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Changes in heat waves indices in Romania over the period 1961–2015

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ABSTRACT

In the last two decades many climate change studies have focused on extreme temperatures as they have a significant impact on environment and society. Among the weather events generated by extreme temperatures, heat waves are some of the most harmful. The main objective of this study was to detect and analyze changes in heat waves in Romania based on daily observation data (maximum and minimum temperature) over the extended summer period (May–Sept) using a set of 10 indices and to explore the spatial patterns of changes. Heat wave data series were derived from daily maximum and minimum temperature data sets recorded in 29 weather stations across Romania over a 55-year period (1961–2015). In this study, the threshold chosen was the 90th percentile calculated based on a 15-day window centered on each calendar day, and for three baseline periods (1961–1990, 1971–2000, and 1981–2010). Two heat wave definitions were considered: at least three consecutive days when maximum temperature exceeds 90th percentile, and at least three consecutive days when minimum temperature exceeds 90th percentile. For each of them, five variables were calculated: amplitude, magnitude, number of events, duration, and frequency. Finally, 10 indices resulted for further analysis. The main results are: most of the indices have statistically significant increasing trends; only one index for one weather station indicated statistically significant decreasing trend; the changes are more intense in case of heat waves detected based on maximum temperature compared to those obtained for heat waves identified based on minimum temperature; western and central regions of Romania are the most exposed to increasing heat waves.

1. Introduction

In the last two decades many climate change studies have focused on extreme temperatures as they have a significant impact on environment and society. Among the weather events generated by extreme temperatures, heat waves (HWs) are some of the most harmful. They are often associated with numerous disasters affecting society in terms of human health and mortality, water quality, and engineered systems (Nairn and Fawcett, 2013; Unal et al., 2013; Liu et al., 2015). Moreover, agricultural production, the retail industry, ecosystem services, and tourism may also be affected (Unal et al., 2013). Numerous studies have indicated the increased risk of heat-related deaths due to extreme heat events in populated areas of Europe (Le Tertre et al., 2006; D'Ippoliti et al., 2010), United States (Zanobetti and Schwartz, 2008; Peterson et al., 2013), and Australia (Loughnan et al., 2010; Tong et al., 2010). The most severe HWs occurred at the beginning of the XXIst century and caused many deaths in Europe and Western Russia (Dole et al., 2011; Runhaar et al., 2012; Bittner et al., 2013; Amengual et al., 2014). Thus, the analysis of changes and prediction of HWs occurrence is of a major importance.

In general, extreme temperature events are differently defined depending on the data series available (daily, monthly etc.) (Radinović and Ćurić, 2012). HWs are generally considered as a period of consecutive days with unusual high temperatures. Recent findings showed that the frequency, duration, and intensity of such events increased in many regions of the world (Coumou and Rahmstorf, 2012; Perkins and Alexander, 2013; Keggenhoff et al., 2015; Keellings and Waylen, 2014; Rusticucci et al., 2015). According to the outputs of global and regional climate models, climate change is expected to intensify the HWs, which will become more frequent and more severe in the following decades (Fischer and Schär, 2010; Seneviratne et al., 2012; Kirtman et al., 2013; Amengual et al., 2014). Amengual et al. (2014) analyzed projections of HWs with high impact on human health in Europe and concluded that the largest increase in the incidence of strong and extreme stress HW attributes are expected to take place in Southern Europe throughout this century. Jacob et al. (2014) also found statistically significant increase in the mean number of HWs over the interval May–September in Europe, especially in the southern areas.

Information on HWs for Romanian territory are available in some studies developed at global, or regional scale. In a recent study, Donat et al. (2013) analyzed indices of extreme temperatures at global scale, including a HW-related one (WSDI) and found significant increasing

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trends over the period 1951–2010 for Romania. Their results are in agreement with those got by Spinoni et al. (2015) who analyzed trends in heat and cold waves in the Carpathian region using a set of HWs indices calculated on gridded data. Their main findings are that the HWs events have become more frequent, longer, more severe and intense in the entire Carpathian Region, especially in summer in the Hungarian Plain and Southern Romania.

Recently, in Romania, few studies were also conducted based on observation data, but usually they focused on smaller areas such as Southern Romania or Barlad Plateau (Dragotă and Havriş, 2015; Huştiu, 2016) or even developed at local scale (Croitoru et al., 2014; Papathoma-Koehle et al., 2016).

The main objectives of this study were i. to detect and analyze changes in HWs in Romania based on daily temperature observation data over the extended summer period (May–Sept) using a set of 10 indices recommended by Expert Team on Sector-specific Climate Indices (ET-SCI) members, and ii. to explore the spatial patterns of changes over the entire Romanian territory. Similar multi-angle investigations of HWs have not been done so far in Romania.

2. Data and methods

2.1. Study area

The area under study is located in Eastern Europe (extending on latitude from 43°40′N to 48°11′N, and on longitude from 20°19′E to 29°66′E), and covers >237,000 km^2 (Fig. 1). It has a temperate climate with prevailing continental influences in the eastern and southern regions and dominated by moist oceanic conditions in central and western regions. Mean multiannual temperature ranges from >11.0 °C in southern regions and on the Black Sea coastline to few degrees below 0, in the mountain areas. Precipitation ranges from 300 to 700 mm in East and South, and generally above 500 mm in central and western areas (Croitoru et al., 2013). It rises higher than 1000 mm in the Carpathians. These climatic differences are mainly determined by the presence of the Carpathian Mountains which are considered as a natural barrier for the western moist air masses toward Eastern Europe.

Romania has a population of 20.1 mil inhabitants with >3 mil. older than 64 years and >1 mil. children between 0 and 4 years. With approximately 20% of the population vulnerable to extreme heat (in terms of age), a complex study on changes in such events are imperiously needed.

2.2. Data

HWs data series were derived from daily maximum temperature (*TX*) and daily minimum temperature (*TN*) data sets recorded in 29 weather stations across Romania over a 55-year period (1961–2015).

The Romanian territory has been divided into six regions: Western Romania, Eastern Romania, Southeastern Romania, Central Romania, Southern Romania and Carpathians Region (Table 1). We have included the Southeastern region, even though it is quite small compared to the others, because this area is greatly influenced by the vicinity of the Black Sea and, usually it has a different climatic behavior compared to Eastern or Southern regions. Spatial distribution and geographical coordinates of the considered weather stations are shown in Fig. 1 and Table 1.

Most of the datasets were freely downloaded from *European Climate Assessment and Database* project database (non-blend data) (Klein Tank et al., 2002) and reconstructed from row synoptic messages available on www.meteomanz.com. For five weather stations (Satu Mare, Oradea, Timisoara, Targu Mures, and Brasov) the data sets were provided by Romanian National Meteorological Administration (RNMA). The 55-year period (1961–2015) was chosen in order to avoid as much as possible inhomogeneities and gaps in the daily data that could be induced by some non-climatic factors, such as changing in the observation practice and timetable (Croitoru et al., 2015). In order to meet the WMO requirements, we rejected stations that have >5% of missing data. Finally, the stations used had no >2.2% missing data (Table 1).

