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Recent changes in Georgia's temperature means and extremes: Annual and seasonal trends between 1961 and 2010

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ABSTRACT

Sixteen temperature minimum and maximum series are used to quantify annual and seasonal changes in temperature means and extremes over Georgia (Southern Caucasus) during the period 1961 and 2010. Along with trends in mean minimum and maximum temperature, eight indices are selected from the list of climate extreme indices as defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) of the Commission for Climatology of the World Meteorological Organization (WMO), for studying trends in temperature extremes. Between the analysis periods 1961–2010, 1971–2010 and 1981–2010 pronounced warming trends are determined for all Georgia-averaged trends in temperature means and extremes, while all magnitudes of trends increase towards the most recent period. During 1981 and 2010, significant warming trends for annual minimum and maximum temperature at a rate of 0.39 °C (0.47 °C) days/decade and particularly for the warm temperature extremes, summer days, warm days and nights and the warm spell duration index are evident, whereas warm extremes show larger trends than cold extremes. The most pronounced trends are determined for summer days 6.2 days/decade, while the warm spell duration index indicates an increase in the occurrence of warm spells by 5.4 days/decade during 1981 and 2010. In the comparison of seasonal changes in temperature means and extremes, the largest magnitudes of warming trends can be observed for temperature maximum in summer and temperature minimum in fall. Between 1981 and 2010, summer maximum temperature shows a significant warming at a rate of 0.84 °C/decade, increasing almost twice as fast as its annual trend (0.47 °C/decade). The Georgia-averaged trends for temperature minimum in fall increase by 0.59 °C/decade. Strongest significant trends in temperature extremes are identified during 1981 and 2010 for warm nights (4.6 days/decade) in summer and fall as well as for warm days (5.6 days/decade) in summer. Analyses demonstrate that there have been increasing warming trends since the 1960s, particularly for warm extremes during summer and fall season, accompanied by a constant warming of temperature means in Georgia.

1. Introduction

Weather and climate extremes have always played an important role in influencing natural systems and society. Given their importance and the prospect of changes in the future, it is very important to understand how and why weather and climate extremes have changed in the past. In its Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), the IPCC (2012) defines an extreme weather or climate event as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable." For decades, climate change affected frequency, intensity, and duration of extreme events as stated in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007). Economic losses from weather- and climate-related disasters have also increased during the last 60 years and will have greater impacts on sectors with closer links to climate, such as water, agriculture and food security. The highest fatality rates and economic losses caused by hydro-meteorological induced disasters are registered in developing countries (IPCC, 2012). In Georgia, weather and climate extreme events are responsible for increasing economic losses, as the high mountainous ranges and adjacent lowlands of the Caucasus experience a highly sensitive reaction to recent climate change (MOE, 2009).

The globally averaged surface temperature data show a linear warming trend of 0.85 °C [0.65–1.06 °C] during the period 1880–2012.

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The total increase between the average of the 1850–1900 period and the 2003–2012 period accounts for 0.78 °C [0.72–0.85 °C], based on the single longest dataset available (IPCC, 2013). However, extreme climate events react more sensitively to climate change than mean climate values and therefore show larger variations and trends (Katz and Brown, 1992; Easterling et al., 1997, 2000; Kunkel et al., 1999; New et al., 2006; IPCC, 2007; Aguilar et al., 2009). Since the 1990s various regional studies have been carried out on temperature extreme indices, which proved that global warming is closely related to significant changes in temperature extremes (Manton et al., 2001; Peterson et al., 2002; Aguilar et al., 2005; Griffiths et al., 2005; Zhang et al., 2005; Haylock et al., 2006; Klein Tank et al., 2006, Moberg and Jones 2005). To date, studies on past observed changes in temperature extremes over Georgia have been carried out based on monthly data and associated weather and climate phenomena, such as drought, hurricanes and frost (Elizbarashvili et al., 2007, 2009a, 2011, and 2012). Elizbarashvili et al. (2013) found that the frequency of extremely hot months during the 20th century increased and extremely cold months decreased faster in the Eastern Georgia than in its Western counterpart. In addition, highest rates on warming trends of mean annual air temperature can be observed in the Caucasus Mountains, while the lowest are detected in the dry eastern plains. In Georgia temperature increased between 0.1–0.5 °C in eastern Georgia and decreased by 0.1–0.5 °C in western Georgia during 1906–1995 (World Bank, 2006). The region's glaciers have retreated during the last 100 years, and runoff from the glacier areas has been increasing, both seasonally and annually, in response to climatic warming (Elizbarashvili et al., 2009b).

Developing and transition countries such as Georgia are subject to numerous political, financial and institutional barriers in implementing a proper climate data monitoring system, including limitations on funding, technology and human resources (Page et al., 2004). The quality and quantity of accessible climate series still limit our understanding of the observed changes in climate extremes in Georgia. At the beginning of the 20th century, 40 meteorological stations were installed on the territory of Georgia to measure daily temperature minimum, maximum and precipitation. By the 1940s this number increased to 200. After the collapse of the Soviet Union in the early 1990s, the number of meteorological stations in Georgia shrank rapidly and the lack of station maintenance caused large measuring gaps. From 1991 to the present the number of meteorological stations has fallen to around 60 (World Bank, 2006). Currently only 13 synoptic weather stations are working on the territory of Georgia (Elizbarashvili et al., 2013).

The diverse physiographic conditions and large-scale circulation patterns over Georgia make it very difficult to detect regional changes with respect to climate extremes. Georgia is located in the Southern Caucasus between 41°–44°N and 40°–47°E and covers an area of 69,700 km². It borders Russia to the North, Azerbaijan to the Southeast and Armenia and Turkey to the South (Fig. 1). The topographic patterns throughout Georgia are very diverse. The relief declines from the Greater Caucasus Range in the North, with an elevation range of 1500–5000 m and the Lesser Caucasus with altitudes up to 3500 m in the South towards Transcaucasia, which stretches from the Black Sea coast to the Eastern Steppe. The Surami mountain chain with a maximum altitude of 1000 m connects the Lesser Caucasus with the Greater Caucasus and divides Transcaucasia into eastern and western lowlands (0–500 m) .

The Greater Caucasus represents an important climatic parting line towards Russia. It protects Transcaucasia from arctic high-pressure systems in winter originating from the Central Asian Region. The Southern Caucasus inhibits the summer heat from the Southeast. The Surami mountain chain avoids wet air masses circulating from the Black Sea towards the Caspian Sea causing high temperatures and humid climate at the western coast, continental climate in inner Transcaucasia up to very dry climate with high temperatures in the eastern lowlands (Shahgedanova, 2002). In general, the west of Georgia is characterized by mild winters and hot summers with mean annual air temperatures of 13–15 °C and high annual precipitation values (1200–2400 mm). The climate in eastern Georgia is continental with much lower annual precipitation (500–600 mm in the lowlands) and a mean temperature between 10–13 °C. In the mountainous areas mean temperature covers a range of −5 to 10 °C and precipitation varies from 800–1400 mm (World Bank, 2006).

