Geospatial analysis of drought tendencies in the Carpathians as reflected in a 50-year time series

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Abstract

Climate change is one of the most important issues related to anthropogenic activities. The increasing drought conditions can cause water shortage and heat waves and can influence the agricultural production or the water supply of cities. The Carpathian region is also affected by this phenomenon; thus, we aimed at identifying the tendencies between 1960 and 2010 applying the CarpatClim (CC) database. We calculated the trends for each grid point of CC, plotted the results on maps, and applied statistical analysis on annual and seasonal level. We revealed that monthly average temperature, maximum temperature and evapotranspiration had similar patterns and had positive trends in all seasons except autumn. Precipitation also had a positive trend, but it had negative values in winter. The geospatial analysis disclosed an increasing trend from West to East and from north to west. A simple binary approach (value of 1 above the upper quartile in case of temperature and evapotranspiration, value of 1 below the lower quartile; 0 for the rest of the data) helped to identify the most sensitive areas where all the involved climatic variables exceeded the threshold: Western Hungary and Eastern Croatia. Results can help to prepare possible mitigation strategies for climate change to help both landowners and planners to draw the conclusions.

Keywords: CarpatClim, climatic change, trend, robust comparisons, sensitivity

Introduction

Drought is a crucial point among the challenges of climate change. There are hot spot areas where drought is a living problem. It is the consequence of the climate and can be regarded as a natural phenomenon, due to temperature increase and precipitation decrease. Large areas are endangered on global scale (MOLNÁR, K. and MIKA, J. 1997; KERTÉSZ, Á. and MIKA, J. 1999; BRADFORD, R.B. 2000; WILHITE, D.A. 2000).

When drought is not just a recurring temporal deviation of a region's climate but it occurs permanently, the phenomenon is called aridification: the length and intensity of the drought periods increase exceeding seasonal changes; furthermore, the increase has a positive trend (TATE, E.L. and GUSTARD, A. 2000). The trends of annual mean temperature changes are identified (MEEHL, G.A. *et al.* 2007). The consciousness of the countries has improved, 168 countries signed the Paris Agreement.

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The Carpathian region is also influenced by several negative consequences, especially the Great Hungarian Plain which is the largest flat area of the region. The lowlands of the region are rather warm and their water supply depends on the availability of runoff water from the surrounding mountains. Mountains and hilly areas are cooler and usually get more precipitation. However, both plains and mountains are influenced by climate change. The intensifying drought generates several problems: mineral dust particle transmission (Varga, G. and Roettig, C.-B. 2018), shrinkage of water resources (Szalai, S. *et al.* 2000; Kertész, Á. 2016; Kundrát, J.T. *et al.* 2016), lower yields (Deák, B. *et al.* 2014; Valkó, O. *et al.* 2014; Milošević, D. *et al.* 2015; Ray, D.K. *et al.* 2015). It threatens even the optimal composition of habitats (Török, P. *et al.* 2018), accelerates the spread of invasive species (Hellmann, J.J. *et al.* 2008), facilitates wildfires (Deák, B. *et al.* 2014).

Several studies dealt with the predicted changes for the Carpathian region pointing to the fact that the region will face substantial changes. Bartholy, J. *et al.* (2009), Mika, J. (2009), Mezősi, G. *et al.* (2016), and Bartholy, J. *et al.* (2015) reported on the increasing probability of heavy rains and as a consequence of this the increasing value of the erosivity factor (it can reach the double of the present value) using climate models (ALADIN, REMO, RCM, PRECIS) and predictions to 2100. If this scenario comes true, the agricultural production has to be prepared for the larger precipitation amounts coming from single events. Pongrácz, R. *et al.* (2014) projected relevant changes for the summers in the 21st century for Central Europe; furthermore, Blanka, V. *et al.* (2013) found that a 4–8 °C increase can be expected up to 2100, and the most endangered area is the Great Hungarian Plain. Garamhegyi, T. *et al.* (2018) and Pálfai, I. and Herceg, Á. (2011) indicated the hazard of drought in the Carpathian Basin and in the Balkan area. Kovács, F. (2018) and Gulácsi, A. and Kovács, F. (2018) applied satellite images with spectral indices and on the basis of a 18 years data series they found that a

relevant decline of biomass can be expected due to the dry periods.

