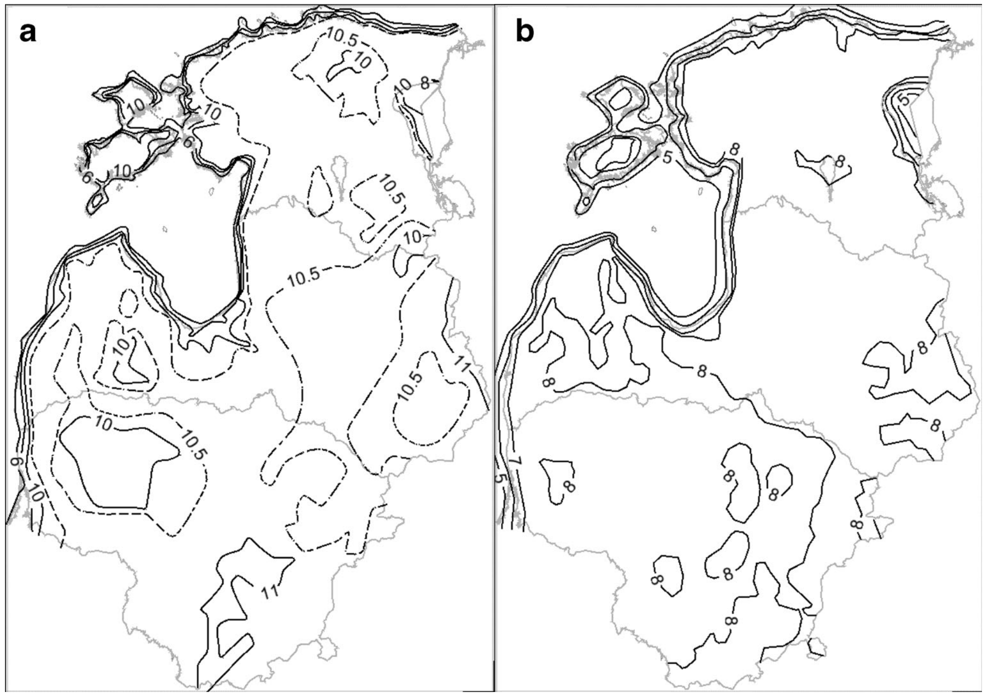

Fig. 3 Monthly mean DTR in July (**a**) and annual mean DTR (**b**) in Lithuania, Latvia and Estonia during 1951–2010. Values on isolines are orientated up to increasing value

large-scale factors—geographical latitude and the Baltic Sea. Generally, in the southern locations, temperature is higher, and in the northern locations, maximum and minimum temperatures are lower. However, the influence of the Baltic Sea plays an important role in temperature regime minimising DTR.

These general regularities are clearly expressed by monthly mean values of maximum and minimum temperatures and of DTR (Tables 1, 2 and 3). In practically all the cases, the highest mean temperatures are observed in Lithuania and the lowest in Estonia. The average temperature difference between them has been 1–2 K, while it was the highest in spring in case of maximum temperature at maritime stations and in winter in case of minimum temperature at continental stations; it was the lowest in midsummer.

The landscape variables selected by machine learning for mapping temperature parameters reveal the factors determining temperature variability in the Baltic countries at the local scale (Table 4). Both the mean minimum and maximum temperatures in January are largely related to the west–east coordinate—westward locations are closer to the Baltic proper and to the flow of mild maritime air from the west. Higher elevation and the proportion of forest cover reduce the Atlantic influence (Fig. 2a, b).

The mean minimum temperature in July can be predicted by land cover and by the distance from the sea coast; it is higher at the sea, on the larger lakes and at larger cities. The summer night temperature remains higher in cities compared to natural landscapes due to the possible effect of an urban heat island. Data from the stations surrounded by a higher proportion of forest (Kuusiku, Türi, Rūjiena and Varėna) indicate relatively low minimum values in July (Fig. 2c).