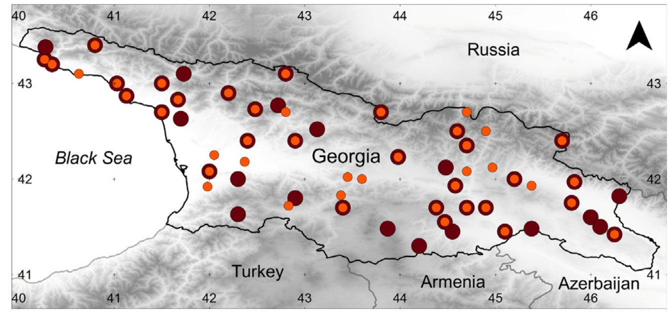

Fig. 1. Stations with daily minimum (orange dots) and maximum (red dots) temperature series for the period 1961–1990.

The aim of this study is to provide a better understanding of annual and seasonal trends of temperature means and extreme events across Georgia. This is achieved by studying daily maximum and minimum temperature means and selected daily temperature extreme indices as well as its anomalies and trends within the periods 1961–2010, 1971–2010 and 1981–2010. Extreme temperature trends are calculated using a set of eight ETCCDI temperature extreme indices from homogenized daily maximum and minimum temperature series. The indices of temperature extremes considered in the present study were recommended by the Expert Team on Climate Change Detection Indices (ETCCDI) of the Commission for Climatology of the World Meteorological Organization (WMO).

The remainder of the paper is structured as follows. Section 2 of the present study describes the data quality control and homogenization as well as the temperature extreme indices and the analytical methods used in this study. Spatial patterns of annual temperature means and extremes and their changes between 1961 and 2010 over Georgia are presented in Section 3.1. Section 3.2 analyzes seasonal trends in mean and extreme temperature within the period 1961–2010. Section 4 summarizes the conclusions.

2. Data and methods

2.1. Data quality control

Daily minimum and maximum temperature series for 87 stations were kindly provided by the National Environmental Agency of Georgia (NEA). Data quality control has been carried out using the computer program RClimDex Software version 1.1 (available at: http://etccdi.pacificclimate.org). As a first step, temperature minimum and maximum time-series with more than 20% missing values within all analysis periods (1961–1990, 1961–2010, 1971–2010 and 1981–2010) were excluded. The analysis periods 1961–2010, 1971, and 1981–2010 were chosen to study changes in recent trends and to maximize the number of stations available for all periods. Quality was tested in order to identify and label potentially wrong values, and correct them from the time-series.

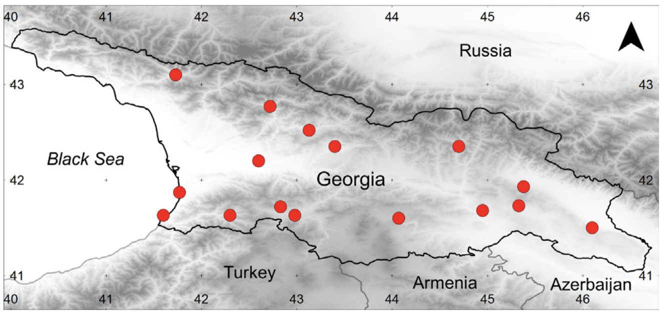

Fig. 2. Stations with daily minimum and maximum temperature series for the period 1961–2010.

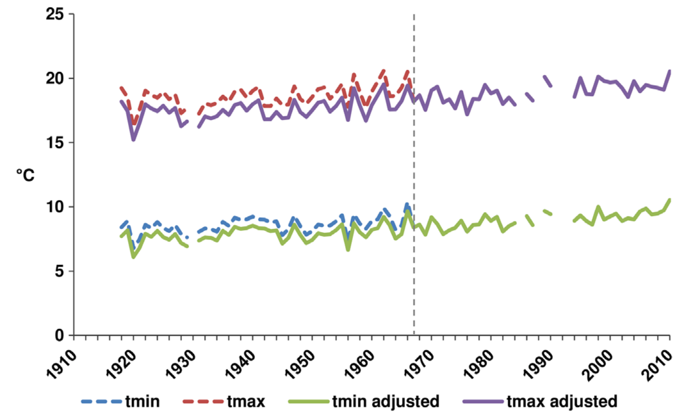

Fig. 3. In homogeneous (*T*min and *T*max) and adjusted (*T*min and *T*max adjusted) annual averaged temperature minimum and maximum time series at Tbilisi station. The dashed vertical line indicates the dates of detected breakpoints.

Gross errors were identified, impossible values such as Tx > 70 °C or Tn < −50 °C were rejected, and any duplication of dates was corrected. Daily maximum and minimum temperature were set to missing values, if daily maximum temperature equals or is lower than minimum temperature. Outliers were detected for daily maximum and minimum temperature exceeding +/− four standard deviation. During the index calculation process the following data quality requirements have been applied in order to include as many Georgian temperature series as possible: (1) a seasonal value is calculated if all months of a season are present; (2) a month is considered as complete if ≤3 days are missing; (3) a station will be rejected from the analysis if more than 5 consecutive months are missing. For threshold indices, a threshold is calculated if at least 70% of data are present.

2.2. Homogeneity test and data homogenization

Observational climate data can be influenced by various non-climatic effects, such as the relocation of weather stations, land-use changes, changes in instruments and observational hours (Peterson et al., 1998; Aguilar et al., 2003). These effects result in inhomogeneity causing a shift in the mean of a time series, which may have first order autoregressive errors. RHtestV3 was used in this study to test data homogeneity and to adjust significant breakpoints. Metadata provided by the National Environmental Agency include information regarding the station name, coordinates, altitude, WMO code, observational periods, missing data during an observation period, and station relocation date. The software package RHtestV3 has been developed for detecting and adjusting multiple breakpoints in a data series with noise that may or may not have first order autocorrelation (Wang and Feng, 2010). It has become the standard for use in the WMO CCl/CLIVAR/JCOMM Expert Team ET2.1 training workshops worldwide. In order to detect breakpoints the Penalized Maximal *F* test was applied, which allows the time series being tested to have a linear trend throughout the whole period of data record (Wang, 2008a, 2008b). The PMFred algorithm is widely used to test multiple discontinuities in a time series (Alexander et al., 2006; Wan et al., 2010; Vincent et al., 2012; Kuglitsch et al., 2012). It is based on a Two-Phase-Regression approach and is embedded in a stepwise testing algorithm. The detection power of the new algorithms is analyzed using Monte Carlo simulations. In order to provide reliable results on changes in temperature means and extremes, time-series with significant breakpoints not documented in the metadata were excluded from the study. The 87 Georgian tested temperature series comprised an averaged number of 0.64 breakpoints. Forty-four homogenous minimum and 47 maximum temperature series were used to present averaged temperature index values for the period 1961–1990 (Fig. 1). The 23 minimum and maximum temperature series matching all quality criteria to be used for comparing trends during the periods 1961–2010, 1971–2010 and 1981–2010 contained 12 series with one significant breakpoint each. For two stations (Tbilisi and Gori) dates of site moves were noted within the metadata, which corresponded to the detected dates of breakpoints. Temperature minimum and maximum series of both stations have been homogenized using RHtestV3, which applies a Quantile Matching (QM) adjustment procedure (Wang and Feng, 2010). This procedure adjusts both, the mean level of daily temperature series and the high-order moments. As stated in Vincent et al. (2012), up to 10 years of data before and after a breakpoint are used to calculate the QM adjustments from the base-minus-reference series. In order to estimate the QM adjustments the following parameters have been used in this study: p.lev = 0.95 (nominal level of confidence at which the test is to be conducted), Iadj = 10,000 (an integer value corresponding to the segment to which the series is to be adjusted), Mq = 10 (the number of points for which the empirical probability distribution function are to be estimated), Ny4a = 0 (the maximum number of years of data immediately before or after a breakpoint to be used to estimate the PDF, with Ny4a = 0 for choosing the whole segment).