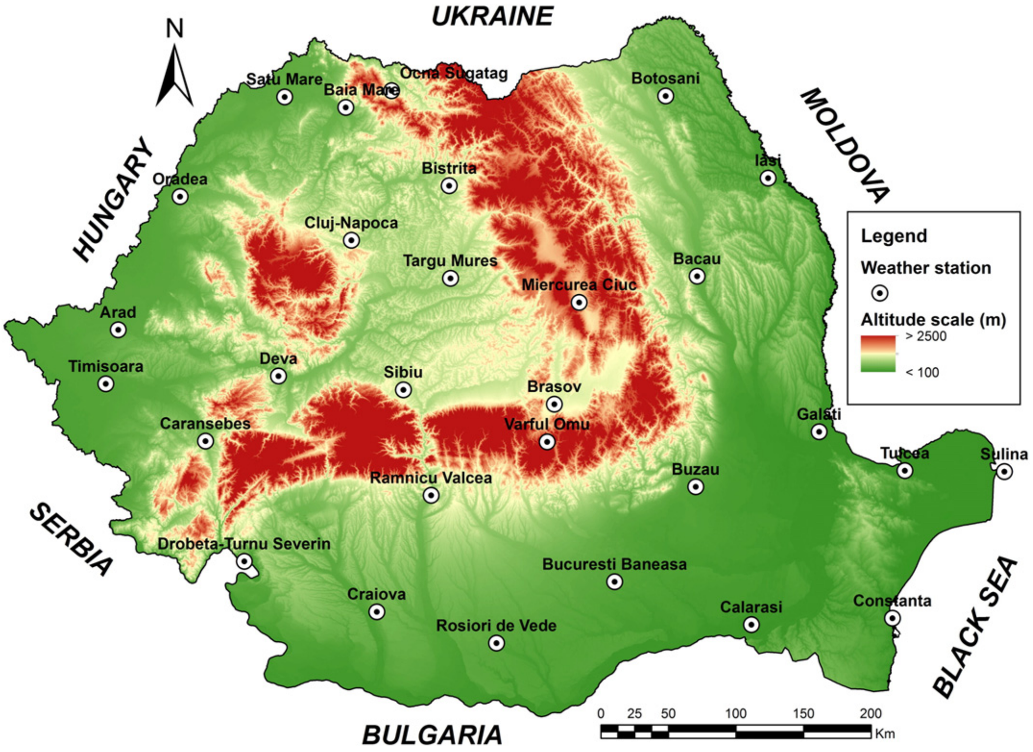

Fig. 1. Study area and weather stations location.

Table 1
Geographical coordinates of the weather stations considered.

No.	Station name[a]	Latitude (N)	Longitude (E)	Altitude (m)	Missing data (%)
Western Romania					
1.	Satu Mare	47°43′18″	22°53′20″	128	0.0
2.	Oradea	47°02′10″	21°53′51″	136	0.0
3.	Arad	46°08′15″	21°21′13″	117	0.0
4.	Timisoara	45°46′17″	21°15′35″	86	0.0
5.	Caransebes	45°25′01″	22°13′30″	241	0.0
Eastern Romania					
6.	Botosani	47°44′08″	26°38′40″	161	0.0
7.	Bacau	46°31′54″	26°54′45″	184	0.0
8.	Iasi	47°10′15″	27°37′42″	102	0.0
9.	Galati	45°28′23″	28°01′56″	71	0.0
Southern Romania					
10.	Buzau	45°07′57″	26°51′05″	97	0.0
11.	Ramnicu Valcea	45°05′19″	24°22′45″	239	0.5
12.	Drobeta-Turnu Severin	44°37′43″	22°37′33″	77	0.3
13.	Bucuresti Baneasa	44°31′00″	26°05′00″	90	0.0
14.	Craiova	44°18′36″	23°52′00″	192	0.0
15.	Calarasi	44°12′22″	27°20′18″	19	0.0
16.	Rosiori de Vede	44°06′26″	24°58′42″	102	0.0
Central Romania					
17.	Bistrita	47°08′56″	24°30′49″	367	0.0
18.	Cluj-Napoca	46°46′39″	23°34′17″	410	0.0
19.	Targu Mures	46°32′01″	24°32′07″	317	0.0
20.	Deva	45°51′52″	22°53′55″	230	0.0
21.	Sibiu	45°47′21″	24°05′28″	444	0.0
22.	Brasov	45°41′46″	25°31′40″	535	0.0
Southwestern Romania					
23.	Tulcea	45°11′26″	28°49′26″	4	0.1
24.	Sulina	45°02′26″	23°16′35″	3	0.2
25.	Constanta	44°12′49″	28°38′41″	13	0.0
Carpathians region					
26.	Ocna Sugatag	47°46′37″	23°56′25″	504	2.1
27.	Baia Mare	47°39′40″	23°29′36″	224	0.0
28.	Miercurea Ciuc	46°22′16″	25°46′21″	661	0.0
29.	Varful Omu	45°26′45″	25°27′24″	2504	0.0

[a] Weather stations are ordered from North to South for each region.

2.3. Methods

2.3.1. Data quality control

Before calculate the indices, data were checked for quality control (QC) by employing ClimPACT2 software developed by Alexander and Herold (2016). As described in the user guide (Alexander and Herold, 2016), the quality control procedure considered seven tests.

1. First, the potential outliers were identified by using the interquartilic technique (IQR). The IQR is the difference between the 75th and 25th percentile. All temperature data falling outside the range defined by 25th − 3 and 75th + 3 interquartilic range is considered outliers. The advantage of this method is that the detection of percentile based outliers is not affected by the presence of larger outliers.
2. The second technique used for QC reports consisted in detection of occurrence of four or more equal consecutive values in temperature data.
3. The third test used for QC reports consisted in detection of the occurrence of values exceeding 50 °C.
4. The fourth technique used for QC reports consisted in identification of the temperature difference between two consecutive values which are equal or higher than 20 °C.
5. The fifth technique used for QC reports: when maximum temperature is lower than minimum temperature has been flagged.
6. The sixth technique used for QC reports: values of maximum and minimum temperature >4 standard deviations away from their respective means were considered for elimination.
7. The seventh technique used for QC reports: rounding problems were also taken in consideration for QC. It assessed how often each of the ten possible values after the decimal point (0.0 to 0.9) appeared. If one or more values are too or less frequent than others, one might consider to discharge the series or use a statistical approach to restitute the data. After data QC check only few errors were found and were eliminated.

2.3.2. HWs identification

Although there is no strict consensus on the definition of a HW, in general, it is defined as an extremely hot period of few consecutive days, usually ranging from a minimum of three to five days. Based on this general definition, a wide variety of methods largely described in scientific literature have been developed to quantify HWs and their variables (Perkins and Alexander, 2013; Croitoru, 2014; Keellings and Waylen, 2014; Radinović and Ćurić, 2014; Keggenhoff et al., 2015; WMO/WHO, 2015; Chen et al., 2016). Most common methods consider that a heat wave occurs when maximum daily temperature exceeds a statistical threshold which can be absolute, or relative thresholds. In the last category, mean values as well as percentile or standard deviation-based thresholds are established (Perkins and Alexander, 2013; Radinović and Ćurić, 2014; WMO/WHO, 2015; Chen et al., 2016). Most of them are based on temperature exceeding a fixed or percentile threshold for a given period (Croitoru, 2014; Keggenhoff et al., 2015). Perkins and Alexander (2013) demonstrated that some commonly used extreme temperature indices and HW definitions (most of which are fixed-threshold based) are not appropriate for various climatic types and suggest the use of percentile-based calculations, as long as the percentile is not set too low or too high. Usually, HWs can be defined as a sequence of consecutive days with air temperature exceeding a certain high percentile threshold, commonly between 90th and 99th (Keellings and Waylen, 2014).

Recently, Expert Team on Sector-Specific Climate Indices (ET-SCI) of the WMO Commission for Climatology and Indices (CCl), in cooperation with sectorial experts in agricultural meteorology, water resources and hydrology, and health, recommended a set of indices to assess a wide range of variables of HWs covering intensity, duration, and frequency (Alexander and Herold, 2016). In this paper, ten of those indices were used.

As intensity threshold, the 90th percentile was employed based on a 15-day window centered on each calendar day (Alexander and Herold, 2016); it was calculated over three baseline periods (1961–1990, 1971–2000, and 1981–2010) because we considered that extra information could be provided and allows a better comparison with other studies using all the three periods.

Two HW definitions were considered as described below:

a) at least three consecutive days when *TX* > 90th percentile (Tx90);
b) at least three consecutive days when *TN* > 90th percentile (Tn90).

The choice of at least three consecutive days for HW indices calculation was justified by studies of human responses to onset of extremely hot weather in which it takes three consecutive days of very hot weather in order the mortality rate to rise significantly above its antecedent rate (Nairn and Fawcett, 2015).