The spatial variability of the mean daily maximum in July is mainly determined by the sea and distance from the coast in coastal regions. The effect of inland water bodies is not evident. The July maximum has a decreasing south–north gradient in the continental part of the study area, and it is less in uplands and in forested areas (Fig. 2d).

The maritime stations have higher maximum temperatures in autumn and winter (October–February, Fig. 2b) and lower values in spring and summer (April–August, Fig. 2d) in comparison with the continental stations. Minimum temperature is higher in maritime stations during the whole year (Fig. 2a, c). Differences in minimum temperature between the maritime and continental stations are the highest during the winter season reaching up to 3 K or even higher. The

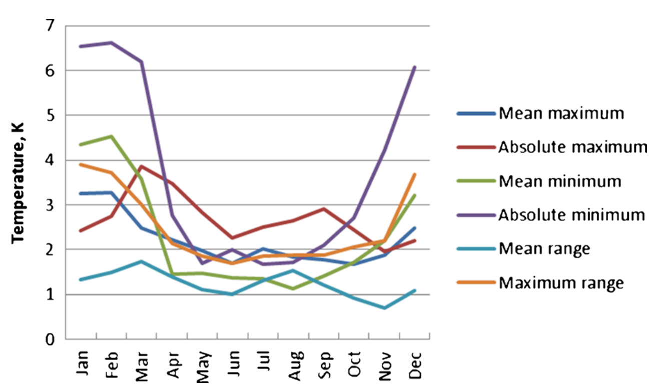

Fig. 4 Average standard deviations of maximum and minimum temperature and DTR in Lithuania, Latvia and Estonia during 1951–2010

Table 5 Trend values of annual and monthly mean maximum temperature (kelvin/decade) spatially averaged by countries and by locations into maritime and continental stations during 1951–2010. Statistically significant trends on $p<0.05$ level are in bold

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Maritime stations	0.38	**0.48**	**0.51**	**0.48**	**0.37**	0.02	**0.37**	**0.38**	0.19	0.04	0.13	0.15	**0.30**
Continental stations	0.45	0.46	**0.58**	**0.60**	**0.35**	−0.07	**0.32**	**0.31**	0.17	0.06	0.14	0.14	**0.30**
All stations	0.46	**0.50**	**0.56**	**0.55**	**0.35**	−0.05	**0.34**	**0.32**	0.16	0.04	0.13	0.16	**0.30**

typical peculiarities of maritime climate revealed in the highest magnitude in the west Estonian archipelago.

Peculiarities of spatiotemporal variability of daily maximum and minimum temperatures determine the character of DTR. Here, it is difficult to draw out any latitudinal tendency (Table 3). Temperature amplitude is mainly related to the amount of water in the vicinity due to the high thermal capacity of water (Fig. 3). The lowest amplitudes have been observed at the Estonian maritime stations and the highest at the Estonian continental stations. This difference is remarkably smaller in Latvia and Lithuania, probably due to the absence of stations on islands with totally maritime conditions (Table 3). The highest mean temperature ranges revealed in May, June and July, the lowest ones in November and December. Differences between the maritime and continental stations are the highest from April to August due to the possible breeze effect that diminishes maximum temperatures in the coastal zone.

The highest maximum temperature in the Baltic countries (36.8 °C) was measured at Varėna, Southern Lithuania, on 13 July 1959. The same records in Latvia (36.0 °C at Jelgava on 13 July 1994) and Estonia (35.6 °C at Võru on 11 August 1992) are a bit lower. Similar values have been measured at other continental stations and only 1–2 °C lower values in the maritime stations. Absolute temperature maxima in January have been observed up to 10 °C in Estonia and more than 12 °C in Lithuania.

The lowest minimum temperatures in the study area during the 60 years were recorded at Daugavpils, southeastern Latvia (−43.2 °C) on 8 February 1956, and at Utena, eastern Lithuania (−42.9 °C) on 1 February 1956. The absolute minima at the coastal stations of Estonia were much higher, not dropping below −30 °C at some westernmost stations. Negative temperatures have been registered during all months except July at all stations and also in August at the maritime stations. As a rule, they are much higher in the coastal region.

