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Temperature Extremes over Georgia: Changes, Patterns and Driving Forces

A dissertation submitted

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by

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Contents

List of Tables

List of Figures

Summary

Trends in daily temperature and precipitation extremes over Georgia, 1971-2010

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

Heat Wave Events over Georgia since 1961: Climatology, Changes and Severity

Severe summer Heat Waves over Georgia: Trends, Patterns and Driving Forces

Abbreviations

AGCM	Atmospheric Global Circulation Model
AMIES	Analysing Multiple Interrelationships between Environmental and Societal Processes in Mountainous Regions of Georgia
BMBF	German Federal Ministry of Education and Research
CCA	Canonical Correlation Analysis
CCI	Commission for Climatology
CDD	Consecutive Dry Days
CEI	Climate Extreme Index
CLIVAR	Climate Variability and Predictability
CRED	Centre for Research on the Epidemiology of Disasters
CRSCI	Climate Risk and Sector-specific Climate Indices
CSDI	Cold spell duration indicator
CTN90p	90th percentile of daily minimum temperature
CTX90p	90th percentile of daily maximum temperature
CWD	Consecutive Wet Days
DAAD	German Academic Exchenge Service
DTR	Diurnal Temperature Range
EHF	Excess Heat Factor
EHF_{85}	85th percentile of the distribution of positive EHF values
EHF_{accl}	accumulated EHF
EHF_{sig}	significant EHF
EM-DAT	International Disaster Database
EMME	East Mediterranean and Middle East
ET	Expert Team
ETCCDI	Expert Team on Climate Change Detection and Indices
FD	Frost Days
GCM	General Circulation Model
GPS	Global Positioning System
HW	Heat Wave
HWA	Heat Wave Amplitude
HWD	Heat Wave Duration
HWday	Heat Wave Days
HWex	Heat Wave Extreme Days
HWF	Heat Wave Frequency
HWF90	Heat Wave Number (see Zittis et al. 2015 for details)
HWM	Heat Wave Mean
HWN	Heat Wave Number
HWN90	Heat Wave Duration (see Zittis et al. 2015 for details)
HWsev	Heat Wave Severe Days
ID	Ice Days
IPCC	Intergovernmental Panel on Climate Change
IPSWaT	International Postgraduate Studies in Water Technologies
ITCZ	African Intertropical Convergence Zone
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
KNMI	Koninklijk Nederlands Meteorologisch Instituut
MEDARE	Mediterranean Climate Data Rescue
MOE	Minister of Environment and Natural Resources Protection of Georgia
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Predictions
NEA	National Environmental Agency of Georgia

NWP	Numerical Weather Prediction
O500	500-hPa Vertical Velocity
OI	Optimum Interpolation
OLR	Outgoing Longwave Radiation
PC	Principal Component
PCA	Principal Component Analysis
PMF	Penalized Maximal F
PRCPTOT	Annual total wet-day precipitation
PROMOS	Program for Mobility of German Students by DAAD
QM	Quantile Matching
R10mm	Number of heavy precipitation days
R1mm	Number of wet days
R20mm	Number of very heavy precipitation days
R95p	Very wet days
R99p	Extremely wet days
RH500	500-hPa Relative Humidity
RR	Total Precipitation
Rx1day	Maximum 1-day precipitation amount
Rx5day	Maximum 5-day precipitation amount
SAT	Surface Air Temperature
SDII	Simple daily intensity index
SLP	Sea Level Pressure
SM	Soil Moisture
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation by the IPCC
SST	Sea Surface Temperature
SU	Summer days
SVD	Singular Value Decomposition
Tmax	Temperature maximum
Tmean95p	95^{th} percentile of daily mean temperature
Tmin	Temperature minimum
TN10p	Cold nights
TN90p	Warm nights
TNn	Monthly minimum of Tmin
TNx	Monthly maximum of Tmin
TR	Tropical nights
TX10p	Cold days
TX90p	Warm days
TXn	Monthly minimum Tmax
TXx	Monthly maximum of Tmax
U-wind500	500-hPa Zonal Wind
UBH	Ural Blocking High
UHI	Urban Heat Island
V-wind500	500-hPa Meridional Wind
WCRP	World Climate Research Programme
WCRP	World Climate Research Programme
WHOSIS	World Health Organization Statistical Information System
WMO	World Meteorological Organization
WSDI	Warm spell duration indicator
Z500	500-hPa geopotential height

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Summary

1. Introduction

"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems. Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia." (IPCC, 2014)

An overall warming of the atmosphere and oceans, a widespread melting of snow and ice, as well as a rising sea level are induced by anthropogenic climate change. Regional changes include an increase in mean temperature, changes in precipitation totals, wind patterns and the intensity, frequency and duration of weather and climate extremes. During the last decades climate change research shifted its focus from detecting changes in monthly and annual means to the analysis of extreme events. However, detecting changes in weather and climate extremes is challenging due to the interactions between changes in mean climate, variability and symmetry of a distribution. Figure 1 demonstrates an increase in the probability of occurrence of temperature extreme events by changes towards warmer mean temperatures, an increase in temperature variance or a change in symmetry of a distribution promoting the hot temperature end of the range.

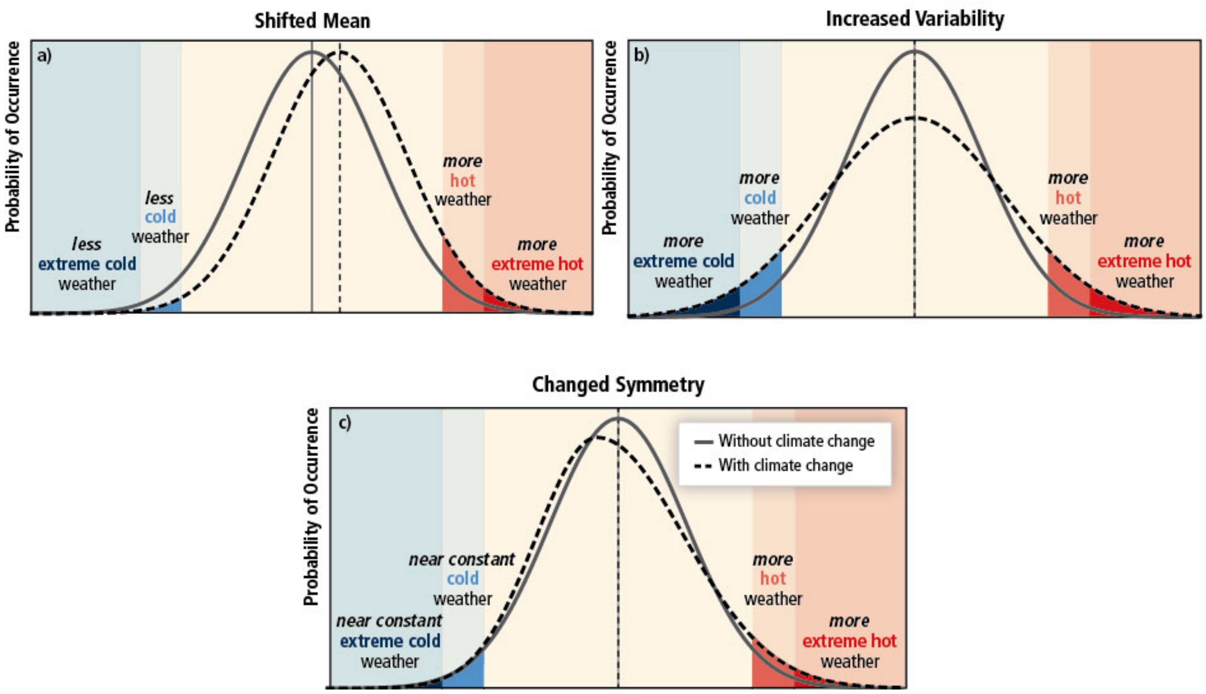

Figure 1: *The effects of changes in temperature distribution on extremes with and without climate change: (a) effects of a simple shift of the entire distribution toward a warmer climate; (b) effects of an increase in temperature variability with no shift in the mean; (c) effects of an altered shape of the distribution, in this example a change in asymmetry toward the hotter part of the distribution (IPCC, 2012).*

Today, extreme weather and climate events represent one of the most discussed issues in climate science. As trends in temperature extreme events react more sensitively to climate change than mean climate, they have a more intense impact on natural and human systems (Katz and Brown, 1992; Easterling et al., 1997; Kunkel et al., 1999; New et al., 2006; IPCC, 2007; Aguilar et al., 2009). Given their importance, it is essential to understand how and why weather and climate extremes have changed in the past. Changes in climate extremes are usually investigated by using climate extreme indices based on absolute or percentile based thresholds (Aguilar et al., 2005; Griffiths et al., 2005; Zhang et al., 2005; Haylock et al., 2006; Klein Tank et al., 2006; Sensoy et al., 2007; Aguilar et al., 2009; Alexander and Armblaster, 2009; Skansi et al., 2013). 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.” Many results on global changes in extreme events have been contributed to the Assessment Reports of the IPCC, which found that temperature extremes demonstrate a significant warming during the second half of the 20th century, citing the highest trends for the most recent periods and for minimum temperature based extreme indices. However, trends in extreme precipitation illustrate a much lower spatial coherence, yet a significant overall wetting trend could be detected, whereas the number of consecutive dry days shows very different regional changes (Frich et al., 2002; Alexander et al., 2006). Figure 2 shows trends and anomaly series for the temperature extreme indices based on the 90th percentile for minimum and maximum temperature between 1951 and 2003.

a) Warm nights b) Warm days

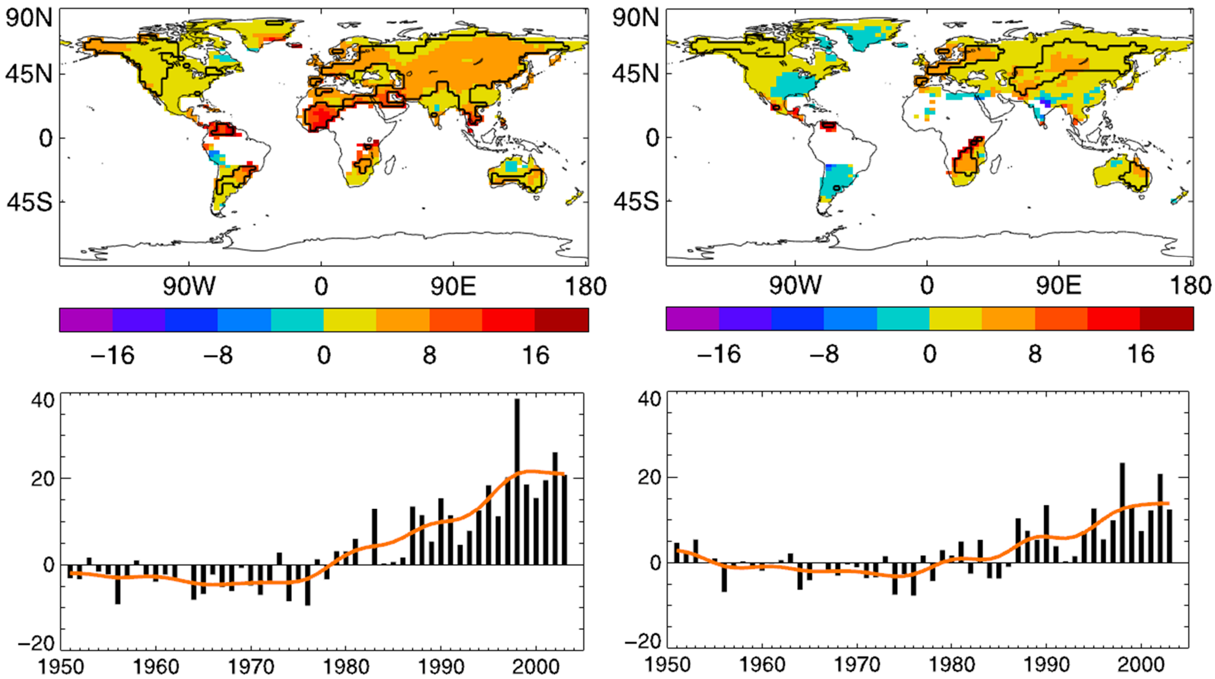

Figure 2: *Trends (in days per decade) and annual time series anomalies relative to 1961-1990 mean values for annual series of percentile temperature indices for 1951-2003 for (a) cold nights (TN10p) and (b) warm days (TN90p). Black lines enclose regions where trends are significant at the 5% level. The red curves on the plots are nonlinear trend estimates obtained by smoothing using a 21-term binomial filter (Alexander et al., 2006).*

Climate extreme indices have also been used to compute and analyze projected future climate conditions based on simulations by GCMs (Tebaldi et al., 2006; Kharin et al., 2007; Alexander and Arblaster, 2009; Russo and Sterl, 2011; Orlowsky and Seneviratne, 2012; Sillmann et al., 2013a; Sillmann et al., 2013b). Especially summer temperature extremes are predicted to increase while extreme cold temperatures will become more moderate. The results also suggest that climate models cannot overcome uncertainties for projecting future changes in extreme events, especially concerning the regional scale with complex physiographic conditions. For that reason, analyzing changes in weather and climate extreme events based on observation data is essential. Meteorological observation data recorded at weather stations are presumed to be the most reliable source for climate change detection. In order to provide profound analyses on weather and climate means and extremes using this data, long, highly resolved, quality tested and homogenized times series are fundamental (Alexandersson and Moberg 1997a, b; Vincent et al. 2002; Caussinus and Mestre 2004; IPCC 2007). However, observational climate data can be influenced by various non-climatic effects causing artificial signals, which have to be corrected (Aguilar et al., 2003; Zhang et al., 2005; Brandsma and Konnen, 2006; Della-Marta and Wanner, 2006; Kuglitsch et al., 2009, Mestre et al., 2013; Mamara et al., 2014).

Climate extremes such as summer heat waves (HWs) are among the most threatening meteorological hazards related to global warming posing impacts to society, economy and ecology. Effects of heat waves can include an increase in morbidity and mortality rates (Trigo et al., 2005; Vandentorren et al., 2006; Tong et al., 2010; Anderson and Bell, 2011), a rising stress on agricultural resources (Ciais et al., 2005; Lanning et al., 2011) and a strain on infrastructure (Smoyer-Tomic et al., 2003). Figure 3 presents the global changes in the yearly sum of heat wave days participating in an event highlighting the Caucasus Region as one of the world's most affected areas by heat wave changes.

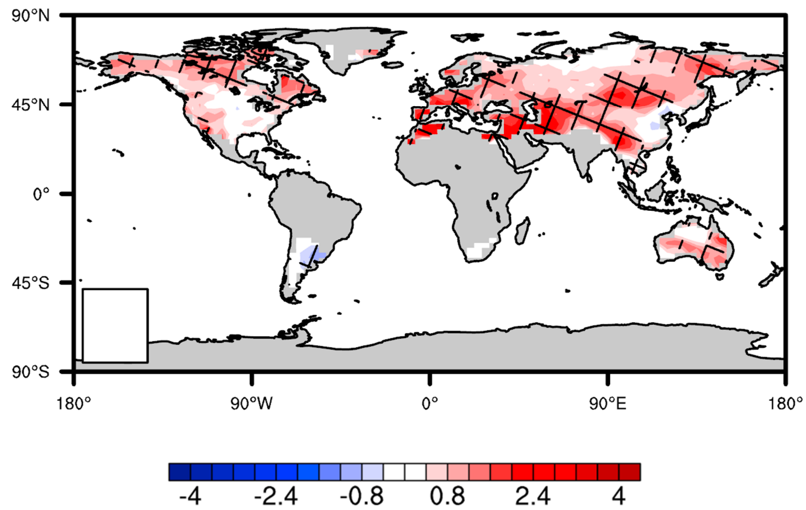

Figure 3: *Heat wave trends in the number of days participating in an event, in which positive Excess Heat Factor (EHF) values persist for at least three consecutive days. Trends are for the period 1950-2011, computed by the non-parametric Kendall slope estimator. Units are percentage of days per decade. Hatching represents where trends are significant at the 5% level, and grey indicates areas where there are insufficient observations (Perkins et al., 2012).*

Heat wave climatology, changes and patterns on global and continental scales have been investigated in various studies (Frich et al. 2002; Stott et al., 2004; Alexander et al., 2006; Della-Marta et al., 2007a, b; Kuglitsch et al., 2010). According to the IPCC anthropogenic influences on climate since the mid-20th century doubled the probability of occurrence of heat waves in some regions of the world (IPCC, 2013). Scenarios predict a further increase in global averaged frequency, duration and intensity of heat waves (Meehl and Tebaldi, 2004; Kharin et al., 2007; Perkins et al., 2012). The driving mechanisms of heat wave events are often related to large-scale atmospheric blocking patterns, enhanced Sea Surface Temperature (SST), heat flux anomalies and reduced antecedent precipitation and soil moisture deficiencies (Della-Marta et al., 2007b; Fischer et al. 2007; McBride et al., 2009; Senerivatne et al., 2010; Feudale and Shukla, 2011; Müller and Seneviratne, 2012; Stefanon et al., 2013; Zittis, et al., 2014).

The high mountainous ranges and adjacent lowlands of the Caucasus are considered as “hot spot” of climate change as it reacts highly sensitive to changes in climate means and extremes (Shaghedanova, 2012). Georgia inhabits around 4.5 million people and is a growing tourist destination with more than 5 million people visiting each year (http://data.worldbank.org). The rapid increase of the population and urbanization in Georgia and its strong dependence on agricultural production put particular pressure and enhance the risk of heat waves (UNDP, 2015).

The aim of this study is to provide a comprehensive understanding of the annual and seasonal climatology and changes in temperature extremes over Georgia. Particular emphasis is set on the investigation of heat-health related heat wave severity, patterns and key mechanisms initiating and amplifying summer heat waves.

1.1 Climate extremes over Georgia

After the collapse of the Sovjet Union in 1991 Georgia has undergone profound transformation processes. Privatization of land, implementation of new institutional structures for land management and the rapid increase of the population and urbanization have caused various environmental and socio-economic problems, resulting in soil degradation, air and water pollution, poverty and migration. Climate change and climate extreme events might enhance those effects. Weather and climate extreme events in Georgia, such as summer heat waves are responsible for increasing human and economic losses (MOE, 2009). The impacts of climate extremes and the potential for disasters result from the climate extremes themselves and from the exposure and vulnerability of human and natural systems. The magnitude of heat wave impacts may be changing related to the vulnerable sectors affected, particularly to those exposed through poor health and high age (Basu and Samet, 2006). Particularly, urban regions are exposed to more frequent heat wave events, due to the urban heat island (UHI) effect and synergistic interactions between heat waves and urban heat islands, such as the lack of surface moisture in urban areas, the low wind speed associated with heat waves, the increase in the ambient temperatures and the difference between urban and rural temperatures (Li and Bou-Zeid, 2013). The rapid increase of the population and urbanization in Georgia and its strong dependence on agricultural production might amplify these negative heat-health impacts (UNDP, 2015). However, heat wave impacts are currently under-reported in Georgia and information on morbidity, mortality and economic consequences are difficult to assess. 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; Elizbarashvili et al., 2009a; Elizbarashvili et al., 2009b; Elizbarashvili et al., 2011; Elizbarashvili et al., 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). According to recent findings by Keggenhoff et al. (2014) Georgia experienced pronounced warming trends and a decrease in wet days (R ≥ 1mm) during 1971 and 2010. Since the 1960s, monthly minimum and maximum temperature increased by 0.22 and 0.36 °C, respectively, while warm extremes show larger trends than cold extremes. The largest magnitudes of significant warming trends for temperature means and the percentile based extreme indices could be detected during the summer season. The trend for warm spells was observed to be significantly increasing by 1.7 days (Keggenhoff et al., 2015a). Findings of (Keggenhoff, et al., 2015b) prove that the intensity, frequency and duration of heat waves in Georgia increased dramatically during the last 50 years. The number of heat waves showed an increase of 0.7 events/decade, the duration of heat waves extended by 1.0 day/decade and heat wave frequency (the number of days participating in an event) increased by 4.3 days/decade. According to research on future heat wave changes in the EMME region including the Caucasus the heat-health risk factor is projected to increase due to the increase in the frequency, intensity and duration of heat waves, the decrease in precipitation and rising air pollution, particularly in urban areas (Zittis et al., 2014, 2015; Lelieveld et al., 2012, 2013). Figure 4 summarizes the projected changes in the summer heat wave frequency and number over the EMME and the Caucasus region for the period 2071-2099, and identifies strong increasing trends throughout Georgia.

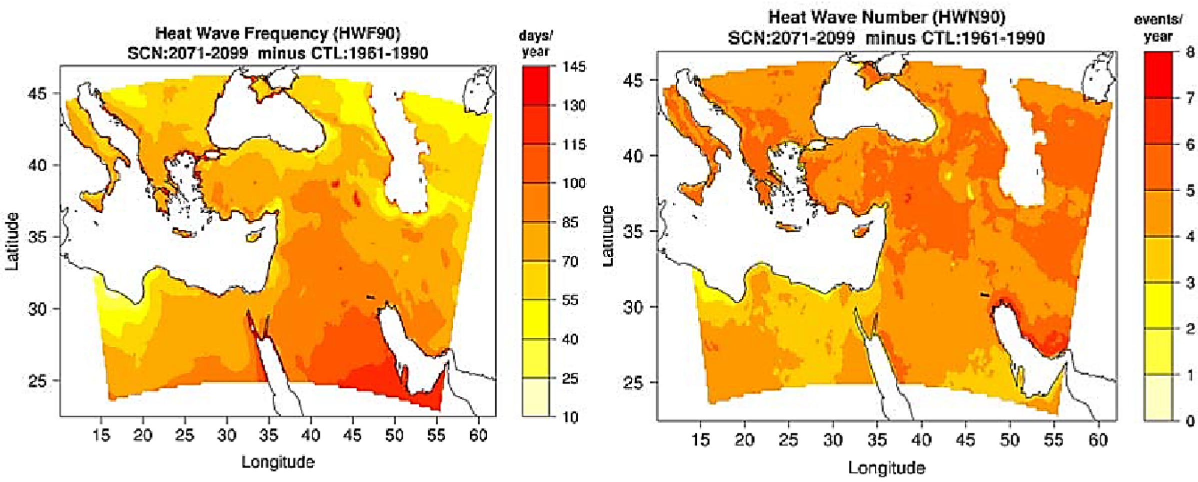

Figure 4: *Projected changes in the heat wave frequency (HWF90) and heat wave number (HWN90) for the summer season (May to September) 2071-2099 with respect to the reference period 1961-1990. Simulations are based the HadRM3P regional climate model and a three ensemble scenario with an optimistic (B2), intermediate (A1B) and pessimistic estimation (A2) (Zittis et al., 2015).*

The frequency, duration and intensity of heat wave events is usually linked to large-scale atmospheric blocking patterns, enhanced SSTs and heat flux anomalies, as well as reduced precipitation and soil moisture deficiencies. A growing number of studies investigated the mechanisms that contribute to the formation and prediction of heat wave events using the example of high-impact events in Eurasia, such as the 2003 European heat wave (Fink et al., 2004; Ogi et al., 2005; Trigo et al., 2005, Ferranti and Viterbo, 2006; Jung et al., 2006; Black et al., 2007; Fischer, 2007; Feudale and Shukla, 2011a, b), or the 2010 Russian heat wave (Barripedro et al., 2011; Dole et al., 2011; Grumm, 2011). Most studies relate heat wave events to anticyclonic blockings in the atmospheric circulation, leading to enhanced heat advection, adiabatic heating by subsidence and solar radiative heating due to reduced cloudiness (Black et al. 2004; Meehl and Tebaldi, 2004; Fink et al. 2004; McBride et al., 2009; Zittis, et al., 2015). Next to synoptic features, SST anomalies (Jung et al. 2006; Black and Sutton 2007; Della-Marta et al., 2007b; Feudale and Shukla 2011a and b) and precipitation and soil moisture deficiencies can represent crucial driving forces contributing to current and future heat wave events (Vautard et al., 2007; Ferranti and Viterbo 2006; Fischer et al. 2007; Seneviratne et al., 2010; Hirschi et al., 2011; Jäger and Seneviratne, 2011; Müller and Seneviratne, 2012; Stefanon et al., 2013; Zittis et al., 2014).

Previous studies investigating climate extremes over Georgia (Elizbarashvili et al., 2007; Elizbarashvili et al., 2009a; Elizbarashvili et al., 2009b; Elizbarashvili et al., 2011; Elizbarashvili et al., 2012) usually lack of daily observation data. Hence, most papers focus on large study areas, excluding regional investigations on climate extremes and aspects of relationships between heat waves and their driving forces. Due to the fact that observation data for Georgia is difficult to access and the country is located at the edge of Europe and Asia, Georgia is often marginalized in common study domains, such as the Europe, Russia or the EMME region. Moreover, recent studies lack a proper application of quality testing, inhomogeneity detection and adjustment techniques of station data (Elizbarashvili, et al. 2014; Elizbarashvili, et al. 2014). This highlights the importance to shift more attention to information and knowledge transfer, close cooperation between scientists and the application of different reliable break detection techniques to minimize the risk of misinterpretation of results.

1.2 Research integration and objectives

Research for this study started in 2010 during my work as an academic assistant at the Department of Geography at Justus Liebig University Giessen. My first research stay in Georgia at the Ivane Javakhishvili Tbilisi State University in the summer of 2010 was supported by the PROMOS Program of Justus Liebig University Giessen. From April 2011 my PhD studies have been funded by a three-year research grant of the BMBF. As a scholar within the IPSWaT Program I was part of a young scientist network with the common objective of sustainable water development by carrying out scientific research in water related issues. During the scholarship three more research stays in Georgia followed in December 2011, June/July 2012 and June 2013. All study stays promoted the close work cooperation with the Georgian project partners, exchange of knowledge and data with governmental and non-governmental organizations, stakeholders and scientists and fostered the forthcoming of my PhD studies. Moreover, I was part of several climatological, hydrological and geomorphological field studies in the research area Kazbegi, Greater Caucasus. During these field studies I could gather information on Georgia's climate monitoring system, the maintenance of climate stations and posts, climate data documentation and forwarding in urban and rural areas. I also contributed to interdisciplinary field studies on soil temperature measurements, hydrological and geological surveying and Glacier leveling.

This PhD thesis has been embedded into the German-Georgian research project AMIES (Analysing multiple interrelationships between environmental and societal processes in mountainous regions of Georgia). The interdisciplinary research project aims at fostering sustainable land use, land development, and quality of life. The methodological concept of the research project involves the classification of landscape patterns, the analysis of interrelationships between environmental and societal processes under consideration of these patterns, and the formulation of regionally differentiated recommendations for sustainable land use and land development. To gain a better understanding of the complex interrelations between the processes the project is divided into four project units (A to D) including eight subprojects:

Project unit A analyses qualitative and quantitative changes in landscape structure and land use since the 1960s.
Project unit B focuses on climate change and natural hazards. Within this project unit, subproject B1 aims at analysing changes in air temperature, precipitation, climate extreme events, and related socio-economic consequences. Subproject B2 aims at strengthening the understanding of recent mass wasting events and at identifying high-risk zones for future landslides.
Project unit C concentrates on changes in phytodiversity. Indicators of past land-use change, significance of root-soil systems for land erosion, and potentials for land development were investigated at various spatial scales.
Project unit D analyses societal changes at the landscape and regional scale. Project D integrated a household survey at the landscape scale, expert-interviews and focus group discussions at the regional scale and the development of a concept for sustainable tourism activities.

Research in all subprojects is carried out in parallel with interdisciplinary exchange on relationships between environmental and societal processes. The interdisciplinary results represent the basis for the project's recommendations on sustainable land use and rural development.

This thesis is written within subproject B1 of project unit B "Climate Change and Natural Hazards" coordinated by Prof. Dr. Lorenz King. The main objectives of subproject B1 are:

- to quantify changes in mean climate and climate extreme events
- to investigate combined effects of climate change, extreme events and natural hazards, such as heat waves and mass movements
- to assess environmental and societal impacts of climate change and extreme events
- to identify adaptation and mitigation strategies in collaboration with regional stakeholders in Georgia.

This PhD thesis aims to investigate climatology and changes in extreme climate events netween 1961 and 2010. The investigation of changes in the intensity, frequency and duration of heat waves, their patterns and driving forces is a key challenge of this thesis. The main objectives of the thesis are:

1. To update and homogenize daily mean, maximum and minimum temperature and precipitation time series
2. To develop new heat wave indices classifying heat wave severity related to heat-health impacts
3. To investigate the annual and seasonal climatology and changes in temperature extremes over Georgia with a focus on the heat wave intensity, frequency and duration
4. To detect and visualize surface and atmospheric heat wave patterns and their large- to mesoscale driving forces

1.3 Outline

This section sums up the main content of **publication 1** to **4**. The topic, data and temporal resolution of data studied, methodology, climate parameters and indices are also summarized in Table 2.

Publication 1: Trends in daily temperature and precipitation extremes over Georgia, 1971-2010 This study represents an introductory investigation on annual changes of temperature and precipitation means and extremes in Georgia between 1971 and 2010 using selected core climate extreme indices defined by the ETCCDI. Due to missing metadata and a low data coverage in relation to a diverse climatic study area like Georgia, I decided to investigate only homogenous daily minimum and maximum temperature and precipitation series well distributed throughout the study area. The trend analysis comprises linear regression analysis for each station and as arithmetic mean over all stations over Georgia. Additionally, I used standardized anomalies to provide an indication of annual fluctuations and further scientific backup of the decadal trend or tendency calculated. This study is the first attempt to investigate trends on climate extremes over Georgia based on daily data. Trend magnitudes could be quantified for single stations and averaged over Georgia. It could be proven that temperature extremes show significant warming trends averaged over Georgia. Significant and pronounced warming trends are found for the indices: FD, SU, TX90p and TN90p and WSDI, whereas warm and night-time based indices show highest trend magnitudes. Trends on precipitation extremes show insignificant results, but the tendencies for extreme events provide sound evidence that the very heavy and extremely heavy precipitation increases between 1971 and 2010, whereas the number of wet days decreases.

Publication 2: Recent changes in Georgia's temperature means and extremes: Annual and seasonal trends between 1961 and 2010 This publication passes on from the general investigation of climate extremes to temperature extremes, with a focus on seasonal changes of percentile based temperature indices (TN10p, TN90p, TN90p, TX90p). 16 temperature minimum and maximum series are investigated using ETCCDI extreme indices to quantify annual and seasonal trends for the periods 1961-2010, 1971-2010 and 1981-2010. A first set of metadata provided by the National Environmental Agency of Georgia (NEA) helped in homogenizing temperature series using the Software RHtestV3. After detecting the spatial climatology (using the normal period 1961-1990) of Georgia's annual temperature means and selected temperature extremes, seasonal changes are analyzed. The study shows pronounced warming trends for all Georgia-averaged trends, while annual and seasonal trend magnitudes increase towards the most recent period 1981-2010. Most pronounced annual warming trends are measured for all warm extremes (SU, TN90p, TX90p and WSDI) in the southern and eastern lowlands of Georgia, whereas the magnitude of trends for night-time indices is larger than those for daytime. Highest trend magnitudes could be proven for warm temperature extremes in summer. Moreover, 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.

Publication 3: Heat Wave Events over Georgia since 1961: Climatology, Changes and Severity This study ties in with the outstanding trends towards a higher frequency and intensity of summer temperature extremes within the last 50 years as described in the previous publication. Hence, in this publication, I shift my attention to heat wave events over Georgia focusing on their climatology, changes and severity in terms of human health since 1961. Using an extended set of metadata a new dataset of 22 homogenized, daily maximum (Tmax) and minimum (Tmin) air temperature series is developed. In order to identify heat wave events, a well-established heat wave index based on the Excess Heat Factor (EHF) is used, which considers heat-health as a combined measure of excess heat and heat stress. The EHF is studied with respect to eight heat wave aspects: event number, duration, participating heat wave days and peak and mean magnitude. In addition, a severe EHF threshold for each station was calculated empirically as the 85th percentile of the distribution of positive EHF values (EHF85) based on the observation record of each station. As a result, three new aspects have been developed in this study to be able to differentiate between low-intensity, severe and extreme heat waves and their potential heat-health impacts: the number of heat wave days, severe and extreme heat wave days. As a case study, Tbilisi station is chosen to investigate heat wave changes considering the UHI effect. Moreover, all heat wave aspects for the heat wave indices based on the EHF, CTN90p and CTX90p were compared. Trends for all Georgia-averaged heat wave aspects demonstrate significant increases in the number, intensity and duration of low-, severe and high-intensity heat waves. Heat wave trend magnitudes for Tbilisi mainly exceed the Georgia-averages and its surrounding stations, implying UHI effects and synergistic interactions between heat waves and UHIs. Comparing heat wave aspects for EHF, CTN90p and CTX90p, trend magnitudes for CTN90p are largest, while the correlation between the annual time-series was very high among all heat wave indices analyzed. This finding reflects the importance of integrating the most suitable heat wave index into a sector-specific impact analysis.

Publication 4: Severe summer heat waves over Georgia: Trends, Patterns and Driving Forces This publication extends the content of publication 3 in investigating recent climatology, changes of extreme heat waves over Georgia comparing the periods 1961-2010 and 1981-2010. In a first step, climatology and trends for eight heat wave aspects based on the EHF are calculated for the periods 1961-2010 and 1981-2010. The new developed heat wave aspects (see publication 3) are used to classify events in terms of heat-health and to identify the most severe heat wave events. A daily composite analysis is carried out to analyze heat wave patterns over Eurasia regarding the Mean Sea Level Pressure (SLP), Geopotential Height at 500mb (Z500), SST, Zonal (u-wind500) and Meridional Wind at 500mb (v-wind500), Vertical Velocity at 500mb (O500), Outgoing Longwave Radiation (OLR), Relative Humidity (RH500), Precipitation (RR) and Soil Moisture (SM) during major events. To investigate the relationship between heat waves and their potential driving forces a Canonical Correlation Analysis (CCA) is carried out. The five longest and most intense heat waves between 1961 and 2010 are detected in the summers of 2007, 2006, 2001, 1998 and 1995. Largest significantly positive trend magnitudes for the number, intensity and duration of low and high-impact heat waves have been found during the last 30 years. All observed and modeled patterns of the most intense heat waves show very close resemblance. A large positive z500 geopotential height anomaly is detected, which attracts warm air masses from the Southwest, enhances subsidence and surface heating, shifts the African Intertropical Convergence Zone (ITCZ) northwards, and causes a northward shift of the subtropical jet. In addition to the synoptic features triggering heat wave formation and persistence, it is shown that a strong positive anomaly of OLR and soil moisture and precipitation deficiency contributes to the severe heat wave occurence over Georgia.

1.4 Publications and author contributions

Table 1 lists the publications written during the PhD study with their titles, authors and publication details.

Table 1: *Overview of the publications with title, authors, journal and publication status*

Publication no.	Publication details
1	Title: **Trends in daily temperature and precipitation extremes over Georgia, 1971-2010** Authors: Keggenhoff, Ina; Elizbarashvili, Mariam; Amiri-Farahani, Anahita; King, Lorenz Journal: Weather and Climate Extremes, Volume 4, August 2014, Pages 75-85 Status: **published**, Accepted 1 May 2014, Available online since 10 May 2014
2	Title: **Recent changes in Georgia's temperature means and extremes: Annual and seasonal trends between 1961 and 2010** Authors: Keggenhoff, Ina; Elizbarashvili, Mariam; King, Lorenz Journal: Weather and Climate Extremes, Volume 8, June 2015, Pages 34-45 Status: **published**, Accepted 17 November 2014, Available online since 7 January 2015
3	Title: **Heat Wave Events over Georgia since 1961: Climatology, Changes and Severity** Authors: Keggenhoff, Ina; Elizbarashvili, Mariam; King, Lorenz Journal: Climate, Special Issue: Climate Impacts on Health, Volume 3, Issue 2, Pages 308-328 Status: **published**, Accepted 30 March 2015, Available online since 16 April 2015
4	Title: **Severe summer Heat Waves over Georgia: Patterns, Driving Forces and Large-Scale Predictability** Authors: Keggenhoff, Ina; Elizbarashvili, Mariam; King, Lorenz Journal: Earth System Dynamics Status: **under review**

The concept in form and content, the complete research analysis and the writing of all papers were conducted by Ina Keggenhoff. Mariam Elizbarashvili established ties to the NEA, assembled and contributed the observation data and Lorenz King supervised the project. In preparation of **publication 1** Anahita Amiri-Farahani contributed her knowledge and skills in programming and supervised me in using the statistical software “R”. All authors discussed the results and implications of the manuscripts. In order to provide knowledge transfer to the public without financial, legal, or technical barriers, **publications 1** to **4** are published in open access journals.

Throughout the thesis period I could highly benefit from close and continuous work collaboration with the Georgian project partner Dr. Mariam Elizbarashvili, a climate scientist and assistant professor at Ivane Javakhishvili Tbilisi State University, Georgia. This cooperation has been leading to a comprehensive list of further joint publications, conference proceedings, scientific posters and oral presentations listed in Appendix A.

2. Data and methodology

2.1 Data and metadata

Observational data

In the course of data recovery and digitalization the NEA kindly contributed daily temperature and precipitation series and metadata to this study. At the end of 2012, 87 daily mean, minimum and maximum temperature and precipitation series were contributed to our subproject. The lengths of data records vary between 20 and 75 years within the period 1936 to 2010. Mean and extreme climatology over Georgia is studied with respect to the period 1961-1990. The analysis periods 1971-2010 (**publication 1**) and 1961-2010 (**publication 2 to 4**) are chosen to study changes in climate means and extremes under anthropogenic influenced climate conditions as well as to optimize spatial coverage with respect to the number of stations available. As the second set of metadata was provided after **publication 2** was published, the final dataset of homogenized time series over Georgia was used in **publication 3** and **4**. In **publication 1** only homogenous time series were investigated. The metadata includes information regarding the station’s name, coordinates, altitude, WMO code, observational periods, missing data during an observation period, and a station’s relocation date.