Fig. 3 shows the monthly mean minimum and maximum temperature series from the Tbilisi meteorological station before and after applying the Quantile Matching (QM) adjustment procedure. It is apparent that between 1918 and 2010, both the temperature minimum and maximum time series pertaining to Tbilisi station have been made warmer after the QM adjustment has been applied. Due to homogenization, the trend of temperature minimum and maximum series has changed from +0.12 °C/decade to +0.23 °C/decade and from +0.13 °C/decade to +0.29 °C/decade, respectively. Metadata indicates a site movement of Tbilisi station as reason for the breakpoint in January 1967.

Tbilisi and Gori time series were tested again for homogeneity after the adjustment of all breakpoints. After the rebreak detection, the homogenized time series at Gori station showed two new significant breakpoints. As they were not listed in the metadata, the time series had to be rejected from the study. The resulting first homogenized daily temperature dataset (1961–2010) comprise daily minimum and maximum temperature series from 16 stations well distributed throughout Georgia (Fig. 2 and Table 1).

2.3. Temperature extreme indices and trend estimation

The Expert Team (ET) and its predecessor, the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) defined 27 core climate extreme indices calculated from daily temperature and precipitation data (Karl et al., 1999;Peterson et al., 2001). The ETCCDI indices agreed upon by the international community aim to monitor changes in "moderate" extremes and to enhance studies on climate extremes using indices that are statistically robust, cover a wide range of climates, and have a high signal-to-noise ratio (Zhang et al., 2011). From the core indices, eight extreme temperature indices were selected for the present study, which are listed in Table 2.

The selected indices have been calculated on an annual and seasonal (winter, spring, summer and fall) basis to provide a better understanding of inter-annual extreme temperature variability. Annual and monthly station values for indices have been calculated using the software RClimDex 1.1. Percentile-based temperature indices have been processed using the standard normal period 1961–1990 to facilitate comparable results with other studies using the same reference period.

Apart from trends for each individual station, trends were also averaged for all Georgian station records. These trends were calculated as the arithmetic average of the annual and seasonal index values. Seasonal and annual Georgian-averaged trends were calculated using the non-parametric Sen's slope estimator based on Kendall's tau (τ) (Sen, 1968). The annual slopes of trends were converted into slope value per decade. The statistical significance has been estimated using the Mann–Kendall test, whereas in the present study a trend was considered to be statistically significant if it was less than or equal to a level of 5% (Mann, 1945; Kendall, 1975).

Table 1
Stations used for trend analysis with station names, WMO code, station coordinates, altitude and the first and last year of the time series used in this study.

Station name	WMO code	North latitude	East longitude	Altitude (m)	First year	Last year
Abastumani	37503	41.72	42.83	1265	1956	2005
Ahalcihe	37506	41.63	42.98	982	1936	2010
Ambrolauri	37308	42.52	43.13	544	1942	2010
Batumi	37484	41.63	41.60	32	1955	2010
Dedopliskaro	37651	41.50	46.10	800	1959	2006
Khulo	37498	41.63	42.30	946	1956	2006
Kobuleti	37481	41.87	41.77	7	1955	2010
Kutaisi	37395	42.20	42.60	116	1936	2010
Lentekhi	37295	42.77	42.72	731	1955	2006
Pasanauri	37432	42.35	44.70	1064	1936	2010
Sachkere	37403	42.35	43.40	455	1955	2006
Sagaredjo	37556	41.73	45.33	806	1936	2006
Tbilisi_HMO	37546	41.68	44.95	427	1918	2010
Telavi	37553	41.93	45.38	562	1956	2010
Tsalka	37537	41.60	44.07	1458	1936	2006
Zemo-Azhara	37196	43.10	41.73	2037	1960	2010

3. Results and discussion

3.1. Annual changes

In the following section, annual changes of temperature means and eight temperature extreme indices are investigated. Changes in mean and station-based trends are analyzed on spatial and temporal scale, comparing the periods 1961–2010, 1971–2010 and 1981–2010.

Table 3 presents the annual values of mean minimum and maximum temperature, the diurnal temperature range and temperature extremes over the standard-normal period 1961–90 for four station series representing different areas of Georgia and for the Georgia-average. The appendix lists all 60 stations used for this investigation, including the respective station name, WMO code, location, altitude, first and last year of the time-series and the homogenous temperature series examined.

Annual large-scale circulation and Georgia's diverse topography result in large spatial and temporal differences of temperature mean and extreme values throughout the study area. Spatial patterns of annual station values for mean minimum and maximum temperature (*T*min and *T*max), summer days (SU), frost days (FD) and the warm spell duration index (WSDI) are shown in Fig. 4. The highest values for annual minimum temperature are located at the western coast and plains (10–15 °C). Minimum temperatures between 10 and 15 °C can be found in continental Transcaucasia at mid-altitudes. Stations with low and very low minimum temperatures (between 5 and −5 °C) are located in the mountainous and high mountainous areas of the Greater and Lesser Caucasus. Highest maximum temperatures (15–20 °C) are widely spread over Transcaucasia, from the east coast to the dry steppe in the west. A wide range of maximum temperatures between 0–15 °C can be found in the mountainous and high mountainous areas of Georgia. In the case of frost days the lowest number can be observed at the western coast and lowlands (0–50 days). Stations with frost days between 50 and 100 days are primarily located in northern Transcaucasia and the eastern plains. Between 100 up to 250 frost days have been detected in the mid-altitudes up to the high mountainous areas of the Greater and Lesser Caucasus. Summer days of 100 up to 150 days per year can be found in the western and eastern plains of Georgia. At the coastal area and mid-altitudes of Transcaucasia there are between 50 and 100 summer days and 0–50 summer days in the mountainous areas of Georgia. However, the highest number of warm spells can be found in the high mountainous areas and eastern lowlands (5–7 days). The largest proportion of stations with 4–5 days of warm spells per year can be found along the Greater

Table 2
ETCCDI temperature indices selected for this study with index names, definitions and units.

ID	Index	Definitions	Units
FD	Frost days	Number of days (per decade) with minimum temperature below 0 °C	days
TN10p	Cool nights	Number of days (per decade) with minimum temperature below a site- and calendar-day-specific threshold value, calculated as the calendar-day 10th percentile of the daily temperature distribution in the 1961–1990 baseline period	days
TX10p	Cool days	Number of days (per decade) with maximum temperature below a site- and calendar-day-specific threshold value, calculated as the calendar-day 10th percentile of the daily temperature distribution in the 1961–1990 baseline period	days
SU	Summer days	Number of days (per decade) with maximum temperature above 25 °C	days
TN90p	Warm nights	Number of days (per decade) with minimum temperature above a site- and calendar-day-specific threshold value, calculated as the calendar-day 90th percentile of the daily temperature distribution in the 1961–1990 baseline period	days
TX90p	Warm days	Number of days (per decade) with maximum temperature above a site- and calendar-day-specific threshold value, calculated as the calendar-day 90th percentile of the daily temperature distribution in the 1961–1990 baseline period	days
WSDI	Warm spell duration index	Number of days (per decade) with at least 6 consecutive days and maximum temperature above a site- and calendar-day-specific threshold value, calculated as the calendar-day 90th percentile of the daily temperature distribution in the 1961–1990 baseline period	days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C

Table 3
Selected mean temperature index values for the reference period 1961–1990 for four stations from different climatic regions of Georgia and for the Georgia-averaged series. The first rows provide mean minimum and maximum temperature and the diurnal temperature range.