The highest DTRs in the eastern Baltic region are typical for its northern part, i.e. for continental Estonia. The maximum range of 38.6 K was measured at the Jõgeva station, eastern Estonia, on 1 February 1956. In the coastal and more southern regions, the amplitudes are much lower.

Standard deviations reflect the temporal variability of studied variables. It is typical that the standard deviation of air temperature is much higher in winter and lower in summer. This regularity appears also in case of monthly mean maximum and minimum temperatures (Fig. 4). The standard deviation of mean maximum temperatures is higher from April to September and that of mean minimum temperature is higher during the cold period (November–March). The highest standard deviation in winter is typical for absolute minimum temperature and in summer for absolute maximum temperature.

Results of regression analysis indicated that DTR on the continental stations is statistically significantly related to the altitude of the stations. The daily temperature range decreases with the increase of the altitude ($r=-0.42$). This relationship is the strongest during the summer months ($r=-0.46$ in July). At higher elevations, the daily temperature range decreases due to stronger winds and turbulence. It is especially evident in summer when the daily temperature contrasts are the greatest. This relationship is supported and graphically depicted by similarity-based DTR map for July (Fig. 3a).

It was found that altitude of the stations has a larger negative influence on maximum temperature, but there were no statistically significant correlations with the minimum temperature. The negative effect of altitude on minimum temperature is usually compensated by stronger turbulence, which reduces the probability of the formation of ground-level inversions. On the other hand, the differences in altitude in the analysed territory are modest (up to 200 m), and the direct effect of altitude on temperature extremes is weak.

Table 6 Trend values of annual and monthly mean minimum temperature (kelvin/decade) spatially averaged by countries and by locations into maritime and continental stations during 1951–2010. Statistically significant trends on $p<0.05$ level are in bold

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Maritime stations	**0.54**	0.62	**0.64**	**0.30**	**0.28**	0.11	**0.24**	**0.23**	0.14	−0.02	0.12	0.18	**0.30**
Continental stations	**0.69**	0.66	**0.72**	**0.23**	0.17	0.03	**0.24**	**0.19**	0.13	−0.01	0.18	0.25	**0.28**
All stations	**0.65**	0.64	**0.72**	**0.25**	**0.22**	0.08	**0.24**	**0.20**	0.12	−0.02	0.15	0.24	**0.29**

Table 7 Trend values of annual and monthly mean DTR (kelvin/decade) spatially averaged by countries and by locations into maritime and continental stations during 1951–2010. Statistically significant trends on $p<0.05$ level are in bold

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Maritime stations	−0.13	−0.10	−0.18	**0.21**	0.07	−0.08	**0.12**	0.16	0.05	0.06	−0.02	0.01	0.01
Continental stations	**−0.18**	−0.14	−0.21	**0.40**	**0.15**	−0.14	0.07	0.12	0.01	0.01	−0.01	−0.07	0.00
All stations	**−0.17**	−0.12	−0.22	**0.35**	**0.11**	**−0.12**	0.07	0.13	0.02	0.02	−0.01	−0.04	0.01

4 Trends

Generalised results of the trend analysis are provided in Tables 5, 6 and 7. It is natural that trends in maximum and minimum temperatures are similar to trends in monthly mean temperature. Statistically significant positive trends were found for the annual mean values as well as for many monthly mean values (Tables 5 and 6). General warming was detected in March, April, July, August and annually. It is evident that the trend values of monthly mean maximum temperature in March and April are notably higher in the continental regions and in July and August in the coastal zone (Fig. 5). Statistically significant trend was detected also for minimum temperature in January and maximum temperature in February, first of all, in case of the maritime stations. The trend values have been slightly higher in the northern part of the study region, especially during the warm half year.

Maximum temperature has increased at nearly all stations in March, April and May, as well as in July and August, and at some stations in January and February. Fluctuations in monthly mean maximum temperatures are rather coherent over the whole territory (Fig. 6) and between the maritime and continental stations (Fig. 7). Maximum temperature on the coast is higher in autumn and winter and lower in spring and summer than in the continental region. These differences are higher in case of cold January and hot April.