Reanalysis data

In **publication 4** reanalysis data was used to detect climatology, spatial and temporal trends for the periods 1961-2010 and 1981-2010. Moreover, it is used to examine the dynamical evolution and surface and atmospheric features associated with heat waves over Georgia using a CCA.

The data used is provided by the National Centers for Environmental Predictions (NCEP), National Center for Atmospheric Research (NCAR) and Kalnay et al. (1996). The NCEP/NCAR reanalysis data contain various climate variables in a global spatial resolution and in a vertical extend from the ground surface to the 10 hPa level. The climate variables are a composite of observations and Numerical Weather Prediction (NWP) model output. The gathered data is quality controlled, assimilated in an Atmospheric Global Circulation

Model (AGCM) and re-analysed by means of a frozen global state-of-the-art AGCM. Every 6 hours the atmosphere model is updated. The records of the used climate parameters are archived in grids of a resolution 1.88º × 1.88º.

2.2 Data quality control and homogenization

Observational data

Data quality control has been carried out using the software RClimDex Software version 1.1 (available at: http://etccdi.pacificclimate.org). Time series with more than 20% missing values within an analysis period were excluded. For the heat wave analysis (**publication 3** and **4**) data records were too sparse for the years 1988, 1992 and 1993 and had to be rejected. Data quality was tested in order to label potentially wrong values, and to reject them from the analysis. Unphysical values, such as Tmax ≥ 70 °C, Tmin ≤ -50 °C, Tmax ≤ Tmin were identified and set to missing values. Outliers were detected and rejected if a daily value exceeds +/- four standard deviation. During the index calculation process the following data quality requirements have been applied: (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.

Observational climate data can be influenced by various non-climatic effects, such as the relocation of weather stations, land-use changes and 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. Inhomogeneity testing and the adjustment of temperature minimum and maximum series were carried out using the software package RHtestV3. It 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, 2010a; Wang, 2010b). It has become a common tool in the WMO CCl/CLIVAR/JCOMM Expert Team training workshops worldwide. In order to detect breakpoints the Penalized Maximal F (PMF) test was applied, which allows the time series being tested to have a linear trend throughout the whole period of data record (Wang, 2008a, b). The PMFred algorithm, which is based on the PMF test, is widely used to test multiple discontinuities in a time series (Alexander et al., 2006; Wan et al., 2010; Vincent 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 algorithm is analyzed using Monte Carlo simulations. In order to provide reliable results, time-series with significant breakpoints not documented in the metadata were excluded from the study. RHtestV3 applies a 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 ten years of data before and after a breakpoint are used to calculate the QM adjustments from the base-minus-reference series. After the adjustment of all breakpoint inhomogeneities, each of the homogenized time series is tested again for breakpoints using the methods described above.

The resulting new high-quality dataset of daily minimum and maximum temperature comprise 22 homogenized Georgian station series and is used in **publication 3** and **4** to study heat wave changes, patterns and their driving forces.

Reanalysis data

In **publication 4** gridded reanalysis data was used to detect climatology, spatial and temporal trends for the periods 1961-2010 and 1981-2010. Moreover, it is used to examine the dynamical evolution and features associated with heat waves over Georgia and Eurasia. In this context the reliability of the NCAP/NCAR temperature data was verified. The NCAP/NCAR reanalysis data covers a period from 1949 until now. As the quality of the reanalysis data is questionable due to data sparseness before 1958, a 50 and 30 year analysis period is chosen (1961-2010 and 1981-2010) for this study. Throughout the analysis, monthly mean data for summer months (May to September) are employed. Moreover, temperature data was verified correlating the reanalysis data with the instrumental observation data (Pearson correlation). Between 1961 and 2010 the mean summer temperature for the field 40.9-43.7°N/39.9-46.9°E correlates very well with the mean temperature (r: 0.76) from the observational data. For Tmax and Tmin the correlation coefficient measures 0.67 and 0.77, respectively.

2.3 Climate Extreme Indices and the Excess Heat Factor

All indices applied in the studies are recommended by the ETCCDI of the WMO CCI, which defined 27 core climate extreme indices. The ETCCDI indices 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). In 2011, a new “core set” of 34 descriptive sector-specific indices has been defined by the WMO CCl Expert Team on Climate Risk and Sector-specific Climate Indices (CRSCI) to improve decision-making for planning, operations, risk management and for adaptation to both climate change and variability. These internationally agreed indices were developed in part from the core set of indices developed and maintained by the ETCCDI. The new core set of indices provide nine additional indices, such as five heat wave indices, to facilitate the use of climate information in users’ decision-support systems for climate risk management and adaptation strategies (Alexander et al., 2013). Annual and monthly station values for indices have been calculated using the software RClimDex 1.1. The heat wave analysis is carried out using the ClimPACT software. In **publication 2**, temperature extreme 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. Heat wave indices have been calculated for the summer season (May to September) only.

Several approaches can be used to define heat waves. In past studies heat wave indices are defined by temperature exceeding a fixed or percentile threshold for a given period, consider maximum or minimum temperature and focus on consecutive or single days where defined conditions above the threshold persist (Meehl and Tebaldi, 2004; Alexander et al., 2006; Kuglitsch et al., 2010; Fischer et al., 2011). However, a common definition of heat waves in scientific literature does not yet exist. The EHF is used in **publication 3** and **4** to define heat wave as a period of at least three days with a positive EHF value. Besides, two indices based on the CTX90p and CTN90p have been investigated in **publication 3** to compare trends in heat wave characteristics for temperature minimum and maximum series separately. The different indices selected for the analyses in **publications 1** to **4** are listed in Table 2.

The EHF combines a measure of excess heat, the deviation from long term mean temperature, calculated with respect to the period 1961-1990, to take into account local geographic acclimatization, and heat stress, the deviation in temperature from mean temperature for the previous 30 days to measure short-term acclimatization. EHF values are calculated from a three-day mean of forecast temperatures to derive an index of heat wave intensity. Two sub-indices are combined to produce the complete EHF index. The first is a measure of significant excess heat relative to local climatic conditions, the 95th percentile of mean temperature conditions (EHFsig):

$$EHI_{sig} = (T_i + T_{i+1} + T_{i+2})/3 - T_{95}\ , \quad (1)$$

The second sub-index is a measure of short-term acclimatization to heat, relative to the mean temperature of the previous 30 days (EHFaccl):

$$EHI_{accl} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \ldots + T_{i-30})/30\ , \quad (2)$$

These two indices are combined to generate the EHF index. The unit of EHF is °C^2:

$$EHF = EHI_{sig} \times max\ (1, EHI_{accl}) \quad (3)$$

The importance of including minimum temperature through the average daily temperature is stated in Pattenden et al. (2003) and Nicholls et al. (2008), highlighting that overnight heat load determines the accumulating thermal load impacting vulnerable people and systems. Moreover, EHF incorporates the effect of humidity on heat tolerance indirectly by using the mean, rather than the maximum daily temperature.

Heat waves are defined as a period of at least three days with EHF ≥ 0 and the combined effect of excess heat and heat stress with respect to the local climate (Nairn and Fawcett, 2013). The heat wave index EHF was selected with regards to heat wave aspects quantifying the intensity, frequency and duration of a heat wave event. This multi-aspect framework is based on that of Fischer and Schär (2010), which was slightly extended by Perkins et al. (2012) to the following five heat wave aspects: HWN – the yearly number of heat waves, HWD – the length (in days) of the longest yearly event, HWF – the sum of participating heat wave days per year HWA – the hottest day (amplitude) of the hottest yearly event and HWM – the mean event intensity averaging all participating event days.

In terms of heat-health, low values of EHF may be considered as uncomfortable and have no or only little impact. Severe heat wave impacts on heat-health are relatively rare, due to the local adaption capacity of the affected population based on the long-term experience to cope with heat waves of low to moderate intensity. Extreme heatwave events have been examined using the EHF regarding major heat wave events in different cities, such as Sydney, Paris, Moscow and Chicago (Nairn, 2011). To classify the severity of heat wave events a severe EHF threshold for each station has been applied. It is calculated empirically as the 85th percentile of the distribution of positive EHF values (EHF_{85}) based on the observation record at a given location. Using the example Tbilisi station, figure 6 presents calculated EHF values for Tbilisi station and its severity threshold.

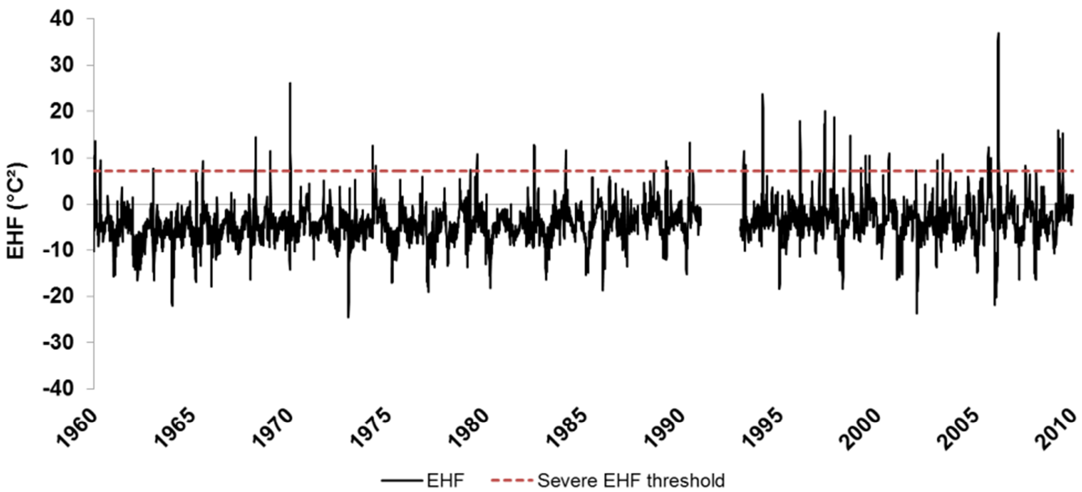

Figure 5: *Determining EHF_{85} and severe heat wave days for Tbilisi station record (1961-2010): Tbilisi EHF values between 1961 and 2010 (black) with Tbilisi severity threshold (dashed, red)*

This method ensures that all EHF values are truly representative of each site's climatology and avoids potential errors by modeling a distribution. Extreme heat waves are defined as an event where EHF values are well in excess of the severity threshold and result in a wide impact based on a cascade of failing systems (Nairn and Fawcett, 2013). In **publication 3** extreme heat waves occur if an EHF value during a heat wave at least doubles the severity threshold ($EHF \geq 2 \times EHF_{85}$). According to (Nairn et al., 2015) heat waves are classified as extreme events, if an EHF value during an event at least triples the severity threshold ($EHF \geq 3 \times EHF_{85}$). This new classification is applied in **publication 4**.
In order to make the heat wave analysis applicable to the assessment of human health impacts, three new heat wave indices have been added to the analysis by applying the station-specific EHF_{85} severity threshold to each time-series:

- HWday – the number of heat wave days,
- HWsev – the number of severe heat wave days and
- HWex – extreme heat wave days.

Heat-health related morbidity and mortality based on the EHF have been investigated in various studies (Perkins et al., 2012; Perkins and Alexander, 2013; Langlois et al., 2013; Wilson et al., 2013; Nairn et al., 2015). These new heat wave indices include the aspect of heat-health considering the exceedance of a station's severe EHF threshold and enable to differentiate between heat waves of low heat-health severity, severe and extreme heat waves (Nairn and Fawcett, 2013; Nairn et al., 2015). Following Nairn et al. (2015), extreme single heat waves are classified in heat wave classes (HW class), depending on the difference between the maximum EHF value of heat wave and the respective station's severe threshold. If a station's EHF value is 2 to 3 times the severe threshold it is classified as HW class 2, a station's EHF value is labelled HW class 6, if it is 6 to 7 times higher, than the station's severe EHF threshold.

Table 2: *Overview over each publication's content, data and climate extreme indices used*

Publication no.	Topic	Geographical Focus	Data	Timely resolution	Analysis periods	Climate Extreme Indices
1	Changes in extreme temperature and precipitation	Georgia	daily station	annual	1971-2010	FD, ID, TN10p, TX10p, TNn, TXn, SU, TR, TN90p, TX90p, TNx, TXx, WSDI, CSDI PRCPTOT, R1mm, R10mm, R20mm, R95p, R99p, Rx1day, Rx5day, CWD, CDD, SDII
2	Climatology and changes in extreme temperature	Georgia	daily station	annual and seasonal	1961-1990, 1961-2010, 1971-2010, 1981-2010	FD, TN10p, TX10p, SU, TN90p, TX90p, WSDI
3	Climatology, changes and heat-health severity of heat waves	Georgia, Tbilisi	daily station	annual, summer (May-September) and monthly	1961-2010	HWN, HWD, HWF, HWA, HWM, HWday, HWsev and HWex based on the EHF, CNT90p or CXT90p based on Tmin or Tmax
4	Severe heat wave identification, changes, patterns and driving forces	Eurasia, Georgia	daily station and daily and monthly reanalysis data	annual, summer (May-September), daily	1961-2010, 1981-2010	HWN, HWD, HWF, HWA, HWM, HWday, HWsev and HWex based on the EHF

2.4 Trend estimation

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 a trend was considered to be statistically significant if it was less than or equal to a level of 5% (Mann, 1945 and Kendall, 1975). Trends have only been calculated for an index if less than 20% of the annual values were missing. In **publication 1**, least-squared linear trends were calculated with respect to a 1971-2000 reference period for averaged anomaly series for each index, to provide an indication of annual fluctuations and for further scientific backup of the decadal trend calculated. In compliance with New et al. (2006) the anomaly series were standardized by dividing them by the standard deviation of the respective station to avoid the average series being dominated by stations with high values and to make stations more comparable given the diverse climatic conditions in Georgia. The 10-year moving average was also used to show the annual variation of climatic extremes within the analysis period.

2.5 Canonical correlation and composite analysis

The statistical relationship between predictor and predictand variables usually is a linear regression relationship. In order to investigate the relationship between Georgian summer heat waves and synoptic to meso-scale patterns over Eurasia, a CCA was performed in **publication 4**. CCA is a common multivariate statistical technique in meteorological and climate science to find linear combinations of two sets of variables such that the linear combinations have the maximum possible correlation (Barnett and Preisendorfer, 1987; Bretherton et al., 1992; Cherry, 1996). The maximization is carried out under orthogonality constraints on the coefficients of the linear combinations. CCA has been used in various studies (e.g. Xoplaki et al., 2003a, b, Haylock and Goodess, 2004, Luterbacher et al., 2009). During data preparation monthly mean anomalies are calculated by subtracting the long-term mean of a calendar month from each individual monthly mean, giving all grid points equal weight. Moreover, a long-term linear trend in the time series is removed. Using Principal Component Analysis (PCA) the predictor and predictand were dimensionally reduced to a number of selected Principal Components (PCs) in order to identify the dominant patterns of variability in each field that account for the most variance (Bretherton et al. 1992, Mo and Straus 2002). Both, the CCA and PCA were performed using a Singular Value Decomposition (SVD). The correlation of the canonical score series of the two variables measures the intensity in the relationship between the pairs. In this study, the 95th percentile of mean temperature (Tmean95p) is used as heat wave predictand derived from daily NCEP/NCAR reanalysis data. It includes both, daily minimum and maximum temperature series and incorporates the effect of humidity on heat tolerance indirectly, by using the mean, rather than the maximum daily temperature, in the calculation. The 95th percentile threshold was chosen as a measure of extreme heat. Data availability ensures a high number of heat days per summer month. As predictors summer SLP, Z500, u-wind500, v-wind500, O500, RH500, OLR, RR and SM were used based on gridded NCEP/NCAR data. The CCA was performed using the KNMI Climate Explorer (available online at http://climexp.knmi.nl). The research domain for the predictors is defined as the area between 0 and 90°E and between

10 and 80°N. The predictand variable focuses on Georgia with the domain located at 39.9° to 46.9°E and 40.9° to 43.7°N. Features in the daily composite anomaly plots take into account the physical realism as they are based on observation data, whereas the derived CCAs are statistically built. To examine the observed features associated with the CCA patterns, daily composite plots are conducted, since the CCA may yield unstable solutions (Della-Marta et al., 2007b). Daily composites are constructed for the heat wave predictand and the ten selected predictors based on the 16 major heat wave days observed over Georgia (see Appendix, **publication 4**).

3. Conclusions and outlook

This PhD thesis contributes to a better understanding of

- The climatology and changes in extreme precipitation and temperature events
- Heat-health severity and impacts of summer heat waves
- Patterns and key mechanisms initiating and amplifying summer heat waves

3.1 Climate data quality control and homogenization

Well established methods for quality control, break detection and correction techniques have been used to develop a high-quality homogenized daily maximum and minimum temperature dataset. For the first time more than 80 Georgian instrumental time series have been quality controlled, homogenized and used for analyzing climate extremes between 1961 and 2010. This thesis shows that the majority of the time series consists of low quality data. It contains many and long data gaps, which mainly occur during 1988 and 1991 to 1993, due to political crisis situations in the study area. Also the metadata only consists in Georgian language and does not correspond with official standards. As the full metadata set was provided after the **publication 2** has been published, the final dataset of homogenized time series over Georgia is used in **publication 3** and **4**. 49 raw data series cover the analysis period 1961 to 2010. 37% of the raw data series had to be rejected; leaving 31 minimum and maximum temperature series matching all quality criteria. The break detection analyses show that 23% of both, temperature minimum and maximum series are affected by seven significant breakpoints, whereas not more than one breakpoint per maximum or minimum time-series was detected. Metadata with information about artificial breakpoints could be used to homogenize two daily temperature minimum and maximum series. Finally the resulting homogenized daily temperature dataset comprise minimum and maximum temperature series from 22 stations (equals 45%) for the analysis period 1961 to 2010 (Keggenhoff, 2015a, b).

3.2 Heat wave indices

In order to make the trend analysis for summer heat waves applicable to the assessment of the magnitude of possible human health impacts, three new heat wave indices have been added to the analysis by applying a severity threshold to each time-series: (1) HWday – the number of heat wave days, (2) HWsev – the number of severe heat wave days and (3)

HWex – extreme heat wave days. The severe EHF threshold is calculated empirically as the 85th percentile of the distribution of positive EHF values (EHF_{85}) based on the observation record at a given location. This method ensures that all EHF values are truly representative of each site's climatology and avoids potential errors by modeling a distribution. The new indices enable the identification of changes in heat wave days of different magnitudes of potential heat-health impacts. Changes in summer heat wave, severe and extreme heat wave days are not only detected over Georgia, but also at Tbilisi, Georgia's main capital.

3.3 Extreme temperature events over Georgia

Keggenhoff et al., (2014) detected for the first time recent annual changes in extreme temperature and precipitation over Georgia based on a homogenized set of instrumental observation data. **Publication 1** shows, that for most of the extreme temperature indices significant warming trends are detected in the Georgia-average. In 2010 there are 13.3 fewer frost days than in 1971, while there are 13.6 more summer days and 7.0 more tropical nights. A large number of stations show significant warming trends for cold and warm days and nights throughout the study area, whereas warm extremes and night-time based temperature indices show larger trends than cold extremes and daytime indices. Additionally, the warm spell duration indicator indicates a significant increase in the frequency of warm spells between 1971 and 2010. The trend per decade averaged over Georgia for TN10p measures -1.0 days/decade. For TX10p a warming trend at a rate of -0.8 days/decade can be observed. The trend per decade in the Georgia-averaged TN90p amounts to 1.9 days/decade, whereas TX90p accounts for 1.2 days/decade. The mean trend over Georgia for WSDI is considerably positive at a rate of 1.7 days/decade. All warm percentile extremes show higher trend magnitudes than those for cold extremes, implying "asymmetric" changes in lower- and upper-tail extremes causing a rising temperature variance. Although all extreme precipitation indices indicate an increasing number and more heavy precipitation events over Georgia during 1971-2010, the changes were not statistically significant. At the same time R1mm decreased. **Publication 2** reveals pronounced warming trends for all trends in temperature means and extremes over Georgia since 1961 (Keggenhoff et al., 2015a). Comparing trend magnitudes between the analysis periods 1961-2010, 1971-2010 and 1981-2010 an increase towards the most recent period is observed. 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 are evident, whereas warm extremes show larger trend magnitudes than cold extremes as observed in **publication 1**. The most pronounced trends are determined for summer days (6.2 days/decade) and the warm spell duration index (5.4 days/decade) during 1981 and 2010. Regarding seasonal changes in temperature means and extremes largest trends are observed for temperature maximum in summer. 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). Strongest significant trends in temperature extremes are identified during 1981 and 2010 for warm days (5.6 days/decade) in summer. In **publication 3**, Keggenhoff (2015b) detects mean climatology for selected summer heat wave indices across the study area, which shows highest values for the heat wave duration, frequency and the number of heat wave days in the Southeast of Georgia. Regarding changes in heat wave events almost all heat wave indices analyzed based on the EHF show significant increasing trends in the Georgia-average. HWday and HWF show by far the largest trend magnitudes across all heat wave indices studied, implying that occurrence-based heat wave aspects possess larger trend magnitudes and drive increases in HWN and HWD, due to the fact that the overall number of heat waves (and their duration) will increase when the number of participating days increases (Perkins et al., 2012; Perkins and Alexander, 2013). Tbilisi station experienced a pronounced increase in the intensity, frequency and duration of heat waves during 1961 and 2010 compared to the Georgian-average and its neighboring stations. Including the strong increase in extreme warm night-time temperatures, these results could be explained by the UHI effect. The most severe summer heat waves in Tbilisi have been identified in the years 1971, 1995, 1997, 1998 and 2007. Comparing the heat wave indices based on CTN90pct and CTX90pct, it is shown, that all trends for night-time based events over Georgia increase faster than for day-time events. These findings highlight the importance of selecting the appropriate index related to the most affected sector investigated.

3.4 Heat wave patterns and driving forces

Publication 3 and **4** reveal a pronounced increase in the trend magnitudes for summer heat wave intensity, frequency and duration between 1961 and 2010. During 1981 and 2010 a trend of 0.8 events/decade for HWN and 1.8 days/decade for HWD could be found. Trends for these heat wave aspects double the trend magnitudes measured between 1961 and 2010. For HWF (and HWex), the trend magnitudes of 6.6 days/decade (0.15 days/decade) for 1981 and 2010 are two to three times higher than the trend magnitudes observed between 1961 and 2010. Spatial patterns of trends over Georgia are difficult to assess, which can be attributed to the low data quality and availability. It is also notable that the linear trend magnitude for all heat wave aspects between the analysis period 1981 and 2010 at least double, compared those during 1961 and 2010, implying that more intense and longer heat waves can be expected in future. **Publication 4** focused on a CCA and composite analysis to investigate recent summer heat wave patterns and their relation to the selected atmospheric and thermal predictors over Eurasia: Mean Sea Level Pressure, Geopotential Height at 500mb, Sea Surface Temperature, Zonal and Meridional Wind at 500mb, Vertical Velocity at 500mb, Outgoing Longwave Radiation, Relative Humidity at 500mb, Precipitation and Soil Moisture. Daily composites were conducted for the 16 most intense heat wave days over Georgia between 1961 and 2010. The CCA was performed based on the heat wave predictand Tmean95p over Georgia. CCA is a statistical technique to find spatial patterns of fields with a maximum correlation. The study showed that all composite and CCA patterns have a very close resemblance, which verifies both, the composite analysis based on observations and the statistical CCA. A heat wave study investigating heat wave patterns and predictability over Georgia has been performed for the first time. The analysis detected increasing SAT anomalies over Georgia from West to East. The slight SST anomalies over the Black and Caspian Sea imply no preferred SST pattern inducing heat waves, but that they might reinforce events. The large increase in SSTs in the Barents and Kara Sea during major heat waves over Georgia in combination with a reduction of the meridional gradient and a decrease of baroclinicity amplifies the northward shift of the subtropical jet, allowing the expansion of the blocking high over the Southern Ural. This large anticyclonic pattern is represented by a large positive anomaly of Z500 over the area. Moreover, severe heat waves over Georgia are attributable to negative SLP anomalies over Southern Scandinavia and the Red and Black Sea area and positive SLP anomalies over western Asia. These surface and mid-tropospheric anticyclonic patterns observed (1) block westerlies, (2) attract warm air masses from the Southwest, (3) enhance subsidence and surface heating, (4) shift the African ITCZ northwards, leading to a northward shift of the descending branch of the Hadley cell, and (5) cause a northward shift of the subtropical jet. The regional effects of the persistent blocking are closely related to both, the large- to meso-scale circulation and the local orography of Georgia. The study revealed that Eastern Georgia is mainly influenced by low warm and dry wind flows, subsidence and surface heating due to clear skies, atmospheric stability and maximum insolation, implied by positive anomalies of O500 and OLR and negative RH500, SM and RR patterns over the area. However, during major heat wave events western Georgia is affected by anomalous strengthened wind speed and warm and moist air. These anomalous southwesterly dry winds from Northeast Africa across the Eastern Mediterranean collect moist over the Mediterranean and Black Sea and lead to atmospheric instability and convective rainfall, reflected by negative anomalies for O500 and positive Vector Wind at 500mb (VW500) and RR anomalies over the area. Precipitation might be amplified by the pronounced soil dryness observed throughout Georgia, which induced atmospheric instability and enhanced air humidity and cooling due to meso-scale circulations over mountainous and coastal areas (Stefanon et al., 2013). Moreover, heat waves over Georgia are attributable to reduced soil moisture across the whole territory of Georgia, implying adjacent precipitation deficiency for a prolonged period (Haarsma et al., 2009). This assumption was verified by precipitation and soil moisture composites for a 20 day-period prior to the detected major summer heat wave events over Georgia. The contribution of lagged precipitation and soil moisture depletion to heat wave events over Georgia will be investigated in more detail in a further study. Observed changes show that all relevant circulation, radiation and soil moisture patterns contributing to heat waves have been intensified between 1961 and 2010. Tmean95p over Georgia and SSTs over the Black and Caspian Sea showed significant warming trends. Largest trends for SSTs are found in the Northern Atlantic and the Kara Sea. Changes in large-scale circulation and radiation patterns reflect a significant increase in surface and mid-troposphere pressure and surface heating throughout Western Asia, while for relative humidity, precipitation and soil moisture significant decreasing trends could be found. Most pronounced trends were observed over Southeast Georgia, implying increasing soil dryness over the area. Based on the fact that surface and mid-troposphere pressure, surface radiation and soil dryness intensified significantly over the study area during the last 50 years, it is likely that Georgia will be exposed to more and longer severe heat waves in future.

3.5 Outlook

Until today Georgia is subject to numerous political, financial and institutional barriers in implementing a proper climate data monitoring system, including limitations on funding, technology and human resources. Digitized high-quality instrumental climate data and metadata and their recovery are fundamental to enhance the understanding of climate change and climate extreme events in Georgia. Since 1991, the number of meteorological stations in Georgia shrank rapidly and the lack of station maintenance due to political instability caused large measuring gaps. From 1991 to the present the number of meteorological stations and posts has fallen from 200 to around 60 (World Bank, 2006). Currently 13 meteorological stations and 20 meteorological posts measuring daily temperature minimum and maximum and precipitation are working on the territory of Georgia (Elizbarashvili et al., 2013). During the last decades Georgia made great efforts in data recovery and transparency, extending the meteorological monitoring system. However, data research in preparation of this study shows, that less than half of the Georgian climate data records are digitalized. Also metadata is not yet officially standardized and misses detailed information on station histories. In the institutional archives there is still instrumental climate data, metadata and data on climate extreme events to be recovered and digitized. As member of the Mediterranean Climate Data Rescue (MEDARE) initiative, and other international initiatives working on instrumental data recovery, Georgia sets particular emphasis on the improvement of data availability since the last decade.

Heat waves belong to the most severe natural disasters causing serious impacts on various sectors, such as human health, agriculture and ecosystems. Summer heat waves are responsible for increasing human and economic losses in Georgia (MOE, 2009). In order to relate documentation on past heat wave events and their impacts to the identified heat wave events in this study (Keggenhoff, 2015b) it is necessary to have detailed documented information on those events. However, information on past heat wave events and their impacts on human health are not available for Georgia. Currently there are a few international initiatives on this topic, such as the International Disaster Database (EM-DAT) by the Epidemiology of Disasters (CRED) and the World Health Organization Statistical Information System (WHOSIS), which incorporate information on human losses caused by droughts and floods in Georgia, but lack of recorded heat wave events.

Research on future climate modelling is based on instrumental data. Regarding climate scenarios it would be challenging to develop future heat wave predictions using the new homogenized dataset for model calibrations. In **publication 3** and **4** a new dataset of 22 daily maximum and minimum temperature series including homogenized series is presented. Data homogenization is needed to optimize data availability and spatial coverage. This issue is particularly important in regions with a highly diverse climate and orography. So far, the application of relative homogenization methods to climate series from spatially exposed stations affected by the different physiographic and climatic conditions across Georgia is not possible and requires more stations, a higher quality of data and methodological improvements.

Appendix A: Further publications during the PhD

Peer-reviewed Scientific Papers, published

Elizbarashvili, E. Sh., Kutaladze, N.B., **Keggenhoff, I.**, Elizbarashvili, M.E., Kikvadze, B.M., and Gogia, N.M.: Climate Indices for the Moistening Regimen in the Territory of Georgia amidst Global Warming, European Researcher, 66, 102, 2014.

Elizbarashvili, E. Sh., Elizbarashvili, M.E., Kutaladze, N.B., **Keggenhoff, I.**, Kikvadze, B.M., and Gogiya, N.M: Geography and dynamics of some temperature indices for assessing the climate change in Georgia, Russian Meteorology and Hydrology, 40, 39-45, 2015.

Scientific Reports

Elizbarashvili, M., Schaefer, M., **Polenthon, I.**, Gogatishvili, N., Keller, T., Gogia, N., and King, L.: Current Trends of Climate Change in the Kazbegi Region, Greater Caucasus, Georgia, Proceeding of the International Multidisciplinary Scientific GeoConference & EXPO – SGEM (Surveying Geology & mining Ecology Management) 2011, Sofia, Bulgaria, 2011.

Gobejishvili, R., King, L., Lomidze, N., Keller, T., Tielidze, L., and **Polenthon, I.**: Relief and geodynamic Processes of High Mountainous Region of Caucasus (Stepantsminda region), Proceeding of the I. International Scientific Conference “Environment and Global Warming 2011”, Tbilisi, Georgia, 2011.

Keller, T., Gaprindashvili, G., Gobejishvili, R., **Keggenhoff, I.**, Elizbarashvili, M., Kalandadze, B., Lomidze, N., and King, L.: Natural hazards in the Great Caucasus range on the background of climate change - risk maps for the Kazbegi and Mleta areas (Georgia), Geophysical Research Abstracts, EGU2013-6093, EGU General Assembly 2013, Vienna, Austria, 2013.

Keggenhoff, I., Elizbarashvili, M., Anahita-Farahani, A., and King, L.: Recent trends in extreme precipitation over Georgia, 1936-2010, Proceeding of the 4th International Geosciences Student Conference, Berlin, Germany, 2013.

Elizbarashvili, M., D., Mikava, B., Kikvadze, N., Gogia, **I., Keggenhoff**, N., Kutaladze, and Managadze, M.: Temperature Indices of Climate Change in Georgia, Proceeding of the International Multidisciplinary Scientific GeoConferences, 14th GeoConference on Energy and Clean Technologies, Sofia, Bulgaria, 2014.

Elizbarashvili, M., N., Gogia, D., Mikava, **I., Keggenhoff**, B., Kikvadze, N., Kutaladze, and Managadze, M.: The Temporal and Spatial Structures of Temperature Indices of Climate Change over Georgia, Proceeding of the ICERE 2014 – International Conference on Environment and Renewable Energy, Paris, France, 2014.

Keggenhoff, I., Elizbarashvili, M., Anahita-Farahani, A., and King, L.: Summer Heat Waves over Georgia between 1961 and 2010: Climatology, Changes and Large-Scale Patterns, Proceeding of the International Scientific Conference “Modern Problems of Geography and Anthropology”, Tbilisi, Georgia, 2015.

Selected Conference Contributions

Polenthon, I., Keller, T., and King, L.: The impacts of climate and land use change on runoff variability and slope processes in the Tergi and Aragvi catchments, Greater Caucasus (Georgia), AK Geomorphologie Jahrestagung 2010, Frankfurt, Germany, 2010. POSTER

Polenthon, I., Keller, T., and King, L.: Auswirkungen von Klimawandel und Landnutzungsänderung auf die Abflussvariabilität und Hangstabilität in Kazbegi, Großer Kaukasus (Georgien), 1. Workshop Klimafolgenforschung, 2011, Giessen, Germany, 2011. POSTER

Keggenhoff, I., Elizbarashvili, M., and King, L.: Spatial and temporal trends of Climate Extreme Indices in the Caucasus Region, International Geographical Congress (IGC) 2012, Cologne, Germany, 2012. POSTER

Keggenhoff, I., Elizbarashvili, M., Anahita-Farahani, A., and King, L.: Recent trends in extreme precipitation over Georgia, 1936-2010, 4th International Geosciences Student Conference, Berlin, Germany, 2013. POSTER

Keggenhoff, I., Elizbarashvili, M., Anahita-Farahani, A., and King, L.: Changes in extreme temperature and precipitation over Georgia, 1936-2010, International Workshop “Extreme Weather and Climate Events in the Southern Caucasus - Black Sea Region”, Tbilisi, Georgia, 2013. ORAL PRESENTATION

Keggenhoff, I., Elizbarashvili, M., Anahita-Farahani, A., and King, L.: Summer Heat Waves over Georgia between 1961 and 2010: Climatology, Changes and Large-Scale Patterns, International Scientific Conference "Modern Problems of Geography and Anthropology", Tbilisi, Georgia, 2015. ORAL PRESENTATION

Appendix B: Supervised theses

Weishaupt, S.: Hydrologische Modellierung von Teileinzugsgebieten des Aragvi, Georgien, mittels HEC-HMS. Bachelor thesis, Justus Liebig University Giessen, Department of Geography, 2011.

Miether, S.: Starkregentrends und Hochwasserrisiko im Oberen Tergi- und Aragvi-Einzugsgebiet – Großer Kaukasus, Georgien. Bachelor thesis, Justus Liebig University Giessen, Department of Geography, 2011.

Eisenwinder, M.: Das weltgrößte Wasserkraftwerk: Ziele und Gefahren des Dreischluchten-Staudamms – Fakten und ihre Darstellung in chinesischen und deutschen Medien. Staatsexamen L3, Justus Liebig University Giessen, Department of Geography, 2011.

Appendix C: Study and field research

06/2013 **Two-week study stay and workshop visit** "Extreme Weather and Climate Events in the Southern Caucasus - Black Sea Region" at Ilia State University in Tbilisi, Georgia funded by IPSWaT/BMBF

06-07/2012 **Two-month field research stay** in Mleta, Georgia (Greater Caucasus) funded by IPSWaT/BMBF

12/2011 **Two-week research stay**, Ivane Javakhishvili Tbilisi State University in Georgia funded by IPSWaT/BMBF

09/2011 **One-week summer school** "R+OSGeo in higher education", Faculty of Civil Engineering, University of Belgrade, Serbia

07/2011 **One-week summer school** "Geographic Information Systems and Water Resources Management" at Cologne University of Applied Sciences, Germany funded by IPSWaT/BMBF

06-07/2010 **Two-month study and field research stay** at Ivane Javakhishvili Tbilisi State University and in Kazbegi, Georgia (Greater Caucasus) funded by Program for German Students in Post Graduate Courses Related to Development Cooperation (PROMOS), German Academic Exchange Service (DAAD)

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Trends in daily temperature and precipitation extremes over Georgia, 1971-2010

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Abstract

Annual changes to climate extreme indices in Georgia (Southern Caucasus) from 1971 to 2010 are studied using homogenized daily minimum and maximum temperature and precipitation series. Fourteen extreme temperature and 11 extreme precipitation indices are selected from the list of core climate extreme indices recommended by the World Meteorological Organization – Commission for Climatology (WMO-CCL) and the research project on Climate Variability and Predictability (CLIVAR) of the World Climate Research Programme (WCRP). Trends in the extreme indices are studied for 10 minimum and 11 maximum temperature and 24 precipitation series for the period 1971-2010. Between 1971 and 2010 most of the temperature extremes show significant warming trends. In 2010 there are 13.3 fewer frost days than in 1971. Within the same time frame there are 13.6 more summer days and 7.0 more tropical nights. A large number of stations show significant warming trends for monthly minimum and maximum temperature as well as for cold and warm days and nights throughout the study area, whereas warm extremes and night-time based temperature indices show greater trends than cold extremes and daytime indices. Additionally, the warm spell duration indicator indicates a significant increase in the frequency of warm spells between 1971 and 2010. Cold spells show an insignificant increase with low spatial coherence. Maximum 1-day and 5-day precipitation, the number of very heavy precipitation days, very wet and extremely wet days as well as the simple daily intensity index all show an increase in Georgia, although all trends manifest a low spatial coherence. The contribution of very heavy and extremely heavy precipitation to total precipitation increased between 1971 and 2010, whereas the number of wet days decreases.