2.3.3. Heat wave variables

For each HW definition considered, five variables were calculated and then analyzed, as the implications of HW variables on specific sectors are very important. The explanations for each variable are shortly presented below (Alexander and Herold, 2016):

Table 2
ET-SCI heat waves indices (after Alexander and Herold, 2016, modified).

Variable	Index	Definition	Units
Heat wave amplitude (HWA)	Tx90	The peak daily value in the hottest heat wave calculated based on *TX* in a year	°C
	Tn90	The peak daily value in the hottest heat wave calculated based on *TN* in a year	°C
Heat wave magnitude (HWM)	Tx90	The mean temperature of all heat waves identified by HWN calculated based on *TX* in a year	°C
	Tn90	The mean temperature of all heat waves identified by HWN calculated based on *TN* in a year	°C
Heat wave number (HWN)	Tx90	The number of individual heat waves calculated based on *TX* in a year	Events
	Tn90	The number of individual heat waves calculated based on *TN* in a year	Events
Heat wave duration (HWD)	Tx90	The length of the longest heat wave identified by HWN calculated based on *TX* in a year	Days
	Tn90	The length of the longest heat wave identified by HWN calculated based on *TN* in a year	Days
Heat wave frequency (HWF)	Tx90	The number of days that contribute to heat waves as identified by HWN calculated based on *TX* in a year	Days
	Tn90	The number of days that contribute to heat waves as identified by HWN calculated based on *TN* in a year	Days

i. *HW amplitude (HWA)* represents the hottest day of the hottest yearly event;
ii. *HW magnitude (HWM)* is the average daily magnitude across all HW events within a year over the period considered (May–Sept);
iii. *HW number (HWN)* is the yearly number of HW events;
iv. *HW duration (HWD)* is the maximum length of a HW event in a year;
v. *HW frequency (HWF)* is the sum of participating HW days according to the definition criteria.

The combination of the two types of data sets (*TX* and *TN*) and the five HWs variables resulted in a set of 10 indices for each location considered and for each baseline period. The indices are briefly described in Table 2.

Using the same calculation procedure, but different temperature parameters (*TX* and *TN* in this case) and defining different indices is a procedure largely used by climatic community in order to detect extreme climate events and it is in agreement with the recommendations of WMO (WMO-TD No. 1500, 2009; Alexander and Herold, 2016). Some authors also considered HWs characteristics (heat wave frequency, longest heat wave duration, heat wave days and high temperature days) as distinct indices (Guo et al., 2016).

In order to get the processed data, the ClimPACT2 software developed by Alexander and Herold (2016) was employed. An earlier version

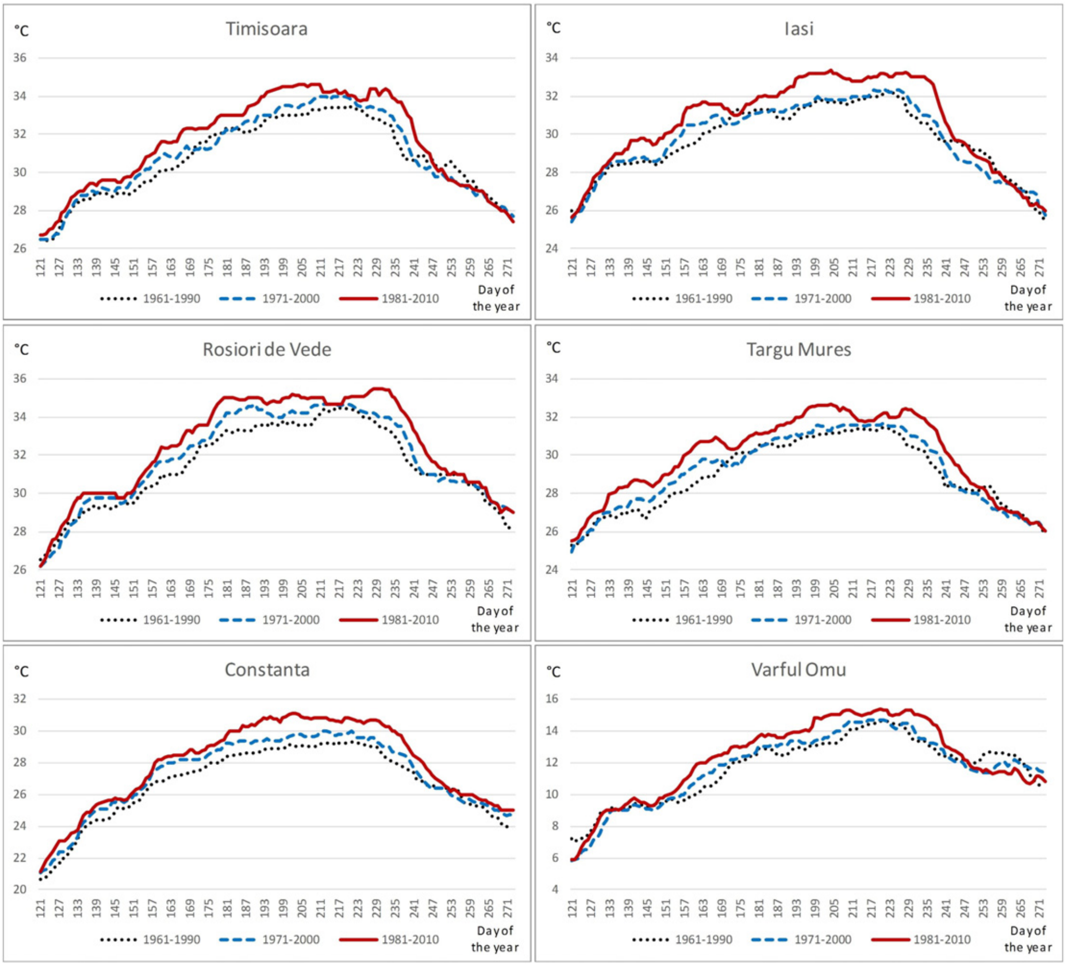

Fig. 2. Daily percentile values calculated for three baseline periods for maximum temperature in six representative weather stations.

