SPATIO-TEMPORAL CHANGES IN ANNUAL TEMPERATURE EXTREMES OVER ROMANIA (1961–2013)

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Abstract. In order to identify changes in the annual temperature extremes, the Mann-Kendall non-parametric trend test has been applied to several thermal indices, recommended by the *Expert Team on Climate Change Detection and Indices* (ETCCDI). The indices were computed from gridded daily data of minimum and maximum temperature at 0.1° resolution (~10 km), freely available within the ROCADA dataset for the period 1961–2013. The results show decreasing trends in cold-related indices, especially in the number of frost days, and increasing trends in warm-related extremes. The trend patterns are consistent over the region, *i.e.*, there are no mixed trends for a given index. The regional differences in climatic trends over Romania are related to altitude, rather than latitude. The key findings suggest a country-wide increasing frequency of summer days, an increase of tropical nights frequency at lower elevations, a reduction of frost season and a widening of the growing season in the extra-Carpathian regions. The duration of warm spells have been increasing over most of Romania. Our results are in agreement with previous temperature-related studies in the region.

Key words: ETCCDI; frost days; summer days; tropical nights; growing season length; warm spell duration index; trend analysis; thermal extremes.

1. INTRODUCTION

Daily maximum and minimum temperatures (Tmax and Tmin) are essential climatic variables particularly involved in determining climate change impacts on society and ecosystems. Several studies conducted at different spatial scales, from planetary to continental, regional, national or event locale scale, have demonstrated the asymmetrical evolution patterns in day-time versus night-time warming [1–3].

The climatic changes in Romania have been showing their environmental, societal and economic effects visibly over the last decades. Several recent climate studies relying on long-term observational time-series provided reliable evidence

of a robust and ongoing warming in summer, winter and spring [4], increasing rain shower frequency [5, 6], decrease in winter snow depth [7, 8] and in wind speed [9]; these changes have been found to affect drought patterns [10–12], natural streamflow regime [13, 14] and even the composition of rainwater [15–17] in many regions across the country. Observational analyses of the variability and trends of extreme events suggest an overall consensus towards a significant increase in the frequency, duration and intensity of warm extremes and intensification of bioclimatic heat stress in the region [18–21].

The influence of *North Atlantic Oscillation* (NAO) on winter temperature, precipitation and snow cover over Romania was demonstrated in several papers [22, 7]. NAO was also proved to influence the Romanian streamflow regime [23–25]. Other teleconnection patterns were recently investigated in the region, too, like the Atlantic Multidecadal Oscillation [26], East Atlantic [27] or East Atlantic / Western Russia [28].

Investigating the regional change patterns in annual thermal extremes under the observed climate evolution (Fig. 1), this paper aims to advance the knowledge base of recent climatic changes in Romania, and to provide a baseline for the foregoing assessments of possible responses of the regional climates to global warming at a larger (regional) scale.
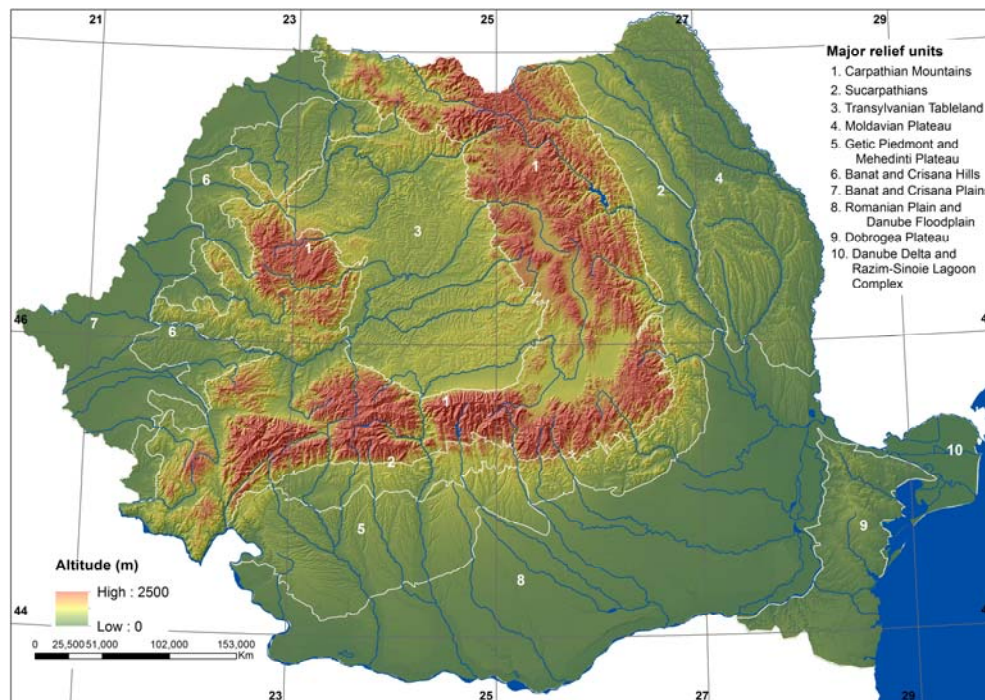