1. Introduction

The globally averaged surface temperature data shows a linear warming trend of 0.85 °C [0.65 to 1.06 °C] during the period 1880-2012. The total increase between the average of the 1850-1900 period and the 2003-2012 period is 0.78 °C [0.72 to 0.85 °C], based on the single longest dataset available (IPCC, 2013). Climate extremes receive much attention as trends in extreme events react more sensitively to climate change than mean climate, and therefore have a more intense impact on natural and human systems. (Katz and Brown, 1992, Easterling et al., 1997, Easterling et al., 2000, Kunkel et al., 1999, New et al., 2006, IPCC, 2007 and Aguilar et al., 2009). The IPCC (2012) stated that there is a high confidence economic losses from weather- and climate-related disasters have 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, whereas the highest fatality rates and economic losses caused by hydro-meteorological induced disasters are registered in developing countries. On a global scale, temperature indices demonstrate a significant warming during the 20th century, citing the highest trends for the most recent periods and for minimum temperature indices. However, trends in extreme precipitation illustrate a much lower spatial coherence, yet on a global scale a significant wetting trend could be detected, whereas the number of consecutive dry days shows very different regional changes (Frich et al., 2002 and Alexander et al., 2006). Since the 1990s, various regional studies pertaining to temperature and precipitation extreme indices have been conducted which provide strong evidence that global warming is related to significant changes in temperature and precipitation extremes. (Zhang et al., 2000, Manton et al., 2001, Peterson et al., 2002, Aguilar et al., 2005, Griffiths et al., 2005, Zhang et al., 2005b, Haylock et al., 2006, Klein Tank et al., 2006, Alexander et al., 2006 and Skansi et al., 2013). Climate extreme indices have also been computed and analyzed for projected future climate conditions based on simulations by Global Climate Models (GCMs) (Sillmann et al., 2013a, Sillmann et al., 2013b, Russo and Sterl, 2011, Tebaldi et al., 2006, Alexander and Arblaster, 2009, Kharin et al., 2007 and Orlowsky and Seneviratne, 2012). Extreme precipitation and extreme warm temperature are both predicted to increase while extreme cold temperatures will become more moderate. The results also suggest that climate models cannot overcome uncertainties for projecting future changes in extreme events, especially concerning the regional scale with complex physiographic conditions. For that reason, analyzing changes in extreme climate events based on observation data is essential. Developing and transition countries such as Georgia face a number of political, financial and institutional barriers for a proper climate data monitoring system, including limitations on funding, technology and human resources (Page et al., 2004). After the collapse of the Soviet Union in the early 1990s the number of meteorological stations in Georgia rapidly decreased and the lack of station maintenance caused large measuring gaps. The quality and quantity of accessible climate series still limit our understanding of the observed changes in climate extremes in Georgia. So far, studies on changes in climate and climate extremes have been carried out based on monthly temperature data and associated weather and climate phenomena, such as drought, hurricanes and frost (Elizbarashvili et al., 2007, Elizbarashvili et al., 2009, Elizbarashvili et al., 2011 and Elizbarashvili et al., 2012). Elizbarashvili (2013) discovered that the frequency of extremely hot months during the 20th century increased, especially over Eastern Georgia, whereas extremely cold months decreased faster in the Eastern than in the Western region. In addition, highest rates for positive trends of mean annual air temperature can be observed in the Caucasus Mountains. The aim of this study is to provide a better understanding of recent changes in the variability, intensity, frequency and duration of climate extreme events across Georgia by investigating trends in selected daily temperature and precipitation extreme indices between1971 and 2010 using the software RClimDex 1.1 (Zhang and Yang, 2004). This is achieved by calculating a set of 25 ETCCDI climate extreme indices from homogenous daily weather data and estimating linear trends. Standardized anomalies of those trends are also investigated. The indices of temperature and precipitation extremes considered in the present study are recommended by the Expert Team on Climate Change Detection Indices (ETCCDI). Section 2 of the current study describes the study area, the quality criteria of the data selection, quality control, homogenization, the climate extreme indices and the analytical methods used in this study. Section 3 presents and discusses the observed regional trends for the analysis period 1971-2010 as averaged regional trends from anomalies and regional trends per decade for each index. Section 4 summarizes the conclusions.

2. Data and methods

2.1 Study area

Georgia is located in the Southern Caucasus between 41 and 44°N and 40 and 47°E and covers an area of 69.700 km² (Fig. 1 and Fig. 2). It borders Russia to the North, Azerbaijan to the Southeast and Armenia and Turkey to the South. 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).

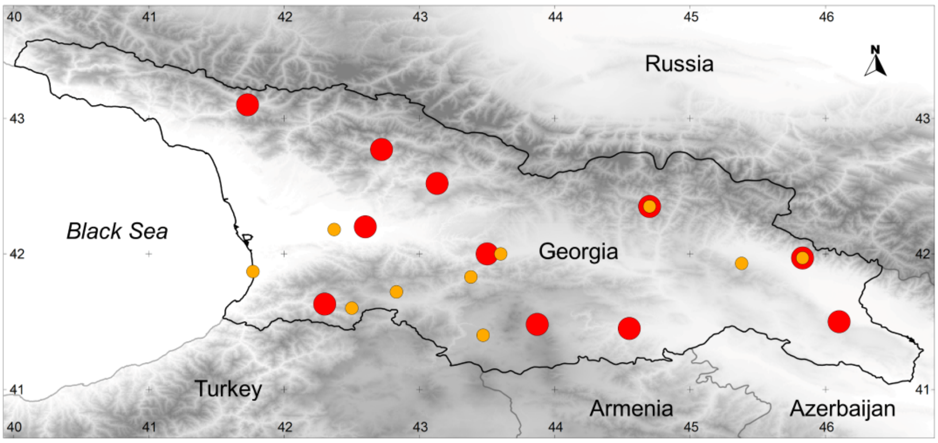


Figure 1: *Stations with daily time series of temperature minimum (orange dots) and maximum (red dots) and precipitation for the period 1971-2010.*

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. Due to the complex annual large-scale circulation and diverse physiographic patterns, large spatial and temporal differences of temperature and precipitation over Georgia can be observed. In general, the west of Georgia is characterized by mild winters and hot summers with mean annual air temperatures of 13 to 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 and 13 °C. In the mountainous areas mean temperature covers a range of −5 to 10 °C and precipitation varies from 800 to 1400 mm (World Bank, 2006).

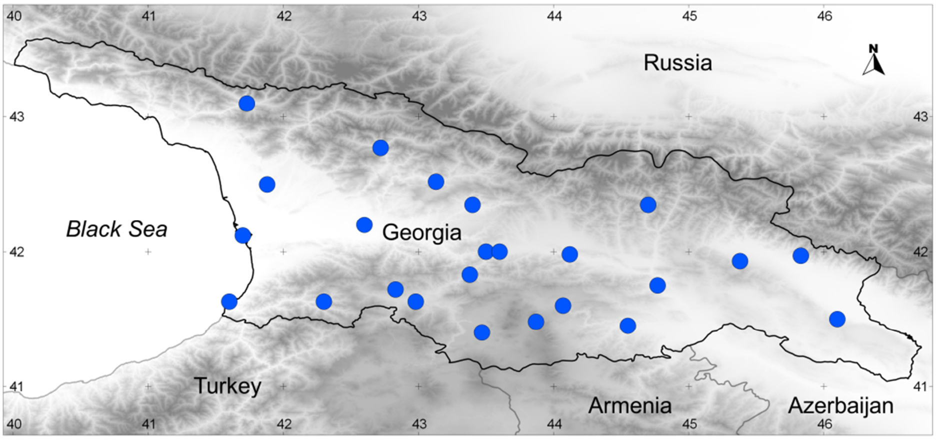


Figure 2: *Stations with daily time series of precipitation for the period 1971-2010.*

2.2 Data, quality control and homogeneity testing

Daily minimum and maximum temperature and daily precipitation for 88 stations were kindly provided by the National Environmental Agency (NEA) of Georgia. The analysis period 1971-2010 was chosen to investigate recent change in extreme temperature and precipitation and to optimize the number of significant trends and data coverage throughout the study area. Data quality and homogeneity testing as well as the detection and adjustment of inhomogeneous time-series have been carried out using the computer program RClimDex 1.1 and its software package RHtestV3 (Wang et al., 2010a) is accessible at: http://etccdi.pacificclimate.org. As a first step, temperature and precipitation time series with more than 20% missing values within the analysis period 1971-2010 were excluded. Outliers in the time series have been identified and temporal consistency was tested according to Aguilar et al. (2003). Unphysical values, such as negative precipitation or maximum temperature lower than minimum temperature were set to missing values. Twenty-six precipitation series and 28 temperature minimum and maximum series fulfilled all quality selection criteria. Observational climate data can be influenced by different non-climatic effects, such as the relocation of weather stations, land-use changes, adjustments in instruments and observational hours (Peterson et al., 1998 and Aguilar et al., 2003). These effects result in inhomogeneity causing a shift in the mean of a time series, which could result in first order autoregressive errors. Breakpoints are not customarily documented in metadata. If metadata does exist, it is often inaccessible from archives, which has also been the case in this study. For the present study only homogenous time series were used (Appendix). In order to detect breakpoints in a data series the Penalized Maximal F test was used, which is embedded in a recursive testing algorithm (Wang, 2008a and Wang, 2008b). 28 minimum and maximum temperature series showed 0.68 breakpoints on average. 10 minimum and 11 maximum temperature series were tested homogenous. Daily precipitation series were tested using the software RHtest_dlyPrcp package recommended by Wang et al. (2010b). Two precipitation series were tested inhomogeneous and were excluded from the further analysis.

2.3 Climate extreme indices and analytical methods

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. The ETCCDI indices agreed 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). The indices are calculated from daily temperature and precipitation data (Karl et al., 1999 and Peterson et al., 2001). From the core extreme indices 14 extreme temperature and 11 extreme precipitation indices were selected for the present study (Table 1). All trends for indices chosen have been calculated annually using the software RClimDex 1.1.

Table 1: *ETCCDI temperature and precipitation indices selected for this study with index names, definitions, units and the number of stations per index for which trends were computed for the period 1971-2010. The list of all core ETCCDI indices is given at http://etccdi.pacificclimate.org/list_27_indices.shtml.*

ID	Index name	Definitions	Units	Number of stations
SU	Summer days	Annual count when TX(daily maximum)>25 °C	days	11
FD	Frost days	Annual count when TN(daily minimum)<0 °C	days	10
ID	Ice days	Annual count when TX(daily maximum)<0 °C	days	11
TR	Tropical nights	Annual count when TN(daily minimum)>20 °C	days	10
TXx	Max Tmax	Monthly maximum value of daily maximum temp	°C	11
TNx	Max Tmin	Monthly maximum value of daily minimum temp	°C	10
TXn	Min Tmax	Monthly minimum value of daily maximum temp	°C	11
TNn	Min Tmin	Monthly minimum value of daily minimum temp	°C	10
TN10p	Cool nights	Percentage of days when TN<10th percentile of 1971-2000	days	10
TX10p	Cool days	Percentage of days when TX<10th percentile of 1971-2000	days	11
TN90p	Warm nights	Percentage of days when TN>90th percentile of 1971-2000	days	10

TX90p	Warm days	Percentage of days when TX>90th percentile of 1971-2000	days	11
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile of 1971-2000	days	11
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile of 1971-2000	days	10
Rx1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm	24
Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm	24
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP>=1.0mm) in the year	mm/day	24
R1mm	Number of wet days	Annual count of days when PRCP>=1 mm	days	24
R10mm	Number of heavy precipitation days	Annual count of days when PRCP>=10 mm	days	24
R20mm	Number of very heavy precipitation days	Annual count of days when PRCP>=20 mm	days	24
R95p	Very wet days	Annual total PRCP when RR>95th percentile of 1971-2000	mm	24
R99p	Extremely wet days	Annual total PRCP when RR>99th percentile of 1971-2000	mm	24
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1 mm	days	24
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1 mm	days	24
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1 mm)	mm	24

Percentile indices were calculated using the standard reference period 1971-2000 to make results easily comparable with other studies using the same reference period. During the trend estimation of the percentile-based indices, RClimDex 1.1 uses the bootstrapping approach to avoid possible bias within the reference period associated with the existing inhomogeneity (Zhang et al., 2005a). Annual trends in temperature and extreme indices are calculated for 10 temperature minimum, 11 temperature maximum and 24 precipitation series. During the calculation process particular data requirements must be met in order to calculate index values using RClimDex. An annual value is considered as incomplete if more than 15 days are missing in a year. A month will not be calculated when ≥3 days are missing, a year will only be calculated when all months are present. A percentile-based index will only be calculated if there is at least 70% data present within the reference period. Additional ETCCDI-recommended standard criteria are applied as described in the RClimDex user manual at: http://etccdi.pacificclimate.org/RClimDex/RClimDexUserManual.doc. After quality testing, RHtestV3 was used to test data homogeneity. These requirements for data completeness resulted in a final number of extreme indices shown in Table 1, which outlines index abbreviations, names, definitions, units and the number of stations for which each index has been computed. The trend calculations in the present study were performed for the period 1971-2010 in order to optimize significant results and data coverage throughout the study area. The magnitude of trends was calculated using the non-parametric Sen′s slope estimator based on Kendall′s tau (τ) (Sen, 1968). 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 and Kendall, 1975). Results at the 25% level are also presented, as per Nicholls (2001). The annual slopes of trends were converted into slope per decade. In addition, least-squared linear trends were calculated with respect to a 1971-2000 reference period for averaged anomaly series for each index, to provide an indication of annual fluctuations and for further scientific backup of the decadal trend or tendency calculated. Trends have only been calculated for an index if less than 20% of the annual values were missing. The anomaly series were calculated as follows:

$$x_{r,t} = \sum_{i=1}^{nt} \left(x_{i,t} - \overline{x}_i\right) / n_t \qquad (1)$$

where

$x_{r,t}$ is the regionally averaged index at year *t*;

$x_{i,t}$ is the index for station *i* at year *t*;

$\overline{x}_i$ is the index mean at station *i* over the period 1971-2010;

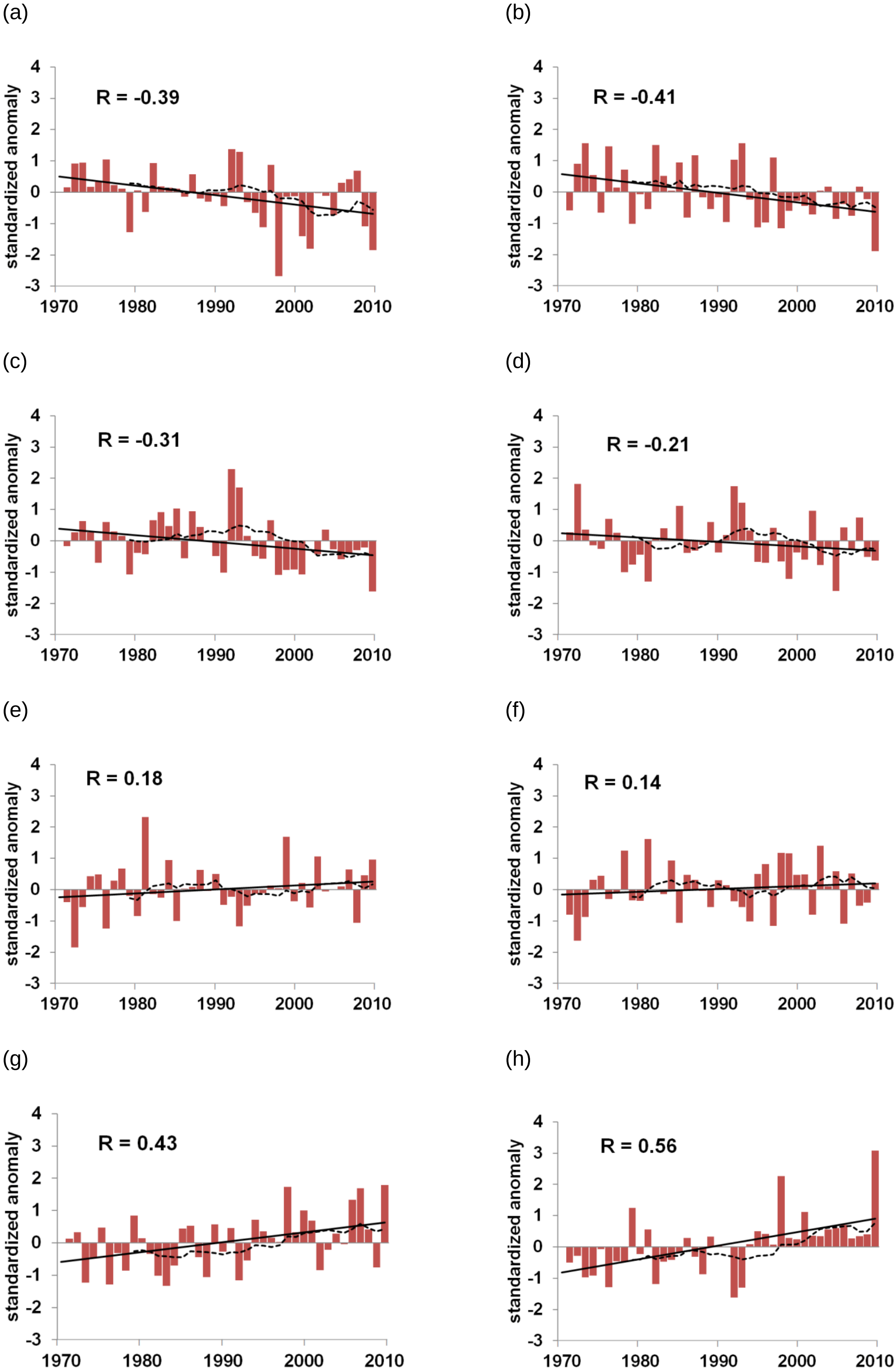
n_t is the number of stations with data in year *t*.

In compliance with New et al. (2006), $x_{i,t}$ and $\overline{x}_i$ were standardized by dividing them by the standard deviation of the respective station to avoid the average series being dominated by stations with high values and to make stations more comparable given the diverse climatic conditions in Georgia. The 10-year moving average was also used to show the annual variation of climatic extremes within the analysis period.

3. Results and discussion

3.1 Trends in temperature extremes

Average regional trends of frost days (FD, summer days (SU), and tropical nights (TR) show significant warming (Figs. 3a, g, and j), whereas ice days (ID) show an insignificant but also increasing trend (Fig. 3d). The trend per decade in the Georgia average significant at the 5% level for the annual number of frost days is −3.3 days/decade; for ice days it is −1.0 days/decade; for summer days this trend is 3.4 days/decade and for tropical nights it is 1.7 days/decade (Table 2). Figs. 4a-d displays a high spatial coherence of the regional warming trends, particularly for frost days (FD) and summer days (SU).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(b)
R = -0.41
(c)
R = -0.31
(d)
R = -0.21
(e)
R = 0.18
(f)
R = 0.14
(g)
R = 0.43
(h)
R = 0.56
standardized anomaly
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3
2
1
0
-1
-2
-3
1970
1980
1990
2000
2010

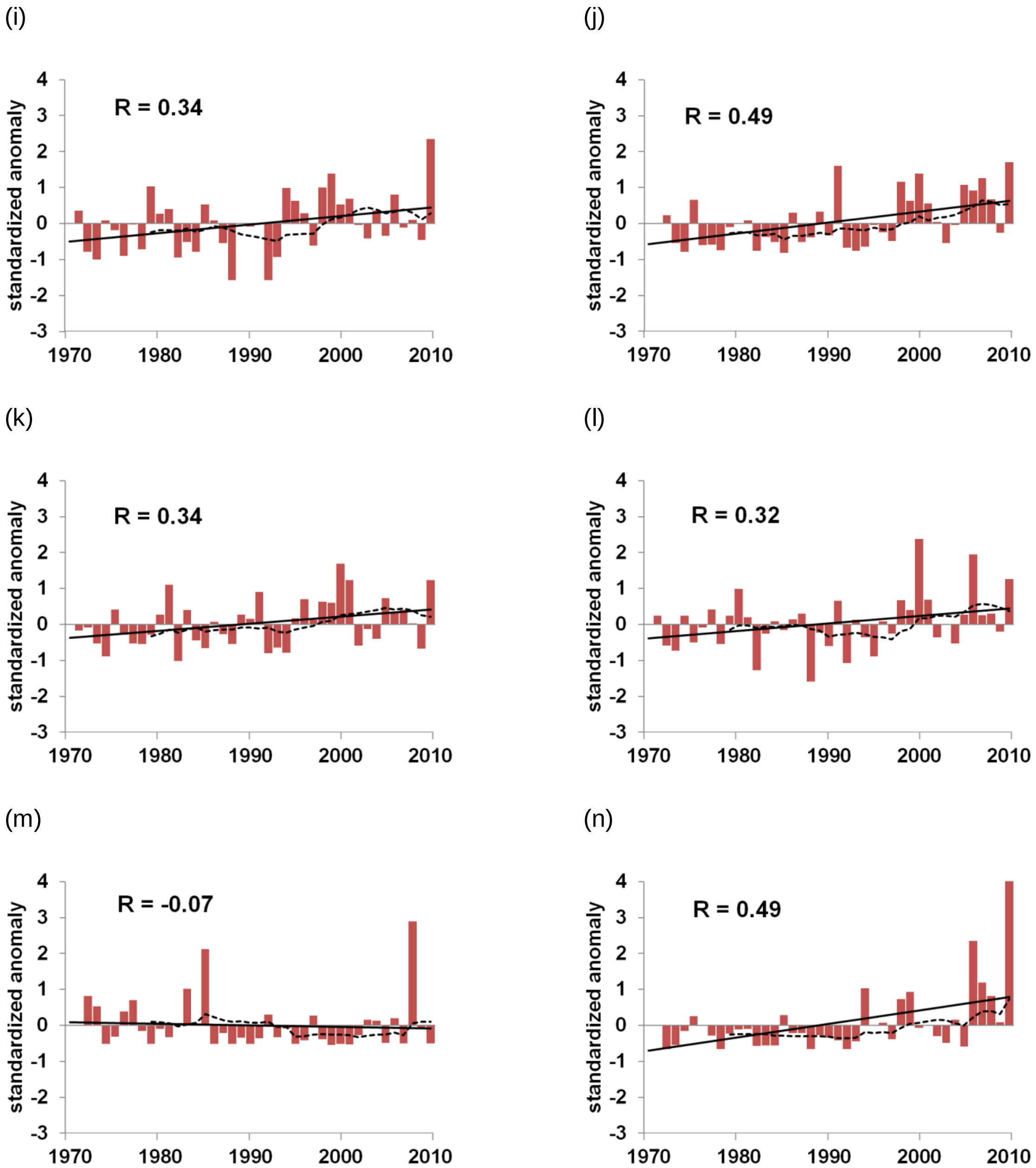


Figure 3: *Standardized anomalies for temperature indices averaged over Georgia between 1971 and 2010: (a) Frost days (FD), (b) Cool nights (TN10p), (c) Cool days (TX10p), (d) Ice days (ID), (e) Monthly minimum of Tmin (TNN), (f) Monthly minimum of Tmax (TXN), (g) Summer days (SU), (h) Warm nights (TN90p), (i) Warm days (TX90p), (j) Tropical nights (TR), (k) Monthly maximum of Tmin (TNX), (l) Monthly maximum of Tmax (TXX), (m) Cold spell duration indicator (CSDI), and (n) Warm spell duration indicator (WSDI) for the period 1971-2010. R is the correlation coefficient of the linear trend. The dashed line is the 10-year moving average.*

There are no cooling trends significant at the 5% or 25% level. The warming trend for FD is significant at the 5% (25%) level for 40% (80%) of all 10 stations analyzed; the significant warming trend for SU is achieved for 64% (91%) of the stations. The warming trend for ID is significant for 9% (27%) of 11 stations, whereas for TR it is significant for 20% (40%) stations (Table 2). From the averaged trends per decade over Georgia, there are 13.3 fewer frost days and 4.0 fewer ice days in the year 2010 than in the year 1971. In the same time period there are 13.6 more summer days and 7.0 more tropical nights.

All averaged anomaly series between 1971 and 2010 in the annual number of cold nights (TN10p), warm nights (TN90p), cold days (TX10p) and warm days (TX90p) show significant warming trends, whereas temperature minimum-based indices show larger trends (Table 2).

No significant cooling trend is apparent (Fig. 4 c-f). For TN10p the warming trend is significant at the 5% (25%) level for 70% (80%) of all 10 stations analyzed. The trend per decade averaged over Georgia in the annual number of cold days is −1.0 days/decade. For TX10p a warming trend at a slightly lower rate of −0.8 days/decade can be observed (Table 2). The trend per decade in the Georgia-average annual number of warm nights amounts to 1.9 days/decade, whereas the trend for warm days accounts for 1.2 days/decade. The considerable warming trend for TN90p is significant at the 5% (25%) level for 80% (80%) out of 10 stations. TX90p shows a warming trend with lower magnitude than TN90p, which is also indicated by the standardized anomalies series in Figs. 3h and i. 45% (82%) of the stations are decidedly increasing for TX90p.

Table 2: *Georgia-averaged trends in temperature extreme indices for the period 1971-2010. Mean trends significant at the 5% level are set in bold and highlighted in green. The percentage of stations with negative and positive trends for all stations and stations significant at the 5 and 25% level for each index.*

Temperature index	Mean	Range	% of stations with neg. trends			% of stations with pos. trends		
			sig. at 5%	sig. at 25%	all	sig. at 5%	sig. at 25%	all
FD [days]	**−3.3**	−4.5 to -0.2	40	80	100	0	0	0
ID [days]	−1.0	−2.3 to 0.3	9	27	82	0	0	18
TN10p [days]	**−1.0**	−1.7 to 0.1	70	80	90	0	0	10
TX10p [days]	**−0.8**	−1.2 to 0.1	18	64	91	0	0	9
TNn [°C]	0.4	0.0 to 1.0	0	0	0	20	40	100
TXn [°C]	0.2	−0.2 to 0.6	0	0	18	0	27	82
SU [days]	**3.4**	0.7 to 6.2	0	0	0	64	91	100
TR [days]	**1.7**	0.0 to 7.1	0	0	0	20	40	100
TN90p [days]	**1.9**	−0.1 to 3.3	0	0	10	80	80	90
TX90p [days]	**1.2**	0.4 to 2.6	0	0	0	45	82	100
TNx [°C]	0.3	−0.1 to 0.5	0	0	10	30	40	90
TXx [°C]	**0.3**	−0.1 to 0.8	0	0	9	18	55	91
WSDI [days]	**1.7**	1.6 to 6.7	0	0	0	55	100	100
CSDI [days]	−0.1	−1.0 to 0.3	10	20	60	0	0	40

The cold spell duration indicator (CSDI) shows an insignificant decreasing trend at a rate of −0.1 days/decade. However, the warm spell duration indicator (WSDI) shows a strong significant warming trend in the regional averages, whereas the spatial coverage of significant trends for WSDI is much higher than for CSDI (Figs. 4g and h). The moving average of the standardized anomaly series of WSDI shows a pronounced fluctuation between 1971 and 2010 (Fig. 3n). There is a steady trend until the mid-1990s and a stronger increasing trend until 2010. The mean trend over Georgia significant at the 5% (25%) level for WSDI is considerably positive at a rate of 1.7 days/decade for 55% (100%) of all stations. The Georgia-averaged trend for CSDI is significant only at the 25% and amounts to −0.1 days/decade (Table 2), whereas the trend of the anomaly series is weak and almost even (Fig. 3m).

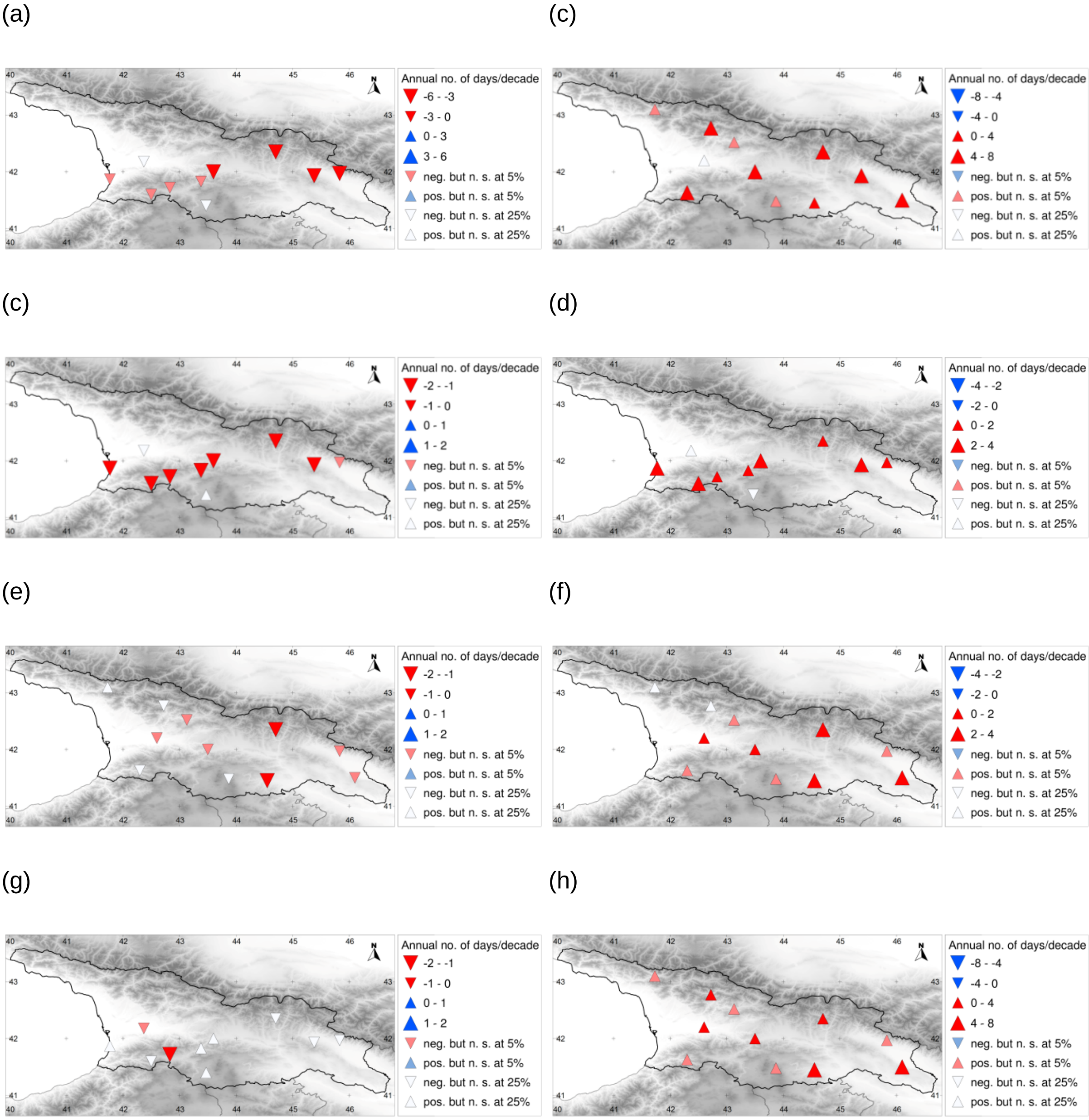


Figure 4: *Station trends for temperature indices between 1971 and 2010 in the (a) annual number of frost days (FD), (b) annual number of summer days (SU), (c) cold nights (TN10p), (d) warm nights (TN90p), (e) cold days (TX10p), (f) warm days (TX90p), (g) cold spell duration indicator (CSDI) and (h) warm spell duration indicator (WSDI) for the period 1971-2010. Positive trends are represented by upward, negative trends by downward triangles. The red color indicates warming trends, blue indicates cooling trends. Light blue and red triangles indicate trends not significant at the 5% level, white triangles are trends not significant at the 25% level.*

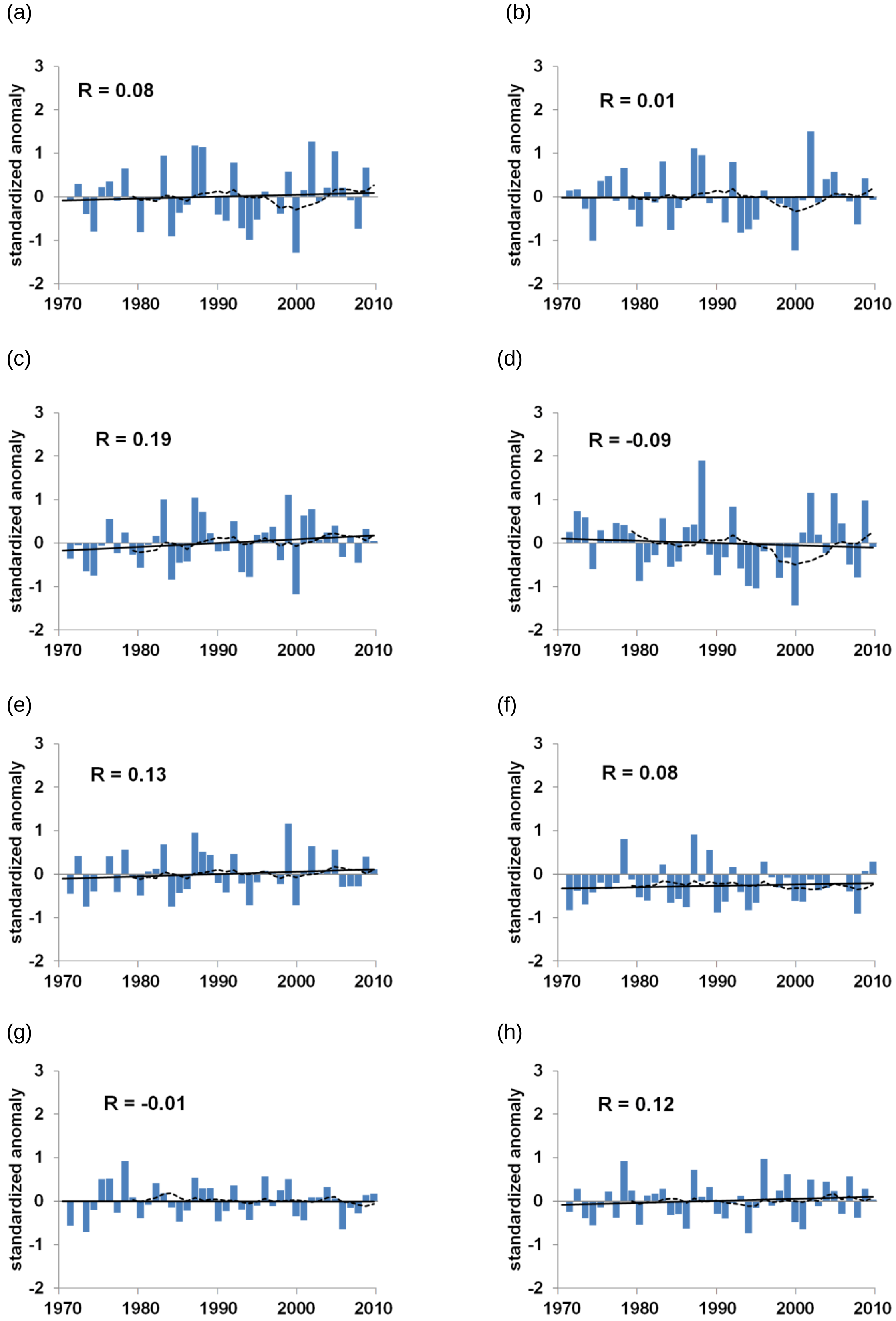
All warm extremes (TN90p and TX90p, WSDI) show higher trend magnitudes than those for cold extremes (TN10p and TX10p, CSDI), implying asymmetric changes in lower- and upper-tail extremes causing a rising temperature variance (Figs. 3b, c, h, i, m and n). This finding is in agreement with earlier studies (Klein Tank and Können, 2003, Zhang et al., 2005b and Moberg et al., 2006) demonstrating that warming since the 1970s is rather caused by the increases of warm extremes than the decrease of cold extremes. All maximum and minimum temperature indices show an increasing trend (Fig. 3 e, f, k and l), while the warmest night temperature (TNx) showed the only significant trend rate of 0.3 days/decade averaged over Georgia. The coldest night temperature (TNn) showed a warming rate of 0.4 °C/decade. For both indices the magnitude and the number of stations with significant trends were larger than for the warmest day temperature (TXn) and the coldest day temperature (TXx). The warming trend for TXn accounts for 0.2 °C/decade (Table 2). For TXx the positive trend is at a rate of 0.3 °C/decade (Figs. 3k and l). Trends in temperature minimum indices (FD, TR, TNx, TNn, TN10p and TN90p) are larger than those of their corresponding maximum extremes (SU, ID, TXn, TXx, TX10p and TX90p) (Figs. 3a−l). These observations correspond to findings in previous studies relating significant changes in temperature extremes with warming. 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 and New et al., 2006).

3.2 Trends in precipitation extremes

The significance of trends in precipitation extremes from 1971-2010 is much lower compared to temperature extremes. A large proportion of stations experienced an increase for the number of very heavy precipitation days, very wet and extremely wet days, maximum 5-day precipitation and the simple daily intensity index, although the percentage of significant trend values was very low (Table 3).

Table 3: *Georgia-averaged trends in precipitation extreme indices for the period 1971-2010. Mean trends are significant at the 25% level. The percentage of stations with negative and positive trends for all stations and stations significant at the 5 and 25% level for each index*.