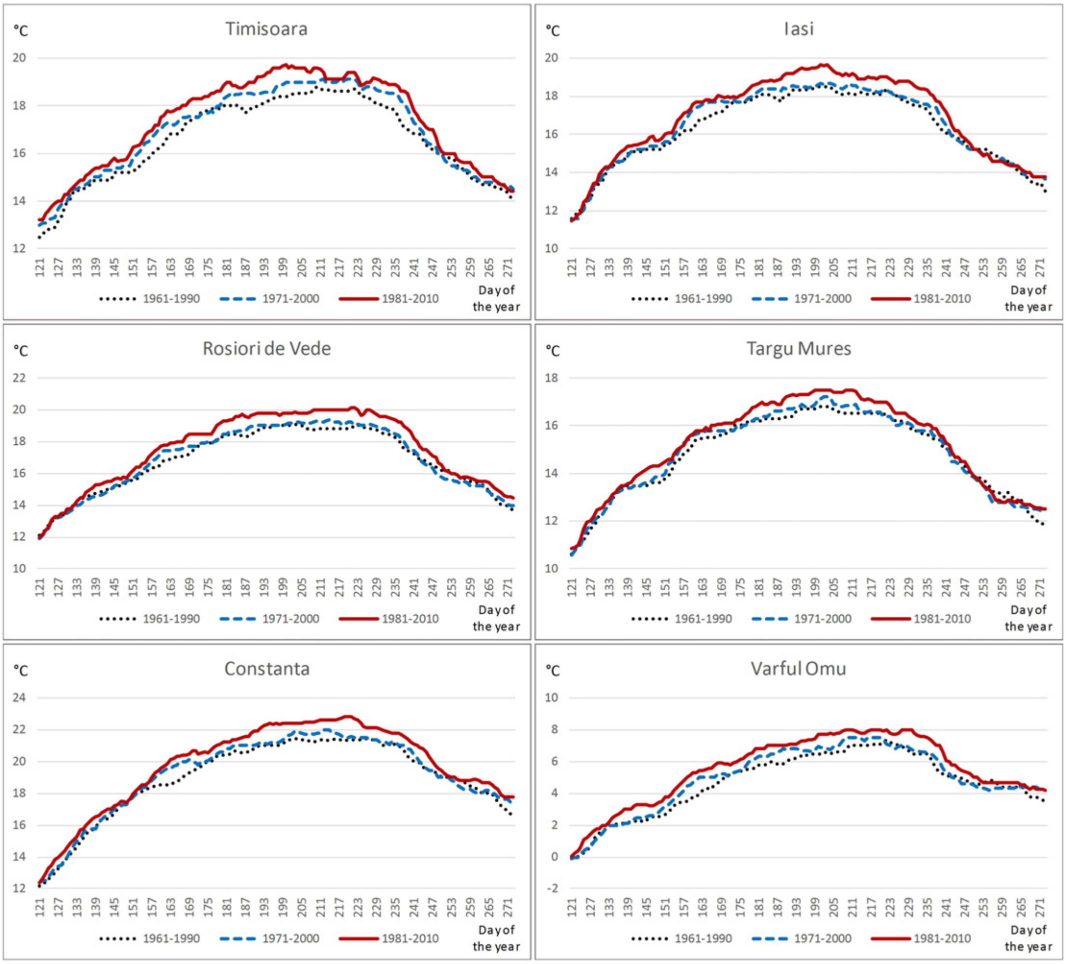

Fig. 3. Daily percentile values calculated for three baseline periods for minimum temperature in six representative weather stations.

of the same software was successfully used by Keggenhoff et al. (2015) for HWs indices detection in Georgia.

2.3.4. Trend detection

Trends were computed using ordinary least square (OLS) and *t*-test methods which are also implemented in the ClimPACT2 software. OLS method uses a linear model to estimate the magnitude of the slope, while *t*-test follows a student's *t*-distribution. The statistical significance of the trends was assessed at the 5% level ($p \le 0.05$).

3. Results and discussions

3.1. Climatology of HWs in Romania

The percentile values changed from one baseline period to another, for both *TX* and *TN* datasets for each weather stations. The difference of percentile values calculated for different baseline period is higher in case of *TX* and during the summer months (Fig. 2) and lower for *TN* data series and during spring and autumn months (Fig. 3). The differences are higher, especially between the percentile calculated for 1981–2010 baseline period and the other two periods, with values that can reach 2.0 °C in summer for *TX* series in Eastern and Southeastern Romania, where the continentalism is more evident. These results justify the use of the three different baseline thresholds. For graphical representations in Figs. 2–3, six weather stations, one representative for each region, were selected to present the results of this analysis.

The mean values of HWN, HWD, and HWF, over the period 1961–2015, were higher in all variables calculated based on *TX* when compared to those calculated by using *TN* (Table 3). In terms of HWA, it is remarkable that all weather stations considered, except that located at >2500 m of altitude, have mean values higher than 30.0 °C. The highest values (usually exceeding 35.0 °C) are specific to Southern Romania, where the warm tropical air advection is more frequent during extended summer period. The lowest occurrence was detected for Southeastern Romania, located mainly on the Black Sea coastline, especially in case of HWs identified based on *TX*. The most appropriate explanation can be the climate moderating effect of the large water body nearby, which does not allow occurrence of high temperature value due to high rate evaporation. Under these conditions, the HWs tend to be weaker and less frequent.

In Romania, the mean multiannual maximum duration of a HW varied from 4.6 to 5.6 days with highest values in central and western regions. The shelter effect of the Carpathians area surrounding slows or even blocks the Mediterranean (especially, in summer) and Atlantic (especially, in spring and autumn) originated air masses movement toward Eastern Europe. Under the impact of “in situ” solar radiation, the HWs could last more in the up-mentioned areas than in other regions. However, because the circulation pattern associated to HWs is extremely important in order to provide a better quality HWs forecast, a detailed analysis is needed and it will be investigated in a different paper. Also, extreme West and extreme East parts of the country, as well as the high mountains areas are the most exposed to the HWs identified based on *TN*.

When maximum values of variables over the 55-yr period are considered, one can notice that they are much higher compared to mean multiannual values (Table 4). The longest HWs can extend over 10

Table 3
Mean values of HWs[a] indices by stations over the period 1961–2015.

Weather station	Tx90					Tn90				
	HWA	HWM	HWN	HWD	HWF	HWA	HWM	HWN	HWD	HWF
Unit	°C	°C	Events	Days	Days	°C	°C	Events	Days	Days
Western Romania										
Satu Mare	33.9	31.6	1.9	5.5	8.8	18.4	16.8	1.2	4.0	4.5
Oradea	34.9	32.6	1.8	5.0	7.9	19.9	18.2	1.5	4.5	6.1
Arad	35.1	32.9	1.8	4.8	7.6	19.7	17.9	1.8	4.6	6.9
Timisoara	35.4	33.1	1.9	5.0	8.2	20.2	18.4	1.3	4.4	5.1
Caransebes	34.3	31.9	1.8	4.8	7.8	20.8	18.3	1.3	3.9	4.4
Eastern Romania										
Botosani	33.8	31.5	1.8	4.9	7.7	20.0	18.0	1.1	4.9	4.4
Bacau	34.6	31.9	2.0	5.0	8.7	18.4	16.8	1.0	4.8	4.3
Iasi	34.1	31.9	1.9	4.9	8.1	20.1	18.3	1.3	4.5	5.2
Galati	35.2	32.8	1.8	4.8	7.4	21.1	19.4	1.3	4.6	5.4
Southern Romania										
Buzau	35.6	33.5	1.5	4.6	6.1	21.9	19.7	1.4	4.5	5.8
Ramnicu Valcea	34.6	32.2	1.8	5.2	8.3	19.6	18.0	1.1	4.8	4.5
Drobeta-Turnu Severin	36.0	33.7	1.6	5.3	7.2	21.5	19.7	1.3	4.4	5.2
Bucuresti Baneasa	36.1	33.5	1.5	4.9	6.1	19.8	17.6	1.4	4.0	5.3
Craiova	36.0	33.4	1.7	4.8	7.2	20.2	18.6	1.3	5.0	5.5
Calarasi	37.1	34.9	1.4	4.8	6.0	20.8	19.1	0.9	4.2	3.4
Rosiori de Vede	36.9	34.5	1.7	4.8	6.8	21.0	18.6	1.1	5.3	4.8
Central Romania										
Bistrita	32.7	30.4	2.0	5.5	9.1	17.5	16	1.1	4.8	4.4
Cluj-Napoca	32.1	29.9	2.0	5.3	9.3	17.5	15.9	1.1	4.2	4.2
Targu Mures	33.6	31.4	1.7	5.1	7.9	17.7	16.1	1.1	3.8	4.0
Deva	34.1	31.7	2.0	5.2	8.8	18.1	16.5	1.0	4.0	3.6
Sibiu	33.1	30.5	1.7	5.6	8.1	17.8	15.9	0.9	4.1	3.5
Brasov	32.3	29.9	1.8	5.0	7.8	15.8	14.6	0.8	3.8	2.6
Southeastern Romania										
Tulcea	34.5	32.4	1.3	5.5	6.0	21.2	19.4	1.0	4.3	3.8
Sulina	30.4	27.7	0.9	5.0	4.0	23.9	22.2	1.4	4.8	5.7
Constanta	32.1	29.6	1.1	4.8	4.3	23.3	21.2	1.2	5.2	5.3
Carpathians region										
Ocna Sugatag	30.9	28.7	1.9	5.4	8.7	17.6	15.9	1.3	4.1	4.8
Baia Mare	33.7	31.2	2.1	5.5	9.7	19.5	17.7	1.2	4.1	4.6
Miercurea Ciuc	31.3	29.0	2.0	5.0	8.7	14.2	12.7	0.7	3.7	2.4
Varful Omu	16.6	14.1	1.7	4.6	6.9	9.5	7.3	1.7	4.8	7.3

[a] The HWs have been detected for this table based on the percentile calculated over the baseline period 1981–2010.

consecutive days or more for all locations considered, and for some weather stations they can reach 18 days. The maximum annual frequency can rise up to 65 days/yr., while the maximum number of events in one year can reach 10, in case of HWs detected based on *TX*. For the HWs calculated based on *TN*, in general, values are lower, but still high compared to those detected for the average values (e.g. up to 49 days/yr in case of HWF) (Table 4).