Temperature indices	Bichvinta, 4 m (West coast)	Tskhratskaro, 2466 m (Southern Caucasus)	Mamisoni Pass, 2854 m (Northern Caucasus)	Gurjaani, 410 m (Eastern steppe)	Georgia average
*T*min (°C)	11.9	−2.5	−4.8	8.6	6.0
*T*max (°C)	18.4	3.9	1.4	18.3	15.2
DTR (°C)	6.6	6.3	6.3	9.7	9.4
FD (days)	5	206	247	53	86
TN10p (days)	10.6	10.3	10.5	10.5	10.4
TX10p (days)	10.6	10.5	10.5	10.5	10.5
SU (days)	85	0	0	110	70
TN90p (days)	10.6	10.4	9.9	10.2	10.4
TX90p (days)	10.5	10.6	10.4	10.4	10.5
WSDI (days)	3.7	6.6	4.0	6.0	4.2

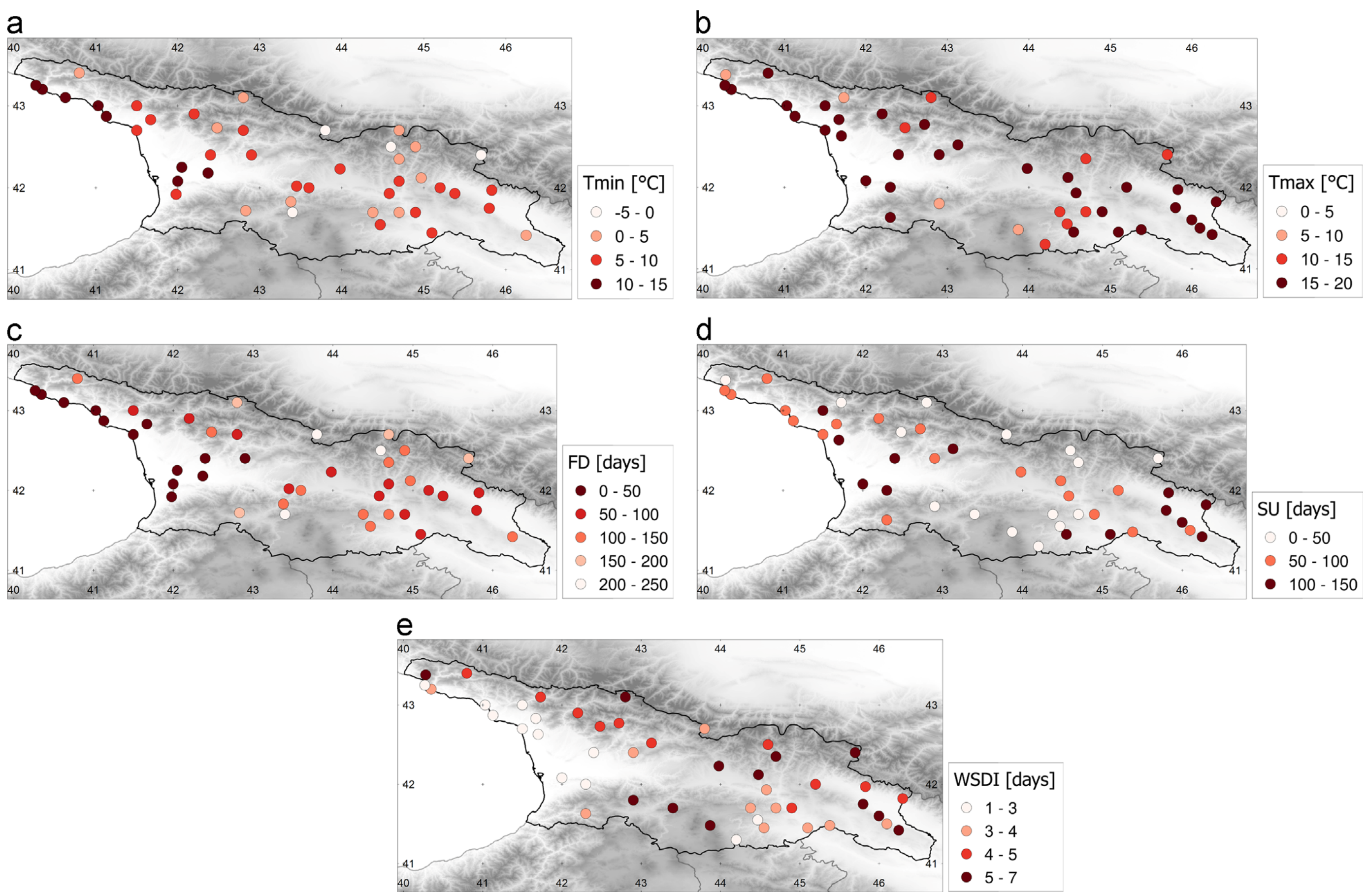

Fig. 4. Averaged annual temperature values for temperature minimum (*T*min), maximum (*T*max) and the temperature extreme indices summer days (SU), frost days (FD), and the warm spell duration index (WSDI) for the period 1961–1990.

Caucasus range. The lowest number of warm spells is located in the western lowlands and the southeast of Georgia (1–3 days) (Fig. 4).

Trends in temperature means reflect a warming in both maximum (*T*max) and minimum temperature (*T*min) throughout Georgia. Georgia-averaged trends for *T*min and *T*max are significant for *T*max between 1961 and 2010 and significant for both, *T*min and *T*max during the periods 1971–2010 and 1981–2010 (Table 4). Most pronounced trends for *T*min and *T*max were identified during the most recent period, 1981–2010. The trends for the diurnal temperature range (DTR) during all analyzing periods are slightly positive, but not significant.

Table 4 shows trends for *T*min, *T*max and the respective ratio of stations with positive, negative and non-significant trends for the analysis periods 1961–2010, 1971–2010 and 1981–2010. A comparison of the periods illustrates that the magnitude of trends for *T*min and *T*max increases from 1961–2010 towards the most recent period. Between 1961 and 2010, 50% of all stations investigated indicate significant warming trends of *T*max (0.22 °C/decade). Within the period 1971–2010 (1981–2010), 63% (38%) out of 16 stations show significant warming trends for *T*max, whereas the trend magnitude increases at a rate of 0.28 °C/decade (0.47 °C/decade). Within the period 1961–2010, *T*min features an insignificant warming trend at a rate of 0.13 °C/decade (1961–2010), and

Table 4
1961–2010: Georgia-averaged trends (°C/decade) for temperature means and the diurnal temperature range and the percentage of stations with significant negative, positive (5% level) and non-significant trends. Trends significant at the 5% level are indicated in bold and highlighted in green.

Index	1961–2010				1971–2010				1981–2010			
	Trend	Neg. (%)	Pos. (%)	Non-sign. (%)	Trend	Neg. (%)	Pos. (%)	Non-sign. (%)	Trend	Neg. (%)	Pos. (%)	Non-sign. (%)
*T*min	0.13	0	44	56	**0.21**	0	69	31	**0.39**	0	69	31
*T*max	**0.22**	0	50	50	**0.28**	0	63	37	**0.47**	0	38	62
DTR	0.06	19	38	43	0.06	25	6	69	0.14	13	13	74

Table 5
1961–2010: Georgia-averaged trends (days/decade) for temperature extremes and the percentage of stations with significant negative, positive (5% level) and non-significant trends. The colors are as described in Table 4.