Precipitation index	Mean	Range	% of stations with neg. trends			% of stations with pos. trends		
			sig. at 5%	sig. at 25%	all	sig. at 5%	sig. at 25%	all
PRCPTOT [mm]	7.9	−58.0 to 56.9	12	29	41	0	29	59
R1mm [days]	−0.8	−12.4 to 3.1	18	29	71	6	12	29
R10mm [days]	−0.1	−2.1 to 2.1	12	24	47	6	12	53
R20mm [days]	0.3	−1.2 to 2.5	0	18	24	6	18	76
R95p [mm]	7.5	−37.4 to 59.0	6	18	29	0	29	71
R99p [mm]	6.3	−14.2 to 28.4	0	6	35	18	35	65
Rx1day [mm]	0.6	−8.4 to 7.4	5	16	42	11	21	58
Rx5day [mm]	2.0	−9.7 to 9.7	0	0	32	11	16	68
CWD [days]	0.0	−2.1 to 0.9	12	12	59	6	12	41
CDD [days]	0.1	−1.8 to 3.9	0	6	59	6	12	41
SDII [mm/day]	0.1	−0.3 to 0.6	6	12	24	6	24	76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R = 0.01
(c)
R = 0.19
(d)
R = -0.09
(e)
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(f)
R = 0.08
(g)
R = -0.01
(h)
R = 0.12
standardized anomaly
1970
1980
1990
2000
2010

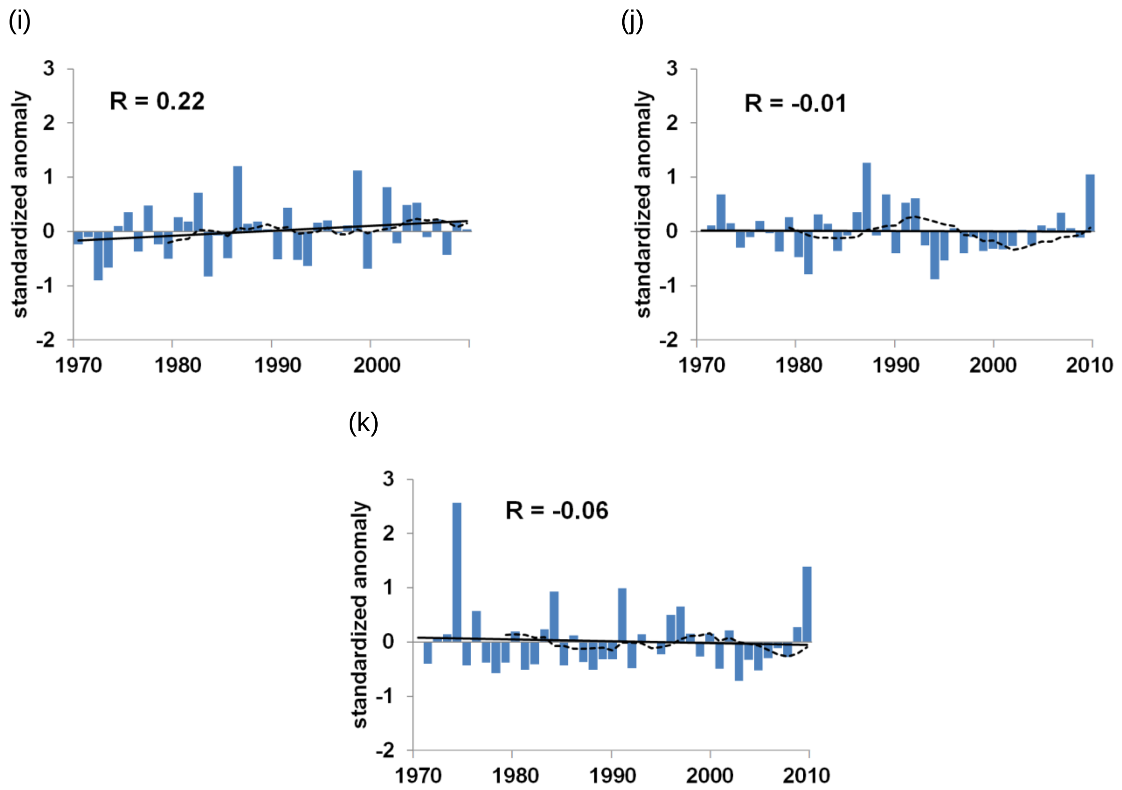

Figure 5: *Standardized anomalies for precipitation indices averaged over Georgia between 1971 and 2010: (a) Annual total wet-day precipitation (PRCPTOT), (b) Number of heavy precipitation days (R10 mm), (c) Number of very heavy precipitation days (R20 mm), (d) Number of wet days (R1 mm), (e) Very wet days (R95p), (f) Extremely wet days (R99p), (g) Maximum 1-day precipitation (Rx1day), (h) Maximum 5-day precipitation (Rx5day), (i) Simple daily intensity index (SDII), (j) Consecutive wet days (CWD), and (k) Consecutive dry days (CDD) for the period 1971-2010. R is the correlation coefficient of the linear trend. The dashed line is the 10-year moving average.*

A negative Georgia-averaged trend was detected for the number of wet days (R1 mm) and the number of heavy precipitation (R10 mm), yet the magnitude of trends for R10 mm was very weak (Fig. 5b). None of the precipitation indices showed significance at the 5% level. Thus, all station trends in the present study were indicated for the 5 and 25% level. The Georgia-averaged trend of total wet-day precipitation (PRCPTOT) was insignificant at a rate of 7.9 days/decade, although the largest proportion of stations show a significant negative trend at the 5% level for 12% for all 24 stations analyzed and the station trends show a low spatial coherence distributed over Georgia and (Table 3 and Fig. 6a). In addition, the trend of the standardized anomaly is very week. It shows a decreasing trend until the end of the 2000s and increases again at a higher magnitude (Fig. 5a). This is also the instance for the number of wet days, heavy precipitation days and consecutive wet days (CWD). However, R1mm and R10mm indicated a decreasing trend of −0.8 days/decade and −0.1 days/decade, respectively, whereas the trend for R10 mm is almost even (Figs. 5b and d). The negative trend for R1mm is significant at the 5% (25%) level for 18% (29%) of all stations analyzed. R10mm is significant at the 5% (25%) level for only 12% (12%) of the stations and those with positive trends account for 12% (24%). For the number of very heavy precipitation days (R20 mm) the Georgia-averaged trend of 0.3 days/decade was observed. It is significant at the 5% (25%) level for 6% (18%) of 24 stations (Table 3).

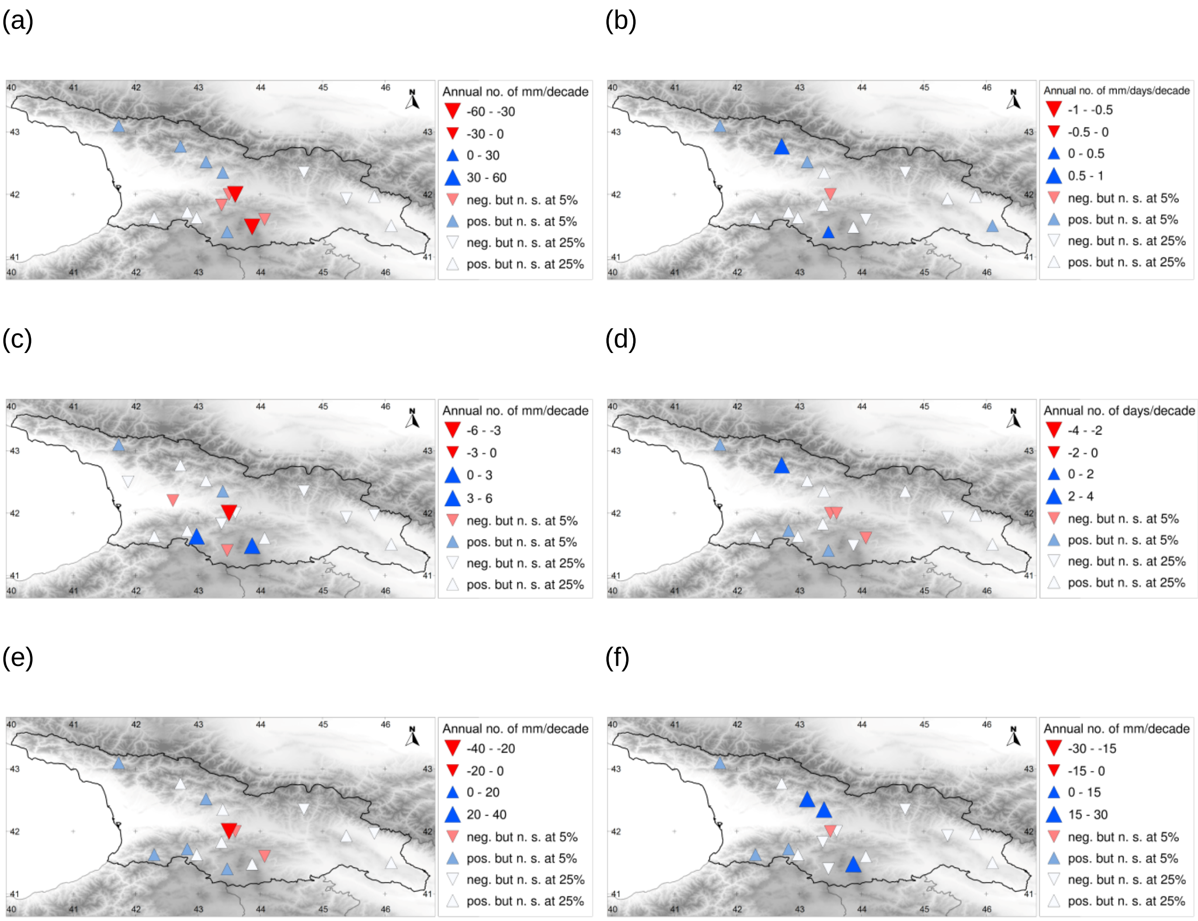

Figure 6: *Station trends for temperature indices between 1971 and 2010 in the (a) annual total wet-day precipitation (PRCPTOT), (b) simple daily intensity index (SDII), (c) maximum 1-day precipitation amount (Rx1day), (d) number of very heavy precipitation days (R20 mm), (e) very wet days (R95p) and (f) extremely wet days (R99p) for the period 1971-2010. Positive trends are represented by upward, negative trends by downward triangles. The red color indicates drying trends, blue indicates wetting trends. Light blue and red triangles indicate trends not significant at the 5% level, white triangles are trends not significant at the 25% level.*

The increase of very wet days (R95p) and extremely wet days (R99p) is continuous and stable (Figs. 5e and f). The Georgia-averaged trend for R95p accounts for 7.5 mm/decade and for R99p 6.3 mm/decade, respectively, whereas the positive trend for R95p is significant at the 5% (25%) level for 0% (29%) and the trend for R99p for 18% (35%) of the 24 stations analyzed (Table 3). The amplified contribution of extreme precipitation to total precipitation was studied by employing the example of Groisman et al. (1999). The fraction of the annual averaged precipitation amount due to very wet days increased by 23% for the period 1971-2010 (range 14% to 33%) (Fig. 7a). The average contribution of extremely wet days increased at a rate of 7% (range 2-12%) (Fig. 7b). This amplified response of extreme precipitation to total precipitation is parallel to the increase of extreme precipitation events in the context of global changes, whereas the tendency for an increase in heavy daily precipitation events can also be found in regions with projected decreases of total precipitation (Groisman et al., 2005, Alexander et al., 2006, IPCC, 2007 and IPCC, 2012).

(a) (b)

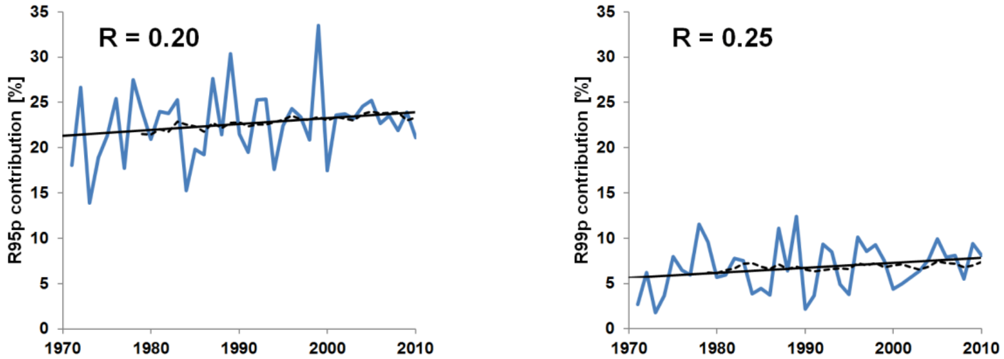

Figure 7: *Contribution of extreme precipitation to total precipitation. Averaged regional indices series show the fraction of precipitation due to (a) very wet days (R95ptot%) and (b) extremely wet days (R99ptot%). R is the correlation coefficient of the linear trend. The dashed line is the 10-year moving average.*

The maximum 1-day precipitation (RX1day) indicated an insignificant increasing trend of 0.6 mm/decade significant at the 5% (25%) level for 11% (21%) of all stations, although it has a very low spatial coherence and even shows a slightly negative tendency for the standardized anomaly series (Fig. 5g). However, maximum 5-day precipitation (Rx5day) demonstrated a positive trend at a rate of 2.0 mm/decade between 1971 and 2010, which is significant at the 5% (25%) level for 11% (16%) (Table 3).

The Georgia-averaged simple daily intensity index (SDII) indicates the most considerable and continuous trends (Fig. 5i) of all precipitation indices. It has experienced a positive trend of 0.1 mm/day/decade significant at the 5% (25%) level for 6% (24%) of the 24 stations analyzed (Table 3). The trend for consecutive dry days (CDD) is positive at a rate of 0.1 days/decade, which is in accordance with the projections for the increase in dryness for the Mediterranean area and central Europe (IPCC, 2012).The trend is significant at the 5% (25%) level for 6% (12%) of the stations, but the number of stations with significant trends has a very low spatial coherence and the proportion of stations with negative and positive trends is almost even (Table 3 and Fig. 5k). CWD showed also a very weak trend of the standardized anomaly series and is even at a rate of 0.0 days/decade, which is significant at the 5% (25%) level for 6% (12%) of the stations analyzed (Table 3).

4. Conclusions

This study analyzed changes in temperature and precipitation extreme indices in Georgia based on daily minimum and maximum temperature and precipitation series for the period 1971-2010. The data was quality controlled and the temperature series was homogenized using the software RClimDex 1.1. Due to moderate data quality many station series had to be rejected during the data quality assessment and computation process of the ETCCDI extreme indices, specifically, series of percentile-based precipitation indices. A large number of temperature series were excluded from the study due to inhomogeneity. Nevertheless, the study could improve the understanding of recent changes in the variability, intensity, frequency and duration of climate extreme events over Georgia. Following changes for temperature and precipitation indices were observed throughout the study area:

- There are significant warming trends in the Georgia-average for SU, FD, TR, TXx, TN90p, TX90p, TN10p, TX10p and WSDI between 1971 and 2010.
- No significant cooling trend was found over Georgia for all temperature indices.
- Most of the stations show significant warming trends for TNx, TNn TXx and TXn.
- The magnitude of trends for night-time indices (FD, TR, TNx, TNn, TN90p, and TN10p) is more pronounced than those for daytime (SU, ID, TXx, TXn, TX90p, and TX10p).
- Averaged trends show “asymmetric” changes in temperature extremes, indicating a more pronounced increase in warm extremes than a decrease in cold extremes.
- Although almost all extreme precipitation indices, such as R20mm, R95p, R99p, Rx1day, Rx5day and SDII indicate an increasing number and more intense extreme precipitation events over Georgia during 1971-2010, the changes were not statistically significant.
- At the same time the number of wet and heavy precipitation days (R1mm, R10mm) decreased
- The contribution of extreme precipitation to total precipitation increased between 1971 and 2010.

Despite the small number of homogenous minimum and maximum temperature series the study could present a high proportion of significant station and Georgia-averaged trends. The study provided evidence that during the last 40 years Georgia was particularly affected by warm extremes based on night-time indices rather than by cold extremes based on day-time indices. Particularly warm days and nights and the warm spell duration indicator showed pronounced warming during 1971 and 2010 indicating that an increase in the frequency, intensity and duration of temperature extremes can be expected in future. However, the sparse number of temperature stations made it impossible to make reliable assumptions on trend patterns over Georgia. The low significance and spatial coherence of trends on precipitation extremes made it also very difficult to detect to provide significant evidence for spatio-temporal changes in extreme precipitation indices during 1971 and 2010. In particular, precipitation patterns over Georgia are very complex, influenced by the diverse topography and large-scale circulation. Thus, a study on the relation between large-scale circulation and changes in extreme temperature and precipitation is necessary with higher temporal resolution (seasonal or monthly) and at smaller spatial scales (e.g. regional and local). A further study on annual and seasonal changes in temperature over Georgia comparing different analysis periods is already in preparation. In addition, future analyses are planned to study the relationship between changes in atmospheric circulation and their contribution to the observed trends in temperature and precipitation extremes.

Appendix

Table 4: *Instrumental station data used in this study with, station name, WMO code, coordinates, altitude (m) and analyzed parameter*

Station name	WMO code	North latitude	East longitude	Altitude [m]	Analyzed parameter
Zemo Azhara	37196	43.10	41.73	952	Tmax/Precipitation
Zugdidi	37279	42.50	41.88	117	Precipitation
Lentekhi	37295	42.77	42.72	731	Tmax/Precipitation
Ambrolauri	37308	42.52	43.13	544	Tmax/Precipitation
Poti	37379	42.12	41.70	1	Precipitation
Samtredia	37385	42.18	42.37	26	Tmin
Kutaisi	37395	42.20	42.60	116	Tmax/Precipitation
Sachkere	37403	42.35	43.40	455	Precipitation
Mta-Sabueti	37409	42.00	43.50	1246	Tmax/Precipitation
Khashuri	37417	42.00	43.60	690	Tmin/Precipitation
Pasanauri	37432	42.35	44.70	1064	Tmin/Tmax/Precipitation
Kobuleti	37481	41.87	41.77	7	Tmin
Batumi Airport	37484	41.63	41.60	32	Precipitation
Khulo	37498	41.63	42.30	946	Tmax/Precipitation
Abastumani	37503	41.72	42.83	1265	Tmin/Precipitation
Ahalcihe	37506	41.63	42.98	982	Precipitation
Goderdzi Pass	37507	41.60	42.50	2025	Tmin
Borjomi	37515	41.83	43.38	794	Tmin/Precipitation
Gori	37531	41.98	44.12	590	Precipitation
Tsalka	37537	41.60	44.07	1458	Precipitation
Tbilisi	37549	41.75	44.77	427	Precipitation
Telavi	37553	41.93	45.38	562	Tmin/Precipitation
Kvareli	37563	41.97	45.83	449	Tmin/Tmax/Precipitation
Akhalkalaki	37602	41.40	43.47	1716	Tmin/Precipitation
Paravani	37603	41.48	43.87	2100	Tmax/Precipitation
Bolnisi	37621	41.45	44.55	534	Tmax/Precipitation
Dedopliskaro	37651	41.50	46.10	800	Tmax/Precipitation

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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. 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, Easterling et al., 2000, Kunkel et al., 1999, New et al., 2006, IPCC, 2007 and 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 and 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, Elizbarashvili et al., 2009a, Elizbarashvili et al., 2009b, Elizbarashvili et al., 2011 and Elizbarashvili et al., 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).

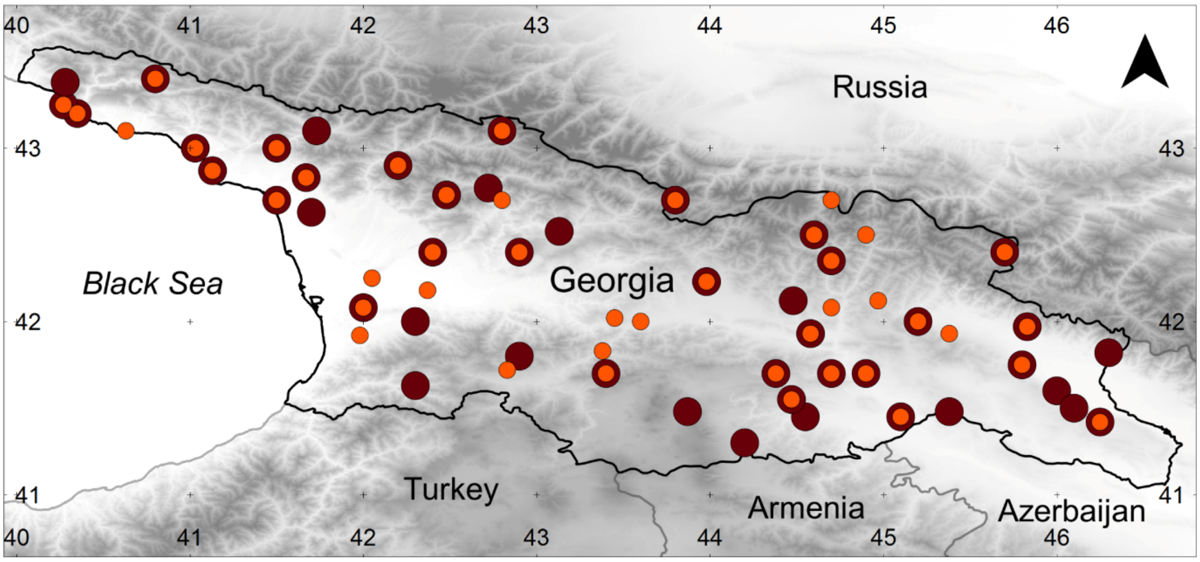

Figure 1: *Stations with daily minimum (orange dots) and maximum (red dots) temperature series for the period 1961-1990*

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).

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. 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 and 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 and Wang, 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 and 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).

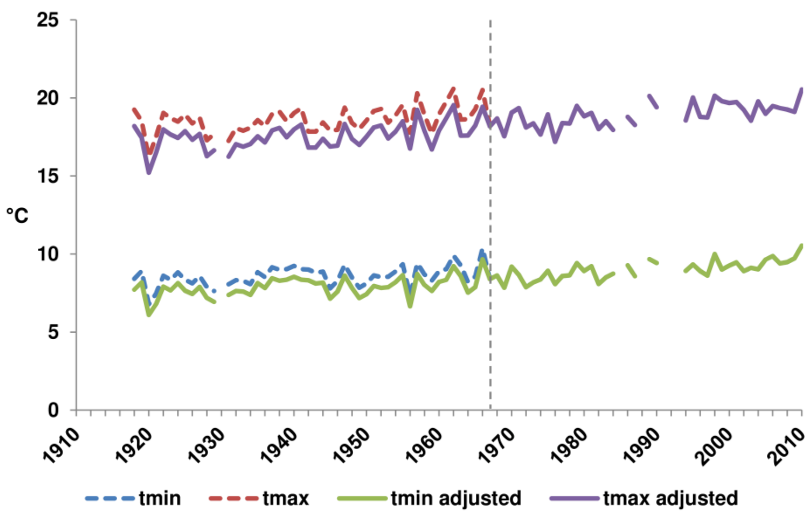

Figure 2: *Inhomogeneous (Tmin and Tmax) and adjusted (Tmin and Tmax adjusted) annual averaged temperature minimum and maximum time series at Tbilisi station. The dashed vertical line indicates the dates of detected breakpoints.*

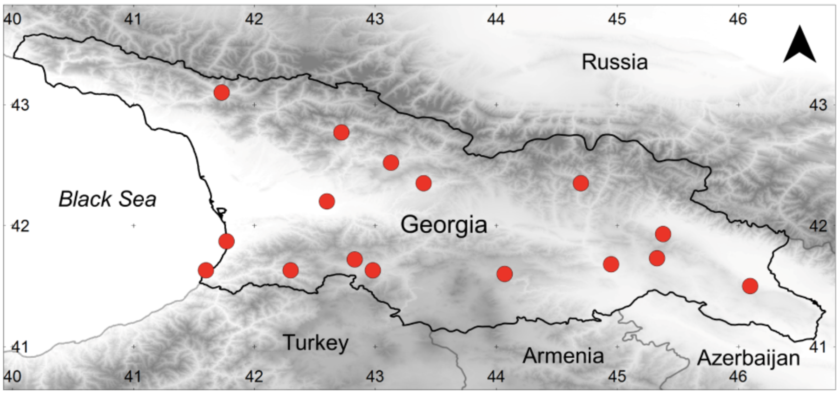

Figure 3: *Stations with daily minimum and maximum temperature series for the period 1961-2010.*

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. 2 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.

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

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. 3 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 and 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.

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

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 and Kendall, 1975).

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.

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

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 (Tmin and Tmax), summer days (SU), frost days (FD) and the warm spell duration index (WSDI) are shown in Fig. 4.

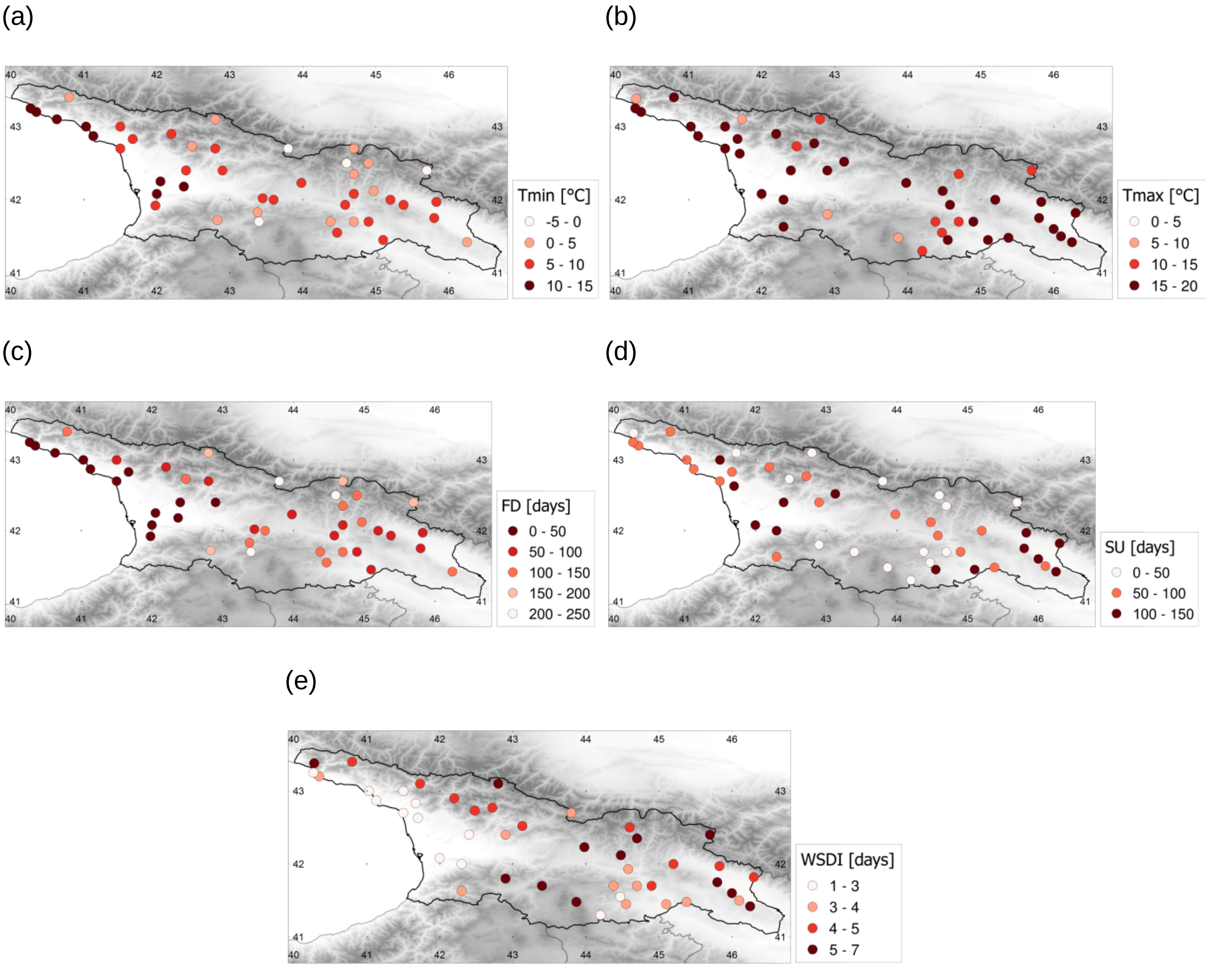

Figure 4: *Averaged annual temperature values for temperature mean and extremes (1961-1990): Temperature minimum (Tmin), maximum (Tmax) and the temperature extreme indices summer days (SU), frost days (FD), and the warm spell duration index (WSDI) for the period 1961-1990.*

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 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 (Tmax) and minimum temperature (Tmin) throughout Georgia. Georgia-averaged trends for Tmin and Tmax are significant for Tmax between 1961 and 2010 and significant for both, Tmin and Tmax during the periods 1971-2010 and 1981-2010 (Table 4). Most pronounced trends for Tmin and Tmax 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 Tmin, Tmax and the respective ratio of stations with positive, negative and non-significant trends for the analysis periods 1961-2010, 1971-2010 and 1981-2010.

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. (%)
Tmin	0.13	0	44	56	**0.21**	0	69	31	**0.39**	0	69	31
Tmax	**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

A comparison of the periods illustrates that the magnitude of trends for Tmin and Tmax increases from 1961-2010 towards the most recent period. Between 1961 and 2010, 50% of all stations investigated indicate significant warming trends of Tmax (0.22 °C/decade). Within the period 1971-2010 (1981-2010), 63% (38%) out of 16 stations show significant warming trends for Tmax, whereas the trend magnitude increases at a rate of 0.28 °C/decade (0.47 °C/decade). Within the period 1961-2010, Tmin features an insignificant warming trend at a rate of 0.13 °C/decade (1961-2010), and 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 Tmin. 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 Tmax is detected than for Tmin. The observed larger magnitude of trends in annual Tmax and rising temperature variability is also in accordance with conclusions derived from earlier studies (Turkes et al., 2002 and 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.

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

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 and 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.

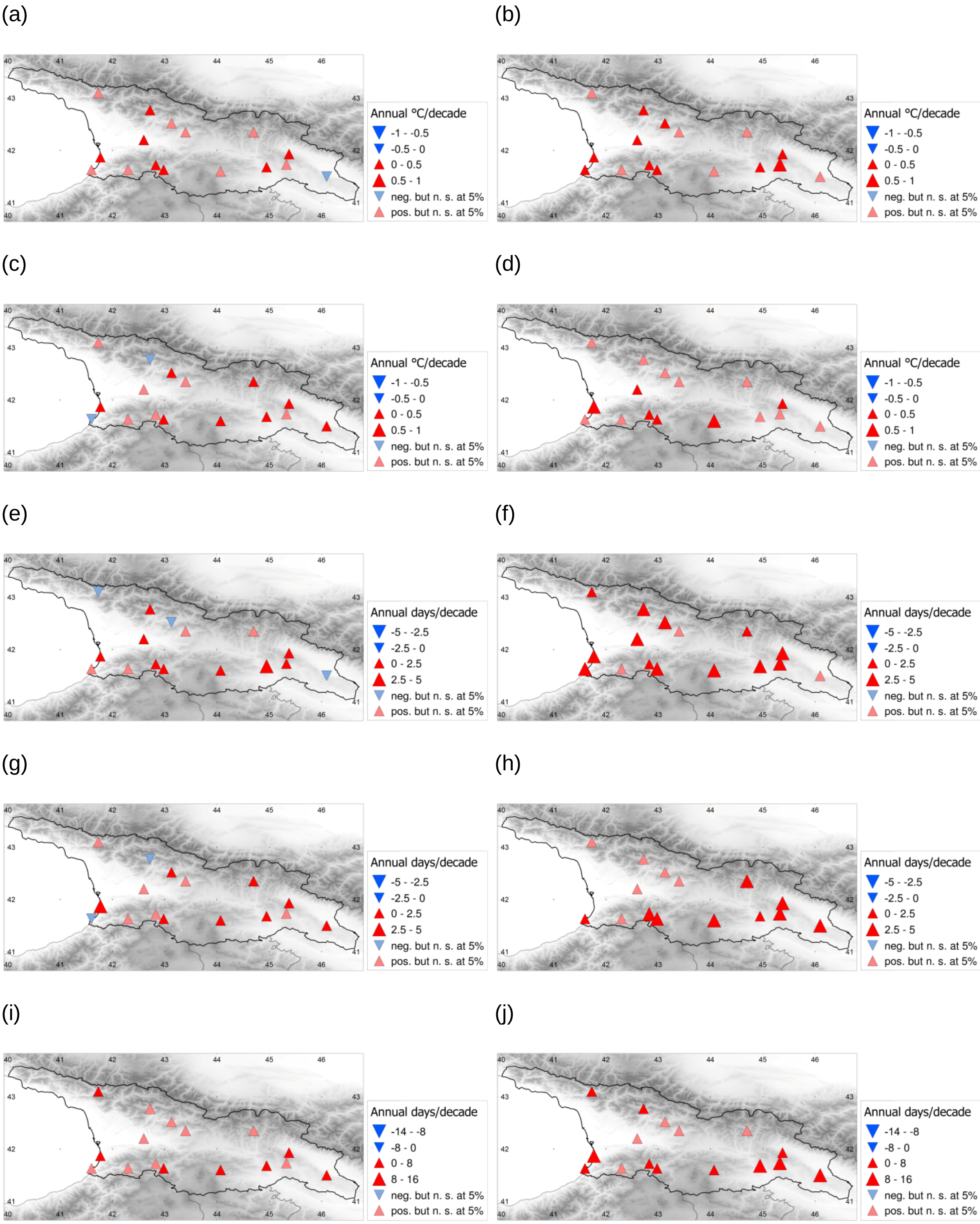

Figure 5: *Annual trends per decade in temperature means and extremes between 1961 and 2010: Tmin (a, b), Tmax (c, d), TN90p (e,f), TX90p (g, h), and WSDI (i, j) during the period 1961-2010 (left) and 1981-2010 (right). Red triangles indicate warming trends, blue indicate cooling trends. Light blue and red triangles indicate trends not significant at the 5% level.*

Fig. 5 (a-j) displays the spatial distribution of regional warming trends for Tmin and Tmax, 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.

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, Tmin and Tmax 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 Tmin and Tmax 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 Tmin and Tmax 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 Tmin during summer (0.47 °C per decade) and fall (0.59 days/decade), and for Tmax 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 Tmin 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	
			Tmin			
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)
			Tmax			
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)

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.

Table 7: *Seasonal trends (days/decade) for percentile-based temperature indices 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.*

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)

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 and Xoplaki et al., 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 and 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.

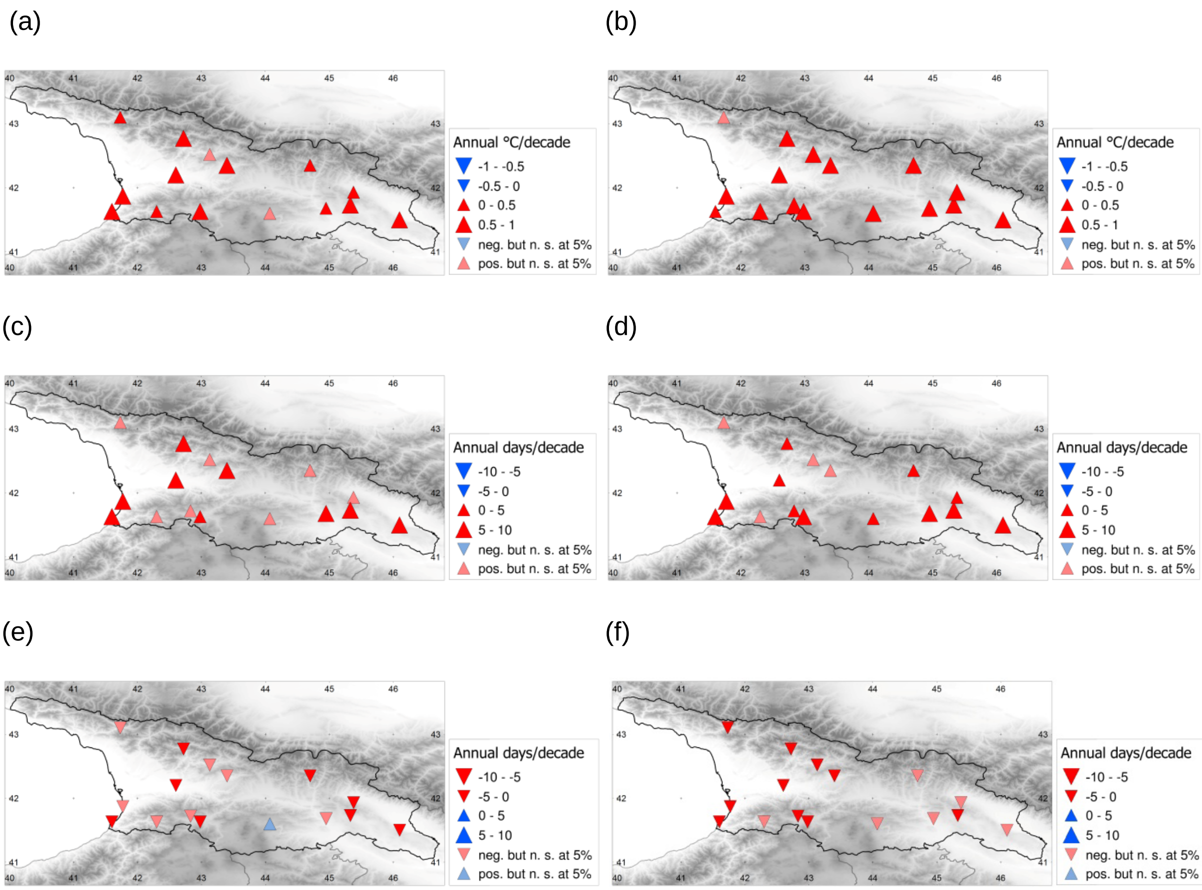

Figure 6: *Summer trends per decade in temperature means and extremes between 1961 and 2010: Tmin (a), Tmax (b), TN10p (c), TX10p (d), TN90p (c), and TX90p (d) for the period 1981-2010. Red triangles indicate warming trends, blue indicate cooling trends. Light blue and red triangles indicate trends not significant at the 5% level.*

Fig. 6(a-f) presents the spatial distribution of regional summer trends for Tmin and Tmax, 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 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 Tmin and Tmax 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.