Fig. 1 – Study area with the main geographical units of Romania.

2. DATA

The data used in this study consist in gridded maximum and minimum air temperature at 0.1° spatial resolution, covering the period 1961–2013, extracted from the ROCADA dataset [29].

Seven annual thermal indices of extremes [30–31] – recommended by the *Expert Team on Climate Change Detection and Indices* (ETCCDI) have been computed, based on the aforementioned dataset, as follows:

(1) FD – **number of frost days**: annual count of days with daily minimum temperature < 0°C.

(2) SU – **number of summer days**: annual count of days with daily maximum temperature > 25°C.

(3) ID – **number of icing days**: annual count of days with daily maximum temperature < 0°C.

(4) TR – **number of tropical nights**: annual count of days with daily minimum temperature > 20°C.

(5) CSDI – **Cold Spell Duration Index**: annual count of days with at least 6 consecutive days with daily minimum temperature < 10th percentile.

(6) WSDI – **Warm Spell Duration Index**: annual count of days with at least 6 consecutive days with daily maximum temperature > 90th percentile.

(7) GSL – **growing season length**: annual count between first span of at least 6 days with daily mean temperature > 5°C and first span after July 1st of (at least) 6 days with daily mean temperature < 5°C.

3. METHODOLOGY

The local significance of trends has been analysed with the nonparametric Mann-Kendall (MK) test [32–33] for each grid cell: for a given index, the 50 annual values (from 1961 to 2013) were computed for each pixel individually, and the MK test was applied to the 2400 time series of the respective index. The MK test is a rank-based procedure, especially suitable for non-normally distributed data, data containing outliers and non-linear trends. The null and the alternative hypothesis of the MK test for trend in the random variable x are:

$$\begin{cases} H_0 : \Pr(x_j > x_i) = 0.5 \ , \quad j > i \\ H_A : \Pr(x_j < x_i) \neq 0.5 \ , \quad \text{(two-sided test)} \end{cases} \tag{1}$$

The MK statistic S is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k) \tag{2}$$

where x_j and x_k are the data values in years j and k, respectively, with $j > k$, n is the total number of years and sgn() is the sign function:

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 \text{ , if } x_j - x_k > 0 \\ 0 \text{ , if } x_j - x_k = 0 \\ -1 \text{ , if } x_j - x_k < 0 \end{cases} \tag{3}$$

For large n, the distribution of S can be well approximated by a normal distribution with mean zero and standard deviation given by:

$$\sigma_S = \sqrt{\frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18}} \tag{4}$$

Equation (4) gives the standard deviation of S with the correction for ties in data, with g being the number of tied groups, and t_i denoting the number of ties of extent i. The standard normal variate Z_S is then used for hypothesis testing.

$$Z_S = \begin{cases} \dfrac{S-1}{\sigma_S} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sigma_S} & \text{if } S < 0 \end{cases} \tag{5}$$

The null hypothesis is rejected at significance level α if $|Z|>Z_{\alpha/2}$ (two-sided), where $Z_{\alpha/2}$ is the value of the standard normal distribution with an exceedance probability $\alpha/2$. In the present analysis, the significance level was fixed at 10% (two-tail test).

4. RESULTS AND DISCUSSION

The spatial distribution of the significant trends is presented in Figure 2 and discussed in detail hereafter. Table 1 summarizes the spatial distribution of upward and downward trends across the major geographical regions of the country, corresponding to its main relief units.