Index	1961–2010				1971–2010				1981–2010			
	Trend	Neg. (%)	Pos. (%)	Non-sign. (%)	Trend	Neg. (%)	Pos. (%)	Non-sign. (%)	Trend	Neg. (%)	Pos. (%)	Non-sign. (%)
FD	−0.2	13	0	87	−1.3	19	0	81	−1.3	13	0	87
TN10p	−**1.3**	38	0	62	−**1.9**	44	0	56	−2.0	38	0	62
TX10p	−**0.7**	25	0	75	−**1.1**	31	0	69	−**2.1**	31	0	69
SU	**3.0**	0	56	44	**4.0**	0	50	50	**6.2**	0	56	44
TN90p	**1.4**	0	50	50	**2.1**	0	63	37	**2.8**	0	81	19
TX90p	**1.3**	0	50	50	**1.9**	0	63	37	**2.3**	0	63	37
WSDI	2.0	0	44	56	3.4	0	50	50	5.4	0	69	31

significant warming trends by 0.21 (1971–2010) and 0.39 °C/decade. Between 1961 and 2010, 44% of all stations show significant warming trends for *T*min. During the period 1971–2010 (1981–2010), positive trends are observed for 69% (69%) of all stations. Overall, a higher magnitude of trends for annual *T*max is detected than for *T*min. The observed larger magnitude of trends in annual *T*max and rising temperature variability is also in accordance with conclusions derived from earlier studies (Turkes et al., 2002; Turkes and Sumer, 2004).

Table 5 shows trends in temperature extremes over Georgia during 1961 and 2010. All absolute and percentile temperature extreme indices indicate warming during the periods 1961–2010, 1971–2010 and 1981–2010. The absolute temperature indices for frost days (FD) and summer days (SU) show highest warming trends during 1981 and 2010 at a rate of −1.3 days/decade, and 6.2 days/decade respectively, although the trend for FD is not significant at the 5% level. The warming trend for FD is significant for 13% of all stations examined, whereas no significant cooling trend has been identified. For SU a significant warming trend is achieved for 56% of all stations. During 1961 and 2010 significant Georgia-averaged warming trends can be found for the percentile-based temperature indices cold nights (TN10p), cold days (TX10p), warm nights (TN90p), warm days (TX90p) and WSDI. During 1971 and 2010 the significant warming trend magnitude for TN10p increased to a rate of −1.9 days/decade. The Georgia-averaged trend per decade for TX10p amounts to −1.1 days/decade during 1971 and 2010. It increases to −2.1 days/decade during the most recent period 1981–2010. For TN90p a marked warming trend at a rate of 1.4 days/decade can be observed during 1961 and 2010, which is significant at the 5% level for 50% of all stations. During 1971–2010 (1981–2010) the Georgia-averaged warming trend for TN90p increases rapidly and is significant at a rate of 2.1 days/decade (2.8 days/decade). A significant warming trend during 1981 and 2010 is achieved for 81% of all stations. TX90p shows a significant warming trend with lower magnitude (1.3 days/decade) significant for 50% during 1961 and 2010. The warming trend magnitude increases up to 2.3 days/decade significant for 63% of all stations. In the case of minimum temperature indices, most increasing trends and high significance throughout the study areas were observed, denoting that warming trends for night-time indices are larger than for daytime indices (Manton et al., 2001; Peterson et al., 2002; Aguilar et al., 2005; Griffiths et al., 2005; Klein Tank and Können, 2003; Klein Tank et al., 2006; New et al., 2006; Keggenhoff et al., 2014). WSDI also indicates significant increasing trends for all analysis periods. The pronounced warming trend in the Georgia-average amounts to 2.0 days/decade for the period 1961–2010 and is significant for 44% of the stations. During 1971–2010 (1981–2010) the trend magnitude for WSDI increases to 3.4 days/decade (5.4 days/decade) and is significant for 50% (69%) of all stations, whereas none of the stations show significant cooling trends during all analysis periods. Overall, warm extremes (SU, TN90p and TX90p) show higher trend magnitudes than cold extremes (FD, TN10p and TX10p). This finding is a consensus with earlier studies demonstrating that warming since the 1960s is caused by the increase of warm extremes rather than the decrease of cold extremes. This asymmetric change of temperature extremes results in an increase in the temperature variance, since the distributions of minimum and maximum temperature are widening, as discussed in Klein Tank and Können, 2003; Zhang et al., 2005; Moberg et al., 2006.

Fig. 5(a–j) displays the spatial distribution of regional warming trends for *T*min and *T*max, as well as the extreme indices Tn90p, Tx90p and WSDI, comparing the analysis periods 1961–2010 and 1981–2010. Between 1981 and 2010 a pronounced increase in the number of significant warming trends is indicated for both, mean temperature minimum and maximum. Spatial patterns of significant regional warming trends for temperature means cannot be observed. Comparing the regional trends in temperature extremes for the two analysis periods 1961–2010 and 1981–2010, a strong increase in the magnitude of regional warming trends is detectable. Largest magnitudes of trends for TX90p can be found in the southern and eastern part of Georgia, which corresponds to the findings of Elizbarashvili et al., 2013. TN90p shows strong significant warming trends well distributed throughout the study area. Despite the pronounced number of warming trends during the period 1961–2010, a low number of insignificant cooling trends are observable. All of them show a change toward warming during 1981 and 2010. However, for WSDI there is no observable cooling trend throughout Georgia. Highest duration rates for warm spells are mainly located in the eastern plains.