Appendix

Table 8: *Instrumental station data used in this study with, station name, WMO code, coordinates, altitude (m) and analyzed parameter*

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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Heat Wave Events over Georgia since 1961: Climatology, Changes and Severity

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Abstract

The Caucasus Region has been affected by an increasing number of heat waves during the last decades, which had serious impacts on human health, agriculture and natural ecosystems. A dataset of 22 homogenized, daily maximum (Tmax) and minimum (Tmin) air temperature series is developed to quantify climatology and summer heat wave changes for Georgia and Tbilisi station between 1961 and 2010 using the extreme heat factor (EHF) as heat wave index. The EHF is studied with respect to eight heat wave aspects: event number, duration, participating heat wave days, peak and mean magnitude, number of heat wave days, severe and extreme heat wave days. A severity threshold for each station was determined by the climatological distribution of heat wave intensity. Moreover, heat wave series of two indices focusing on the 90th percentile of daily minimum temperature (CTN90p) and the 90th percentile of daily maximum temperature (CTX90p) were compared. The spatial distribution of heat wave characteristics over Georgia showed a concentration of high heat wave amplitudes and mean magnitudes in the Southwest. The longest and most frequently occurring heat wave events were observed in the Southeast of Georgia. Most severe heat wave events were found in both regions. Regarding the monthly distribution of heat waves, the largest proportion of severe events and highest intensities are measured during May. Trends for all Georgia-averaged heat wave aspects demonstrate significant increases in the number, intensity and duration of low- and high-intensity heat waves. However, for the heat wave mean magnitude no change was observed. Heat wave trend magnitudes for Tbilisi mainly exceed the Georgia-averages and its surrounding stations, implying urban heat island (UHI) effects and synergistic interactions between heat waves and UHIs. Comparing heat wave aspects for CTN90p and CTX90p, all trend magnitudes for CTN90p were larger, while the correlation between the annual time-series was very high among all heat wave indices analyzed. This finding reflects the importance of integrating the most suitable heat wave index into a sector-specific impact analysis.

1. Introduction

Heat waves are among the most threatening meteorological hazards related to global warming posing impacts to society, economy and ecology. Effects of heat waves can include an increase in morbidity and mortality rates [e.g. 1-5], a rising stress on agricultural resources [e.g. 6, 7] and a strain on infrastructure [e.g. 8]. According to the Intergovernmental Panel on Climate Change (IPCC) anthropogenic influences on climate since the mid-20th century resulted in a change of frequency and intensity of daily temperature extremes and doubled the probability of occurrence of heat waves in some regions of the world [9] and the global averaged frequency, duration and intensity of heat waves are projected to increase [10-13]. The severe heat waves during the years 2001, 2003, 2006 and 2007 in Europe and Russia in 2010 and its impacts have been investigated in various studies [14-21]. The fact that in West Asia heat waves are likely to increase in frequency and/or duration, makes it even more important to investigate observed heat wave changes with special regards to regional impacts, the communities involved, and the climatic fields affected [13].

Georgia is located in the Southern Caucasus Region between 41°-44°N and 40°-47°E at the border of Europe and Asia. Although it covers a small area of 69,700 km², the country's physiographic and climatic conditions are very diverse. The relief declines from the Greater Caucasus Range in the North and the Southern Caucasus towards Transcaucasia, which stretches from the Black Sea coast in the West to the Eastern Steppe, near the Caspian Sea in the East. The Surami mountain chain divides Transcaucasia into eastern and western lowlands. While the west of Georgia is characterized by mild winters and hot summers with mean annual air temperatures of 13 to 15°C and high annual precipitation values (1200-2400mm), the climate in eastern Georgia is continental with much lower annual precipitation (500-600mm 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 800-1400mm [22].

According to findings by [23] Georgia experienced pronounced summer warming trends for monthly minimum and maximum temperature means and extremes, whereas warm extremes show larger trends than cold extremes. Moreover, the trend for warm spells was observed to be significantly increasing since the 1960s. Heat waves in Georgia are one of the most common natural hazards observed and cause increasing human health impacts and economic losses [24]. Most vulnerable groups to severe heat waves can be characterized by poor health, high age and/or pronounced social isolation [25]. The rapid increase of the population and urbanization in Georgia and its strong dependence on agricultural production might amplify these negative effects. Tbilisi, Georgia's main capital is by far the most populated city in Georgia, with over one million inhabitants and a rapid rising number of residents. Particularly, urban regions are exposed to more frequent heat wave events, due to the urban heat island effect and synergistic interactions between heat waves and urban heat islands, such as the lack of surface moisture in urban areas, the low wind speed associated with heat waves, the increase in the ambient temperatures and the difference between urban and rural temperatures [26]. According to [27-30], who investigated recent and future heat wave changes in the East Mediterranean and Middle East (EMME) region, the health risk factor due to the projected increase in the number of heat waves, the decrease in precipitation and rising air pollution, will increase, particularly in urban areas.

Heat wave impacts are currently under-reported in Georgia and information on morbidity, mortality and economic consequences are difficult to assess. During the last decades Georgia made great efforts in data recovery and monitoring extreme events and their impacts. Currently 13 meteorological stations and 20 meteorological posts measuring temperature minimum and maximum and precipitation are working on the territory of Georgia [31]. In the course of data recovery and digitalization the National Environmental Agency of Georgia (NEA) kindly contributed metadata to this study giving information about observation periods, and changes of locations of meteorological stations and posts.

In past studies most heat wave indices are defined by temperature exceeding a fixed or percentile threshold for a given period, consider maximum or minimum and focus on consecutive or single days where defined conditions above the threshold persist [14, 19, 32, 33]. A common definition of heat waves in scientific literature does not yet exist. Following [34, 35] the heat wave indicator in the present study is defined by three or more consecutive days above positive Excess Heat Factor conditions. The EHF considers the local geographic acclimatization to temperature, the total heat load, and the recent deviation in temperature from mean temperature and therefore provides a comparative measure of intensity, load, duration and spatial distribution of a heat wave event [25]. Moreover, indices based on the 90^{th} percentile for maximum temperature and the 90^{th} percentile for minimum temperature have been investigated to compare trends in heat wave characteristics for temperature minimum and maximum series separately. Based on [18, 36] multiple heat wave aspects are studied for all three indices: the heat wave number, duration, participating days, the peak and mean magnitudes. The heat wave indices and aspects are recommended by the Commission for Climatology (CCl) Expert Team on Climate Risk and Sector-specific Climate Indices (ET CRSCI) of the World Meteorological Organization (WMO) World Climate Programme. Three new heat wave aspects have been added to the analysis by applying a severity threshold to each time-series: the number of positive, severe and extreme heat wave days, enabling the identification of potential heat-health impacts [37]. Heat-health related morbidity and mortality based on the EHF have been investigated in various studies [11, 25, 36-39].

The aim of this study is to provide a better understanding of the climatology and changes in the frequency, duration and intensity of summer heat wave events over Georgia and the case study Tbilisi, as the most urbanized city in Georgia. Climatologies and trends of heat wave aspects are presented using a new databank of homogenized daily temperature series from 22 stations well distributed throughout Georgia. Section 2 describes the quality control, homogenization methods of the used observation data, the heat wave indices and aspects investigated and methods used for determining heat wave severity. The annual and seasonal climatology and annual changes in the intensity, duration and frequency of heat waves over Georgia and Tbilisi are presented and discussed in section 3. Moreover, the five most severe heat waves over Tbilisi during 1961 and 2010 have been identified and illustrated. In section 4 results are discussed and conclusions are summarized.

2. Data and Methods

2.1 Data Quality and Homogeneity Adjustment

Investigating the climatology and trends on observed heat waves over Georgia 87 daily minimum and maximum temperature series over Georgia for the period 1936 to 2010 were provided by the National Environmental Agency of Georgia. The analysis period 1961-2010 was chosen to study changes in heat wave characteristics under anthropogenic influenced climate conditions as well as to optimize spatial coverage and the number of stations available for the trend analysis. During 1988, 1992 and 1993 data availability for observation data records was very low and had to be rejected from the analysis of Georgian-averaged climatologies and changes. Climatologies of all heat wave aspects over Georgia have been investigated for the normal period 1961 to 1990. Temperature minimum and maximum series with more than 20% missing values within the analysis period were excluded. Data quality control has been carried out using the computer program RClimDex Software version 1.1 available on http://etccdi.pacificclimate.org. Data quality was tested in order to label potentially wrong values, and to reject them from the analysis. Unphysical values, such as Tmax ≥ 70 °C, Tmin ≤ -50 °C, Tmax ≤ Tmin were identified and set to missing values. Outliers were detected and rejected for daily maximum and minimum temperature exceed +/- four standard deviation. After quality control a final number of 31 minimum and maximum temperature series were left for homogeneity testing and adjustment. 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 summer value is calculated if all months are present (May to September); (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. For the analysis period 1961-2010 31 temperature minimum and maximum series matched all quality criteria. Inhomogeneity of time-series was tested using the software package RHtestV3 and to adjust significant breakpoints. Metadata provided by the National Environmental Agency include information of regarding the station's name, coordinates, altitude, WMO code, observational periods, missing data during an observation period, and the station's relocation date. In order to provide reliable results on the climatology and changes in heat waves, time-series with significant breakpoints not documented in the metadata were excluded from the study. 31 stations were left matching all quality criteria as described above. Seven significant breakpoints were found, whereas not more than one breakpoint per maximum or minimum time-series was detected. For two stations (Tbilisi and Gori) dates of site moves were noted within the metadata, which could be confirmed by the detected breakpoints. In this study the Quantile-Matching (QM) adjustment procedure of RHtestV3 is used to adjust daily temperature series [40, 41]. Details on the homogeneity testing and adjustment procedure and parameter usage during the QM adjustment procedure are stated in [23]. The resulting homogenized daily temperature dataset comprise minimum and maximum temperature series from 22 stations for the analysis period 1961 to 2010 (see Appendix).

2.2 Heat Wave Indices and Characteristics

In 2011 a “core set” of 34 descriptive sector-specific indices has been defined by the World Meteorological Organization (WMO) Commission for Climatology (CCl) Expert Team on Climate Risk and Sector-specific Indices (ET CRSCI) to improve decision-making for planning, operations, risk management and for adaptation to both climate change and variability. These internationally agreed indices were developed in part from the core set of indices that are developed and maintained by the Expert Team on Climate Change Detection and Indices (ETCCDI) monitoring changes in “moderate” extremes. However, the new core set of indices provide nine additional indices, such as five heat wave indices, to facilitate the use of climate information in users’ decision-support systems for climate risk management and adaptation strategies [36]. All selected indices were calculated using the ClimPACT software, an R-based software provided to calculate the indices from the ET CRSCI website [42]. The present study uses the Excess Heat Factor (EHF) as heat wave index defined by [25]. Both maximum and minimum temperatures are used in this assessment. The EHF combines a measure of excess heat, the deviation from long term mean temperature, calculated with respect to the period 1961-1990, to take into account local geographic acclimatization, and heat stress, the deviation in temperature from mean temperature for the previous 30 days to measure short-term acclimatization. EHF values are calculated from a three-day mean of forecast temperatures to derive an index of heat wave intensity. Two sub-indices are combined to produce the complete EHF index. The first is a measure of significant excess heat relative to local climatic conditions, the 95th percentile of mean temperature conditions (EHFsig):

$$EHI_{sig} = (T_i + T_{i+1} + T_{i+2})/3 - T_{95} \ , \qquad (1)$$

The second sub-index is a measure of short-term acclimatization to heat, relative to the mean temperature of the previous 30 days (EHFaccl):

$$EHI_{accl} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \ldots + T_{i-30})/30 \ , \qquad (2)$$

These two indices are combined to generate the EHF index. The unit of EHF is °C^2:

$$EHF = EHI_{sig} \times max\,(1, EHI_{accl}) \qquad (3)$$

EHF incorporates the effect of humidity on heat tolerance indirectly, by using the mean, rather than the maximum daily temperature, in the calculation. It provides a comparative measure of intensity, load, duration and spatial distribution of a heat wave event and has a strong signal-to-noise ratio. With an increase in Excess Heat (EHFsig) and Heat Stress (EHFaccl), EHF increases as a quadratic response to increasing heat load. Heat waves are defined as a period of at least three days with EHF ≥ 0 and the combined effect of excess heat and heat stress with respect to the local climate [25]. The heat wave index EHF was selected with regards to eight heat wave aspects quantifying the intensity, frequency and duration of a heat wave event. This multi-aspect framework is based on that of [18], which was slightly extended by [11] to the following five attributes of heat wave aspects:

1. HWN – the yearly number of heat waves;
2. HWD – the length (in days) of the longest yearly event;
3. HWF – the sum of participating heat wave days per year
4. HWA – the hottest day (amplitude) of the hottest yearly event;
5. HWM – the mean event intensity averaging all participating event days

Further to these five heat wave aspects three new aspects have been included in the heat wave analysis based on the Excess Heat Factor: HWday – the number of heat wave days, HWsev – the number of severe heat wave days and HWex – extreme heat wave days. These heat wave aspects enable to differentiate between heat wave days, severe and extreme heat wave days and include the aspect of heat-health considering the exceedance of a station's severe EHF threshold (section 2.3). The resulting heat wave aspects analyzed are summarized in table 1. All eight aspects are calculated annually over the summer season, which is defined as a period from May to September (153 days).

Table 1: *Heat wave aspects analyzed based on the EHF with index names, definitions, and units*

ID	Heat Wave Aspect	Definition	Unit
HWN	Heat wave number	The annual number of summer (May-Sep) heat waves where conditions persist for at least 3 consecutive days with positive EHF values	Number of events
HWD	Heat wave duration	The length of the longest summer (May-Sep) heat wave where conditions persist for at least 3 consecutive days with positive EHF values	days
HWF	Heat wave day frequency	The total number of days each summer (May-Sep) that contribute to all heat waves where conditions persist for at least 3 consecutive days with positive EHF values	days
HWA	Heat wave amplitude	The hottest day of the hottest summer (May-Sep) heat wave where conditions persist for at least 3 consecutive days with positive EHF values	°C²
HWM	Heat wave mean	Average magnitude of all summer (May-Sep) heat wave days where conditions persist for at least 3 consecutive days with positive EHF values	°C²
HWday	Heat wave days	The annual number of all summer (May-Sep) heat wave days with positive EHF values	days
HWsev	Heat wave severe days	The annual number of all severe summer (May-Sep) heat wave days with positive EHF values above the station's severe EHF threshold at EHF_{85} (85^{th} percentile of the station's distribution of positive EHF values)	days
HWex	Heat wave extreme days	The annual number of all extreme summer (May-Sep) heat wave days with positive EHF values that at least double the station's severe EHF threshold at EHF_{85} (85^{th} percentile of the station's distribution of positive EHF values)	days

In order to compare the differences between Georgia-averaged trends in heat wave characteristics based on temperature minimum and maximum series separately the heat wave aspects HWN (the yearly number of heat waves), HWD (the length of the longest yearly event), HWF (the sum of participating heat wave days per year), HWA (the hottest day the hottest yearly event) and HWM (the mean event intensity averaging all participating event days) based on the 90^{th} percentile for maximum temperature (CTX90pct), the 90^{th} percentile for minimum temperature were calculated (CTN90pct). Heat wave indices based on daily Tmin and Tmax are defined as follows:

1. CTN90pct – the calendar day 90th percentile of daily Tmin calculated for a five-day window centered on each calendar day in the base period,
2. CTX90pct – the calendar day 90th percentile of daily Tmax, as described for Tmin.

The unit of CTN90pct and CTX90pct is °C. Due to the low amount of measurable events a set of 14 time series for all three heat wave indices was used for this analysis. All trends were calculated by the non-parametric Sen's slope estimator based on Kendall's tau (τ) [43]. The annual slopes of trends were converted into slope 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% [44, 45]. Station trends have only been estimated if data requirements are met as described above. 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 summer index values at all stations.

2.3 Severe and Extreme Heat Waves

In terms of heat-health, low values of EHF may be considered as uncomfortable and have no or only little impact. Severe heat wave impacts on heat-health are relatively rare, due to the local adaption capacity of the affected population based on the long-term experience to cope with heat waves of low to moderate intensity. In the present study severe heat waves are defined by an event where EHF values exceed a threshold for severity that is specific to the climatology of each location following [25]. To identify severe and extreme heat wave events during 1961 and 2010 over Georgia a severe EHF threshold for each station has been detected. Using the example of Tbilisi time series (figure 1) it is shown that the upper end of the EHF distribution is fat-tailed which allows the identification of a threshold between more-frequent lower-intensity events and less-frequent higher intensity events.

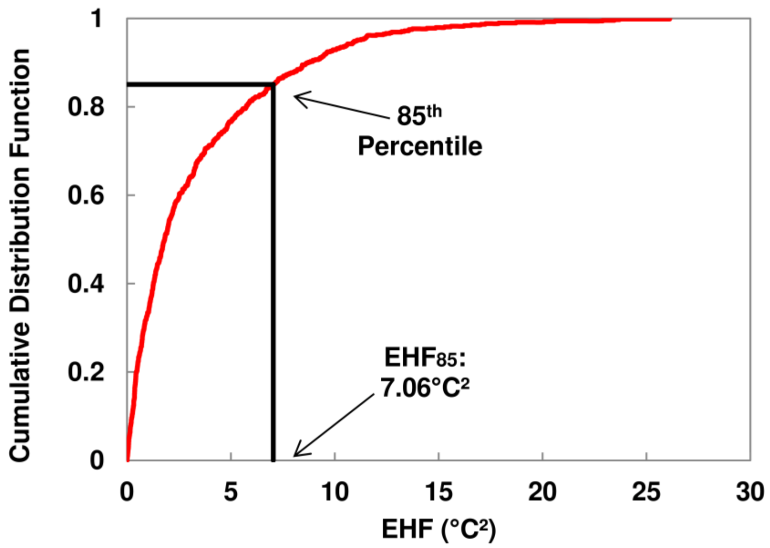

Figure 1: *Determining EHF85 and severe heat wave days for Tbilisi station (1961-2010): Tbilisi cumulative distribution of positive EHF (red line) and the severe EHF threshold at the 85th percentile (black line)*

The severe EHF threshold is calculated empirically as the 85th percentile of the distribution of positive EHF values (EHF_{85}) based on the observation record at a given location. This method ensures that all EHF values are truly representative of each site's climatology and avoids potential errors by modeling a distribution. Extreme heat waves are defined as an event where EHF values are well in excess of the severity threshold and result in a wide impact based on a cascade of failing systems (Nairn and Fawcett, 2013). In the present study extreme heat waves occur if an EHF value during a heat wave at least doubles the severity threshold ($EHF \geq 2 \times EHF_{85}$).

3. Results and Discussion

3.1 Heat Wave Climatology

In this section the climatological Georgia-average during the period 1961-1990 is investigated with respect to selected heat wave aspects.

Table 2: *Georgia-averaged heat wave climatology for the period 1961-1990 for the heat wave aspects: HWN, HWD, HWF, HWA, HWM, HWday, HWsev and HWex*

Heat wave aspect for EHF index*	Annual average (1961-1990)
Heat Wave Number (no. of events)	1.7
Heat Wave Duration (days)	5.5
Heat Wave Frequency (days)	10.4
Heat Wave Amplitude (°C²)	12.2
Heat Wave Mean Magnitude (°C²)	4.3
Heat Wave Days (days)	10.3
Severe Heat Wave Days (days)	1.3
Extreme Heat Wave Days (days)	0.3

In table 2, it is shown that the Georgia-average HWN amounts to 1.7 events/year. Highest numbers of annual events range between 1.7 and 1.9 events/year and can be found throughout the whole territory of Georgia. Lowest numbers of HWN are observed at the Western coast (1.3-1.5 events/year), while a general distribution for all heat wave numbers across Georgia does not show clear spatial patterns (Fig. 2a). However, spatial patterns can be found for HWD, which measures 5,5 days/year in the Georgia-average. Highest averaged values for HWD are concentrated in the southeastern dry steppe (6-7 days/year). Heat waves with a mean duration of 5 to 6 days per year are predominantly located in the Western part of Georgia. The shortest heat waves (4-5 days/year) are observed in central Georgia (Fig. 2b). The Georgia-average for HWF (yearly sum of participating heat wave days) measures 10.4 days/year (Tab. 2). Eleven to 15 days contribute at most to all summer heat waves in Georgia. Similar to HWD, the highest HWF values can be found in the Southeast, lowest values in central Georgia (9-10 days/year) (Fig. 2c). HWA means measure 12.2°C²/year between 1961 and 1990 (Tab. 2). Highest station heat wave amplitudes per year measure 17-24 °C² averaged over Georgia. Strongest heat wave peaks are located in the Western part of Georgia with highest HWA means (17-25 °C²/year) in the Southwest (Fig. 2d). Similar to HWA, highest station means for HWM (6-

9°C²/year) are concentrated in the Southwestern part of Georgia (Fig. 2e) with a Georgia-average of 4.3°C²/year (Tab. 2). Lowest magnitudes (2-4°C²/year) are predominantly found in the eastern part of Georgia.

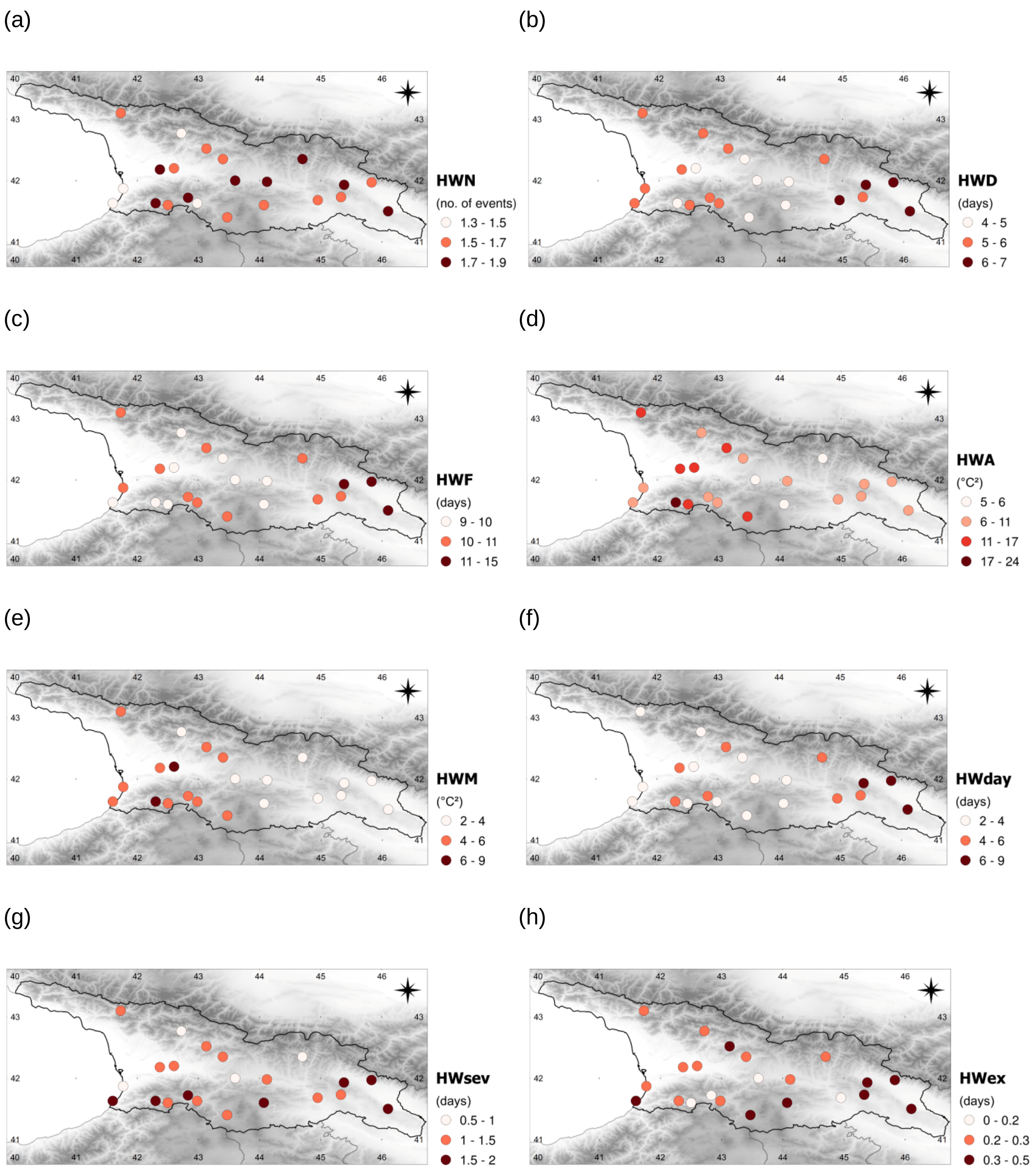

Figure 2: *Station heat wave climatologies over Georgia for the period 1961-1990 and the selected heat wave aspects: (a) Heat Wave Number (no. of events), (b) Heat Wave Duration (days), (c) Heat Wave Frequency (days), (d) Heat Wave Amplitude (°C²), (e) Heat Wave Magnitude (°C²), (f) Heat Wave Days (days) and (g) Severe Heat Wave Days (days) and (h) Extreme Heat Wave Days (days).*

Most positive EHF values (11-12 days/year) can be found in the Southeastern part of the study area, while most severe (40-50 days/year) and extreme days (0.4-0.5 days/year) can be observed in the Southeast and the Southwest (Fig. 2f-h). Georgia-averaged climatologies for HWday measure 10.3 days/year. For severe and extreme days an annual mean of 1.3

days/year and 0.3 days/year can be found, respectively (Tab. 2). The monthly distribution of the mean number and mean intensity (positive EHF values) of summer HWday (Heat Wave Days), HWsev (Severe Heat Wave Days) and HWex (Extreme Heat Wave Days) between 1961 and 2010 is shown in figure 3. Highest numbers of HWday can be found in August (3.4 days/month), lowest in May (1.8 days/month). However, in the Georgia-average most HWsev and HWex occur during May with decreasing numbers toward September. The highest mean intensity for HWday, HWsev and HWex was observed during May at a rate of 7.0°C², 16.1°C² and 23.8°C², respectively. While the heat wave aspects HWday and HWsev show decreasing intensities towards September, the intensity of HWex decreases until July and peaks again in September measuring 23.5°C².

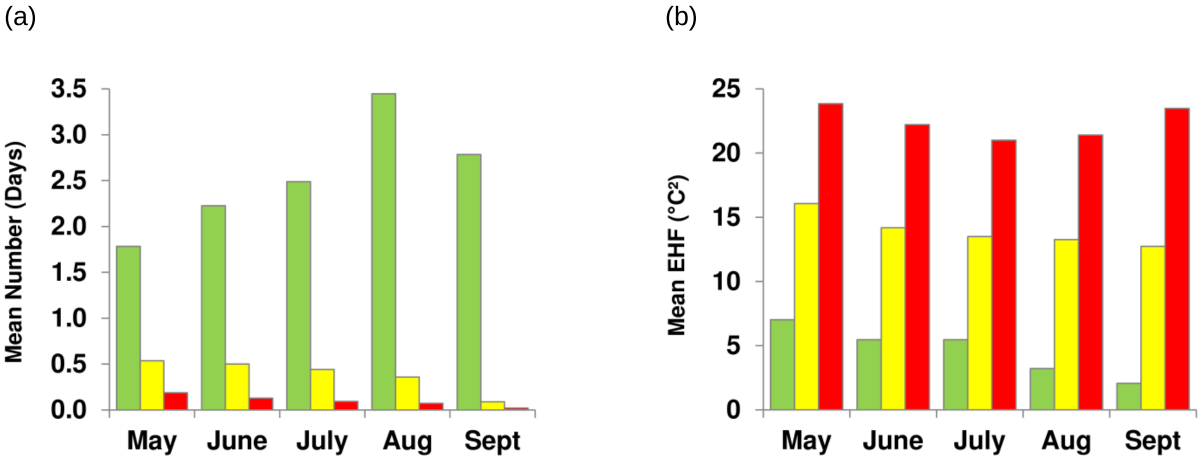

Figure 3: *Seasonal distribution of heat wave events between 1961 and 2010 for (a) the mean number (days) and (b) the mean EHF value (°C) of HWday (green bars), HWsev (yellow bars) and HWex (red bars) averaged over Georgia for the period 1961-2010*

On the whole, highest EHF intensities are spread across the lowest count of monthly EHF days during May. Regarding the heat wave aspects HWsev and HWex, highest intensities are found among the highest number of positive EHF days in May. However, lowest numbers of HWsev and HWex during September show almost the same intensity of mean EHF than in May, implying high peak amplitudes of severe and extreme heat wave days during September.

3.2 Changes in Heat Wave Characteristics

In this section heat wave changes in the Georgia-average during the period 1961 to 2010 are investigated. As table 3 shows, all trends were found significantly positive, with the exception of the annual trend for HWM (average magnitude of all yearly heat waves), which shows an insignificant trend of approximately zero. For HWN a significant increasing trend of 0.4 events/decade can be observed (Tab. 3). All single station trends throughout Georgia were found to be positive (Fig. 4a). During the period 1961-2010 12 of 22 stations analyzed indicate significantly positive trends. Five of them show trend magnitudes of 0.5-1 events/decade, while 10 of all stations are approximately zero, indicating that the yearly number of heat waves for these stations did not change during 1961 and 2010. For HWD (the length of the longest yearly heat wave event) a significant magnitude of 0.9 days/decade was found in the Georgia-average (Tab. 3). Similar to HWN, no decreasing trend could be observed throughout Georgia. Twelve stations show significant trends, of which 4 stations show trend magnitudes between 1 and 2 days/decade (Fig. 4b).

Table 3: *Annual averaged trends for investigated heat wave aspects between 1961 and 2010 with respective confidence intervals (95%). Trends significant at the 5 % level are indicated in bold and highlighted in green.*

Heat wave aspect for EHF index	Trend magnitude/decade (1961-2010)
Heat Wave Number (no. of events)	**0.4 (0.2 to 0.6)**
Heat Wave Duration (days)	**0.9 (0.5 to 1.5)**
Heat Wave Frequency (days)	**2.9 (1.5 to 4.7)**
Heat Wave Amplitude (°C²)	**1.1 (0.2 to 2.2)**
Heat Wave Mean Magnitude (°C²)	0.0 (-0.4 to 0.3)
Heat Wave Days (days)	**3.3 (1.9 to 5.2)**
Severe Heat Wave Days (days)	**0.37 (0.14 to 0.77)**
Extreme Heat Wave Days (days)	**0.05 (0.00 to 0.17)**

The heat wave aspect HWF (yearly sum of participating heat wave days) shows the largest trends of up to 6 days/decade during the period 1961 to 2010 (Fig. 4c). Similar to HWN and HWD all station trends are increasing and stations with statistically significant trends for HWN and HWD are also statistically significant for HWF. The Georgia average trend amounts to 2.9 days/decade (Tab. 3). These findings are in accordance with [36], demonstrating that the high trend magnitude of HWF drives increases in HWN and HWD, as the number of heat wave days represents an influencing factor in the calculation of event length and occurrence. HWA (the averaged peak of the hottest summer day) and HWM (the average magnitude of all summer heat waves) show lower and less significant station trends. Although few negative station trends can be observed for HWA a significant positive trend of 1.1 °C/decade can be found in the Georgia average (Tab. 3). HWA and HWM (the average magnitude of all summer heat waves) show lower and less significant averaged station trends. For HWM an insignificant averaged trend approximating zero can be observed, indicating no change of the mean magnitude of all summer heat waves during 1961 and 2010. However, regarding Georgia-averaged HWday (positive EHF days), HWsev (severe days) and HWex (extreme days) significant increasing trends could be found. For HWday all station trends are increasing and a high proportion of 13 stations show significant trends measuring up to 6 days/decade. Trends with the highest magnitudes are predominantly located in Eastern and Western Georgia (Fig. 4f). In the Georgia-average a significant positive trend of 3.3 days/decade for HWday was observed. Severe days and extreme days increased at a significant rate of 0.4 days/decade and 0.05 days/decade, respectively (Tab. 3). Also for HWsev all station trends are increasing, while only 3 stations show significant trends. Due to the low number of observed extreme days per year, trends for HWex show either insignificant slopes throughout Georgia or trends approximating zero. There are predominantly positive trends noted, only 2 station trends were found to be insignificantly negative (Fig. 4h). In order to be able to compare trends between temperature minimum and maximum series separately and to investigate which of the series shows more response to trends in heat wave aspects, trends for the 90th percentile maximum temperature (CTX90pct), the 90th percentile minimum temperature were calculated (CTN90pct). It is shown, that all trends for CTN90pct demonstrate a higher magnitude than for CTX90pct, which corresponds to global heat wave observations [11].

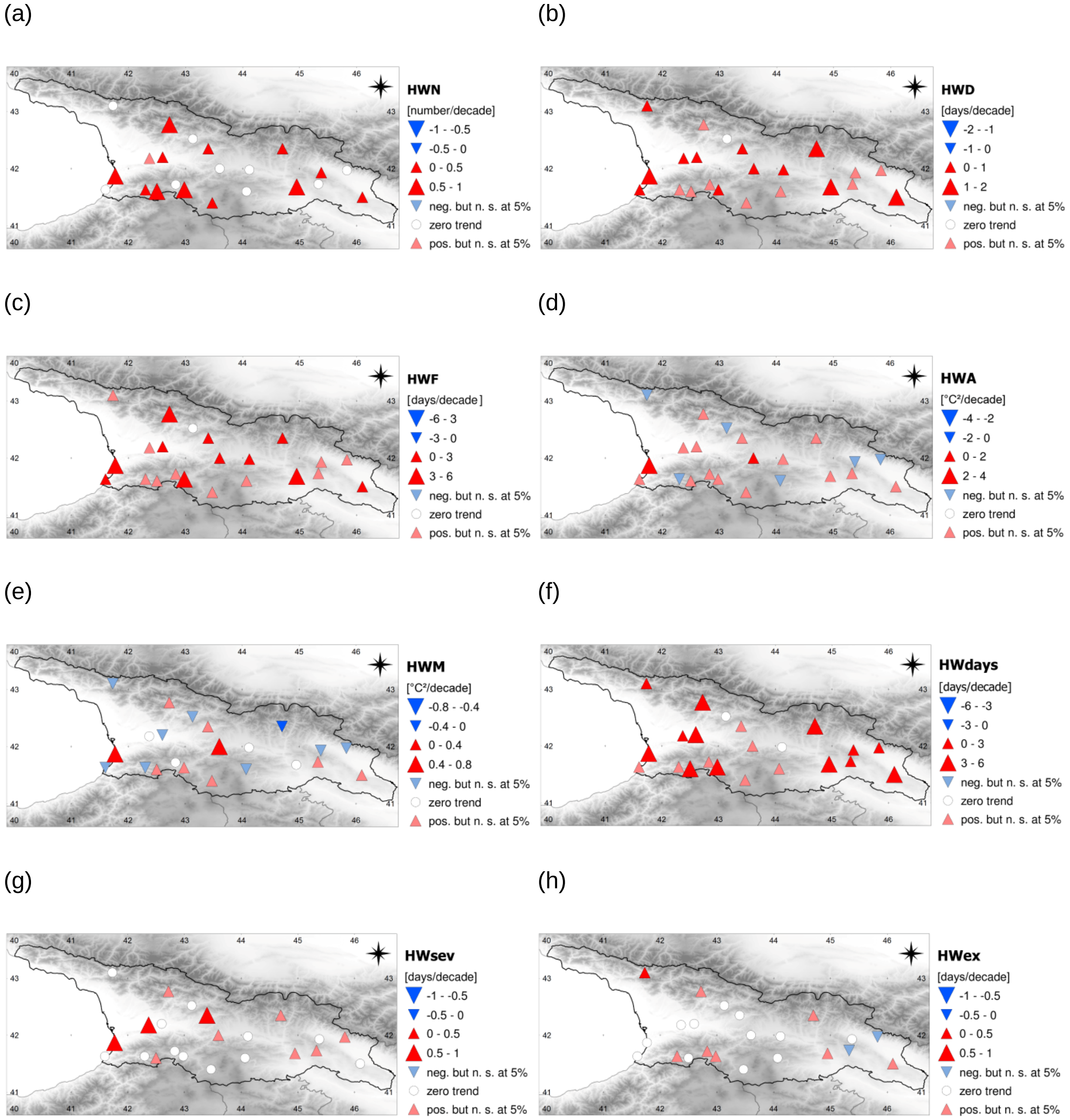

Figure 4: *Station trends of selected heat wave aspects over Georgia for the period 1961-2010: (a) Heat Wave Number (no. of events), (b) Heat Wave Duration (days), (c) Heat Wave Frequency (days), (d) Heat Wave Amplitude (°C²), (e) Heat Wave Magnitude (°C²), (f) Heat Wave Days (days) and (g) Severe Heat Wave Days (days) and (h) Extreme Heat Wave Days (days). Red triangles indicate warming trends, blue indicate cooling trends. Light blue and red triangles indicate trends not significant at the 5% level.*

As shown in table 3, heat wave trends for HWN measure a significant increase of 0.50 heat wave events/decade averaged over Georgia, regarding the heat wave index CTN90pct. However, for CTX90pct a significant trend at a rate of 0.41 events/ decade can be observed, suggesting that consecutive days of extreme high temperature maxima are less common over Georgia than consecutive nights of extreme temperature minima. Regarding the heat wave aspect HWD, a significant increase for both indices could be found, while CTN90p shows a higher trend magnitude averaged over Georgia (0.65 days/decade). Similar to results for the heat wave index EHF Georgia-averaged trends for HWF are of higher magnitude compared to HMN and HWD. CTN90pct measures a significant positive trend of 2.8 days/decade. For CTX90pct a lower trend of 1.8 days/decade can be observed. Also for HWA and HWM the index CTN90pct shows a higher trend magnitude throughout Georgia, than CTX90pct. CTN90pct-HWA and CTN90pct-HWM measure significant increasing trends of 0.53 °C/decade and 0.32 °C/decade, respectively. For CTX90pct-HWA and CTX90pct-HWM insignificant positive trends were observed.

Table 4: *Georgia-averaged trends in CTN90pct and CTX90pct between 1961 and 2010 with respective confidence intervals (95%). Trends significant at the 5 % level are indicated in bold and highlighted in green.*

Heat wave index*	HWN	HWD	HWF	HWA	HWM
CTN90pct	**0.50 (-0.2 to 0.4)**	**0.65 (0.2 to 1.2)**	**2.82 (1.0 to 4.7)**	**0.53 (0.2 to 0.9)**	**0.32 (0.1 to 0.6)**
CTX90pct	**0.41 (0.0 to 0.5)**	**0.62 (0.3 to 1.0)**	**1.80 (0.6 to 3.0)**	0.32 (-0.1 to 0.7)	0.24 (0.0 to 0.5)

* Units are number of events per decade (HWN); number of days/decade (HWD); days/decade (HWF); and °C/decade for HWA and HWM.