It has to emphasize that Tn90_HWA and Tn90_HWM, in most locations considered, except those in mountain region, exceeded 20.0 °C and, under this circumstances, it would be interesting to find out whether those nights follow hot days and how much they last, as in such cases the impact on human health could be more severe, due to continuous heat stress.

3.2. Changes in HWs indices in Romania

Results of changes in HW indices series are presented first as overall values, and after that, in the following sub-sections, they are detailed according to the five variables defined in methods chapter: HWA, HWM, HWN, HWD, and HWF.

In order to identify changes in HWs, 870 time series were analyzed for this study. The results indicated remarkable changes occurred in HWs indices during the extended summer season over the period 1961–2015. The great majority of the analyzed time series increased (95%) and >81% of them were found statistically significant, when the percentile threshold was calculated over the baseline period 1961–1990 (Fig. 4, Supplementary material no. 1). Only <5% of the series recorded decreasing trends, and they are not statistically significant. When 1971–2000, and respectively 1981–2010, baseline periods were used for thresholds calculation, results showed similar values of the frequency for positive slope, while those statistically significant slowly decreased (78%, and respectively 74% of time series). Stationary trends missed for the analysis performed based on 1961–1990 percentile threshold and they were detected in <1% of the series when 1971–2000 and 1981–2010 baseline periods were considered. Decreasing trends were found just for few indices and only when the 1981–2010 baseline period percentile threshold was employed; only one of them was found statistically significant.

As overall, Southeastern Romania, greatly influenced by the Black Sea climatic conditions, which could attenuate the accelerating warming, is the less affected area in the country. However, we should be cautious since it could be only a temporary situation and we could expect in the near future to an evolution toward significant upward trends for all HWs variables as is the situation on the Black Sea Northern Coast (Crimean Peninsula) reported by Shevchenko et al. (2014).

3.2.1. Heat wave amplitude (HWA)

Changes in the intensity of HWs were evaluated by using HWA indicator. The Tx90_HWA index series increased significantly for the great majority of the locations considered (>79%) for all baseline periods

Table 4
Maximum values of HWs[a] indices by stations over the period 1961–2015.

Region/weather station	Tx90					Tn90				
	HWA	HWM	HWN	HWD	HWF	HWA	HWM	HWN	HWD	HWF
Unit	°C	°C	Events	Days	Days	°C	°C	Events	Days	Days
Western Romania										
Satu Mare	39.3	34.9	8	14	47	22.4	19.4	6	7	23
Oradea	40.4	35.9	8	12	40	22.9	20.6	7	15	46
Arad	39.9	36.4	9	13	39	22.8	20.6	10	9	45
Timisoara	39.9	37.5	7	13	41	23.6	20.9	7	7	34
Caransebes	40.3	35.4	8	12	46	23.8	21.3	6	6	24
Eastern Romania										
Botosani	40.9	34.6	8	12	47	23.5	20.3	6	12	27
Bacau	40.3	34.9	11	14	65	22.5	20.6	5	18	24
Iasi	40.1	34.9	9	12	46	24.8	21.0	8	9	31
Galati	40.4	36.0	7	11	38	26.8	22.6	6	17	33
Southern Romania										
Buzau	40.3	36.5	6	10	28	25.8	23.4	5	12	30
Ramnicu Valcea	40.6	35.2	10	13	59	22.7	20.5	5	9	21
Drobeta-Turnu Severin	42.6	39.0	6	10	35	25.8	21.8	6	9	27
Bucuresti Baneasa	42.2	36.5	8	10	35	24.4	19.8	7	8	27
Craiova	42.6	37.4	7	11	40	23.5	21.2	5	11	23
Calarasi	42.1	37.9	8	10	42	27.1	21.9	5	15	25
Rosiori de Vede	42.7	38.1	7	10	34	24.4	21.4	7	9	32
Central Romania										
Bistrita	38.0	32.7	9	14	56	20.2	18.8	8	10	35
Cluj-Napoca	38.5	32.7	7	13	52	21.2	17.8	5	9	26
Targu Mures	38.8	33.9	8	12	57	21.2	18.7	6	10	22
Deva	40.0	35.1	9	12	49	20.5	18.4	6	7	30
Sibiu	38.9	33.7	7	13	46	22.3	18.3	7	6	23
Brasov	37.2	32.5	9	10	54	19.2	17.1	5	7	16
Southwestern Romania										
Tulcea	39.9	36.0	7	14	44	25.8	24.6	6	12	31
Sulina	34.4	30.5	4	18	25	27.0	24.6	8	9	27
Constanta	38.5	33.7	5	17	26	27.0	23.8	6	16	29
Carpathians region										
Ocna Sugatag	35.8	31.6	8	14	48	20.3	18.5	6	8	22
Baia Mare	39.4	34.0	9	14	46	24.9	20.9	5	7	19
Miercurea Ciuc	36.0	32.0	10	12	65	16.7	15.2	4	7	16
Varful Omu	22.1	17.0	7	10	41	12.5	9.9	9	9	49

[a] The HWs have been detected for this table based on the percentile calculated over the baseline period 1981–2010.

thresholds employed. Spatial distribution analysis showed that statistically insignificant increasing trends were found especially in southern areas of Romania, whereas only one weather station experience downward trend in the same area (Fig. 5). From year to year a great variability was detected (Supplementary material no. 2).

Although the frequency of significant increasing trends for the series calculated based on 1961–1990 percentile thresholds is higher (Fig. 5a) compared to the last two baseline periods (Fig. 5b, c), the values detected based on recent decades thresholds are still high (Table 5).

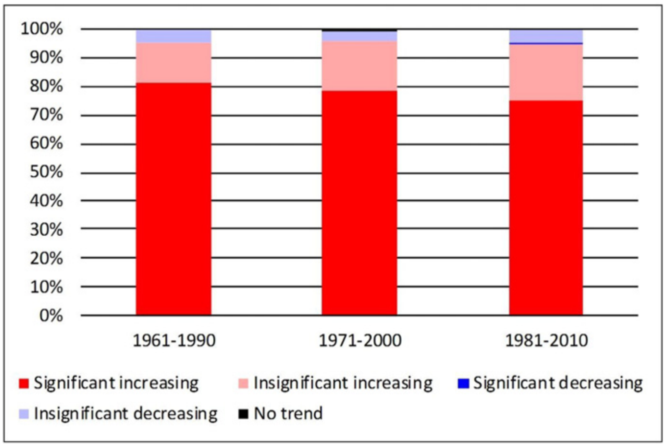

Fig. 4. Type of changes detected for HWs indices.

The slopes of Tx90_HWA series are slightly lower for the first two baseline periods threshold (0.60 and 0.61 °C/decade, respectively) than for the last one (0.67 °C/decade), as country overall average, indicating a more intense increase in the last three decades (Table 5, Supplementary materials no. 3–5).

Tn90_HWA also indicates statistically significant increase in most of the weather stations but, compared to the results obtained for Tx90_HWA, a wider variation using different baseline period thresholds was found. The western half of Romania seems to be the most exposed to significant changes (Fig. 5d–f). Few decreasing trends were registered for all thresholds, but they were statistically insignificant.