The annual absolute maximum temperature has not increased significantly. A trend revealed only in the monthly time series for February and March and in the northern regions of the study area also for April and August.

It is important to mention that monthly mean minimum temperature has increased more intensely than maximum temperature during the cold half year (Table 6). Significant positive trends revealed in January and March and in Lithuania also in February (Fig. 8). During the other months, the trend values were much smaller. Statistically significant trends were observed also in April, May, July and August, at 31, 20, 36 and 26 stations, correspondingly.

Monthly mean minimum temperature is generally higher in the coastal regions than at the continental stations because of the influence of the thermal inertia of sea surface (Fig. 9). The only exception revealed in April when the mean minimum temperature in the maritime and continental stations is practically on the same level. It can be explained by low sea surface temperatures during the period of melting of sea ice. On the western coast of Estonia, temperature minima in April are nearly similar to minima in January because the ice cover on sea surface has not yet fully formed in January.

Absolute minimum temperature has not changed as much as mean minimum temperature. Significant trends were determined only in March (at all stations), by 1 K or even more, in February, April, July and August. Annual trends were found only for maritime stations in Estonia and Lithuania.

Trend in DTR depends on trends in daily maximum and minimum temperature. Changes in DTR are not similar throughout a year (Table 7 and Figs. 10 and 11). A decrease

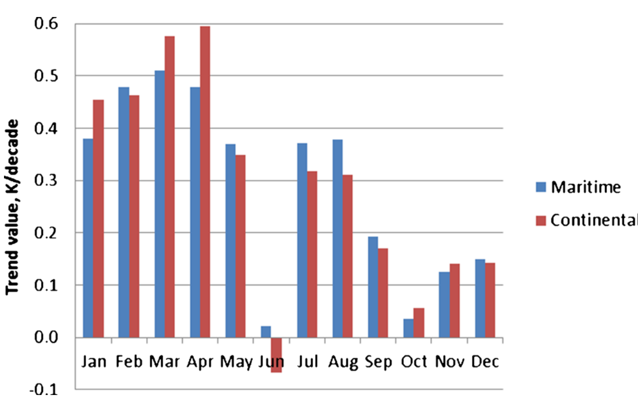

Fig. 5 Trend values for monthly mean maximum temperature in 1951–2010 averaged for the maritime and continental stations

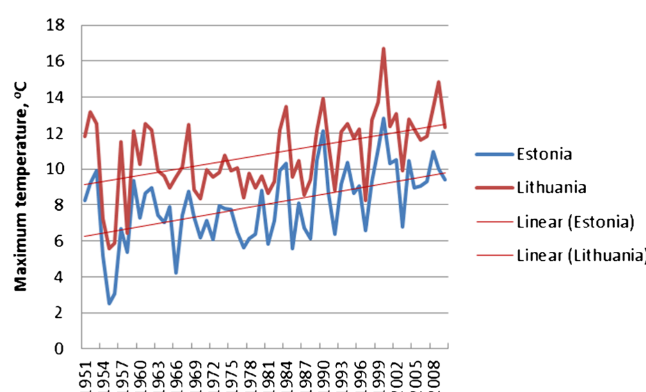

Fig. 6 Time series of monthly mean maximum temperature in April averaged by all stations in Estonia and Lithuania during 1951–2010 and their linear trend lines. All the trends are statistically significant on $p<0.05$

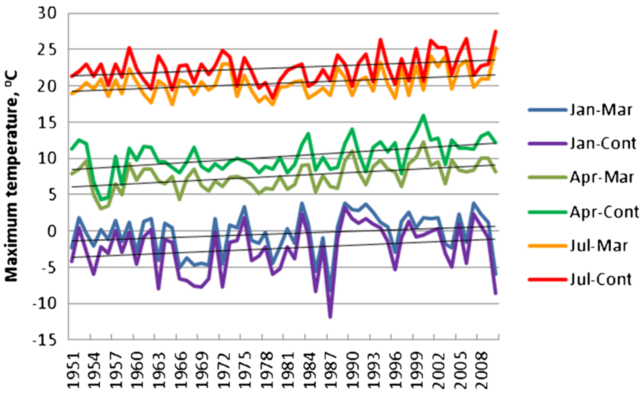

Fig. 7 Time series of monthly mean maximum temperature averaged by the maritime and continental stations for January, April and July during 1951–2010 and their linear trend lines. The trends are statistically significant on $p<0.05$ level in April and July but not in January