Figure 5 shows, that although the quantitative observations of the annual values and trend magnitudes vary for all three indices (Tab. 4), the annual time-series show qualitatively similar patterns among each of the three indices. A quantitative comparison cannot be conducted, due to the different number of stations used for the analysis on heat wave indices EHF and CTN90pct/CTX90pct.

(a) (b)

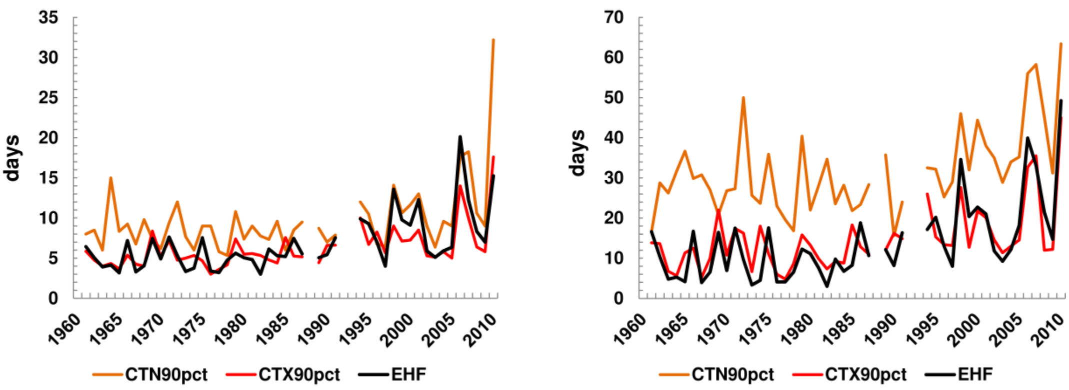

Figure 5: *Comparison of annual (a) Heat Wave Duration and (b) Heat Wave Frequency for heat wave indices EHF, CTN90pct and CTX90pct during the period 1961-2010.*

3.3 Severe Heat Waves over Tbilisi

In this section the climatology and changes in heat waves over Tbilisi station have been investigated, considering the city as an urban heat island. Moreover, the five most severe heat waves between 1961 and 2010 have been identified and illustrated.

Tbilisi experiences by far the highest trend magnitudes for all summer temperature variables analyzed compared to the Georgian mean as well as the surrounding stations (not shown). As shown in table 5, summertime minimum and maximum temperature averages 16°C and 27.4°C, respectively. The annual summer trends measure 0.32°C/per decade for Tmin and 0.38°/decade for Tmax. Comparing these trends with the surrounding neighboring stations (not shown) or the Georgian-averages for summertime temperature minimum (0.20 °C/decade) and maximum (0.31°C/decade), Tbilisi shows pronounced high trend magnitudes for Tmin and Tmax and a lower temperature variability. Moreover, for warm nights a much higher trend magnitude (3.4°C/decade) is observed during summer than for warm days. Also compared to its neighboring stations Tbilisi shows a higher trend magnitude (not shown). Regarding Tbilisi's heat wave climatology the city shows a HWN value of 0.7events/year, the mean heat wave duration measures 6.2days/year and 11.0 days participate in yearly heat wave events. The peak and mean magnitude for Tbilisi averages 8.2°C²/year and 3.2°C²/year, respectively. For the number of heat wave days a mean value of 10.9 days/year could be found, while the climatologies for severe heat wave days (extreme heat wave days) measure 1.2 days/year (0.1 days/year). While Tbilisi shows lower means for HWA and HWM, it demonstrates similar mean climatological values for HWN, HWday, HWsev and highly exceeds the Georgia-averages for the heat wave aspects HWD and HWF (Tab. 2 and 3).

Table 5: *Climatology and annual trends for summer Tmin and Tmax, temperature extremes and selected heat wave aspects at Tbilisi, 1961 and 2010. Trends and respective confidence intervals (95%) significant at the 5 % level are indicated in bold and highlighted in green.*

Parameter	Annual average (1961-1990)	Annual trend / decade
Tmin (°C)	16.0	**0.32 (0.22 to 0.43)**
Tmax (°C)	27.4	**0.38 (0.18 to 0.57)**
TN90p (°C)	10.3	**3.4 (2.3 to 5.0)**
TX90p (°C)	10.7	**2.7 (1.2 to 4.3)**
HWN (no. of events)	1.7	**0.7 (0.3 to 1.1)**
HWD (days)	6.2	**1.0 (0.3 to 1.8)**
HWF (days)	11.0	**4.3 (1.6 to 6.7)**
HWA (°C²)	8.2	0.9 (-0.2 to 2.2)
HWM (°C²)	3.2	0.0 (-0.4 to 0.5)
HWday (days)	10.9	**5.5 (2.8 to 7.1)**
HWsev (days)	1.2	**0.32 (0.0 to 1.1)**
HWex (days)	0.1	n/a

Figure 6 shows the annual numbers of heat wave days, severe and extreme heat wave days. It is notable that the largest proportion of low- and high-intensity heat wave days can be found in the last 20 decades. An increasing number of heat waves of 0.7 events/decade was observed, the heat wave length increased by 1.0 days/decade and the trend for HWF measured 2.9 days/decade. Also for HWA (0.9°C²/decade) and HWday (5.5.days/decade) Tbilisi station shows a higher trend magnitude, than the Georgia averages and its neighboring stations (not shown). However, for the number of severe heat wave days Tbilisi shows a slightly lower trend magnitude (0.32 days/decade) compared to the Georgia-average. For HWM there is a trend measured approximating zero. Due to the low number of extreme heat wave days distributed over 50 summers the trend magnitude for HWex was not denoted.

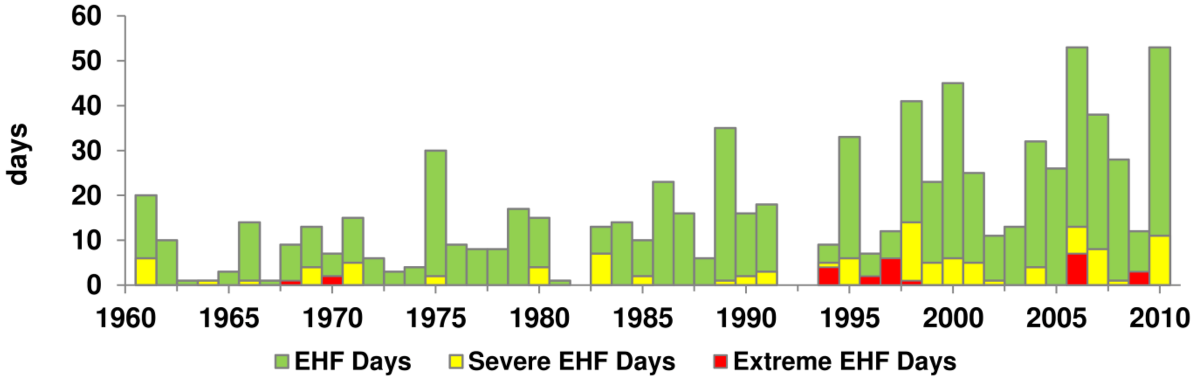

Figure 6: *The annual number of heat wave days (green bars), severe heat wave days (yellow bars) and extreme heat wave days (red bars) at Tbilisi station, 1961-2010*

Table 6 presents the five most severe heat wave events measured at Tbilisi station between 1961 and 2010 and their intensity (peak EHF value, °C²), EHF event duration (days) and accumulated heat load (°C²). The accumulated heat load is defined as the sum of the consecutive positive EHF values. By means of comparisons of international extreme heat wave events and their impacts, the peak heat load (highest EHF value) over a station's severe EHF threshold represents the most crucial indicator determining the severity of a single station heat wave [1, 25].

Table 6: *Top ranked severe heat waves measured at Tbilisi station during 1961 and 2010 listed by year: Rank, peak day of event (Date), peak EHF value (°C²), accumulated and average heat load (°C²) and EHF event duration (days). Tbilisi's severe EHF threshold accounts for 7.06 (°C²)*

Year	Rank	Date	Peak EHF (°C²)	Heat load (°C²)	Average heat load (°C²)	EHF event duration (days)
1971	2	May, 6	26.1	78	12.9	6
1995	3	May, 24	23.7	103	12.9	8
1997	5	May, 10	17.9	57	11.3	5
1998	4	Aug, 31	20.1	147	10.5	14
2007	1	May, 28	36.9	203	20.3	10

It is notable that during 1961 and 2010 four of five top-ranked severe heat wave events were found in the second half of the analysis period. The highest peak EHF value observed was measured between 25th May and 3rd June, 2007. The EHF value of 36.9°C² is over six times the magnitude of Tbilisi's severe EHF threshold (7.1°C²), which classifies this heat wave as an extreme event. The high average heat load and EHF event duration of 8 severe days result in a huge accumulated heat load (203 °C²) and impose high amplitudes of heat stress on the population, and other affected sectors (Fig. 7a). The 1971 EHF time series shows Tbilisi's second ranked extreme heat wave. The peak magnitude for this event is almost 4 times the severe EHF threshold (26.2°C). Figure 7(b) shows a short period of positive EHF values with a relatively high average heat load of 12.9°C² during the heat wave. The third ranked peak heat load observed (23.7°C²) was measured in May 24th, 1995 and is over three times the magnitude of Tbilisi's severe EHF threshold. It was found among six severe heat wave days (Fig. 7c). The fourth highest classified heat wave event observed at Tbilisi station occurred in August 1998. The event peak of 20.1°C is six to seven times the magnitude of Tbilisi's severe EHF threshold (Tab. 6) and is one of 14 heat wave days and nine consecutive severe EHF days (not shown). The fifth ranked peak EHF event of 17.9°C² exceeds the station's severe EHF threshold by circa 2.5 times.

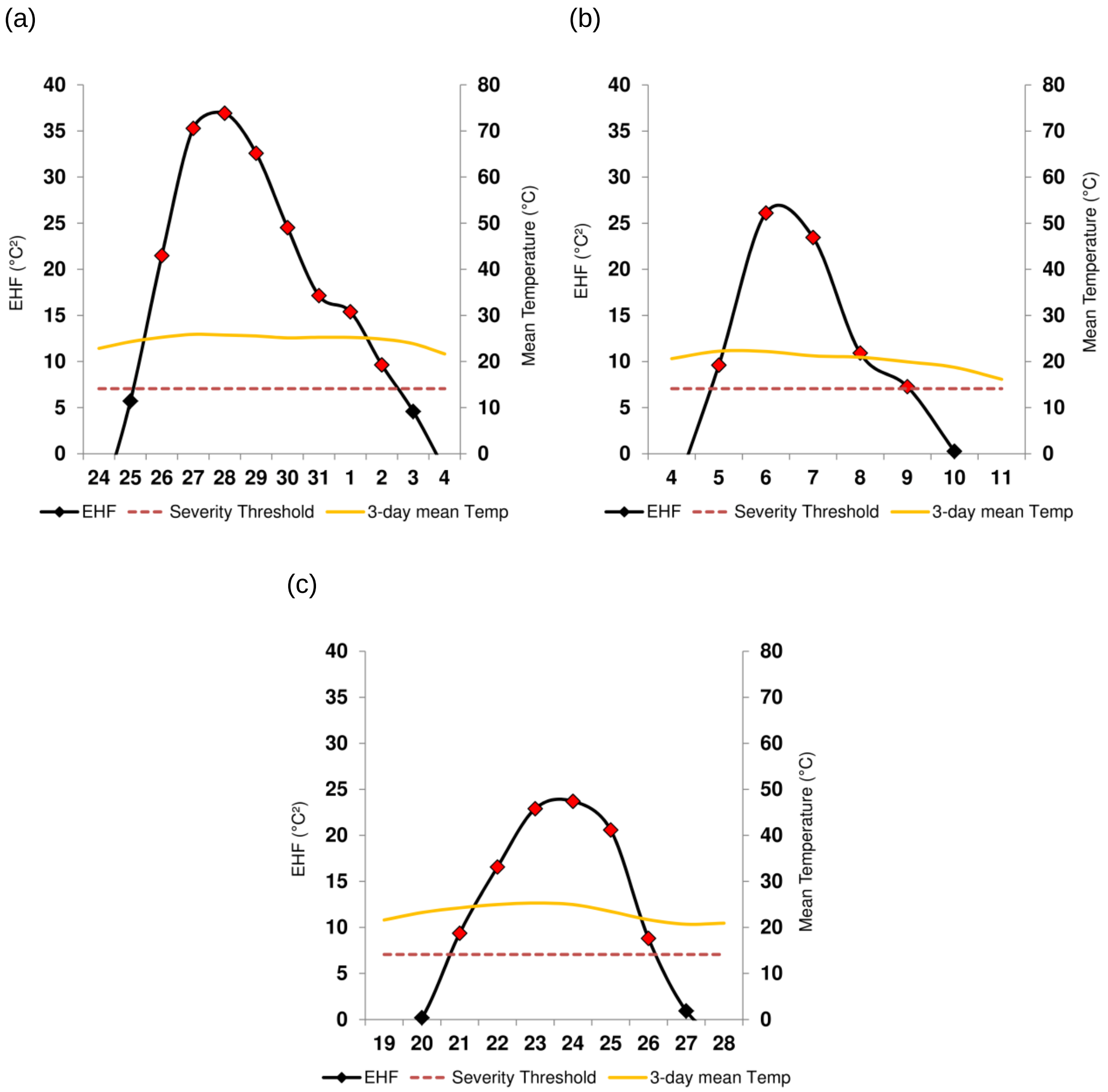

Figure 7: *The three most severe summer heat wave events over Tbilisi during 1961 and 2010: Observed daily EHF values and severity threshold (dashed red line) during May 2007 (a), May 1971 (b) and May 1995 (c). Red dots indicate EHF values above the station's severity threshold (EHF= 7.06°C²). The three-day-averaged daily mean temperature (yellow line) is superimposed.*

4. Discussion and Conclusions

This study analyzed climatology and changes in summer heat wave events over Georgia since the 1960s using a new dataset of daily minimum and maximum temperature series. The data was carefully quality controlled and homogeneity was tested using the software RClimDex 1.1. Metadata could be used to identify the date of breakpoints in a time-series. Inhomogeneous time-series could be adjusted using RHVtest 4. For the investigation of heat wave climatology, changes and single severe single heat waves over Georgia and at Tbilisi station the Excess Heat Factor was, chosen a combined indicator of excess heat and heat stress and comparative a measure of intensity, load, duration and spatial distribution of a heat wave event. The EHF was analyzed with respect to eight heat wave aspects: the yearly number of heat waves (HWN), length of the longest yearly event (HWD), the yearly sum of participating heat wave days (HWF), the hottest day of hottest yearly event (HWA), and the average magnitude of all yearly heat waves (HWM). Three new heat wave aspects have been applied to the study: the number of heat wave days (HWday), the number of severe heat wave days (HWsev) and extreme heat wave days (HWex) to allow a differentiated assessment of the spatial and temporal characteristics of low-intensity, severe and extreme heat waves. Severe and extreme heat waves have been detected applying a threshold, the 85th percentile of the distribution of positive EHF values, to each station. This multi-aspect heat wave analysis provides a more profound study of heat wave changes in Georgia than carried out in previous scientific studies. Next to EHF, the heat wave indices CTN90p and CTX90p were used to study heat wave aspects regarding temperature minimum and maximum series separately.

The study could improve the understanding in the spatial and temporal characteristics and changes in past summer heat wave events over Georgia. Climatologies across the study area show clear patterns for most of the heat wave aspects. Stations with highest climatological values for HWD, HWF and HWday are located in the Southeast. Highest values for mean HWA and HWM are found in the Southwest of the study area. For HWsev and HWex both regions demonstrate highest climatological values. For all aspects lowest heat wave impacts can be expected in central Georgia. The seasonal distribution of HWday, HWsev and HWex between 1961 and 2010 implies the occurrence of highest heat wave intensities in May and September. Highest numbers of high-intensity heat wave days are measured in May, while most low-intensity heat wave days can be found during August. Regarding changes in heat wave events almost all heat wave aspects analyzed based on the indices EHF, CTX90pct and CTN90pct show significant increasing trends in the Georgia-average. However, HWA and HWM show predominantly insignificant and only small changes during the analysis period. HWday and HWF show by far the largest trend magnitudes across all heat wave indices studied (EHF, CTN90pct and CTX90pct), which is consistent with findings of [11, 18], stating that occurrence-based heat wave aspects possess larger trend magnitudes. They also found that the high magnitudes of trends for HWF are driving increases in HWN and HWD, due to the fact that the overall number of heat waves (and their duration) will increase when the number of participating days increases. Spatial patterns of trends over Georgia are difficult to assess, which can be attributed to the moderate data quality of several time-series. Nevertheless, it is notable that for the heat wave aspects HWN, HWF, HWD and HWday the highest proportion of increasing station trends can be observed in the Southeastern and Southwestern region of Georgia. Tbilisi station experienced a pronounced increase in the intensity, frequency and duration of heat waves during 1961 and 2010 compared to the Georgian-average and its neighboring stations. This result corresponds well with findings by [27-30] projecting an increasing number of heat wave events in the EMME region, particularly in urban areas. Including the strong increase in extreme warm night-time temperatures, these results could be explained by the UHI effect, the enhanced heat absorption and storage in sealed surface during the day and the slow release at night, and combined interactions between heat waves and urban heat islands [26, 46]. The most severe summer heat waves in Tbilisi have been identified in the years 1971, 1995, 1997, 1998 and 2007. Comparing the indices CTN90pct and CTX90pct, it is shown, that all trends for Tmin (night-time) based events over Georgia increase faster than for days-time events, which corresponds to global heat wave observations [11] and changes for extreme Tmin and Tmax events [16, 32, 47-49]. These findings highlight the importance of selecting the appropriate index related to the most affected sector investigated. Heat wave studies based on minimum temperature rather consider impacts on sectors, such as agriculture, whereas temperature maximum-based heat wave indices are appropriately used to determine impacts on infrastructure. However, for investigations on power consumption and human health impacts a heat wave index based on a combination of minimum and maximum temperature might be the most suitable choice. In order to obtain a more detailed insight in the connections of large-scale drivers on the occurrence of heat waves, a further study on contributions of land-atmosphere coupling and large-scale atmospheric circulation over the Caucasus region is necessary.

Appendix

Table 7: *Stations used for the heat wave analysis with station names, WMO code, station coordinates, altitude and the temperature series used in this study*

Station name	WMO code	North latitude	East longitude	Altitude (m)
Abastumani	37503	41.72	42.83	1265
Ahalcihe	37506	41.63	42.98	982
Akhalkalaki	37602	41.40	43.47	1716
Ambrolauri	37308	42.52	43.13	544
Batumi	37484	41.63	41.60	32
Dedopliskaro	37651	41.50	46.10	800
Goderdzi Pass	37507	41.60	42.50	2025
Gori	37531	41.98	44.12	590
Kashuri	37417	42.00	43.60	690
Khulo	37498	41.63	42.30	946
Kobuleti	37481	41.87	41.77	7
Kutaisi	37395	42.20	42.60	116
Kvareli	37563	41.97	45.83	449
Lentekhi	37295	42.77	42.72	731
Pasanauri	37432	42.35	44.70	1064
Sachkere	37403	42.35	43.40	455
Sagaredjo	37556	41.73	45.33	806
Samtredia	37385	42.18	42.37	26
Tbilisi	37546	41.68	44.95	427
Telavi	37553	41.93	45.38	562
Tsalka	37537	41.60	44.07	1458
Zemo-Azhara	37196	43.10	41.73	2037

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Severe summer heat waves over Georgia: Trends, Patterns and Driving Forces

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Abstract

During the last 50 years Georgia experienced a rising number of severe summer heat waves causing increasing heat-health impacts. In this study, the 10 most severe heat waves between 1961 and 2010 and recent changes in heat wave characteristics have been detected from 22 homogenized temperature minimum and maximum series using the Excess Heat Factor. A composite and canonical correlation analysis have been performed to study summer heat wave patterns and their relationships to the selected predictors: Mean Sea Level Pressure, Geopotential Height at 500mb, Sea Surface Temperature, Zonal and Meridional Wind at 500mb, Vertical Velocity at 500mb, Outgoing Longwave Radiation, Relative Humidity, Precipitation and Soil Moisture. Most severe heat events during the last 50 years are identified in 2007, 2006 and 1998. Largest significant trend magnitudes for the number, intensity and duration of low and high-impact heat waves have been found during the last 30 years. Significant changes in the heat wave predictors reveal that all relevant surface and atmospheric patterns contributing to heat waves have been intensified between 1961 and 2010. Heat wave patterns provide evidence of a large anticyclonic blocking over the southern Ural Mountains, which attracts warm air masses from the Southwest, enhances subsidence and surface heating, shifts the African Intertropical Convergence Zone northwards, and causes a northward shift of the subtropical jet. Moreover, pronounced precipitation and soil moisture deficiency throughout Georgia contribute to the heat wave formation and persistence over Georgia. Due to different large- to mesoscale circulation patterns and the local terrain, heat wave effects over Eastern Georgia are dominated by subsidence and surface heating, while convective rainfall and cooling are observed in the West.

1. Introduction

Anthropogenic influences on climate since the mid-20th century resulted in a change of frequency and intensity of daily temperature extremes and doubled the probability of occurrence of heat waves in some regions of the world (Beniston and Stephenson, 2004; Stott et al., 2004; Jones et al., 2008; Christidis et al., 2011; Christidis et al., 2012; IPCC, 2014). The fact that the global averaged heat waves are projected to increase in frequency, intensity and duration (Meehl and Tebaldi 2004; Perkins et al., 2012) makes it important to investigate their driving mechanisms with special regards to large-scale atmospheric circulation, land-sea interactions and regional processes.

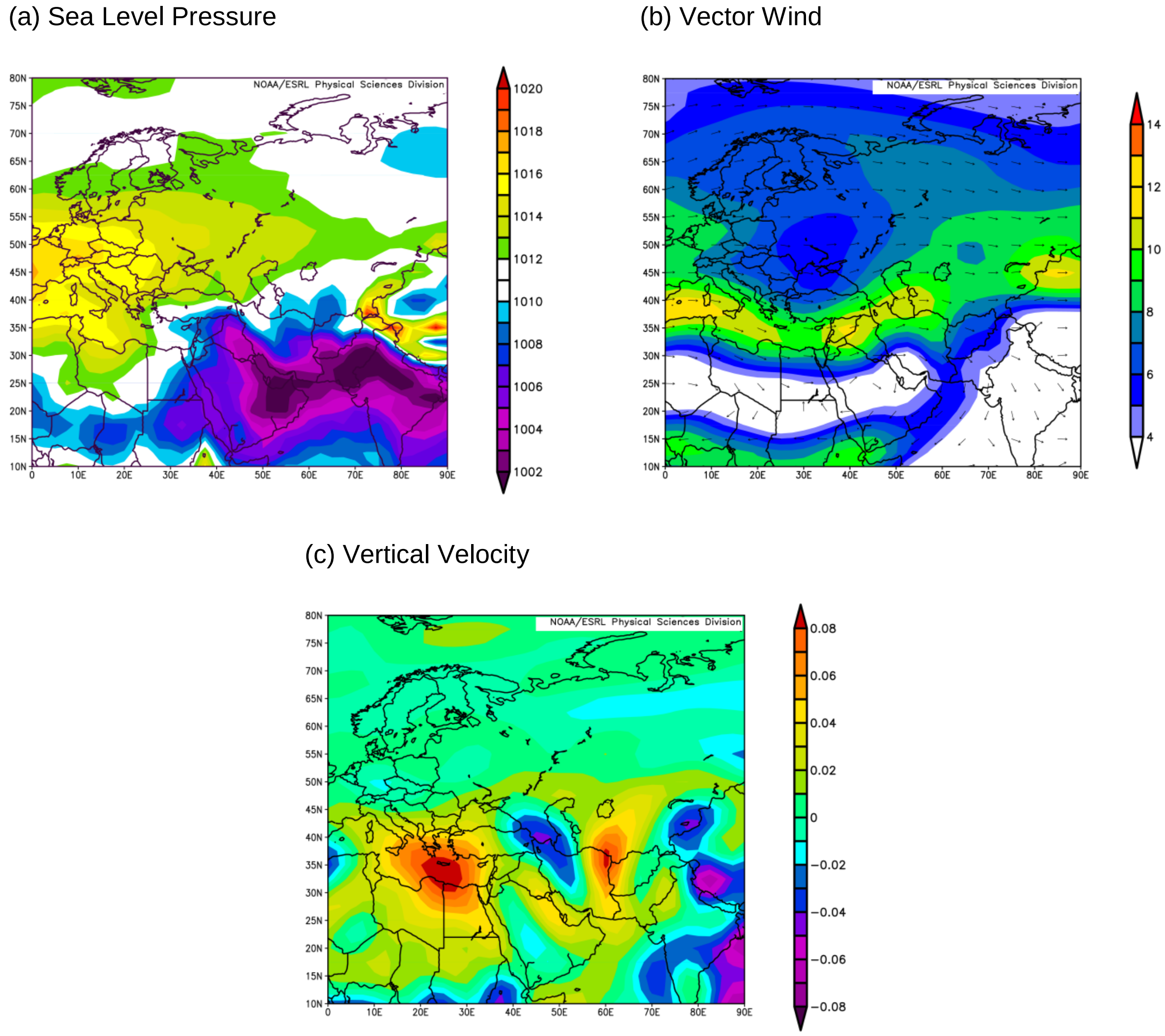


Figure 1: *Averaged atmospheric patterns over Eurasia during summer 1981 to 2010: Composite means for summer (a) Sea Level Pressure (mb) (b) Vector Wind (VW500, m/s), and (c) Vertical Velocity (Pa/s)*

Heat wave patterns in Georgia are highly dependent on the large scale synoptic, thermic patterns and the local terrain. Temperature tends to increase eastwards with increasing continentality in combination with a decrease in precipitation. The Stavropol upland in the Caucasus Foreland and the Surami Ridge in Transcaucasia form important climatic divides. The air, advected by depressions from the Black Sea, loses most of its moisture over the

Colchis lowland and, having crossed the Surami Ridge, descends in the Kura lowland as a dry airflow. The summer circulation patterns over Georgia are influenced by a subtropical high pressure in the west and the Asian depression in the east (Ziv et al., 2004; de Vries et al., 2013). The lower levels are dominated by the so-called “Red Sea trough” and the “Persian trough”, surface low-pressure troughs that extends from the Asian monsoon across the Red Sea and Persian Gulf to southern Turkey (Fig. 1a). As a result of the Red Sea and Persian trough and the subtropical anticyclone of the Atlantic (Azores), northwesterly winds blow over the Black Sea. In accordance with Arkhipkin (2014) these winds yield a continual cool advection from Eastern Europe, as seen in the average wind fields (Fig. 1b). In addition, Georgia is dominated by summer convection centered over the Armenian-Dzavakhetian volcanic plateau as shown in the low vertical pressure velocity field (Fig. 1c). The Greater and Southern Caucasus block northwesterly winds from the East European plain and orographic convection is induced followed by low to heavy precipitation events at the windward slopes of the high mountain ridges.

The Caucasus represents one of world’s hot spots most vulnerable to climate change (Shahgedanova, 2002). According to findings by Keggenhoff et al. (2014) Georgia experienced pronounced warming trends in temperature extremes and a decrease in wet days (R ≥ 1mm) during 1971 and 2010. Since 1960s, monthly minimum and maximum temperature increased by 0.22 and 0.36 °C, respectively, while warm extremes show larger trends than cold extremes. The trend for warm spells was observed to be significantly increasing by 1.7 days (Keggenhoff et al., 2015a). Future climate extreme projections by Lieferheld et al. (2012; 2013) show a pronounced increase in summer temperature projected by the end of the 21st century (relative to the 1961-1990 period), especially for temperature maxima (by over 6°C) over the western part of Georgia. The number of dry days will increase significantly in Eastern Georgia between the projection period 2040 to 2069. However, for Western Georgia a negative trend for the number of dry days is projected.

Heat waves are among the most threatening meteorological hazards related to global warming posing impacts to society, economy and ecology. Heat-related morbidity and mortality in Georgia is expected to increase due to significant positive trends in the intensity, frequency and duration of heat waves during the last 50 years (Keggenhoff, et al., 2015b). The magnitude of heat wave impacts may be changing related to the vulnerable sectors affected, particularly to those exposed through poor health and low and high age (Basu and Samet, 2006). The rapid increase of the population and urbanization in Georgia and its strong dependence on agricultural production might amplify these negative heat-health impacts (UNDP, 2015). Yet, heat-health is an under-reported sector in Georgia with economic consequences that are currently difficult to assess.

Excess mortality has been observed during several heat wave events over the last five decades (Semenza, et al., 1996; Changnon et al., 1996; Nairn, 2011, Nairn and Fawcett, 2013; Langlois, 2013). In the present study the heat wave index based on the Excess Heat Factor is used to investigate heat wave changes during the last 50 to 30 years and to identify high-impact heat waves over Georgia and their patterns using daily composites. The Excess Heat Factor (EHF) considers the local geographic acclimatization to temperature, the total heat load, and the recent deviation in temperature from mean temperature (Nairn, 2011; Nairn and Fawcett, 2013; Nairn et al., 2015). Next to maximum temperature, the increase in morbidity and mortality is sensitive to high minimum temperatures. Minimum temperature, which is dissipated precedent to a very hot day, determines the accumulating daytime thermal load impacting vulnerable people and systems (Pattenden et al. 2003, Nicholls et al.

2008). In general, the health effect may be induced by both, a combination of high intensity maximum and minimum temperature and long heat wave duration (Nairn et al., 2015).

The frequency, duration and intensity of heat wave events is usually linked to large-scale atmospheric blocking patterns enhancing Sea Surface Temperature, solar radiation and heat flux anomalies due to reduced cloudiness and/or antecedent precipitation and soil moisture deficiencies. The core mechanisms for heat accumulation are (1) advection from lower latitudes, (2) large-scale subsidence transporting higher potential temperature air from upper levels, or (3) surface heating, development of the diurnal mixed layer, and replacement from below by the new mixed layer for the successive day (McBride et al., 2009). A growing number of studies have investigated the mechanisms that contribute to the formation and prediction of heat wave events using the example of high-impact events in Eurasia, such as the 2003 European heat wave (Black et al. 2004; Fink et al. 2004; Ogi et al. 2005; Trigo et al. 2005, Ferranti and Viterbo, 2006; Jung et al., 2006; Fischer et al., 2007; Black and Sutton, 2007; Feudale and Shukla, 2011a, b), or the 2010 Russian heat wave (Barripedro et al., 2011; Dole et al., 2011; Grumm, 2011). Most studies relate heat wave events to anticyclonic circulation anomalies, leading to enhanced heat advection, adiabatic heating by subsidence and solar radiative heating due to reduced cloudiness (Black et al. 2004; Meehl and Tebaldi, 2004; Fink et al. 2004; Della-Marta et al., 2007; McBride et al., 2009; Cassou et al., 2005; Carril et al., 2008; Stefanon et al., 2012; Pfahl and Wernli, 2012; Zittis, et al., 2014). Next to synoptic features Sea Surface Temperature (SST) anomalies (Jung et al. 2006; Black and Sutton 2007; Della-Marta et al., 2007; Feudale and Shukla 2011a and b), precipitation and soil moisture deficiencies can represent crucial driving forces contributing to current and future heat wave events (Ferranti and Viterbo 2006; Fischer et al. 2007; Zampieri et al., 2009; Seneviratne et al., 2010, Hirschi et al., 2011; Jäger and Seneviratne, 2011; Müller and Seneviratne, 2012; Quesada et al., 2012, Stefanon et al., 2014; Zittis et al., 2014).

Current scientific literature investigated relationships between heat wave events and their mechanisms of formation and prediction, using the example of selected patterns or in the context of single heat wave events. Moreover, most papers focus on large study areas, excluding regional aspects of relationships between heat waves and their driving forces. Due to the fact that observation data for Georgia is difficult to access and the country is located at in a transition zone between Europe and Asia and common study areas, such as the Mediterranean and the Eastern Mediterranean and Middle East (EMME) Region, Georgia is often marginalized in study domains. The aim of this study is to quantify summer heat wave changes and variability over Georgia and to provide a comprehensive understanding of their forcing mechanisms. In Sect. 2 data and methods utilized are presented. Sect. 3.1 demonstrates major severe summer heat wave identification. Sect. 3.2 presents the climatology and trends in the summer heat wave number intensity, duration and their potential forcing predictors during the analysis periods 1981 to 2010 and 1961 to 2010. In Sect. 3.3 results on heat wave patterns from daily composites and a canonical correlation analysis (CCA) are discussed. Section 4 summarizes results and the conclusions of the study.

2. Data and methods

2.1 Observation data

For the heat wave trend and identification analysis 22 daily minimum and maximum temperature series covering the period 1961 to 2010 have been used (Fig. 2). Data and Metadata for homogenization adjustment was kindly provided by the National Environmental Agency of Georgia. The analysis period 1961-2010 was chosen to study changes in heat wave characteristics under anthropogenic influenced climate conditions as well as to optimize the number of stations available and spatial coverage. The stations are well distributed over Georgia.

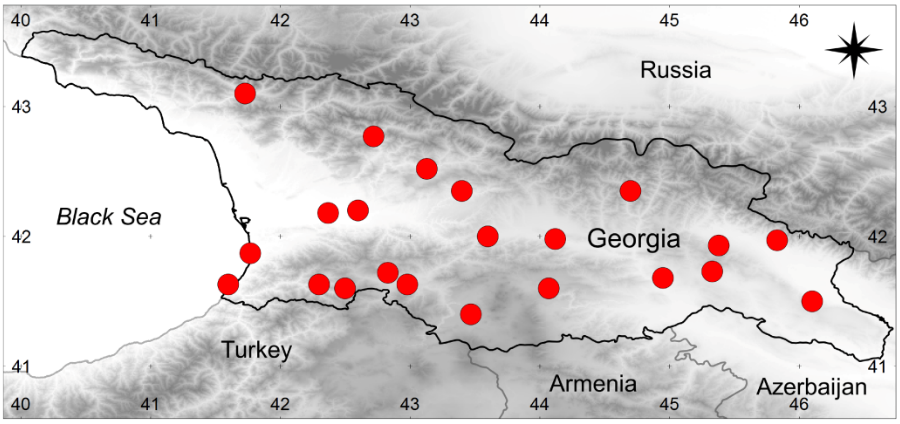


Figure 2: *Temperature stations over Georgia used in this study*

During 1988, 1992 and 1993 data availability for observation data records was very low and had to be rejected from the analysis. Data quality control has been carried out using the computer program RClimDex Software version 1.1 available on http://etccdi.pacificclimate.org. 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 summer value is calculated if all months are present (May to September); (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. In order to test data homogeneity and to adjust significant breakpoint, the software package RHtestV3 was used. It has been developed in order to detect and adjust multiple breakpoints in a data series with noise that may or may not have first order autocorrelation (Wang and Feng, 2010, Wang, 2015). Details on quality control, homogeneity testing and adjustment procedure and parameter usage during the QM adjustment procedure are stated in Keggenhoff et al. (2015a).

2.2 Reanalysis data

Reanalysis data is used to detect spatial and temporal absolute differences and trends and to examine the dynamical evolution and features associated with heat waves over Georgia and Eurasia. Data was provided by the National Centers for Environmental Predictions-National Center for Atmospheric Research (NCEP-NCAR) and Kalnay et al. (1996). For Sea Surface Temperature (SST) the Reynolds Optimum Interpolation (OI) Analysis V2 data-set is used (Reynolds et al. 2002). The NCEP-NCAR records are archived in grids of a resolution 1.88º × 1.88º, the spatial resolution of the SST reanalysis data measures 1.00° x 1.00°. The reliability of the NCAP/NCAR temperature data was verified correlating the reanalysis data with the observed data (Pearson correlation). Between 1961 and 2010 the mean summer temperature for the field 39.9-46.9°E / 40.9-43.7°N correlates very well with the mean temperature (r: 0.76) from the observational data. For Tmax and Tmin the correlation coefficient measures 0.67 and 0.77, respectively.