The increase in HWA indices has a greater impact on agriculture, usually due to high values of evapotranspiration and severe drought associated to HWs and these results could be useful for stakeholders in agriculture, since the greatest part of lowlands in Romania is used for crop production. Under HWA increasing conditions, the yields could be severely damaged during HWs, especially due to lack of irrigation systems that have been completely destroyed after the communism collapse in 1989.

3.2.2. Heat wave magnitude (HWM)

Over the considered period, in case of HWM indices the increase seems to be more pronounced in the last decades, for most of the weather stations considered (Supplementary material no. 6).

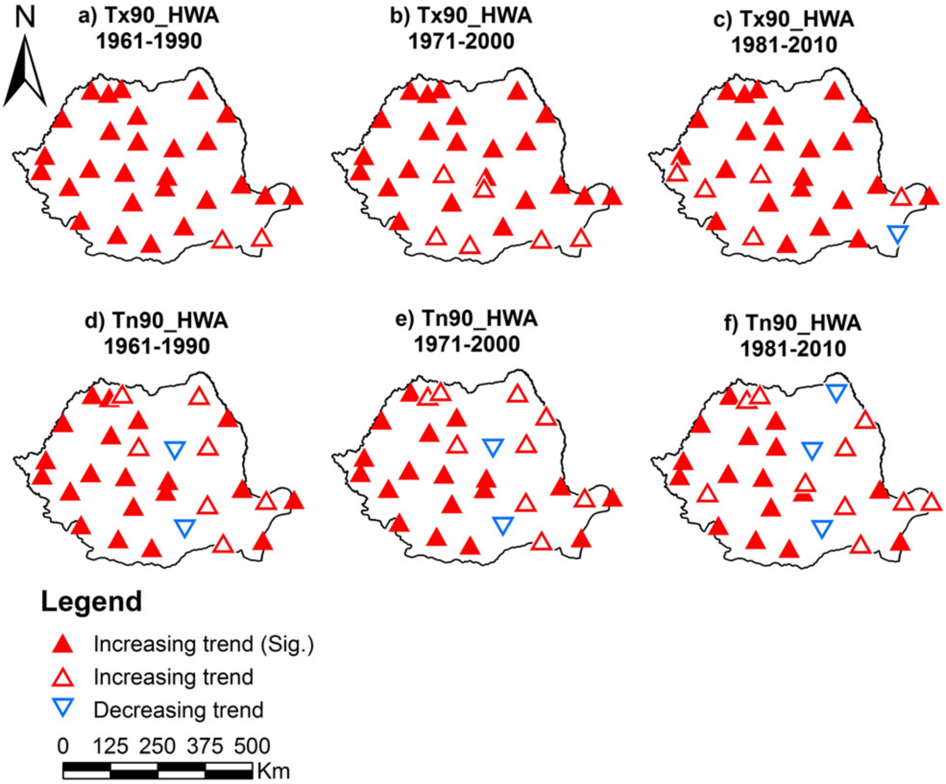

Fig. 5. Spatial distribution of trends in HWA indices.

In terms of changes, similar to Tx90_HWA, Tx90_HWM increased significantly in most of the analyzed locations for all baseline period thresholds considered. The highest number of positive slopes was recorded for the 1971–2000 baseline period threshold (Supplementary material no. 1), and reached 83%, but the slopes values calculated based on 1981–2010 threshold were the highest as country overall average (0.45 °C/decade) (Table 5). Only one weather station recorded decreasing trend in the Southeastern Romania for all thresholds, but statistically insignificant (Fig. 6a–c).

Tn90_HWM increased in about 65% of the locations, but the upward trends were found statistically significant in <21% of them. It is remarkable that even though the number of increasing series maintained, the number of statistical significant changes increased from 13% to >20% from the first baseline period for threshold calculation to the last one (Fig. 6, Supplementary material no. 1). The average value of the slopes calculated for this index for all weather stations considered was 0.2 °C/decade or less for all thresholds (Table 5). Spatial distribution analysis showed a significant increasing change in Southwestern Romania for all thresholds considered (Fig. 6d–f), while decreasing trends were recorded mainly in the southern and southeastern regions of the country.

3.2.3. Heat wave number (HWN)

HWN recorded a spectacular increase for the extended summer season over the period 1961–2015, more accelerated from the beginning of '90s in case of Tn90_HWD (Fig. 7a) and from the beginning of 80's in case of Tx90_HWN (Fig. 7b). The highest values are specific to the last 15 years associated to the sharp increase in mean and extreme temperature in Romania (Busuioc et al., 2010; Croitoru and Piticar, 2013). Significant changes cover all locations and all thresholds considered (Fig. 8a–c).

On average, the highest slopes were recorded for Tx90_HWN index when 1961–1990 baseline period threshold was used (0.78 events/decade), while the lowest value was found for the most recent baseline period threshold (0.50 events/decade) (Table 5, Supplementary materials no. 3–5).

These results are similar to those got by Rusticucci et al. (2015) in a recent study focused on HWs in Buenos Aires, by using the 90th percentile calculated over the 1961–1990 period. They found significant increasing trends for both indices (Tx90_HWN and Tn90_HWN) in the warm season over the period 1961–2010.

In case of Tn90_HWN, the frequency of increasing significant changes is still very high (>89%), while decreasing trends have been identified in <7% of the series (Fig. 8d–f, Supplementary material no. 1). However, the slopes are lower (0.63…0.37 events/decade), compared to those calculated for the Tx90_HWN (Supplementary materials no. 3–5).

3.2.4. Heat wave duration (HWD)

The fourth category of indices considered duration of the longest HW of each year. The time series of the two indices series

Table 5
Slopes[a] calculated, as average values, for all weather stations in the country for HWs indices.

Baseline period	Tx90					Tn90				
	HWA	HWM	HWN	HWD	HWF	HWA	HWM	HWN	HWD	HWF
1961–1990	0.60	0.27	0.78	0.79	4.52	0.38	0.12	0.63	0.61	3.18
1971–2000	0.61	0.34	0.69	0.63	3.80	0.39	0.15	0.53	0.53	2.58
1981–2010	0.67	0.45	0.50	0.56	2.67	0.40	0.20	0.37	0.38	1.67

[a] The slopes are calculated per decade.

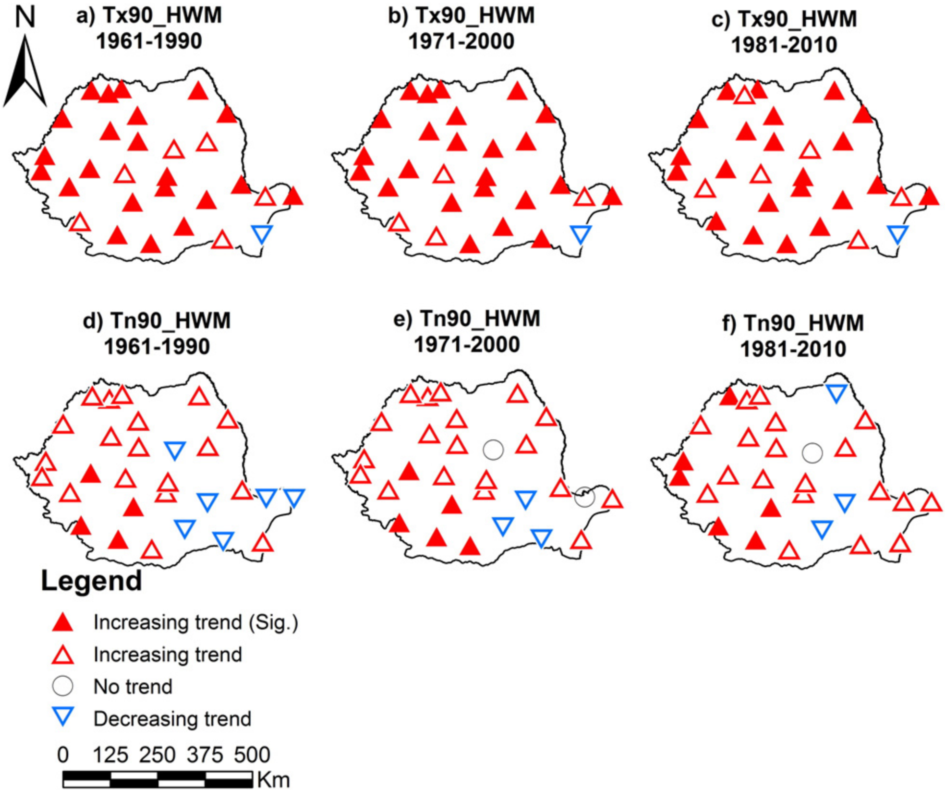

Fig. 6. Spatial distribution of trends in HWM indices.