4.1. CHANGES IN WARM EXTREMES

Although the climate warming magnitude is not uniform across the country, the trend analysis of the three warm-related indices (SU, TR and WDSI) provides

strong evidence of heat stress intensification over extended areas, especially in the last few decades when the observed temperature rise was the steepest since AD 1961.
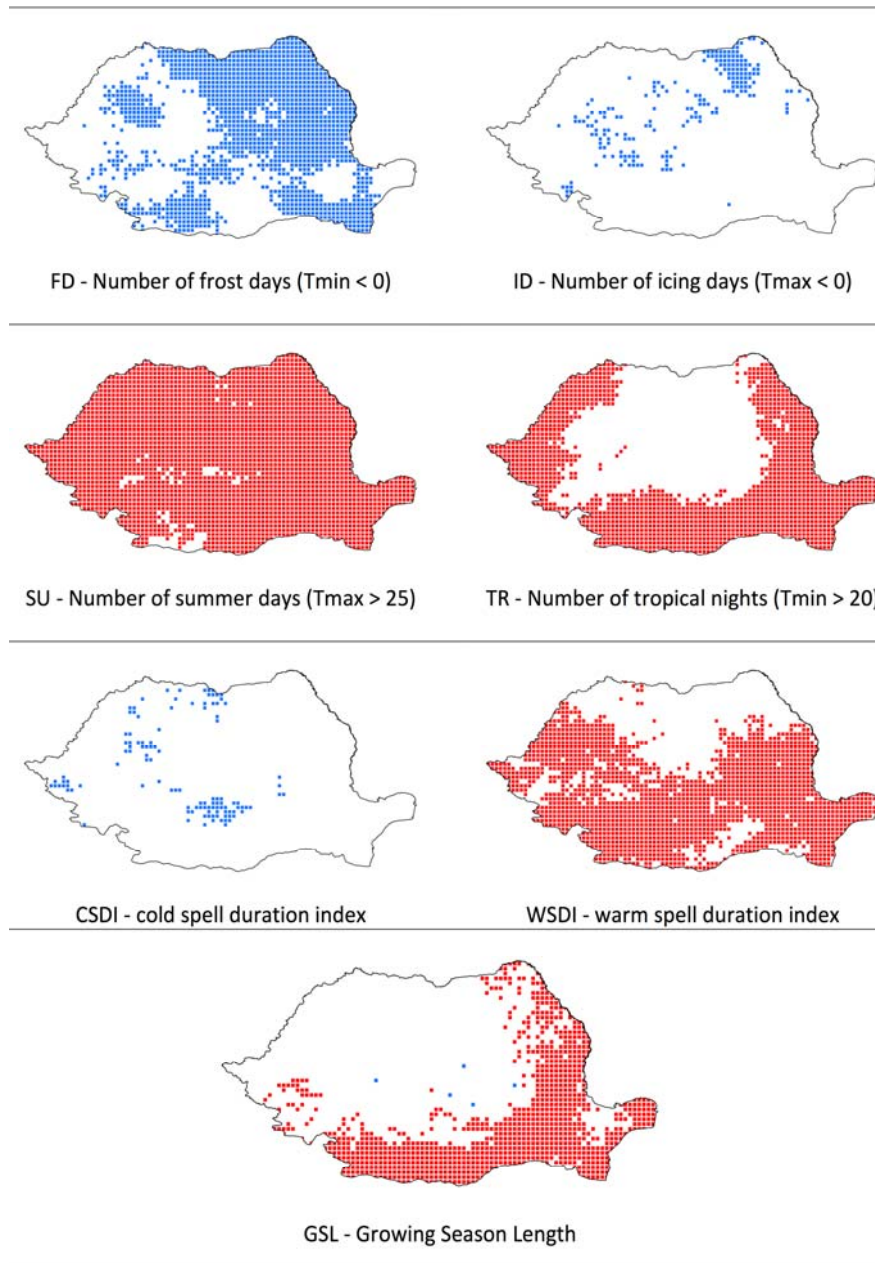

Fig. 2 – (Color online) Trends in annual thermal indices of extreme in the Carpathians. The grid cells presenting significant increasing (decreasing) trends at 10% level (two-tailed) are in red (blue).