2.3 Heat wave identification and severity classification

For generating daily composites for major extreme heat wave days this study uses the heat wave index based on the EHF as defined by Nairn (2011). The EHF was calculated using the *Clim*PACT software, a R-based software. It includes both, daily maximum and minimum temperature series and incorporates the effect of humidity on heat tolerance indirectly, by using the mean, rather than the maximum daily temperature, in the calculation. EHF values are calculated from a three-day mean of forecast temperatures to derive an index of heat wave severity. Two sub-indices are combined to produce the complete EHF index. The first is a measure of significant excess heat relative to local climatic conditions, the 95th percentile of mean temperature conditions:

$$EHI_{sig} = (T_i + T_{i+1} + T_{i+2})/3 - T_{95} \;, \qquad (1)$$

The second sub-index is a measure of short-term acclimatization to heat, relative to the mean temperature of the previous 30 days (EHFaccl):

$$EHI_{accl} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \ldots + T_{i-30})/30 \;, \qquad (2)$$

These two indices are combined to generate the EHF index. The unit of EHF is °C²:

$$EHF = EHI_{sig} \times max\,(1, EHI_{accl}) \qquad (3)$$

The EHF provides a comparative measure of intensity, load, duration and spatial distribution of a heatwave event and has a strong signal-to-noise ratio. According to Collins et al. (2000) and Pezza et al. (2012) the definition of the heat wave index comprises three or more consecutive days above positive EHF conditions. The magnitude of heat-health impacts caused by heat waves is indicated foremost by the peak heat load (°C²) of a heat wave (Nairn and Fawcett, 2013). To distinguish between EHF days, severe and extreme heat wave days during 1961 and 2010 the severe EHF threshold for each station has been included in the analysis, which is calculated according to Nairn and Fawcett (2013). Severe heat waves are defined by an event where EHF values exceed a threshold for severity that is specific to the climatology of each location. The severe EHF threshold is calculated empirically as the 85th percentile of the distribution of positive EHF values (EHF_{85}) based on the observation record at a given location. This method ensures that all EHF values are truly representative of each site's climatology and avoids potential errors by modelling a distribution. Extreme Heatwaves are defined as an event where EHF values are well in excess of the severity threshold and result in a wide impact based on a cascade of failing systems. According to Nairn et al. (2015), extreme heat waves are detected if an EHF value during a heat wave at least triples the station's severity threshold ($EHF \geq 3 \times EHF_{85}$). The resulting heat wave aspects: HWday – the number of heat wave days (days with positive

EHF value), HWsev – the number of severe heat wave days and HWex – extreme heat wave days enable to differentiate between heat waves with low to high heat-health impacts based on their exceedance of a station's severe EHF threshold. The heat wave aspects are calculated annually over a 5-month summer, which is defined as a period from May to September (153 days). In order to identify the major single heat wave days for the daily composite analysis extreme EHF values are classified as heat wave classes (HW class), depending on the difference between an EHF value and the respective station's severe threshold. In the present study all extreme EHF values could be classified into five different classes (HW class 2 to 6) with a maximum heat wave class of six. The 16 major heat wave days between 1961 and 2010 over Georgia were detected selecting all heat wave days equal or above heat wave class 4 ($EHF \geq 4 \times EHF_{85}$). All identified heat wave days are listed in the Appendix.

Mean absolute differences (subtracting the period 1961-1990 from 1981-2010) and trends between the periods 1961-2010 and 1981-2010 have been detected for observed heat wave events and the selected predictand and predictor variables. Observed heat wave events have been calculated for four heat wave aspects: HWN – the yearly number of heat waves, HWD – the length (in days) of the longest yearly event, HWF – the sum of participating heat wave days per year, and HWex – extreme heat wave days. Throughout the analysis, monthly mean data for summer months (May to September) are used. All trends were calculated by the non-parametric Sen's slope estimator based on Kendall's tau (τ) (Sen, 1986). Observed trends are calculated as the arithmetic average of the summer index values of stations with more less than 20% missing data. The annual slopes of trends were converted into slope per decade. The statistical significance has been estimated using the Mann-Kendall test and the statistical significance level of the 5% has been used (Mann, 1945; Kendall, 1975). In this study any use of the word ''significant'' implies statistical significance at the 5% level.

2.4 CCA and composite analysis

The statistical relationship between predictor and predictand variables ususally is a linear regression relationship. In order to investigate the relationship between Georgian summer heat waves and synoptic to meso-scale patterns over Eurasia, a CCA was performed. CCA is a common multivariate statistical technique in meteorological and climate science to find linear combinations of two sets of variables such that the linear combinations have the maximum possible correlation (Barnett and Preisendorfer, 1987, Bretherton et al., 1992, Cherry, 1996). The maximization is carried out under orthogonality constraints on the coefficients of the linear combinations. CCA has been used in various studies (e.g. Xoplaki et al., 2003a, b, Haylock and Goodess, 2004, Luterbacher et al., 2009). During data preparation monthly mean anomalies are calculated by subtracting the long-term mean of a calendar month from each individual monthly mean, giving all grid points equal weight. Moreover, a long-term linear trend in the time series is removed. Using Principal Component Analysis (PCA) the predictor and predictand were dimensionally reduced to a number of selected Principal Components (PCs) in order to identify the dominant patterns of variability in each field that account for the most variance (Bretherton et al. 1992, Mo and Straus 2002). Both, the CCA and PCA were performed using a Singular Value Decomposition (SVD) using the KNMI Climate Explorer (http://climexp.knmi.nl). The correlation of the canonical score series of the two variables measures the intensity in the relationship between the pairs. In this study, the 95th percentile of mean temperature (Tmean95p) is used as heat wave predictand derived from daily NCEP/NCAR reanalysis data. It includes both, daily minimum and maximum temperature series and incorporates the effect of humidity on heat tolerance indirectly, by using the mean, rather than the maximum daily temperature, in the calculation. The 95th percentile threshold was chosen as a measure of extreme heat. Data availability ensures a high number of heat days per summer month. As predictors summer Mean Sea Level Pressure (SLP), Geopotential Height at 500mb (Z500), Zonal (u-wind500) and Meridional Wind at 500mb (v-wind500), Vertical Velocity at 500mb (O500), Outgoing Longwave Radiation (OLR), Relative Humidity at 500mb (RH500), Total Precipitation (RR) and Soil Moisture Fraction (SM) were used based on gridded NCEP-NCAR data have been used. The research domain for the predictors is defined as the area between 0 and 90°E and between 10 and 80°N. The predictand variable focuses on Georgia with the domain located at 39.9° to 46.9°E and 40.9° to 43.7°N. Features in the daily composite anomaly plots take into account the physical realism as they are based on observation data, whereas the derived CCAs are statistically built. To examine the observed features associated with the CCA patterns, daily composite plots are conducted, since the CCA may yield unstable solutions (Della-Marta et al., 2007). Daily composites are constructed for the heat wave predictand and the ten selected predictors based on the 16 major heat wave days observed over Georgia listed in the Appendix.

3. Results and discussion

3.1 Heat wave identification

A heat wave is defined as a period of three or more consecutive days above EHF conditions. All station heat waves during 1961 and 2010 have been identified and their duration (days), heat load (°C²) and accumulated heat load (°C²) have been determined. According to Nairn and Fawcett (2013) the heat load of a heat wave is defined as the mean all EHF values of a heat wave. The accumulated heat load represents the sum of all EHF values of a heat wave. In the present study most severe heat waves have been ranked by their Georgia-average accumulated heat load considering the average duration of a heat wave and its heat load as their product. Table 1 lists the 10 summers with the most severe heat wave events over Georgia since 1961. It describes the rank, the date of the peak EHF (Date), the duration (days), intensity (°C²) and the accumulated heat load (°C²) averaged over the all stations analyzed, respectively. Heat waves with a mean accumulated heat load of less than 15°C² were not listed.

As shown in table 1 only two heat waves (June 1966 and 1969), which are among the ten most severe heat waves, occurred before 1990. Major heat waves observed after 1990 comprise the highest ranked accumulated heat loads, heat loads, lengths and number of occurrence. The three most severe heat waves identified occurred in May 2007, in August 2006 and in June, 1998 and agree with the most fatally heat waves reported by EM-DAT for the region (The International Disaster Database, www.em-dat.be). The highest Georgia-averaged accumulated heat load (200°C²) was observed for the severe heat wave in May 2007. The mean heat load of this event was the highest measured during 1961and 2010 (20.0°C²), although the mean duration for this heat wave is mid-ranged (10 days), implying strong health impacts by a high intensity of heat load. All stations analyzed have been affected by this event and at the same time show extraordinary high peak EHF values of up to 57.5°C² (HW class 6). The second ranked heat wave was observed during mid- August. It shows an extraordinary long averaged duration of 18 days, resulting in a mean accumulated heat load of 127°C². At the same time the mean heat load (7.1 °C²) is relatively mid-ranked. The heat wave is closely followed by another severe heat wave, which is ranked 7, implying strong heat impacts caused by the long averaged duration of both events and their close occurrence. For the third most severe heat wave identified (June, 1998) a mean accumulated heat load of 114°C² was determined. Both, the event's averaged duration (14 days) and the averaged heat load (8.4°C²) are clearly above average values and the proportion of affected stations is very high, which results in a high averaged accumulated heat load. This heat wave was observed among four other summer heat waves in 1998, which is – next to 2010 – a year with the highest count of summer heat waves measured.

Table 1: *The 10 most severe heat waves over Georgia between 1961 and 2010. Heat waves are characterized by their year of occurrence, rank, date of the peak EHF (Date), duration (days), intensity (°C²) and accumulated heat load (°C²).*

Year	Rank	Date of Peak EHF	EHF event duration (days)	Heat load (°C²)	Acc. heat load (°C²)
1966	9	June, 7	5	10.8	55
		July, 27	5	5.0	25
1969	6	June, 9	7	9.9	70
1995	5	May, 24	8	10.3	81
1998		May, 6	3	10.7	33
	3	June, 22	14	8.4	114
		July, 31	5	3.5	17
		August, 30	7	6.7	49
		September, 16	8	3.0	25
2000		July, 22	7	7.7	52
	8	August, 1	7	8.5	57
2001		June, 15	1	12.2	17
	4	July, 24	15	6.3	94
		August,14	4	3.8	15
2006		June, 5	5	6.0	32
	2	August, 14	18	7.1	127
	7	August, 29	14	4.3	61
2007	1	May, 28	10	20.0	200
		August, 1	5	4.0	21
		August, 13	6	2.9	18
		September, 6	9	2.3	21
2010		June, 6	4	11.0	47
		June, 15	6	5.6	35
	10	July, 12	12	4.6	55
		August, 2	13	4.0	50
		September, 2	9	2.3	20

3.2 Climatology and heat wave changes

3.2.1 Observed long-term trends

In this section the climatology and recent changes in observed summer heat waves during the periods 1961 and 2010 and 1981 and 2010 are investigated. As shown in table 2, the absolute Georgia-average for HWN (the number of heat wave events) amounts to 1.7 events/year and shows a significant increasing trend of 0.4 events/decade. HWD (the length of the longest yearly heat wave event) measures 5.5 days/year in the Georgia-average and a significant positive trend of 0.9 days/decade is found. The Georgia-average for HWF (yearly sum of participating heat wave days) measures 10.4 days/year. Similar to HWN and HWD, no decreasing station trend could be observed throughout Georgia (not shown). The Georgia average trend amounts to 2.9 days/decade (Tab. 2). These findings are in accordance with Perkins et al. (2012) and Perkins and Alexander (2013), demonstrating that the high trend magnitudes for HWF drive increases in HWN and HWD, as the number of heat wave days represents an influencing factor in the calculation of event length and occurrence. For HWex (extreme heat wave days) an absolute mean of 0.3 days and a significantly increasing trend of 0.05 days/decade are observed.

Table 2: *Annual Georgia-averaged trends for heat wave aspects HWN, HWD, HWF, HWex between 1961 and 2010 with respective confidence intervals (95%). Trends significant at the 5 % level are indicated in bold and highlighted in green.*

Heat wave aspect	Climatology (1961-1990)	Trend magnitude/decade (1961-2010)	Trend magnitude/decade (1981-2010)
Heat Wave Number (no. of events)	1.7	**0.4 (0.2 to 0.6)**	**0.8 (0.5 to 1.3)**
Heat Wave Duration (days)	5.5	**0.9 (0.5 to 1.5)**	**1.8 (0.5 to 3.6)**
Heat Wave Frequency (days)	10.4	**2.9 (1.5 to 4.7)**	**6.6 (2.7 to 10.7)**
Extreme Heat Wave Days (days)	0.3	**0.05 (0.00 to 0.17)**	0.15 (0.00 to 0.60)

As figure 3 shows all mean absolute differences for the heat wave occurrence, intensity and duration were found to be positive. For HWN an absolute increase between 0 and 1 event can be observed during the period 1981 and 2010 (with respect to the period 1961-1990). A few stations in the south and northwest of Georgia show an increase of 1 to 2 events. HWD shows an increase between 0 and 3 days for the major proportion of stations analyzed. For 5 of 22 stations the duration of heat waves increased to 3 to 6 days between 1981 and 2010. The heat wave aspect HWF shows an increase of 8 to 16 days for 6 of 22 stations analyzed during 1981 and 2010. For HWex an increase between 0 and 2 days can be found for the highest proportion of stations. For seven stations a strong increase by 3 to 6 extreme heat wave days is found.

Comparing the trends in the heat wave aspects HWN, HWD, HWF and HWex over Georgia for the two analysis periods 1961-2010 and 1981-2010, a pronounced increase in the magnitude of all trends is observable. Significant trends are found for HWN, HWD and HWF. As table 2 shows trends for HWN and HWD (1981-2010) double the trend magnitudes measured for the period 1961-2010. A trend of 0.8 events/decade for HWN and 1.8 days/decade for HWD could be found. For HWF (and HWex), the trend magnitudes of 6.6

days/decade (0.15 days/decade) for 1981 and 2010 are even two to three times higher the trend magnitudes observed between 1961 and 2010.

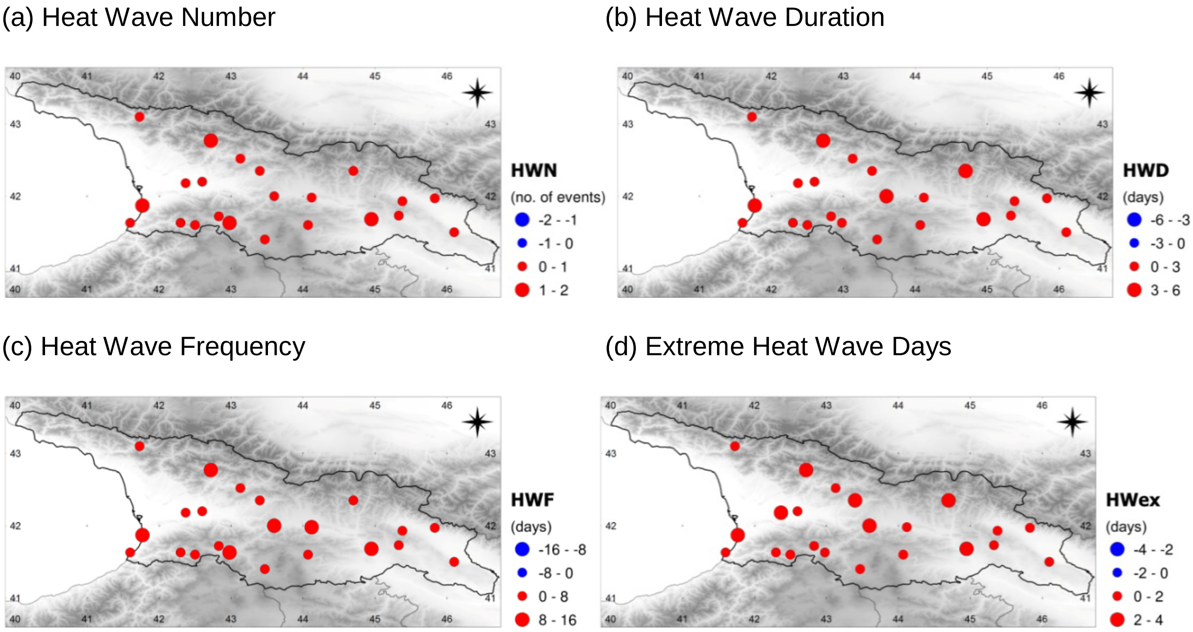


Figure 3: *Absolute heat wave changes between 1961 and 2010 over Georgia: Mean absolute differences between the periods 1961-1990 and 1981-2010 for the (a) Heat Wave Number (HWN) in number of events, (b) Heat Wave Duration (HWD) in days, (c) Heat Wave Frequency (HWF) in days and (d) Extreme Heat Wave days in days.*

3.2.2 Trends in the heat wave predictand and predictors

In this section the climatology and spatio-temporal changes of the heat wave predictand and selected predictors for the analysis periods 1961 to 2010 and 1981 to 2010 are presented. As table 3 shows, the climatological mean for Tmean95p averaged over Georgia was measured 20.4°C. The absolute increase comparing the periods 1961-1990 and 1981-2010 amounts to 0.1°C. Trends for the heat wave predictand Tmean95p were observed to be positive. During the analysis period 1961-2010 an insignificant warming trend of 0.2°C/decade (significant at the 10% level) could be found over Georgia. A significant trend for Tmean95p was observed between 1981 and 2010, which measures 0.4°C/decade. As shown in figure 4a spatial changes in Tmean95p, large areas with an absolute temperature difference of more than 0.6°C from Eastern Europe to the Ural Mountains are detected with peaks of up to 1°C, although no significant difference could be found. Also for Turkey and eastern Georgia an insignificant increase of 0.2 to 0.6°C could be observed. However, in western Georgia an insignificant increase in Tmean95p of at most 0.2°C was found. As presented in table 3, the Caspian Sea shows a higher climatological mean for SST (21.6°C) than the Black Sea (20.2°C). For the Caspian Sea a significant SST trend magnitude of 0.7°C/decade during the period 1981 to 2010 could be observed, while for the Black Sea a significant magnitude of 0.6°C/decade was found. The spatial distribution of SST absolute differences shows significant warming in the North Atlantic, The Mediterranean, Black and Caspian Sea (Fig. 4b). Largest differences of significant warming over Eurasia are found in the North and Baltic Sea and in the Kara Sea (0.6-0.8°C).

Table 3: *Changes in the heat wave predictand and predictors averaged over Georgia between 1961 and 2010. Trends significant at the 5% level are indicated in bold and highlighted in green. Respective confidence intervals (95%) are set in brackets. Reanalysis data focus on an area between 38.8° to 47.8°E and 38.8° to 43.8°N, except for the Black Sea (24° to 42°E and 40° to 47°N) and Caspian Sea (47° to 55°E and 36° to 47°N).*

Heat wave predictand*/ predictors	Climatology (1961-1990)	Mean Difference (1981-2010)	Trend magnitude/decade (1961-2010)	Trend magnitude/decade (1981-2010)
***Tmean95p (°C)**	20.4	0.1	0.2 (0.0 to 0.4)	**0.4 (0.0 to 0.9)**
SST (Caspian Sea) (°C)	21.7*	-	-	**0.7 (0.4 to 1.0)**
SST (Black Sea) (°C)	20.7*	-	-	**0.6 (0.4 to 0.8)**
SLP (mb)	1012	1.2	**0.5 (0.3 to 0.7)**	0.0 (-0.3 to 0.3)
Z500 (m)	5753	15.9	**8.7 (5.4 to 11.1)**	2.3 (-1.4 to 9.2)
u-wind (m/s)	6.8	0.6	0.25 (0.0 to 0.6)	-0.4 (-0.1 to 0.12)
v-wind (m/s)	3.7	-0.5	**-0.2 (-0.4 to 0.0)**	0.0 (-0.5 to 0.4)
Outgoing Longwave Radiation (W/m²)	246	5.8	**2.9 (1.7 to 4.0)**	3.1 (0.6 to 5.4)
Vertical Velocity at 500mb (Pa/s)	-0.04	0.01	**0.01 (0.00 to 0.01)**	0.02 (0.00 to 0.03)
Relative Humidity at 500mb (%)	44	-4.8	**-2.4 (-3.2 to -1.5)**	-3.7 (-5.5 to -2.0)
Precipitation (mm/day)	5	-0.7	**-0.35 (-0.47 to -0.23)**	-0.58 (-0.95 to -0.28)
Soil Moisture (fraction)	0.3	-0.01	**-0.004 (0.006 to 0.002)**	-0.007 (0.012 to 0.002)

* Due to data availability only climatological values and trends for the period 1981-2010 could be presented.

The climatology for SLP measures 1012mb with an absolute increase throughout Georgia of 1.2mb. While a significant trend magnitude for the period 1961-2010 of 0.5mb/decade could be observed, no change between 1981 and 2010 was detected. Figure 4c shows large areas of significant positive trends in the eastern Mediterranean, Western Asia and Northern Africa. A maximum of significant absolute change in SLP is found in northeast Turkey and stretching throughout Georgia measuring an increase of up to 2mb.

For Z500 a mean climatology of 5753m was detected over Georgia and an absolute increase of 15.9m with respect to the period 1961-1990 (Tab. 3). A significant positive trend for Z500 of 8.7m/decade could be found during the period 1961 and 2010. However, the trend magnitude for the period 1981-2010 was smaller (2.3m/decade) and insignificant. As shown in figure 4d, throughout southern Eurasia a significant absolute increase of Z500 of up to 20m is observed, which corresponds to observations for Western Asia by Kuglitsch et al. (2010). These findings highlight a changing atmospheric circulation over Georgia, implying an increase in warm air advection from the Southwest, large-scale subsidence and surface heating, which might have enhanced the formation and persistence of heat waves in recent years. Moreover, the increase in Z500 is usually connected with the increase in stability and the inhibition of convection over the area.

For u-wind an absolute decrease of 0.6m/s is observed comparing the periods 1961-1990 and 1981-2010. Georgia-averaged climatological mean measures 6.8m/s (Tab. 3). Trends for the zonal wind are insignificant during both analyzing periods. The climatology for v-winds measures 3.7m/s with an absolute decrease throughout Georgia of -0.5m/s. While a significant trend magnitude for the period 1961-2010 of -0.2m/s*decade could be observed, an insignificant change of 0.0m/s*decade between 1981 and 2010 was detected.

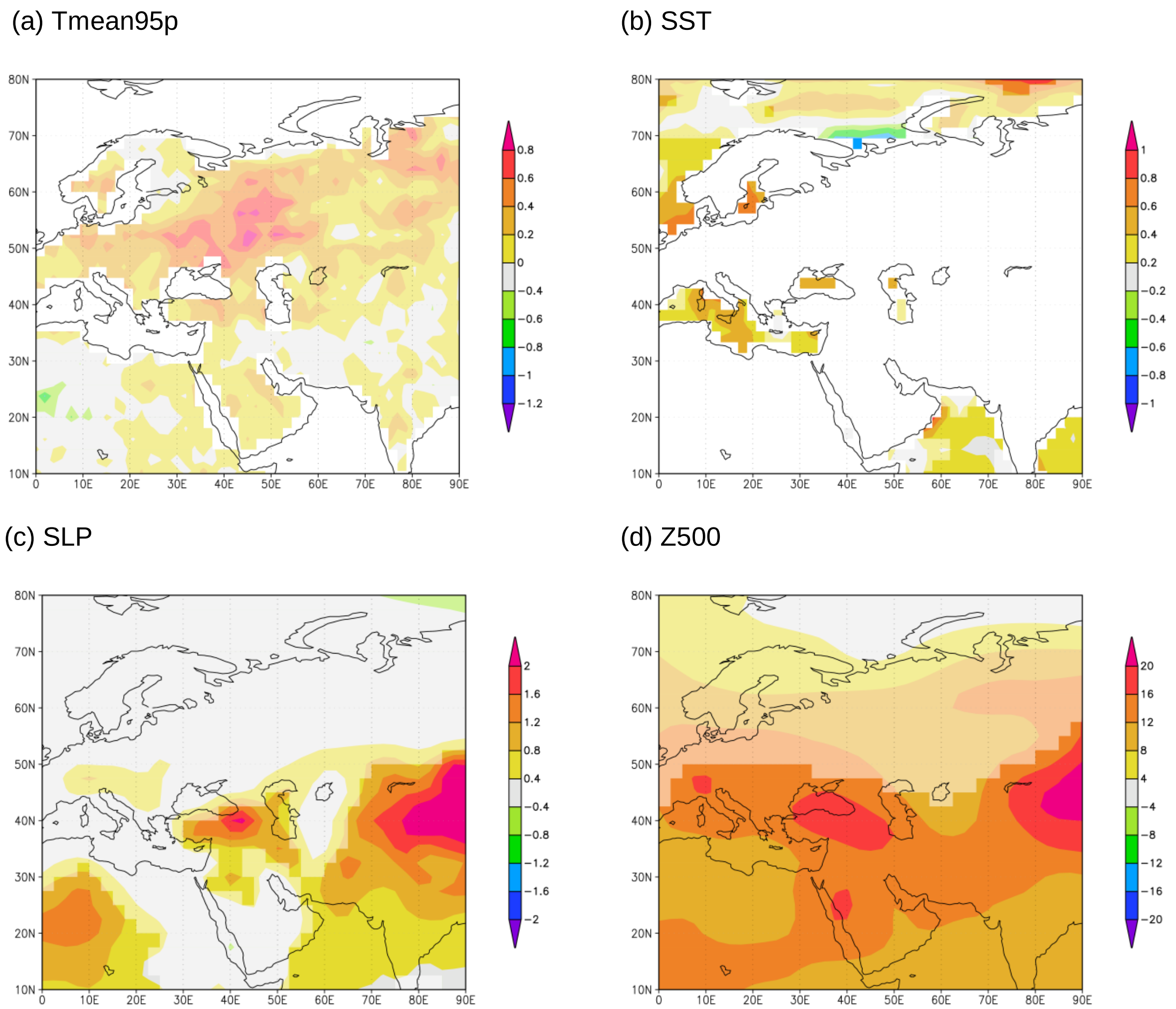


Figure 4: *Changes in the heat wave predictand and large-scale circulation over Eurasia between 1961 and 2010: Absolute differences between the periods 1961-1990 and 1981-2010 for (a) Tmean95p (°C), (b) SST (°C), (c) SLP (Pa), and (b) Z500 (m). Bright colored fields indicate significant changes (at the 5% level). Light colored fields imply insignificance.*

As shown in figure 5a OLR measures a mean climatological value of 246 W/m² and an absolute increase of 5.8 W/m², implying a decrease in cloudiness and an increase in maximum insolation. During the period 1961-2010 a significant positive trend of 2.9 W/m²*decade could be observed. As all other predictors OLR shows an increase in the trend rate during 1981 and 2010 compared to the period 1961-2010 (3.1 W/m²*decade) (Tab. 3). The spatial distribution of OLR trends shows an increase throughout Western Asia with the highest absolute increase of up to 12 W/m² located across the Caspian Sea (including Eastern Georgia).

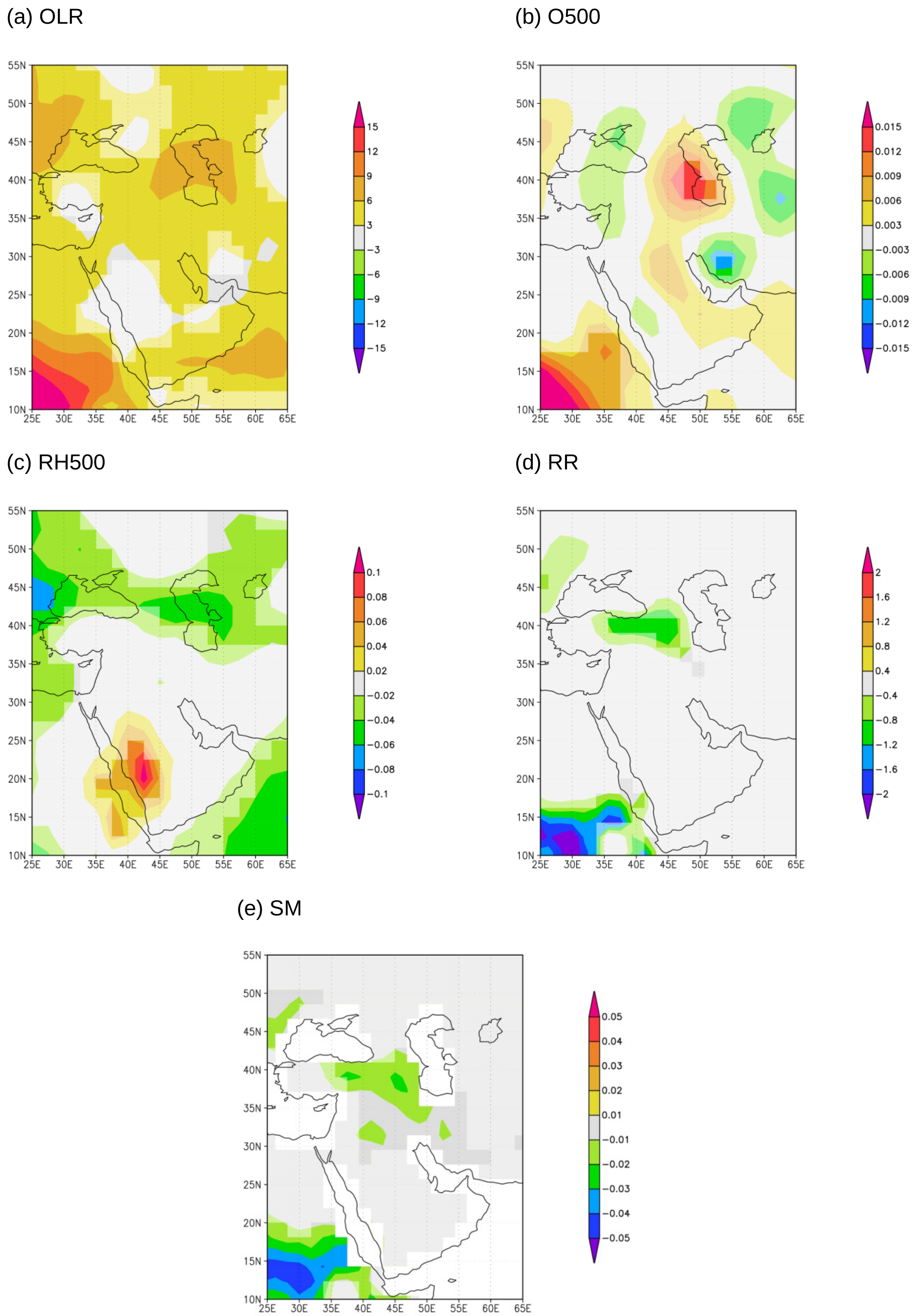


Figure 5: *Changes in meso-scale thermal processes between 1961 and 2010 over West Asia: Absolute differences between the periods 1961- 2010 and 1981-2010 for (a) OLR (W/m²), (b) O500 (Pa/s), (c) RH500 (%), (d) RR (mm/day), and (e) SM (%). Bright colored fields indicate significant changes (at the 5% level). Light colored fields imply insignificance.*

Vertical Velocity at 500mb measures an absolute increase of 0.01Pa/s comparing the periods 1961-1990 and 1981-2010 averaged over Georgia. The trend magnitude during the period 1961 to 2010 measures a significant increase of 0.01 Pa/decade over Georgia. The trend for the period 1981-2010 shows a higher magnitude of 0.02Pa/decade, but is insignificant. Regarding the spatial distribution of absolute changes during 1961 and 2010 a significant positive difference of up to 0.015Pa/s is located in Azerbaijan and northern Iran (Fig. 5b), suggesting an increase in atmospheric stability and subsidence. However, negative but mainly insignificant areas are located across the eastern Mediterranean and Black Sea as well as in the east of the Red and Caspian Sea and the Persian Gulf, implying an increase in instability and convergence. The location of these areas resembles the centers of zero trends in the OLR trend map (Fig. 5a), supporting the implication of local decreases in clear skies and insolation. Georgia shows a maximum absolute change of around 0.01Pa/s in the eastern part decreasing towards the western coast until approximately zero. As presented in table 3 for RH500 a climatological value of 44% could be observed. An absolute decrease of -4.8% was found and a significant trend of -2.4%/decade was measured during 1961 and 2010. The spatial distribution of absolute changes shows similar patterns. RH500 shows significant decreases of up to -0.06% across the Caspian Sea (Fig. 5c) with lowest values in the eastern part of Georgia and higher insignificant differences of around -0.04% to the West of Georgia. The reduction of air humidity is also found by Kuglitsch et al. (2010) detecting decreasing RH500 over West Asia accompanied by an increase in minimum and maximum temperature, Z500 and SLP.

For RR an absolute decrease of -0.7mm/day observed comparing the periods 1961-1990 and 1981-2010. Georgia-averaged climatological mean for RR measures 5mm/day (Tab. 3). Trends for RR are significantly decreasing by -0.35mm/day*decade regarding the period 1961 and 2010. The negative trend magnitude of -0.58mm/day*decade for the period 1981 to 2010 was even larger, but insignificant (Tab. 3). As implied by figure 5d, absolute differences in the spatial distribution of total precipitation shows a large area of significant decreasing rates by -1.2mm/day predominantly in the east of Turkey, southern Georgia, Armenia, Azerbaijan and northern Iran. Similar to the RR, SM shows decreasing trends over the last five decades. As table 3 shows, the climatological mean averaged over Georgia was measured 0.3% and the absolute decrease amounts to -0.01% comparing the periods 1961-1990 and 1981-2010. Trends for the heat wave predictor SM were found to be negative. During the analysis period 1961-2010 a significant decreasing trend of -0.004%/decade could be found over Georgia. However, the trend magnitude for the period 1981-2010 was even larger (-0.007%/decade), but insignificant. Regarding the spatial distribution of SM change, significant decreasing rates are found in central and eastern Turkey, northern Iran and the Southern Caucasus. Towards northwestern Georgia the trend measures approximately zero. The spatial location of high reduction rates of RR, SM and RH500 have a strong resemblance of those measuring a high increase in SLP, Z500, OLR and O500, which supports the assumption, that the increase in surface heating, subsidence and warm air advection drive the reduction in air humidity, total precipitation and soil moisture.

3.3 Heat wave related weather patterns

In order to examine the related features associated with the 16 major summer heat wave days over Georgia, daily composites of ten large- to meso-scale surface and mid-troposphere fields over Eurasia are presented. All anomalies were calculated with respect to the period 1981 to 2010. Moreover, the coupled variability of the selected predictors and the heat wave predictand (Tmean95p) is investigated by performing a CCA. All CCA patterns show a close resemblance to the daily heat wave composites. Because the higher CCA modes explain negligible amounts of variance, this paper focuses only on the analyses of the first CCA mode for each predictor, respectively. For the sake of brevity, CCAs for the heat wave predictand over Georgia are not shown.

Table 4: *Results of the CCAs between selected predictors and the heat wave predictand. Listed are the predictor's abbreviation, the selected domain, r is the correlation coefficient between the canonical score series, the explained variance refers to the variance of summer heat waves HWs explained by each CCA, the correlation skill score of all grid points with an approximate 95% confidence interval.*

Predictor	Domain	r	Explained Variance (%)	Confidence Interval (95%)
SST (Eurasia)	10-80 N, 0-90 E	0.56	52.3%	0.43 - 0.66
SST (Black Sea)	40-47 N, 27-42 E	0.43	88.3%	0.27 - 0.59
SST (Caspian Sea)	36-47 N, 47-55 E	0.66	88.6%	0.55 - 0.75
Z500	10-80 N, 0-90 E	0.74	61.6%	0.67 - 0.80
SLP	10-80 N, 0-90 E	0.62	61.2%	0.50 - 0.71
u-wind500	10-80 N, 0-90 E	-0.77	59.4%	-0.83 - -0.70
v-wind500	10-80 N, 0-90 E	0.76	62.4%	0.70 - 0.82
O500	10-80 N, 0-90 E	0.81	55.5%	0.74 - 0.87
RH500	10-80 N, 0-90 E	0.78	52.1%	0.71 - 0.82
OLR	10-80 N, 0-90 E	0.81	51.0%	0.75 - 0.85
RR	10-80 N, 0-90 E	-0.84	51.2%	-0.87 - -0.78
SM	10-80 N, 0-90 E	-0.76	50.0%	-0.81 - -0.70

Table 4 shows the results of the CCA listing the potential heat wave drivers, their domain, the temporal correlation coefficients of the score series between each predictor and local extreme temperature and their explained variance with the respective 95% confidence interval to validate the model skill across the domain. As shown in table 4, all confidence intervals suggest a good to very good skill over the entire domain, except for the SST and SLP domains for Eurasia and the Black Sea, which are rather good to poor.

3.3.1 Temperature and SST patterns

As shown in figure 6a, western and central Europe and western Asia are dominated by negative SAT fields, associated with the surface cyclones over the area. However, Eastern Europe, the Mediterranean and Middle East as well as from Northern Africa to Western Russia warm centers are observed during major heat wave events over Georgia. Two centers of high SAT anomalies of up to 5°C were found in Armenia and in the southern Ural Mountains. The SAT anomaly over Georgia stretches from 2.5°C in the Northwest up to 5°C in the Southeast, implying strongest heat wave intensity here. The centers of negative SAT anomalies with a maximum of -3°C lie southeasterly and southwesterly of the positive heat anomalies below the middle level cyclones (see Fig. 7b).