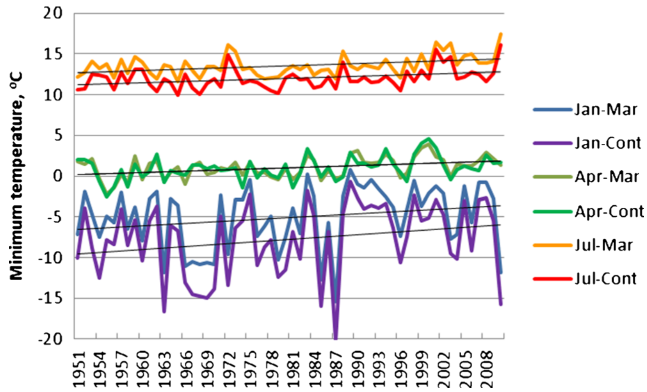

Fig. 9 Time series of monthly mean minimum temperature averaged by the maritime and continental stations for January, April and July during 1951–2010 and their linear trend lines. All the trends are statistically significant on $p<0.05$ level

has been observed during the cold season (December–March) and in June. At the same time, statistically significant increasing trends at nearly all stations were detected for April and at many stations also for May. All these trends were remarkably stronger on the continental regions. The current tendencies lead to the decrease in the DTR differences in January and to the increase in April (Fig. 11). During the months from July to October, a weak positive tendency revealed, which was significant only at some stations, mostly in the coastal zone of Estonia.

These trends have are some spatial peculiarities. The increase in DTR in April was much higher in the continental regions of the Baltic countries and lower in the coastal regions. This change is stronger in the southern part of the study area and weaker in its northern part. At the same time, the increase of DTR during the period from July to October was higher in Estonia. The decrease in DTR in January and March was higher in Estonia, and in February, it was higher in Lithuania. The trend values in Latvia were mostly intermediates between the values obtained from Estonia and Lithuania.

5 Discussion

Climatology of maximum and minimum temperatures and DTR in the Baltic countries is analysed in relation to three main factors—latitude, the Baltic Sea and the elevation of a station. It is natural that mean maximum and minimum temperatures in the southern part of the study area are generally higher and in the northern part lower. This difference was mostly 1–2 K. The largest latitudinal gradient for maximum temperature was observed in April when daily warming in the south is much higher than in the north. These differences become more even for the midsummer. The highest latitudinal differences in mean minimum temperatures were observed in February and March, especially at the continental stations. It can be explained by the higher frequency of cold air masses and anti-cyclonic weather conditions in Estonia. There are no significant latitudinal differences in DTR over the study region.

The Baltic Sea has a strong influence on air temperature and its dynamics. The large thermal inertia of the sea reduces the temperature ranges in the coastal zone, in contrast to the

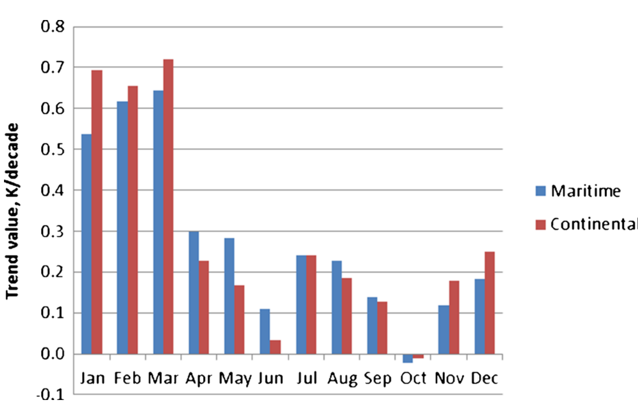

Fig. 8 Trend values (kelvin/decade) for monthly mean minimum temperature in 1951–2010 averaged for the maritime and continental stations