Table 1

Summary of significant trends (as % of total) classified by major geographical region

Region	Trend	FD	SU	ID	TR	CSDI	WSDI	GSL
1. Carpathian Mountains	Up	0	96	0	6	0	82	3
	Down	71	0	14	0	14	0	1
2. Subcarpathians	Up	0	100	0	31	0	92	28
	Down	71	0	5	0	3	0	0
3. Transylvanian Tableland	Up	0	100	0	2	0	92	0
	Down	24	0	15	0	1	0	0
4. Moldavian Plateau	Up	0	100	0	74	0	57	36
	Down	96	0	20	0	0	0	0
5. Getic Piedmont and Mehedinţi Plateau	Up	0	100	0	86	0	100	54
	Down	19	0	0	0	0	0	0
6. Dobrogea Plateau	Up	0	100	0	100	0	97	52
	Down	56	0	0	0	0	0	0
7. Banat and Crişana Hills	Up	0	100	0	73	0	100	1
	Down	17	0	3	0	1	0	0
8. Romanian Plain and Danube Floodplain	Up	0	100	0	98	0	98	83
	Down	10	0	0	0	0	0	0
9. Banat and Crişana Plains	Up	0	100	0	99	0	98	2
	Down	2	0	0	0	0	0	0
10. Danube Delta and Razim-Sinoie Lagoon Complex	Up	0	100	0	100	0	100	41
	Down	0	0	0	0	0	0	0

The changing signal in the annual frequency of *summer days* (SU) is particularly robust, both statistically and spatially, regardless the elevation (Table 1). The country-wide pattern of this highly significant change is attributed to the positive shifts in the upper tails of daily maximum temperatures over the last 30 years (after mid 1980s or early 1990s), observed during the summer months. Despite the limited exposure to heat stress induced by elevation, the Carpathian Mountains are placed among the major hotspot regions of the country by means of SU. The upward trends in summer days frequency across this mountain region is very consistent (96% of the territory), providing indication of an extensive and intense summer warming. On average, summers in the Carpathians are rather cool (especially in its southern and eastern branches), with seasonal averages of maximum temperatures below 20°C in the high-elevation areas (>800 m) and 25°C in low-elevation ones. During the hot summers of the last two decades (*e.g.*, 2000, 2007 and 2010), which hold about 60% of the total maximum temperature records in the areas above 800 m, occurrences of hot days with daily maximum temperatures above 25°C or even 30°C increased significantly in some low-elevation locations (below 1,500 m), especially during the peak intensity moments of some persistent heat spells (*e.g.*, up to 5 cases/month in July 2007 at Predeal station). For only very scattered areas in the Southern and Eastern Carpathians SU evolution is stable.

The MK test estimates indicate consistent upwards in the frequency of *tropical nights* (TR) only in the southern, western and eastern lowland areas, located outside the Carpathian Chain, corresponding to the major plains (the Romanian Plain, the Banat and Crisana Plain) and tableland regions of the country (*e.g.*, the Getic, Moldavian

and Dobrogea tablelands), generally over 70% of their territory. With an elevation below 600–800 m, these regions area particularly exposed to persistent and intense summer heat spells, both during the day and night. TR are not characteristic to the Carpathian Mountains, where climate warming appears to exacerbate the thermal extremes mainly in the upper tails of day-time maxima and less in those of night-time minima. The mountain areas subject to positive changes in the occurrence of TR are very scattered across the Carpathians, significant increasing trends being present only in some spots in the North-Western Carpathians (counting for up to 6% of the entire region) (Table 1). TR upwards are also statistically consistent in the areas under the prevailing influence of the Black Sea and Danube, with a strong role of thermal moderator (the Black Sea littoral area, the Danube Delta and the Razim-Sinoe lagoon Complex). The TR upwards in these areas have been estimated over 98% of their territory. However, these trends could be detrimental to the bioclimatic thermal discomfort during peak months of summer tourism season in these areas.

The warm spell duration index (WSDI) highlights the exposure to extended intervals of above-normal heat stress with potential adverse consequences on population and vegetation health. The lengthening trend of warm spells is statistically significant over the most of the Romanian territory (Table 1). The change patterns of WDSI appear more related to the geographical position than to elevation. The lengthening signals are particularly consistent in the southern half of the country, roughly corresponding to the regions located below 45–46° lat N, which are also those most frequently exposed to dry and warm tropical airflows of North African origins in summer, *e.g.*, the Romanian Plain, the Danube Floodplain, the Banat Plain, the Dobrogea Tableland, the southern areas of the Moldavian Tableland. MK test estimated consistent upwards in WDSI also over extended areas of the Western and Southern Carpathians and over the southern parts of the Eastern Carpathians.