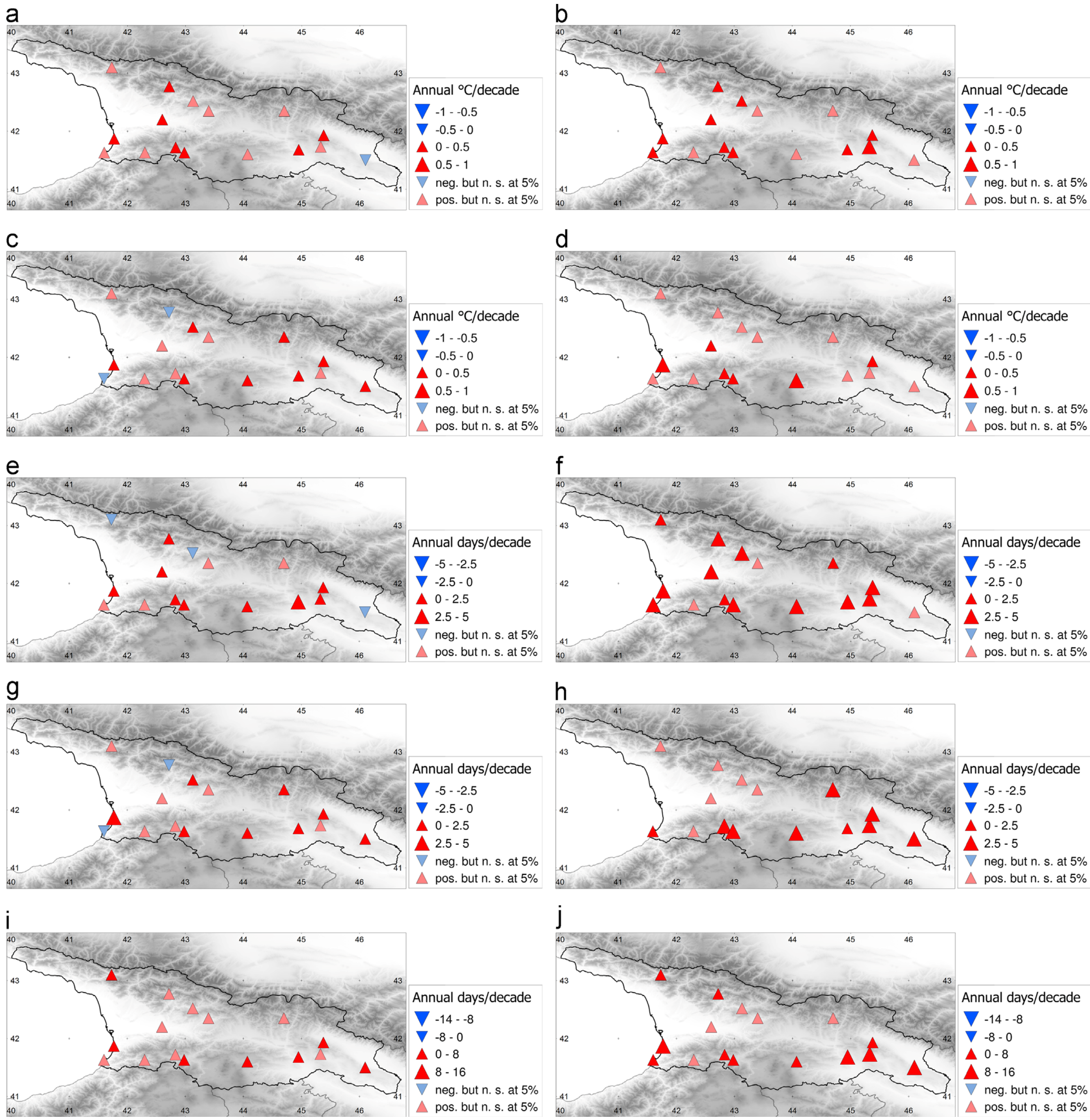

Fig. 5. Annual trends per decade in *T*min (a, b), *T*max (c, d), TN90p (e,f), TX90p (g, h), and WSDI (i, j) during the period 1961–2010 (left) and 1981–2010 (right). Red triangles indicate warming trends, blue indicate cooling trends. Light blue and red triangles indicate trends not significant at the 5% level.

3.2. *Seasonal changes*

For the analysis of trends in seasonal temperature means and extremes for the periods 1961–2010, 1971–2010 and 1981–2010, *T*min and *T*max as well as the percentile-based extremes TN10p, Tx10p, TN90p and TX90p have been selected. Seasons are defined as winter (December–February), spring (March–May), summer (June–August) and fall (September–November).

Table 6 shows the Georgia-averaged trends for temperature minimum and maximum for each season with respective confidence intervals (95%). For *T*min and *T*max warming trends are indicated during all analysis periods. A comparison of the trends between the analysis periods 1961–2010, 1971–2010 and 1981–2010 indicates the largest magnitudes of warming trends for *T*min and *T*max were found during summer and fall, whereas strongest warming trends were identified during the most recent period 1981–2010. Most remarkable and significant warming trends could be observed between 1981 and 2010 for *T*min during summer (0.47 °C per decade) and fall (0.59 days/decade), and for *T*max during summer (0.84 °C/decade) and fall (0.57 °C/decade). Along with the high number of significant warming trends in summer and fall, a remarkable warming trend for *T*min in winter is observable, which is significant at a rate of 0.37 days/decade during the period 1971–2010.

Table 6
Seasonal trends (°C/decade) for temperature minimum and maximum over Georgia within the periods 1961–2010, 1971–2010 and 1981–2010 and respective confidence intervals (95%). The colors are as described in Table 4.

Season	1961–2010		1971–2010		1981–2010	
***T*min**						
Winter	0.15	(−0.18 to 0.42)	**0.37**	(0.02 to 0.79)	0.40	(−0.19 to 0.94)
Spring	0.03	(−0.16 to 0.19)	0.06	(−0.20 to 0.32)	0.23	(−0.18 to 0.70)
Summer	**0.22**	(0.08 to 0.37)	**0.32**	(0.11 to 0.54)	**0.47**	(0.11 to 0.82)
Fall	0.18	(0.00 to 0.37)	**0.33**	(0.06 to 0.57)	**0.59**	(0.30 to 0.95)
***T*max**						
Winter	0.10	(−0.26 to 0.40)	0.36	(−0.02 to 0.72)	0.36	(−0.22 to 0.99)
Spring	0.04	(−0.20 to 0.25)	0.03	(−0.30 to 0.34)	0.20	(−0.27 to 0.73)
Summer	**0.36**	(0.14 to 0.59)	**0.47**	(0.15 to 0.82)	**0.84**	(0.27 to 1.33)
Fall	0.12	(−0.12 to 0.33)	0.24	(−0.11 to 0.54)	**0.57**	(0.05 to 1.07)

Table 7
Seasonal trends (days/decade) for percentile-based temperature indices over Georgia within the periods 1961–2010, 1971–2010 and respective confidence intervals (95%). The colors are as described in Table 4.

Index	1961–2010		1971–2010		1981–2010	
Winter						
TN10p	−0.4	(−1.7 to 0.6)	−1.4	(−3.2 to 0.2)	−1.4	(−3.6 to 0.6)
TX10p	0.3	(−1.0 to 1.4)	−0.9	(−2.1 to 0.8)	−1.1	(−3.5 to 1.8)
TN90p	−0.4	(−1.1 to 1.7)	1.6	(−0.1 to 3.3)	1.0	(−1.7 to 3.8)
TX90p	0.0	(−1.5 to 1.4)	1.2	(−0.4 to 3.0)	0.3	(−2.4 to 3.5)
Spring						
TN10p	0.2	(−0.8 to 1.1)	0.3	(−1.2 to 1.6)	−0.8	(−2.9 to 1.1)
TX10p	−0.2	(−1.2 to 0.7)	0.0	(−1.3 to 1.1)	−1.4	(−3.0 to 0.4)
TN90p	−0.6	(−0.4 to 1.5)	1.0	(−0.4 to 2.5)	2.0	(−0.3 to 4.5)
TX90p	0.5	(−0.5 to 1.6)	0.8	(−0.6 to 2.2)	1.9	(−0.1 to 3.6)
Summer						
TN10p	**−1.4**	(−2.3 to −0.6)	**−1.7**	(−3.3 to −0.5)	**−2.5**	(−4.4 to −0.6)
TX10p	**−1.5**	(−2.3 to −0.6)	**−1.8**	(−3.2 to −0.4)	**−2.9**	(−4.9 to −0.9)
TN90p	**2.2**	(1.0 to 3.5)	**3.2**	(1.5 to 5.3)	**4.6**	(1.6 to 8.0)
TX90p	**2.4**	(0.9 to 4.0)	**3.2**	(1.1 to 5.8)	**5.6**	(2.5 to 10.6)
Fall						
TN10p	**−1.1**	(−2.1 to −0.1)	**−1.4**	(−2.8 to −0.2)	**−2.4**	(−4.0 to −0.7)
TX10p	**−1.0**	(−1.8 to −0.1)	−1.2	(−2.4 to 0.0)	**−2.1**	(−4.2 to −0.5)
TN90p	**1.5**	(0.5 to 2.6)	**2.6**	(1.1 to 3.9)	**4.6**	(2.8 to 6.6)
TX90p	0.7	(−0.1 to 1.8)	**1.3**	(0.0 to 2.9)	2.0	(−0.1 to 5.4)

Seasonal Georgia-averaged trends for the lower- and upper-tail extreme temperature indices (TN10p, TX10p, TN90p and TX90p) during the analysis periods 1961–2010, 1971–2010 and 1981–2010 are listed in Table 7. Most warming trends (significant at the 5%) for warm and cold percentile-indices are determined in summer, whereas largest magnitudes of trends can be found during the most recent analysis period 1981–2010.