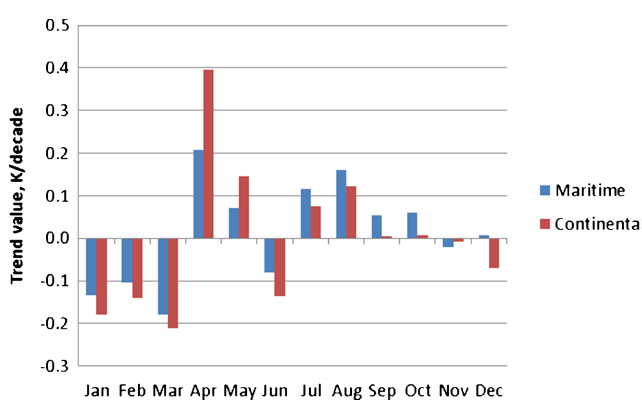

Fig. 10 Trend values (kelvin/decade) for monthly mean DTR in 1951–2010 averaged by the maritime and continental stations

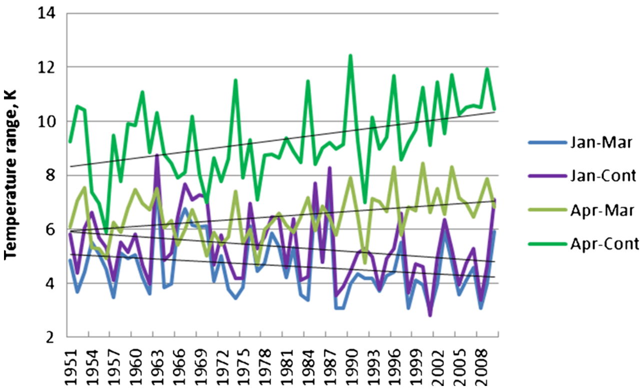

Fig. 11 Time series of monthly mean DTR averaged by the maritime and continental stations for January and April during 1951–2010 and their linear trend lines. All the trends are statistically significant on $p<0.05$ level

continental region. The difference between the continental and coastal stations varies through seasons. The highest positive maximum temperature values (1.5–3.5 K) are typical for April, May and June when the sea surface has not yet warmed up. The opposite situation when maximum temperature is higher in the maritime stations is observed with the highest magnitude in December and January.

Minimum temperature is always higher at the maritime stations and lower at the continental ones. Differences between them are even higher than in case of maximum temperature. The lowest differences (below 1 K) are observed in spring, while the highest ones are recorded during the period from August to February.

DTR has always been lower at the maritime stations and higher at the continental ones. The highest contrasts are observed during the warm half year, from April to September. In winter, the DTRs are much lower due to the minimal effect of the sun. Differences between the maritime and continental stations are also small in winter. It is very typical that the differences between the maritime and continental stations are significantly higher in Estonia in comparison with Latvia and Lithuania. There are only a few maritime stations in Latvia and Lithuania, located on the coast of the continental area. At the same time, a number of stations are located on the coast of small islands in Estonia.

The absolute height has an effect on DTR at the continental stations. On higher elevations, the range is generally lower and on lower elevations higher. This relationship is expressed in a higher magnitude in summer and less in winter.

Predictive sets of explanatory variables and their weights selected by iterative fitting in Constud (Table 4) are not the only possible feature combinations for predictive mapping of temperature parameters—different combinations of features can yield in almost equally effective predictions if the number of inter-correlated explanatory variables is large. The modest number of stations is far from representing all combinations of landscape features. Therefore, the all-cover maps and the combinations of explanatory features selected by machine learning in Constud should be regarded as one option out of many.