4.2. CHANGES IN COLD EXTREMES

The regional response to the strengthen of temperature warming since the late 20th century is confirmed by a general decreasing trend in cold-related indices. The trends in the frequency of *frost days* (FD) give a valuable indication of the changing exposure to cold extremes of the national territory. Winter freezing season in the regions lying in the eastern half of the country, under the influence of arctic and polar maritime and continental airflows in winter, is on a visible reduction. Regionally, the Eastern Carpathians, the Moldavian Tableland, the Subcarpathians (especially the Moldavian and Curvature ones), with a colder winter climate, are particularly affected. In these regions the significant downward trends of FD have been observed over 71 to 96% of their territory (Table 1). Other regions recognized for their mild winters in the average climate, due to the oceanic, Mediterranean or Black Sea moderator influence, are also under a consistent downward trend of FD (*e.g.*, large parts of the Dobrogea Tableland, some northern and southern areas of

the Western Carpathians, the western parts of the Romanian Plain). The sensitivity of frost occurrence to recent temperature evolution during the last two decades is also shown by the upward trends in the duration of frost-free interval in most of the aforementioned regions.

There is a decreasing trend in the frequency of *icing conditions* (ID), which could be attributed to the shifts in the lower tails of the daily minimum temperature distribution, favouring an extended increase in the probability of warmer winter temperatures. In general, the change signal in ID has a lower spatial consistency and was observed over scattered areas in the Carpathian Mountain range (14%), in the Transylvanian Tableland (15%), as well as in some northern parts of the Moldavian Tableland (20%). There are no statistically significant changes in ID frequency found in low-elevation areas of the country (below 500 m).

Cold spell duration index (CSDI) provides a reliable measure for analysing the potential implications of intense and persistent below-normal cold weather on human health and economic activities. However, the areas experiencing significant decreases of cold spell duration are very sparsely distributed across the country, with no elevation-dependent patterns. In general, the shortening trends in cold spells duration appear sporadically in some mountain areas (more extended in the Southern Carpathians, counting for about 14% of the Carpathian territory).

Sparks and Menzel [34] indicated that the number of *frost days* (FD) and the *growing season length* (GSL) are valuable agrometeorological indicators of analysing and understanding the changes in the phenology and active growth of cultivated plants. The decreasing frequency of frost days is likely to be beneficial for crop variety and multiple harvests, particularly in the agricultural regions of eastern and southern Romania, where the reduction of frost season was observed over more extended areas. Generally, the duration of the growing season is on a statistically significant widening in the southern plains and eastern tablelands of the country (up to 83% of their territory), corresponding to the most important agricultural regions of Romania. Several studies revealed both the positive and negative implications of the warming trend for biodiversity – like a visible thermophilisation trend, increase in species richness, increasing pest outbreaks [35].

Our results are in good agreement with previous recent studies on long-term temperature trends in the region [36–38].

5. CONCLUSIONS

This paper provided an overview of observed changes in annual thermal extremes over Romania, by means of trend analysis for seven indices. Regional differences in climate extreme trends within the region are generally linked to altitude and less with latitude. The signal of the significant trends is consistent as there are no areas of mixed trends within the study region. The main conclusions are summarised below:

(1) There is a significant warming signal across the country, with warm-related indices presenting more significant trends than the cold-related ones, with more coherent spatial patterns of change inside the region.

(2) Trends towards higher summer heat stress and milder winter climate conditions have been observed over extended areas across the country, especially in most recent decades, when the temperature rise was steeper. Changes in the number of summer days, warm spell duration and frost days are particularly robust (both statistically and spatially) and suggestive in the light of the recent temperature evolution at national scale.

(3) There are asymmetrical evolution patterns in day- and night-time warming, with stronger increases in maximum temperature-related indices (*e.g.*, summer days *vs.* tropical nights).

(4) Under recent climate warming, the growing season widens especially in the southern and eastern agricultural regions of the country.

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