(Tx90_HWD and Tn90_HWD) recorded mainly upward trends for all definitions and thresholds considered (Fig. 9, Supplementary materials no. 1, 3–5, and 7). >80% of trends detected in the data sets were found as having statistically significant increasing when indices were calculated based on 1961–1990 baseline period; the most intense change was of 0.79, and respectively 0.61 days/decade. The HWD increased at lower rates for both Tx90_HWN and Tn90_HWN indices when changing the baseline period from the oldest to the most recent one (Table 5).

Only few isolated decreasing trends were recorded in Tn90_HWD index including a significant one in Southern Romania. The slopes calculated in Romania are higher compared to those got by Unal et al. (2013), who also found increasing trends in HWN and HWD in Western Turkey. However, they analyzed HWs for a shorter season (June–August) and over a shorter period (1965–2006) by using apparent temperature which combines the effects of temperature and humidity.

HWD was found to have a greater impact on human mortality and water quality than other HWs characteristics (D'Ippoliti et al., 2010; Liu et al., 2015; Kim et al., 2016). Recently, HWD was used as predictor of human deaths and found that maximum duration of HWs is of a greater concern than the HWN (Kim et al., 2016). Considering the results of this paper and the fact that most of the weather stations chosen for this study are located near big cities with continuous urbanization development and urban heat islands extension, we can estimate that inside cities, the temperature can be 1 to 4 °C higher according to recent measurements (Racoviceanu et al., 2016; Herbel et al., 2016).

Under these circumstances, one can state that the vulnerability increased for the most part of Romanian territory, except for the Carpathians region and the areas located near the big water bodies (the Black Sea coast and the Danube). These findings could be of great importance for developing biometeorology studies in the near future in Romania and to confirm this hypothesis.

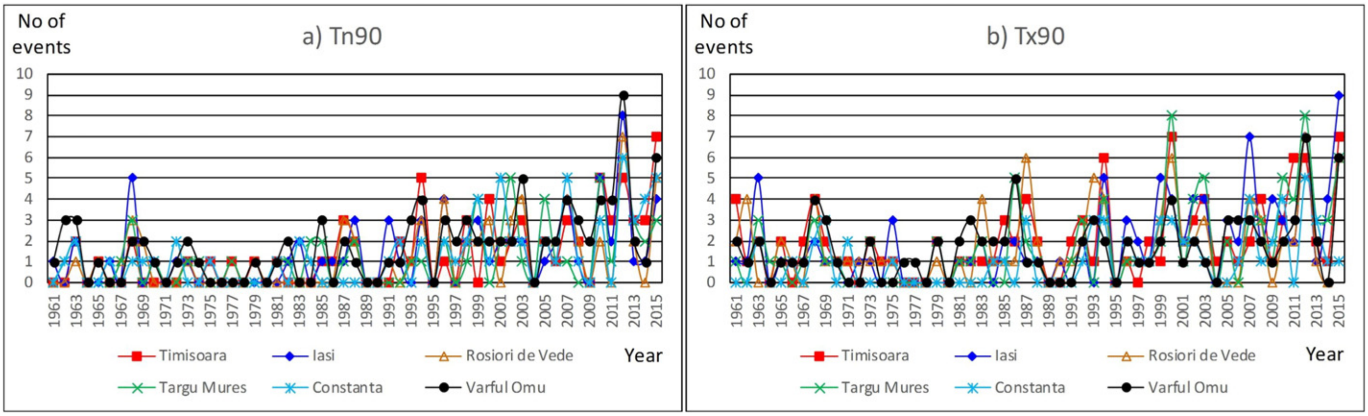

Fig. 7. HWs annual number over the period 1961–2015 detected based on 1981–2010 percentile threshold.

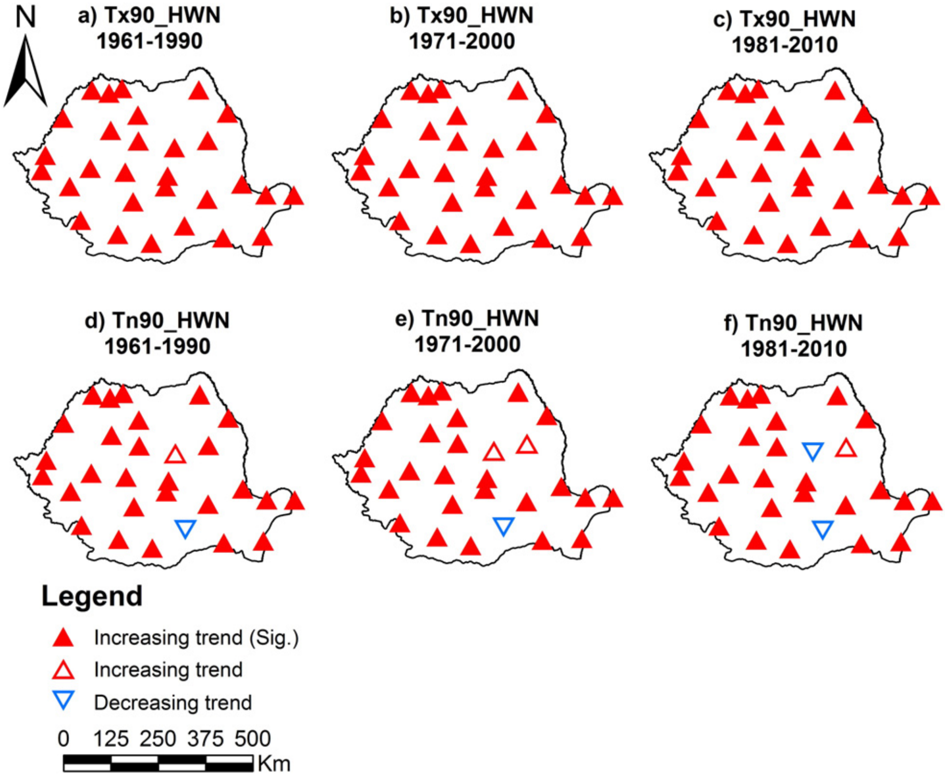

Fig. 8. Spatial distribution of trends in HWN indices.

3.2.5. Heat wave frequency (HWF)

Tx90_HWF index increased significantly, especially after mid'80s in all weather stations and for all thresholds (Fig. 10a–c, Supplementary no. 1, 3–5, and 8). Isolated statistically insignificant decreasing trends were detected only in the Tn90_HWF data sets of two weather stations (Fig. 10d–f).