Trend analysis revealed a substantial increase in maximum and minimum temperatures in the Baltic countries. Not surprisingly, this result is in line with the increasing trend in mean temperature in the same region during more or less the same period (Bukantis and Rimkus 2005; Jaagus 2006; Lizuma et al. 2007; Kont et al. 2011; Kriaučiuniené et al. 2012). The most significant change has occurred not only in March, April, July and August, but also in January, February and May. The warming has been slightly higher in the northern part of the study area. When annual mean air temperature has increased in Estonia by 0.2–0.3 K/decade during 1951–2000 (Jaagus 2006), then the increase in annual mean maximum and minimum temperature during 1951–2010 presented in this study was about 0.3 K/decade. We can explain the continuous warming with hot summers during the first decade of the twenty-first century (Kont et al. 2011).

The trends in DTR are less pronounced and not exactly similar to the global ones. If globally a general decrease in DTR is prevailing (Karl et al. 1993; Easterling et al. 1997; Stone and Weaver 2002; Vose et al. 2005; Alexander et al. 2006), then a weak decrease in the Baltic countries is observed only in winter months and in June. No trend or positive trends revealed during the other months. The highest increase in DTR was typical for April and also for May. This result is not totally new. Similar results have been obtained by a previous study from Latvia (Lizuma et al. 2007). It can be concluded that trend analysis of DTR needs more detailed analysis than only using annual values. These trends might be different at different seasons and months not only in the Baltic countries, but also in the much wider regions.

Trends in DTR can be related to long-term changes in cloudiness, which, in turn, are related to changes in large-scale atmospheric circulation. Higher DTR corresponds to lower cloudiness and vice versa. There have been studies demonstrating an increasing cloudiness in the Baltic countries during the second half of the twentieth century especially in the cold half year (Stankūnavičius 1998; Keevallik and Russak 2001; Russak 2009). It lies in a good correspondence with the decreasing trends in winter DTR. At the same time, a decreasing trend in cloud cover over the Baltic Sea region was detected in spring during 1970–2008 (Lehmann et al. 2011). It explains the increasing of DTR in April and May. Higher cloudiness in winter can be directly related to the intensification of westerly airflow, positive phase of the North Atlantic Oscillation (Hurrell et al. 2003) and increase in cyclonic activity over the northern Europe (Sepp et al. 2005). Decrease in the duration of snow cover during the study period (Jaagus 1997; Draveniece et al. 2007) is also a factor causing the decrease in DTR.

6 Conclusions

The analysis of diurnal maximum and minimum surface air temperature as well as of DTR in Lithuania, Latvia and Estonia in 1951–2010 revealed many interesting results.

- Long-term trends in DTR have been different in different seasons and months. A decrease in DTR that is observed in many regions of the world was in our case detected only in winter months (January–March) and also in June. Much stronger positive trend in DTR occurred in April and with the less magnitude in May. Weaker increasing trends revealed at some stations during the other months of the warm period (July–October). There was no trend in annual mean DTR.
- Changes in daily maximum and minimum temperatures are generally coherent with changes in mean temperature. Statistically significant increasing trends were detected for March, April, May, July, August and annual mean values. The trend is significant also in January for minimum temperature and in February for maximum temperature. The increase in minimum temperature is remarkably higher in winter and the increase in maximum temperature in spring.
- Long-term variability and trends in daily maximum and minimum temperature and in DTR are highly correlated between all stations over the study region. Warming has been a bit higher in the northern part of the Baltic countries, i.e. in Estonia.
- The influence of general factors determining temperature extremes—latitude and the Baltic Sea—appears clearly on maps of mean distribution of maximum and minimum temperature. Temperature in the southern part (Lithuania) is by 1–2 K higher than in the northern part (Estonia) of the study region. DTR in the coastal zone is many times lower than in the hinterland.
- Differences of daily maximum and minimum temperatures between the maritime and continental stations are the highest during the period from April to August. The lowest values of DTR have been observed at maritime stations located in the northern part of Baltic region, and the highest values of DTR are typical for the northern continental stations.
- Similarity-based mapping using local landscape variables enabled to estimate temperature mean, maximum and DTR values and to create detailed maps of these parameters.

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