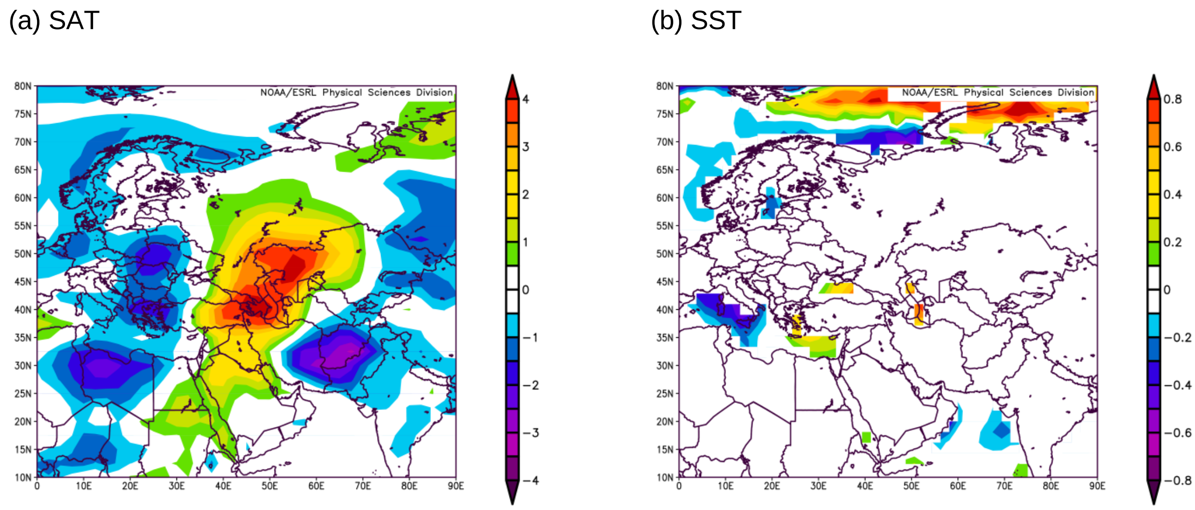


Figure 6: *Composites of SAT and SST during major summer heat waves over Georgia between 1961 and 2010: Composite anomalies for daily (a) SAT (°C) and (b) SST (°C). Anomalies are calculated with respect to the 1981-2010 period. Data is based on daily NCEP/NCAR Reanalysis.*

SST anomalies suggest a close relationship between large-scale dynamic patterns as shown in figure 6b. While the Northern Atlantic and Eastern Mediterranean Sea show negative SST anomalies of up to -0.6°C, positive SST anomalies are observed in the Caspian Sea of up to 0.7°C. Lower positive SST anomalies can be found in the Eastern Black Sea (0.5°C). Highest anomalies are found in the Barents and Kara Sea of up to 1°C during heat wave events over Georgia. The SST pattern for the first CCA mode over Eurasia demonstrates a very close resemblance to the SST composite for observed heat wave events and accounts for approximately 52.3% of the summer heat wave variability over Georgia (Fig. 6b, 9g). The correlation between the summer SST and heat wave pattern is 0.56. Although a close relationship between SSTs and heat waves could be observed, it does not necessarily mean that the SST anomalies are responsible for heat waves over Georgia. It is far more likely that SST anomalies are an accompanied phenomenon of extreme temperature events. Nevertheless, the possibility that an individual heat wave might be affected by local SST anomalies cannot be excluded. Composite and CCA fields have a strong resemblance with the SAT and Z500 fields suggesting enhanced local air advection, subsidence and maximum insolation over strong SST warming fields during heat wave events, which is in accordance with Feudale and Shukla (2011a). Moreover, the reduction of meridional winds over sea, mainly apparent over the southern Caspian Sea, prevents the generation of lee waves and cyclones (Fig. 7d). Hence, the cooling effect by wind-induced mixing is reduced, which further warms up the SST (Buzzi and Tibaldi, 1978). The simultaneous SST anomalies in the Caspian, Northern Barents and Kara Sea can be explained by a reduction of baroclinic instability between the Southern Caucasus and the Northern Barents and Kara Sea, as discussed by Feudale and Shukla (2011a) for the simultaneous SST anomalies in the Mediterranean and the Northern Atlantic during the heat wave 2003. The prevention of baroclinicity is caused by a diminishing land-sea temperature gradient, which is reflected by the negative anomalies of v-winds over the Northern Barents Sea and West Asia stretching from Northeastern Africa across the Southern Caspian Sea to the Kara Sea (Fig. 7d) resulting in a northward shift and intensification of the subtropical jet and a northward shift of the African Intertropical Convergence Zone (ITCZ).

3.3.2 Large-scale circulation and mid-troposphere patterns

As shown in figure 7a, a deep surface trough is found over Southern Scandinavia extending across the Black Sea area towards the Persian Gulf and the Red Sea. The persistent surface lows are known as the “Persian Gulf trough” and “the Red Sea trough”, which govern a strong relation to heat waves and heavy precipitation in the Mediterranean (e.g. Ziv et al., 2004; de Vries et al., 2013). At the same time, pronounced anticyclones are located over the Ural Mountains, the Mediterranean Sea, North Africa and Iran, implying warm air attraction from the Mediterranean and Middle East to Georgia (Fig. 7a). The SLP composite and CCA mode over Eurasia show similar patterns during heat wave events (Fig. 7a, 9a). The first CCA mode captures 61.2% of the summer heat wave variability. The correlation between the summer SLP and heat wave predictand amounts to 0.62. The observed heat wave patterns have a strong resemblance to those found for heat waves in Western Asia by Kuglitsch et al. (2010).

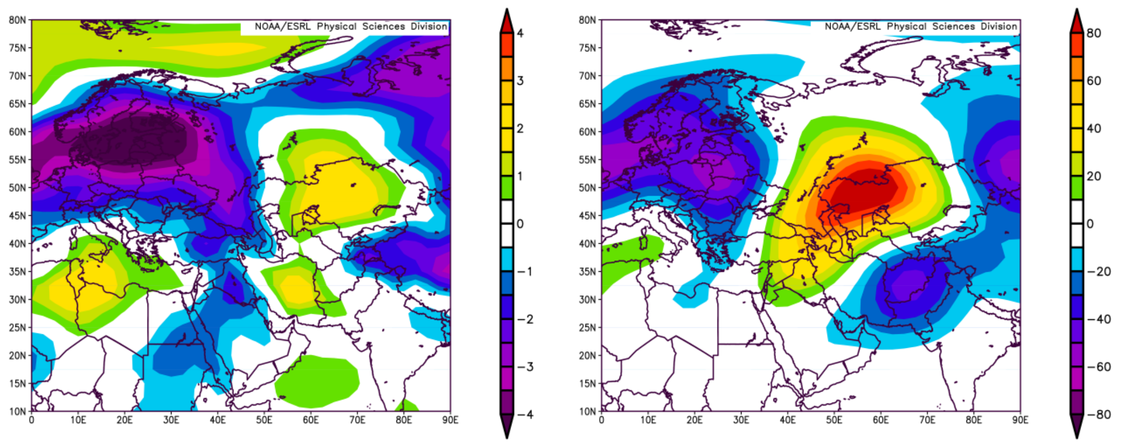
Composite and CCA patterns for Z500 demonstrate a large anticyclonic vortex with anomaly maxima of 90m during major heat wave events. Negative anomalies of up to -60m are located westerly over the British Isles, Southern Scandinavia and easterly over central Asia and central Russia. Over eastern Georgia positive anomalies of around 60m are found, while towards the western coast the intensity decreases to 40m. The first CCA mode shows a close resemblance to the composite and captures 61.6% of the summer heat wave variability (Fig. 7b, 9b). The correlation between the summer Z500 and the heat wave predictand measures to 0.74. The location of the middle tropospheric troughs over Scandinavia and West Asia are in southeasterly and southwesterly location aside of the anticyclonic center resembling a typical west-oriented omega high, a nearly-stationary anticyclonic pressure field closely associated to high-impact heat waves (Fig. 7b). The observed pattern can be referred to the “RU (Russian) cluster” identified as one of six heat wave blocking patterns identified by Stefanon et al., 2012 or to the “Eurasia” region, one of three regions, in which the frequency of the extremely hot days per month homogeneously varies (Carril et al., 2008). Due to its location it is known as the Ural Blocking High pattern and is associated with the 2010 Russian heatwave investigated by Barriopedro et al. (2011), Dole et al. (2011) and Grumm (2011). The blocking of westerlies is caused by a reduction of baroclinicity, which is typical for the mid-latitudes. In general, baroclinic instability enhances the blocking persistence, the interruption of the mid-latitude westerlies, the deflection of the west-east storm tracks, large-scale subsidence and incoming solar radiation. Baroclinicity usually limits the northern branch of the Hadley cell expanding to the North. Reduced baroclinic activity during heat waves leads to a northward shift of the descending branch of the Hadley cell and the African ITCZ, which is consistent with studies on heat waves over Eurasia by Cassou et al. (2005) and Carril et al. (2008). As shown in figure 8b, the precipitation composite over the central Sahel implies a northerly shift of the African ITCZ. This relation was first investigated by Rowell (2003), which observed an increase of rainfall over the western African Sahel and a northern shift of the African ITCZ during warm Mediterranean SST.

The u-wind composite and CCA mode is consistent with reduced baroclinicity and shows reduced zonal wind activity throughout central Asia of up to -9m/s. An enhanced zonal wind flow is deflected by the anticyclonic center, implying a northward shift of the subtropical jet. Regarding Georgia, reduced wind speeds of -4m/s are found in the eastern part and increase towards 1m/s in the West, implying stronger influence of the anticyclonic blocking and associated subsidence in the Western part of Georgia (Fig. 7c). V-winds at 500mb intensify over Western Russia by up to 9m/s, proving warm and dry air masses are attracted from south-southwest during major heat wave events. Negative anomalies are found from Northeastern Africa across the Southern Caspian Sea to the Kara Sea, implying a reduced meridional gradient between continental central Asia and the Northern Barents and Kara Sea (Fig. 7d). In western Georgia positive anomalies of over 7m/s can be observed, while anomalies in the southeast of approximately zero can be found, implying a stronger relation of warm air advection and heat wave events are found in the West. The u- and v-wind composites and CCA modes show a strong resemblance (Fig. 7c,d and 8c,d). The correlation between the summer zonal wind and the heat wave predictand amounts to -0.77. The first CCA mode for u-wind captures 59.4%, whereas the CCA pattern for v-wind accounts for 62.4% of the summer heat wave variability (Fig. 9c, d). The correlation between the summer meridional wind and the heat wave predictand measures 0.76.

The analysis of vertical pressure velocity at 500 hPa reveals two opposing patterns affecting Eastern and Western Georgia differently (Fig. 7e, 9e). The first O500 CCA mode captures 55.5% of the summer heat wave variability. The correlation between the summer O500 pattern and the heat wave predictand amounts to 0.81, implying a strong relation between subsidence patterns and the heat wave occurrence in Eastern Georgia. Similar to the CCA pattern, the composite detects intensified O500 of up to 0.7 Pa/s located over the Caspian Sea and central Asia associated with local stability, subsidence, clear skies and maximum insolation during major heat wave events. Throughout Western Russia and the Barents Sea positive, but weaker anomalies are observed. These patterns mainly influence heat wave patterns over eastern Georgia, whereas a band of negative O500 anomalies (correlation fields) is found across the eastern Black Sea and West Georgia. Reduced vertical pressure velocity over Southern Scandinavia and central Asia as well as those stretching from northeast Africa to southwestern Russia are characterized by instability, convection and cloudiness, reflected by the decrease in enhanced surface heating and precipitation (Fig. 8 a, c). High SATs combined with high SSTs lead to increased latent heat fluxes (Xoplaki et al., 2003 a) and increased air humidity, hence convection and precipitation.

(a) SLP

(b) Z500



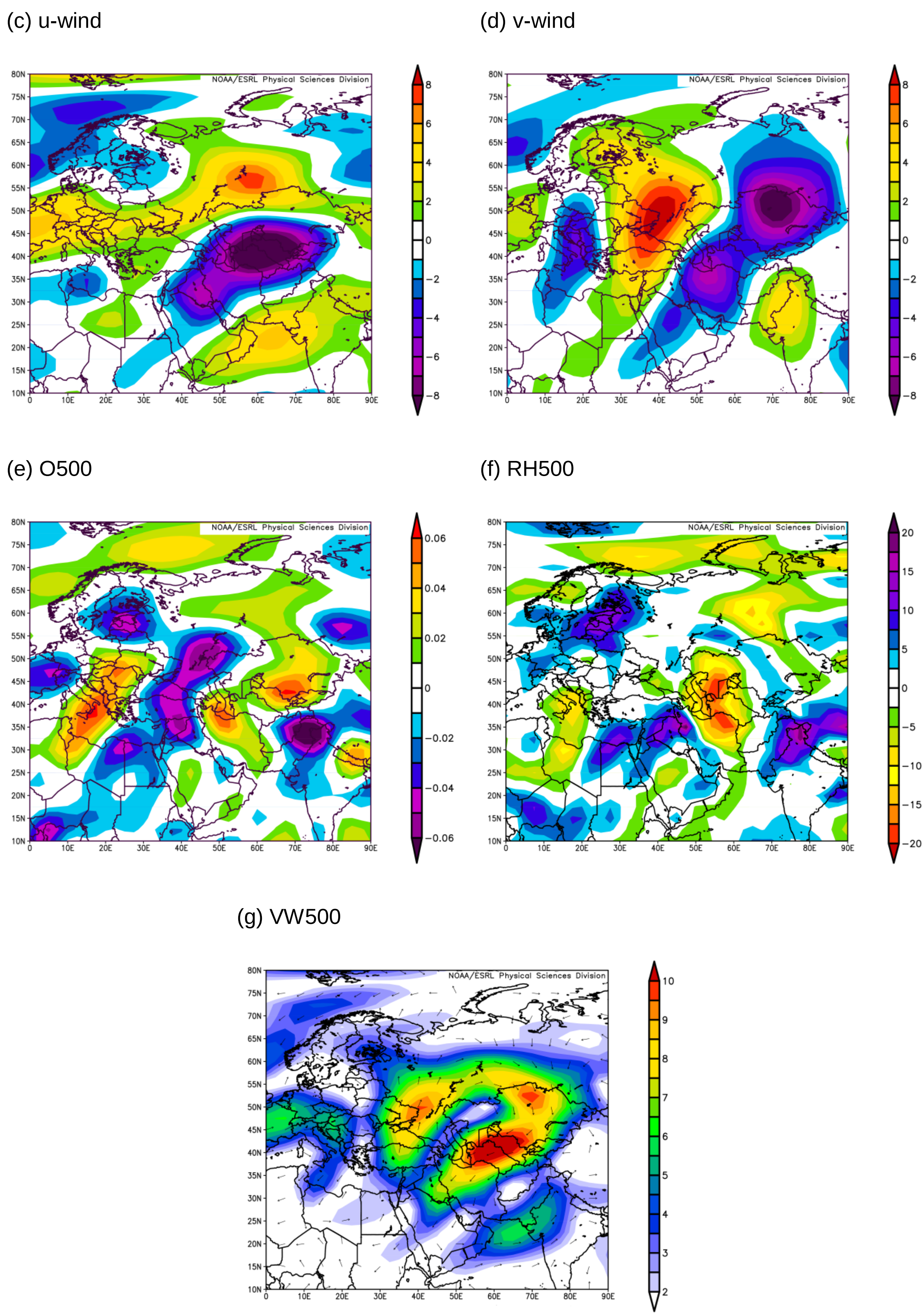


Figure 7: *Composites of large-scale circulation and middle troposphere patterns during major summer heat waves over Georgia between 1961 and 2010: Anomalies for daily (a) SLP (hPa), (b) Z500 (m), (c) u-wind at 500mb (m/s), (d) v-wind at 500mb (m/s), (e) O500 (Pa/s), (f) RH500m (%), and (g) VW500 (m/s). Anomalies are calculated with respect to the 1981-2010 period. Data is based on daily NCEP/NCAR Reanalysis.*

As presented in figure 7f, composite anomalies for relative humidity at 500mb during major heat wave events show lowest values of up to -20% over central Asia, eastern and southeastern of the Caspian Sea. Negative fields are also found northeastern of the Black Sea, over central Russia and the Barents and Kara Sea. The observed heat wave patterns have a strong resemblance to climate composites of major heat wave events in the eastern Mediterranean found by Kuglitsch et al. (2010). They also show a close relation to SLP, O500 and OLR patterns (Fig. 7a, e, 8a). Because of the atmospheric stability, vertical motion is restricted to the lower boundary layer, where solar radiation is maximized and the warm air is trapped. The spatial distribution of RH500 CCA fields shows similar patterns (Fig. 9f). The first CCA for RH500 mode captures 52.1% of the summer heat wave variability. The correlation between the summer fields for RH500 and the heat wave predictand over Georgia amounts to 0.78.

Figure 7g shows a vector wind composite during heat wave events and provides evidence, that anomalously strong, warm and dry winds collect moist over the warm eastern Mediterranean and Black Sea producing cyclones and strong convective rainfall events above western Georgia (Fig. 8c). While western Georgia is dominated by moist air masses, eastern Georgia is influenced by warm and rather dry winds from North Africa and the Middle East of much lower wind speed anomalies. Moreover, the Surami Mountain chain dividing western and eastern Transcaucasia holds moist air masses and leads to adiabatic heating by foehns in on the luv side bringing dry air to the East.

3.3.3 Meso-scale surface patterns

High Outgoing Longwave Radiation rates are usually well correlated with high surface temperature, low soil moisture and water vapor concentration in the planetary boundary layer (Fischer et al., 2007). Figure 8a shows highest OLR anomalies of up to 28W/m² east of the Caspian Sea during major heat wave events. The spatial distribution of high OLR anomalies corresponds well with areas of high SLP, Z500 and O500 anomalies (Fig. 7a,b,e) as well as low anomalies of relative humidity and zonal winds at 500mb (Fig. 7c,f), implying enhanced subsidence, clear skies and maximum radiation leading to surface heating. Over eastern Georgia positive anomalies of 8W/m² can be observed, while west Georgia shows negative OLR anomalies of -8W/m², which suggests enhanced cloudiness and atmospheric instability.

Heat waves are usually connected to adjacent rainfall and soil moisture deficits, which is in agreement with Ferranti and Viterbo (2006), Fischer et al. (2007) and Seneviratne (2010). According to precipitation and soil moisture composites illustrating the 20 days prior to the detected major heat wave days, adjacent soil dryness dominates the whole territory of Georgia (not shown). Precipitation patterns during heat wave events are highly influenced by both, the large-scale circulation and local orographic patterns. Large-scale precipitation composite (correlation) fields over Eurasia correspond well with SLP, Z500 and O500 patterns (Fig. 7a,b,e and 9a,b,e). Local precipitation fields are mainly found over mountainous and coastal areas due to moist air advection, instability and convection. Soil moisture fields resemble well the SAT and RR composite and CCA patterns and show negative composite (correlation) fields over Turkey across the Southern Caucasus to Southern Russia (Fig. 6a, 8c, 9i). Over eastern Georgia simultaneous negative precipitation

(-2mm) and SM fraction anomalies (-0.04) are observed, which supports the evidence of warm and dry air advection, subsidence and surface heating.

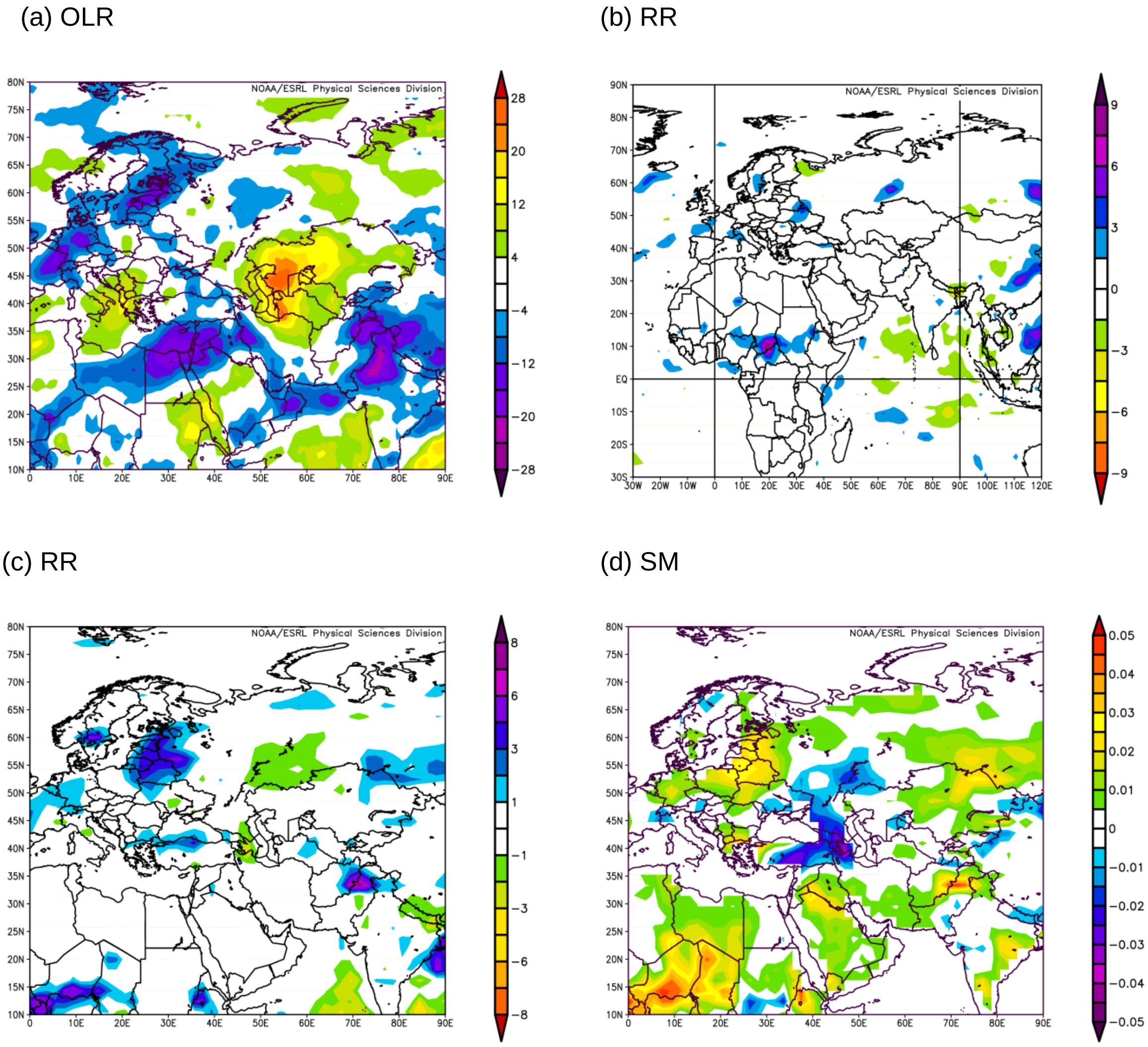
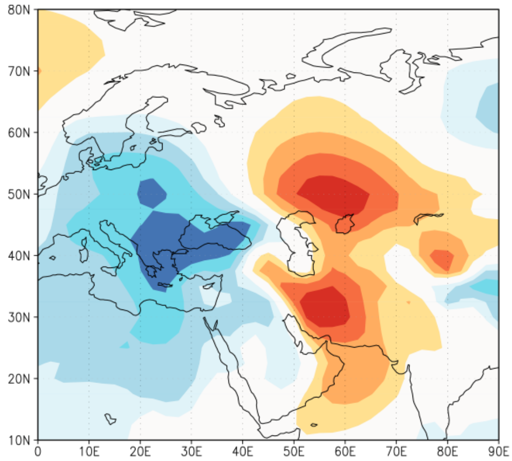


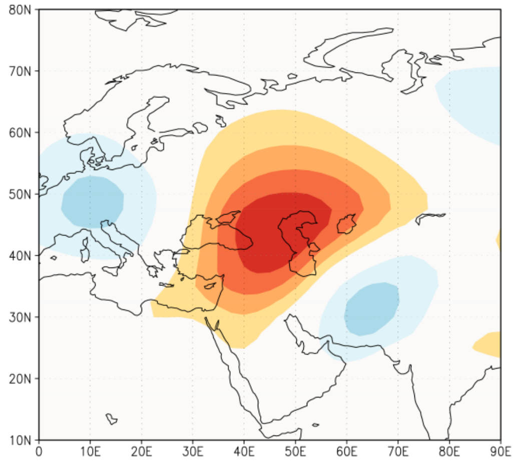
Figure 8: *Composites of meso-scale surface patterns during major summer heat waves over Georgia between 1961 and 2010: Anomalies for daily (a) OLR (W/m²), (b, c) RR (mm/day), and (d) SM (fraction). Anomalies are calculated with respect to the 1981-2010 period. Data is based on daily NCEP/NCAR Reanalysis.*

At the same time, positive RR anomalies of 0.15mm and negative SM fraction anomalies of -0.03 are observed over West Georgia. Similar to the composite, the CCA pattern detects reduced precipitation over eastern Georgia. The first precipitation and soil moisture CCA mode captures 51.2% (50.0%) of the summer heat wave variability (Fig. 9i, j). The correlation between the summer precipitation (soil moisture) patterns and the heat wave predictand amounts to -0.81 (-0.76), implying a strong relation between precipitation and soil moisture deficits during heat wave days over Eastern Georgia. This finding is in accordance with Haarsma et al. (2009), who found that summer SAT warming is enhanced due to soil moisture depletion which limits the cooling of the land surface by evaporation. However, as shown in figure 7g, 8e and 9i the anomalous southwesterly subtropical winds bring moist air masses to the high mountain ridges of the Caucasus Mountains in Western Georgia, leading to local precipitation maxima at luv sides due to enhanced orographic convection (Kostianoy and Kosarev, 2008). Moreover, soil dryness during heat wave events in mountainous and coastal areas drive instability and air humidity due to meso-scale circulations leading to enhanced precipitation and cooling (Stefanon et al., 2013). This effect could amplify precipitation events and further reduce temperature in mountainous and coastal areas during heat wave events over Georgia.

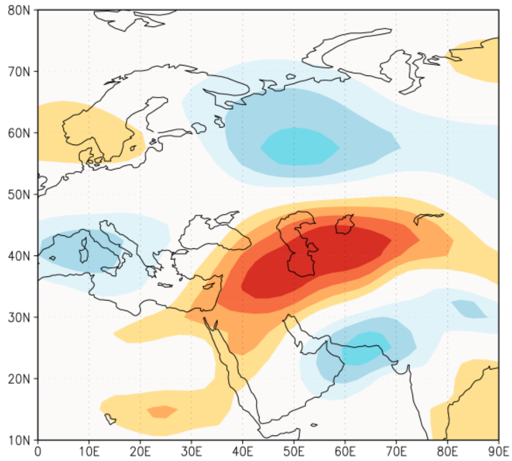
(a) SLP, r = 0.62



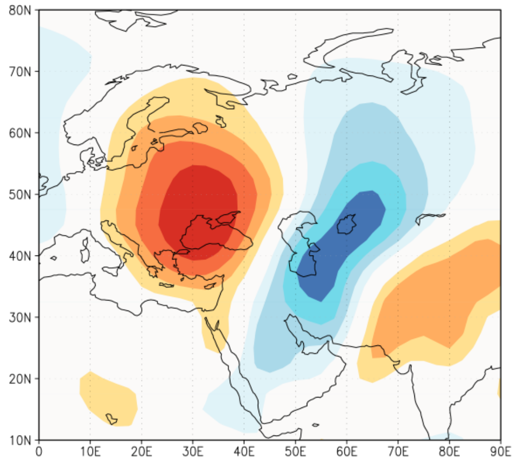
(b) Z500, r = 0.74



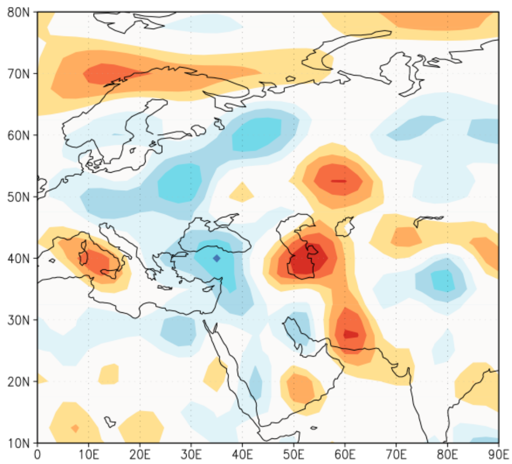
(c) u-wind, r = -0.77



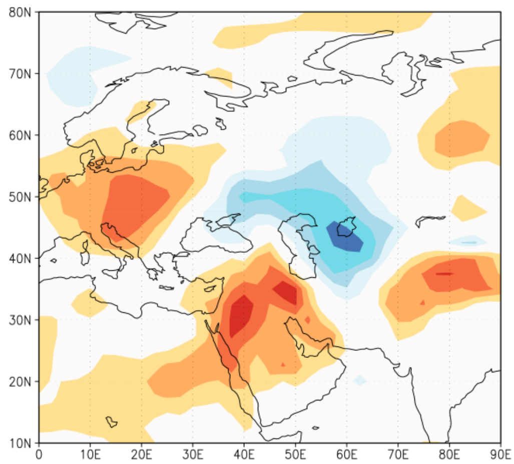
(d) v-wind, r = 0.76



(e) O500, r = 0.81



(f) RH500, r = 0.78



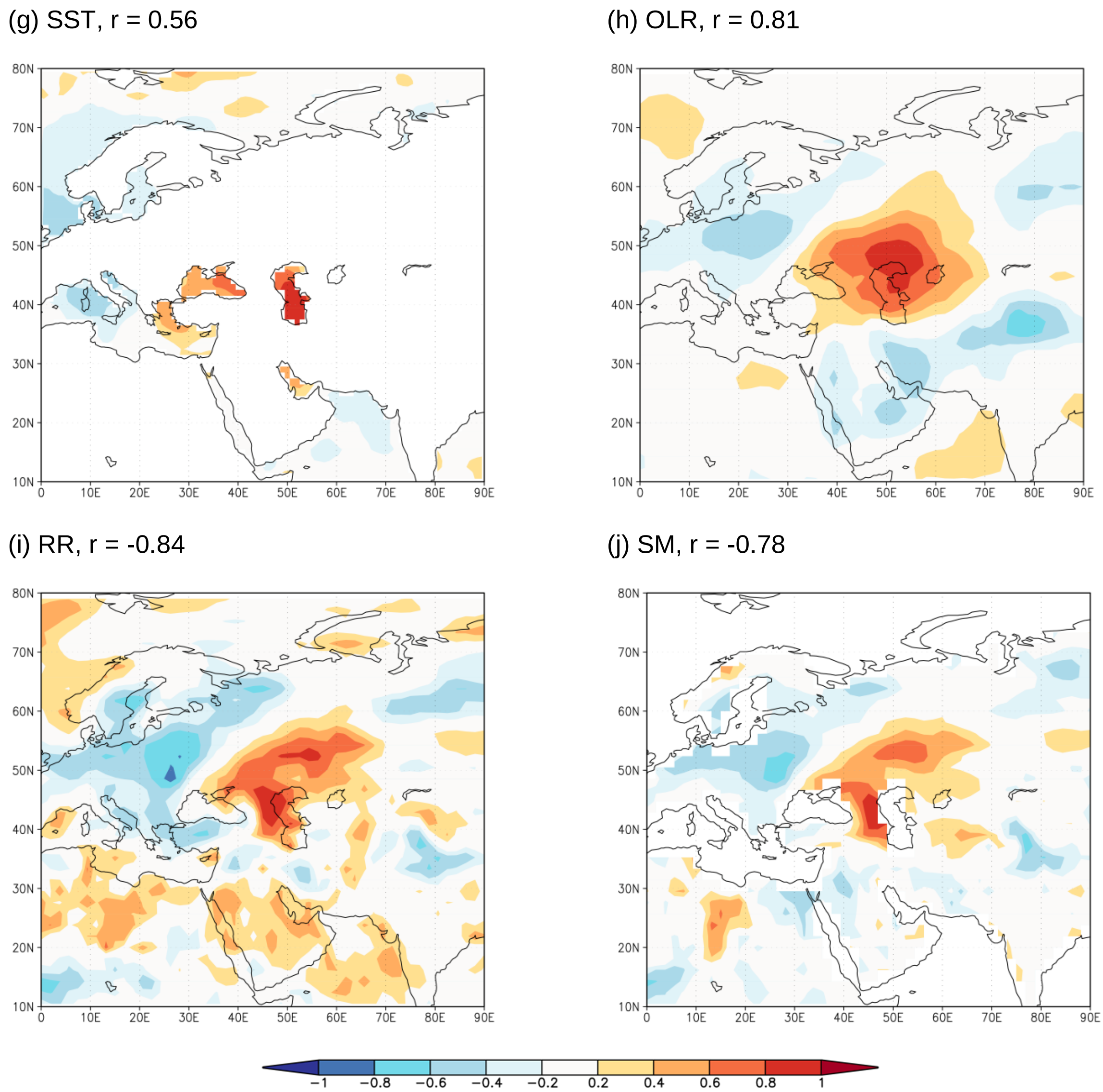


Figure 9: *First CCAs between the summer heat wave predictand and selected predictors: CCA modes with the correlation coefficient for (a) SLP, (b) Z500, (c) u-wind at 500mb, (d) v-wind at 500mb, (e) O500, (f) RH, (g) SST, (h) OLR, (i) RR, and (j) SM. Canonical correlation coefficients are displayed on the top of each panel.*

4. Summary and conclusions

This study detected severity and changes of summer heat wave events over Georgia between 1961 and 2010 and their relationships to large- and meso-scale predictors to identify potential driving mechanisms. Based on the Excess Heat Factor the ten summer heat waves with highest heat-health impacts over Georgia were identified in 2007, 2006, 1998, 2001 and 1995. Climatology and heat wave changes between 1961 and 2010 were examined in terms of low- and high-impact intensity, frequency and duration. The observation data used was carefully quality controlled. Homogeneity was tested using the software RClimDex 1.1. Metadata could be used to detect breakpoints and to adjust inhomogeneous time-series using RHVtest4 (Keggenhoff et al., 2015b).

Summer heat wave changes between the periods 1961-2010 and 1981-2010 revealed significant increasing trends in the Georgia-average. A significant increase for high-impact heat waves (HWex) was measured between 1961 and 2010. HWF shows by far the largest trend magnitudes, which is consistent with findings of (Perkins et al., 2012; Perkins and Alexander, 2013), stating that occurrence-based heat wave aspects possess larger trend magnitudes. They also found that the high magnitudes of trends for HWF are driving increases in HWN and HWD, due to the fact that the overall number of heat waves (and their duration) will increase when the number of participating days increases. Spatial patterns of trends over Georgia are difficult to assess, which can be attributed to the low data quality and availability. It is also notable that the linear trend magnitude for all heat wave aspects between the analysis period 1981 and 2010 at least double, compared those during 1961 and 2010, implying that more intense and longer heat waves can be expected in future.

The present study focused on a CCA and composite analysis to investigate recent summer heat wave patterns and their relation to the selected atmospheric and thermal predictors over Eurasia: Mean Sea Level Pressure, Geopotential Height at 500mb, Sea Surface Temperature, Zonal and Meridional Wind at 500mb, Vertical Velocity at 500mb, Outgoing Longwave Radiation, Relative Humidity at 500mb, Precipitation and Soil Moisture. Daily composites were conducted for the 16 most intense heat wave days over Georgia between 1961 and 2010. The CCA was performed based on the heat wave predictand Tmean95p over Georgia. CCA is a statistical technique to find spatial patterns of fields with a maximum correlation. The study showed that all composite and CCA patterns have a close resemblance, which verifies both, the composite analysis based on observations and the statistical CCA.

A heat wave study investigating heat wave patterns and driving mechanisms over Georgia has been performed for the first time. The results confirmed that large-scale circulation, radiation, precipitation and soil moisture over Eurasia were strongly related to Georgian heat wave events. The analysis detected increasing SAT anomalies over Georgia from West to East. The slight SST anomalies over the Black and Caspian Sea imply no preferred SST pattern inducing heat waves, but that they might reinforce events. The large increase in SSTs in the Barents and Kara Sea during major heat waves over Georgia in combination with a reduction of the meridional gradient and a decrease of baroclinicity amplifies the northward shift of the subtropical jet, allowing the expansion of the blocking high over the Southern Ural. This large anticyclonic pattern is represented by a positive anomaly of Z500 over the area. Moreover, severe heat waves over Georgia are attributable to negative SLP anomalies over Southern Scandinavia and the Red and Black Sea area and positive SLP anomalies over western Asia. These surface and mid-tropospheric anticyclonic patterns observed (1) block westerlies, (2) attract warm air masses from the Southwest, (3) enhance subsidence and surface heating, (4) shift the African ITCZ northwards, leading to a northward shift of the descending branch of the Hadley cell, and (5) cause a northward shift of the subtropical jet. The regional effects of the persistent blocking are closely related to both, the large- to meso-scale circulation and the local orography of Georgia. The study revealed that Eastern Georgia is mainly influenced by low warm and dry wind flows, subsidence and surface heating due to clear skies, atmospheric stability and maximum insolation, implied by positive anomalies of O500 and OLR and negative RH500, SM and RR patterns over the area. However, during major heat wave events western Georgia is affected by anomalous strengthened wind speed and warm and moist air. These anomalous southwesterly dry winds from Northeast Africa across the Eastern Mediterranean collect moist over the Mediterranean and Black Sea and lead to atmospheric instability and convective rainfall, reflected by negative anomalies for O500 and positive VW500 and RR anomalies over the area. Precipitation might be amplified by the pronounced soil dryness observed throughout Georgia, which induced atmospheric instability and enhanced air humidity and cooling due to meso-scale circulations over mountainous and coastal areas (Stefanon et al., 2013). Moreover, heat waves over Georgia are attributable to reduced soil moisture across the whole territory of Georgia, implying adjacent precipitation deficiency for a prolonged period (Haarsma et al., 2009). This assumption was verified by precipitation and soil moisture composites for a 20 day-period prior to the major summer heat wave events over Georgia. The contribution of lagged precipitation and soil moisture depletion to heat wave events over Georgia will be investigated in more detail in a further study.

Observed changes show that all relevant circulation, radiation and soil moisture patterns contributing to heat waves have been intensified between 1961 and 2010. Tmean95p over Georgia and SSTs over the Black and Caspian Sea showed significant warming trends. Largest trends for SSTs are found in the Northern Atlantic and the Kara Sea. Changes in large-scale circulation and radiation patterns reflect a significant increase in surface and mid-troposphere pressure and surface heating throughout Western Asia, while for relative humidity, precipitation and soil moisture significant decreasing trends could be found. Most pronounced trends were observed over Southeast Georgia, implying increasing soil dryness over the area. Based on the fact that surface and mid-troposphere pressure, surface radiation and soil dryness intensified significantly over Western Asia during the last 50 years, it is likely, that Georgia will be exposed to more and longer severe heat waves in future.

Appendix

Table 5: *Extreme summer heat wave events over Georgia between 1961 and 2010. Listed are the year, HW number, Intensity of peak heat wave (HW class), date of peak EHF (Date), duration (days), accumulated heat load (°C²), and accumulated heat load (°C²) of peak extreme heat waves*

Year	HW no.	Date	Peak Intensity (HW class)	Duration (EHF days)	Distribution (% of stations)
1961	1	May, 5	4	4	27
	2	May, 15	4	5	18
1966	3	June, 7	4	7	29
1967	4	May, 24	4	3	9
1980	5	July, 14	4	5	5
1996	6	July, 17	4	14	6
1998	7	May, 7	4	4	15
1999	8	August, 6	4	8	124
2000	9	July, 17	4	9	11
	10	August, 2	4	7	24
2001	11	June, 15	5	5	6
2003	12	May, 26	5	4	5
2005	13	May, 22	4	3	5
2007	14	May, 9	6	3	13
	15	May, 28	6	6	75
2009	16	June, 5	4	4	13

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