Despite the overall warming trends in summer and fall during the periods 1961–2010, 1971–2010 and 1981–2010, the seasonal resolution of trends implies a cooling of cold extremes, particularly in spring. Towards the more recent periods a reversal of all cooling trends to pronounced warming is presented, although trends for cold extremes in winter and spring are insignificant. During the fall season of the period 1981–2010 a large proportion of trends is significant at the 5% level. Between 1981 and 2010 a rapid warming of TN10p, TX10p and TN90p of up to −2.4, −2.1 and 4.6 days/decade, respectively, can be observed. However, largest magnitudes of trends could be determined for summer, while all indices show significant warming trends during the analysis periods. Highest magnitudes of warming trends were identified for TN90p at a rate of 4.6 days/decade and for TX90p at a rate of 5.6 days/decade. As in the case of annual changes, warm extremes (TN90p and TX90p) show larger trend magnitudes than cold extremes (TN10p and TX10p). These asymmetric changes in lower- and upper-tail extremes imply an increase in the temperature variance, particularly in summer, which corresponds to the findings of Xoplaki et al. (2003, 2006). In accordance with earlier studies (Horton et al., 2001; Yan et al., 2002; Klein Tank and Können, 2003; Zhang et al., 2005; Moberg et al., 2006; Della-Marta et al., 2007) warming since the 1960s is caused by the increase of warm extremes as opposed to the decrease of cold extremes. Asymmetry in the changes of warm and cold extremes can be related to the large scale circulation and airflow characteristics over the Southern Caucasus/Black Sea area. Cold extremes in winter are caused by arctic high-pressure systems from the Central Asian Region and in summer by airflow from the Black Sea. Following the assumptions of Klein Tank and Können (2003), cold extremes are less sensitive to large-scale warming than warm extremes, due to the latent heat of snow and the thermal inertia of water. Consequently, small changes in the frequency of atmospheric circulation patterns in a warming scenario may be capable of stabilizing or increasing the number of cold extremes.

Fig. 6(a–f) presents the spatial distribution of regional summer trends for *T*min and *T*max, and the percentile-based indices TN10p, TX10p, TN90p, TX90p during the period 1981–2010. A pronounced increase in the magnitude of regional warming trends for summer means and extremes can observed compared to the corresponding annual trends throughout Georgia. For all temperature means and extremes warming trends could be found, with the exception of one insignificant regional cooling trend for TX10p. Although a large proportion of significant regional warming trends for minimum and maximum temperature and TN10p, TX10p, TN90p, TX90p could be determined, there is only small evidence for spatial patterns of summer trends. However, for TX90p largest significant warming trends can be observed particularly in the southern and eastern part of Georgia. For Tx10p the

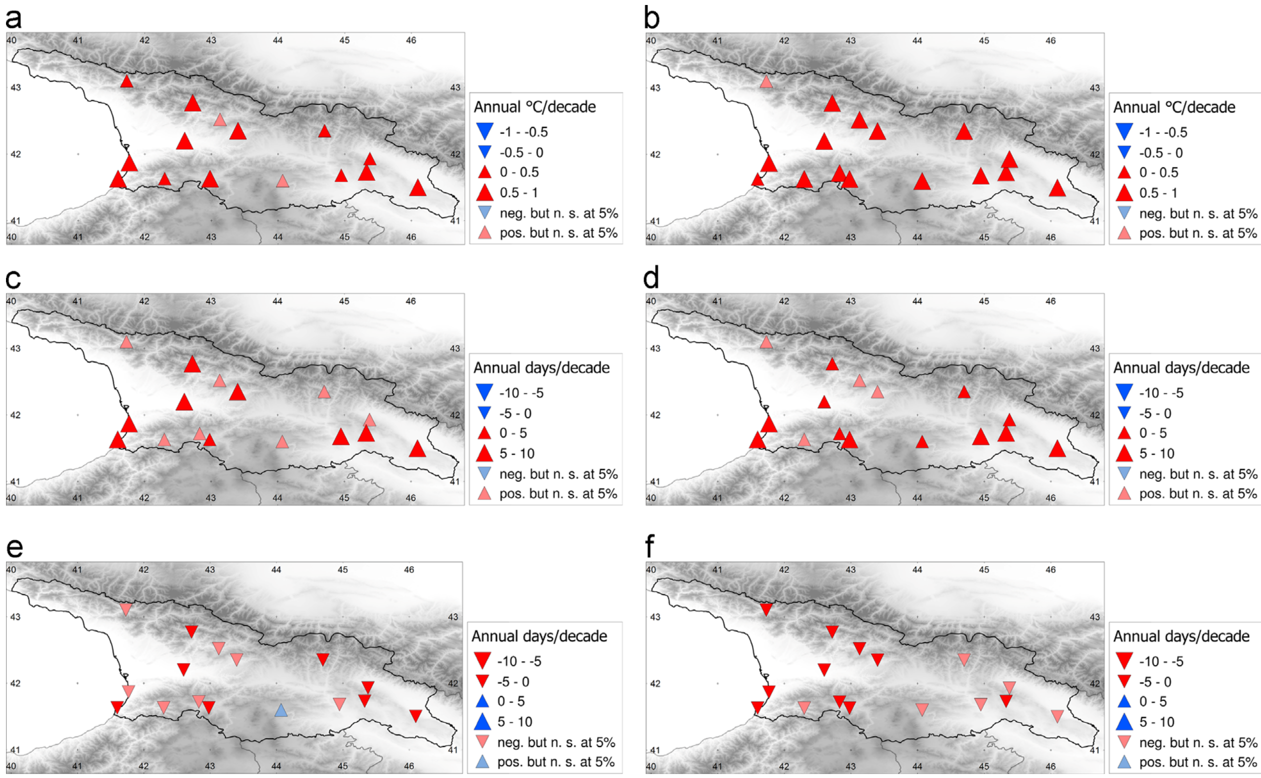

Fig. 6. Summer trends per decade in *T*min (a), *T*max (b), TN10p (c), TX10p (d), TN90p (c), and TX90p (d) for the period 1981–2010. Red triangles indicate warming trends, blue indicate cooling trends. Light blue and red triangles indicate trends not significant at the 5% level.

strongest summer trends are located in the western part. During summer the highest number of significant regional warming trends in Georgia was determined for TX10p and TX90p, while the magnitude of several regional warming trends for warm extremes (TN90p and TX90p) was found to be twice as large as those for cold extremes. In terms of seasonal changes in temperature extremes since the 1960s, it is evident that warm extreme events in Georgia mainly occur during the summer season.