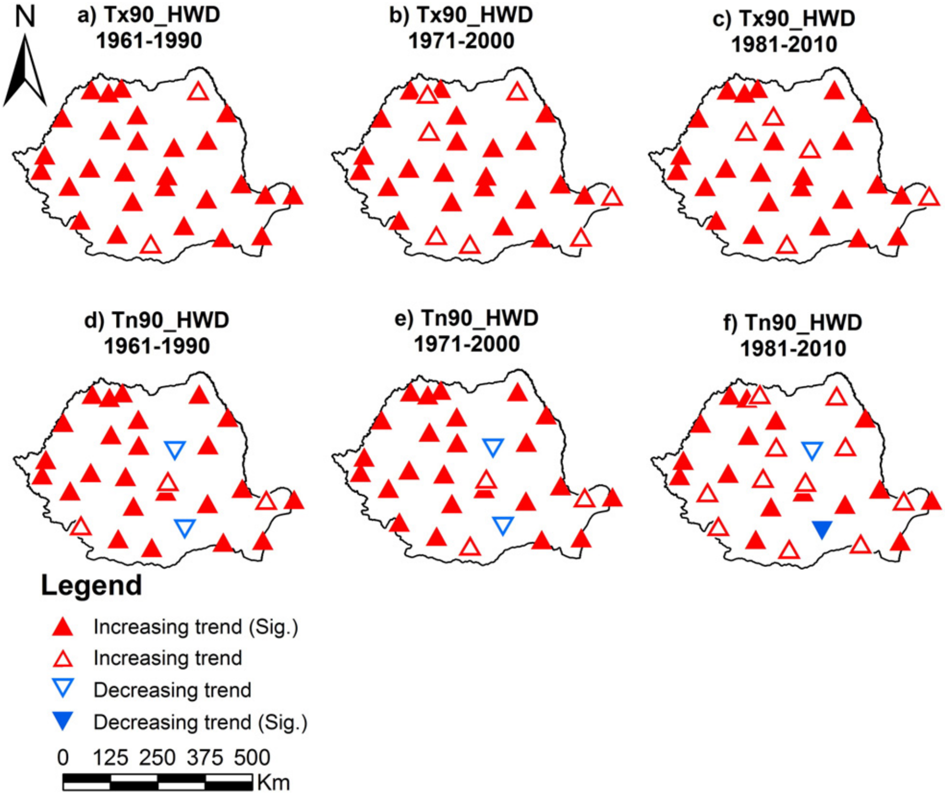

Fig. 9. Spatial distribution of trends in HWD indices.

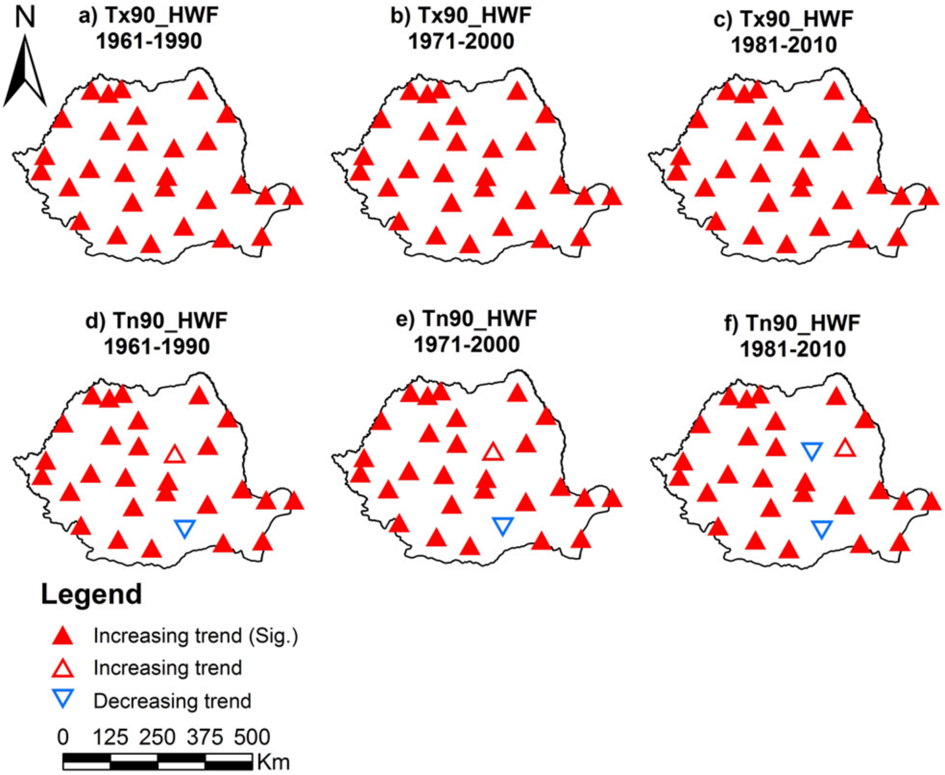

Fig. 10. Spatial distribution of trends in HWF indices.

The most intense increase was recorded for Tx90_HWF, but the slopes became lower for both Tx90_HWF and Tn90_HWF when the threshold calculated based on the recent baseline periods was used (Table 5, Supplementary materials no. 3–5).

Accounting for both maximum and minimum air temperature enables a more in-depth analysis of changes in HWs. The results suggest a strong increase of HWs indices not only during daytime, but also during nighttime. The slopes are higher for Tx90_HWF for all stations indicating that daytime events are warming faster than the nighttime ones. These results are similar to those found in other areas of the globe (Perkins and Alexander, 2013).

As it can be observed, there are many similarities between changes in HWF and HWN indices, but this can be easily explained since a change in the number of participating days directly induces a change in the number of HWs (Perkins and Alexander, 2013).

However, because the warming of consecutive nights exacerbates daytime HWs conditions (Perkins and Alexander, 2013), it would be very useful to analyze whether the HWs detected based on *TX* and *TN* occur simultaneously or not. This type of analysis supposes a combined approach of HWs detected based on the two types of time series, but unfortunately, the application used for data processing in this paper (ClimPACT2), does not allow detection of such HWs and does not provide information on the exactly date of HWs occurrence as identification of start and end data of each events.

Also, detailed studies on HWs impact on human health, agriculture, water resources or other interest domains are needed as they could provide information on which are the most suitable indices to be used in the future for such approach.

4. Conclusions

In this study, changes in HWs for the extended summer season (May–September) over a 55-year period (1961–2015) were analyzed. The HWs were identified based on *TX* and *TN*, and after that the two HWs series were combined with five HWs variables (amplitude, magnitude, number, duration, and frequency), resulting in a set of 10 indices recommended by ET-SCI. The results suggest that assessing changes in HWs only by *TX* can lead to a lack of understanding of the complexity of HWs changes and implications, which could arise since comparisons among different definitions and variables used in this study showed differences. The three baseline periods employed for thresholds calculation provide additional information which indicates that intense changes in HWs did not occur only in relation to earlier and colder periods, but they occurred also with similar rates when the current and hotter baseline period (1981–2010), recommended by WMO, was considered.

Our study reveals a worrying increase in all HWs indices over the interval May–Sept, which seems to be present even when HWs were identified based on the recent and warmer 1981–2010 baseline period threshold. The most severe change was found for indices calculated based on *TX*, which had the highest frequency of significant trends (between 76% and 100%). In terms of indices, the most important changes were recorded in the annual number of HWs (HWN) and in the amount of participating HW days (HWF), with frequency of significant increasing trends of 100% in case of definition based on *TX*. Present analysis showed that intensity of HWs (HWA) is increasing faster than average conditions (HWM).

The general results of this study could lead to the hypothesis that HWs had an important contribution on general temperature increase in Romania detected over the last decades.

Also, it should be mentioned that in general, frequency and slopes of significant increasing trends slightly decreased when the threshold was considered for recent baseline periods.

Results of this research could be of great interest for decision-makers in different fields since HWs may become more exacerbated in all features and definitions with important impact on human health and mortality, agriculture, ecosystems, water resources, and infrastructure. As HWs become longer and more intense, they induce a temporary high rise of water temperatures to the point when the quality is deteriorated by the intensification of organic and biological processes (Liu et al., 2015). Another important sector affected by changes in HWs is agriculture. Intense and prolonged heat and evapotranspiration during HWs associated with the lack of precipitation, are of critical considerations from food security and economical perspective under the changing conditions in Romania (Croitoru et al., 2013; Bogawski and Bednorz, 2015).

Under these circumstances further research needs to be undertaken in order to investigate whether changes in HWs detected based on *TX* and *TN* occur with the same rate above higher percentile thresholds (i.e. 95th, 98th, 99th) and to study the consequences of changes in such events on specific sectors and systems in different seasons.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gloplacha.2016.08.016.

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