4. Conclusions

This study analyzed annual and seasonal changes in temperature means and extreme indices within the period 1961–2010 over Georgia by using a dataset of 16 daily minimum and maximum temperature series. Time series were quality controlled and homogeneity was tested using the software RClimDex 1.1. Due to metadata availability, time series at Tbilisi station could be homogenized using RHtestV3 and was added to the dataset. The following changes for annual and seasonal temperature means and extreme indices were observed throughout the study area:

- Annual mean temperature minimum and maximum and selected temperature extreme indices showed pronounced warming trends during all analysis periods (1961–2010, 1971–2010 and 1981–2010) and an increase in the diurnal temperature range.
- Most significant (at the 5% level) annual warming trends for temperature means and extremes could be found during 1971–2010 and 1981–2010, whereas the magnitude of trends for night-time indices is more pronounced than those for daytime.
- Most pronounced annual warming trends were detected for all warm extremes (SU, TN90p, TX90p and WSDI) in the southern and eastern lowlands of Georgia
- An overall increase in the proportion of stations with warming trends and in the magnitude of warming trends towards the most recent analysis period 1981–2010 could be observed for annual and seasonal trends.
- The largest magnitudes of significant warming trends for *T*min and *T*max and the percentile based extreme indices could be detected during the summer season.
- Georgia-averaged trends show "asymmetric" changes in annual and seasonal warm and cold temperature extremes during all analysis periods, indicating a trend towards an increase of the temperature variance, particularly in summer.

The study could improve the understanding of recent changes in the variability, intensity, frequency and duration of temperature means and extreme events over Georgia. The study demonstrated that since the 1960s the occurrence of summer days, warm days and nights and the duration of warm spells in Georgia strongly increased, while cold extremes showed comparatively moderate warming trends. Nevertheless, the presented results need to be considered with limitations. Temperature stations revealed numerous data gaps and a complete set of metadata was not available. Due to a large proportion of inhomogeneity, many stations had to be rejected, which limits data coverage and can lead to an overrepresentation of areas with a higher density of stations in the Georgian average. Thus, it is essential to enhance metadata recovery and access in Georgia. In order to obtain a more detailed insight in the temporal development of the indices at the large-scale atmospheric circulation, it is also important to carry out a climate composite analysis. Annual and seasonal changes in heat additional temperature extremes, such as heat waves in relation to anomalies of the atmospheric circulation in different altitudes and the Sea Level Pressure over the Caucasus region is already planned to better understand some of the driving forces of extreme events in Georgia.

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Appendix A

See appendix Table A1 here.

Table A1

Station	WMO code	North latitude	East longitude	Altitude [m]	First year	Last year	Temperature series used
Abastumani	37503	41.72	42.83	1265	1956	2005	*T*min
Akhalgori	37429	42.12	44.48	760	1955	2004	*T*max
Akhmeta	37448	42.00	45.20	567	1957	1992	*T*min & *T*max
Ambrolauri	37308	42.52	43.13	544	1942	2010	*T*max
Anaseuli	37483	41.92	41.98	174	1957	1992	*T*min
Babushera	37260	42.52	41.08	43	1955	1992	*T*min & *T*max
Barisaho	37433	42.50	44.90	1315	1936	2004	*T*min
Bichvinta	37178	43.20	40.35	4	1955	1992	*T*min & *T*max
Bolnisi	37621	41.45	44.55	534	1936	2010	*T*max
Borjomi	37515	41.83	43.38	794	1936	2010	*T*min
Chohatauri	37388	42.00	42.30	221	1936	2006	*T*max
Cnori	37577	41.60	46.00	223	1936	1992	*T*max
Dedopliskaro	37651	41.50	46.10	800	1955	2010	*T*max
Dmanisi	37612	41.30	44.20	1256	1936	1992	*T*max
Dusheti	37437	42.08	44.70	902	1957	2006	*T*min
Gagra	37177	43.25	40.27	7	1957	1992	*T*min & *T*max
Gagris Kedi	37175	43.38	40.28	1644	1936	1992	*T*max
Gali	37278	42.63	41.70	63	1957	1992	*T*max
Gardabani	37632	41.45	45.10	303	1936	2006	*T*min & *T*max
Gudauta	37187	43.10	40.63	11	1956	1992	*T*min
Gurjaani	37566	41.75	45.80	410	1955	2006	*T*min & *T*max
Haisi	37281	42.90	42.20	730	1955	1992	*T*min & *T*max
Jvris Pass	37420	42.50	44.60	2395	1957	1992	*T*min & *T*max
Khashuri	37417	42.00	43.60	690	1959	2010	*T*min
Khulo	37498	41.63	42.30	946	1956	2010	*T*max
Kojori	37544	41.70	44.70	1338	1955	1992	*T*min & *T*max
Kvareli	37563	41.97	45.83	449	1936	2006	*T*min & *T*max
Lagodehi	37572	41.82	46.30	435	1955	2010	*T*max
Lanchkhuti	37386	42.08	42.00	20	1955	1992	*T*min & *T*max
Lata	37198	43.00	41.50	299	1955	1992	*T*min & *T*max
Lebarde	37286	42.73	42.48	1610	1936	1992	*T*min & *T*max
Lentekhi	37295	42.77	42.72	731	1955	2006	*T*max
Mamisoni Pass	37316	42.70	43.80	2854	1957	1992	*T*min & *T*max
Manglisi	37535	41.70	44.38	1195	1955	1992	*T*min & *T*max
Martvili	37390	42.40	42.40	170	1955	1992	*T*min & *T*max
Mestia	37209	43.10	42.80	1441	1959	1992	*T*min & *T*max
Mukhrani	37541	41.93	44.58	551	1936	1992	*T*min & *T*max
Ochamchire	37267	42.70	41.47	5	1956	1992	*T*min & *T*max
Omalo	37452	42.40	45.70	1880	1955	1992	*T*min & *T*max
Paravani	37603	41.48	43.87	2100	1960	2006	*T*max
Pasanauri	37432	42.35	44.70	1064	1936	2010	*T*min & *T*max
Pskhu	37183	43.40	40.80	685	1956	1992	*T*min & *T*max
Samtredia	37385	42.18	42.37	26	1936	2005	*T*min
Senaki	37380	42.25	42.05	34	1957	2006	*T*min
Shiraki	37651	41.42	46.25	801	1955	1992	*T*min & *T*max
Stepantsminda	37335	42.70	44.70	1744	1955	2010	*T*min
Sukhumi	37189	43.00	41.03	37	1957	1991	*T*min & *T*max
Telavi	37553	41.93	45.38	562	1956	2010	*T*min
Tetri-Tskaro	37539	41.55	44.47	1140	1955	1992	*T*min & *T*max
Tianeti	37439	42.12	44.97	1091	1936	2010	*T*min
Tkibuli	37393	42.40	42.90	541	1956	1992	*T*min & *T*max
Tkvarcheli	37272	42.83	41.67	266	1936	1992	*T*min & *T*max
Tsageri	37298	42.70	42.80	474	1957	2006	*T*min
Tsipa	37513	42.02	43.45	673	1955	2004	*T*min
Tskhinvali	37416	42.23	43.98	871	1957	1990	*T*min & *T*max
Tskhratskaro	37525	41.70	43.40	2466	1957	1991	*T*min & *T*max
Udabno_Mount	37633	41.48	45.38	750	1955	1992	*T*max
Varketili	37542	41.70	44.90	549	1955	1992	*T*min & *T*max
Zekaris Pass	37503	41.80	42.90	2180	1961	1992	*T*max
Zemo-Azhara	37196	43.10	41.73	952	1960	2010	*T*max

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