Previous studies proved the negative effects of climate change tendencies using mainly the climatic variables in the analyses. Based on a limited number of stations included the CarpatClim dataset it is possible to analyse both the features of the data series of the climatic variables and spatial characteristics at the same time. Our objective was therefore to perform a thorough research on the trends. Our hypothesis is as follows: (1) there is a positive trend regarding temperature and a negative trend concerning precipitation, (2) there is an increasing trend from West to East and from North to South regarding climatic variables.

Methods

Study area

The CarpatClim dataset covers 470,700 km², including 9 countries (Croatia, Czech Republic, Hungary, Poland, Romania, Serbia, Slovakia, Bulgaria and Ukraine) mainly in the region of the Carpathians, including mountains and basins. Corresponding to the large East–West (750 km) and North–South (650 km) distances and to the big range of elevation differences (~50–2,655 m), the climatic conditions also have a large variance.

The average annual temperature in the Carpathian Basin in the cold season has a decrease from W-SW to E-NE. The higher values are about –1 °C in the western part of Hungary and in the northern part of Serbia gradually decreasing towards the Eastern and Southern Carpathians by –3, –4 °C. In the Carpathians the lowest temperatures are below –9 °C. In July, however, the average temperature increases from northwest to southeast from 18 °C to 23 °C, but in the higher mountains, locally in the closed basins and on the highest peaks, the temperature does not exceed 10 °C. In the western part of the area the cool oceanic air masses coming from the west have a relevant influence on the cli-

mate, and this effect diminishes until the line of the Danube and increasing continentality plays the prevailing role. (Rusu, T. *et al.* 2014).

We divided the study area into a chess-board-like smaller set of regions (*Figure 1*). In the text, we referred to the regions with "#" sign.
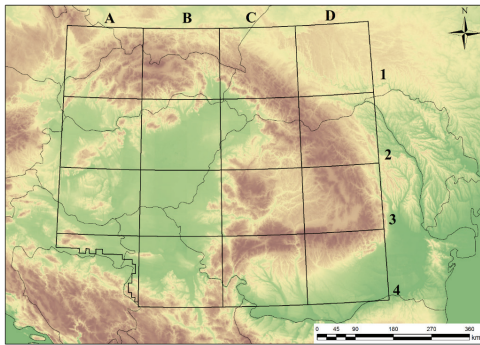

Fig. 1. Location of the study area, including the country borders and the grid for spatial analysis

The distribution of precipitation in the Carpathians is uneven in time with most precipitation occurring in late spring and early summer. The amount varies between 500–1,700 mm annually. In July in some areas, mainly on the lowlands the lowest value is 50–100 mm and the biggest value is almost 250 mm (Carpathian Mountains and Apuseni Mountains, #C3). The drought period in the Great Hungarian Plain (#B2 and #B3) is from July to August due to the effects of the high pressure atmospheric systems (Dövényi, Z. 2010; Bihari, Z. *et al.* 2018). The above characterization is based on the CarpatClim Atlas.

Datasets

Climatic data

Climatic variables were obtained from the CarpatClim (CC) database (Lakatos, M. *et al.* 2013; Spinoni, J. *et al.* 2015a,b). CC is published as a free source of several climatic factors as an initiation to provide data for better international co-operations regarding environmental issues. The spatial resolution is 0.1° x 0.1° and covers 9 countries in ~470,700 km² with 5,895 grid points in a time range of 1960–2010. The dataset is homogenized with the (Multiple Analysis of Series for Homogenization) MASH method, which is important because of missing data and possible differences of measuring protocols (Lakatos, M. *et al.* 2011; Szentimrey, T. 2011). There were more than 300 stations for temperature and more than 600 stations for precipitation data as input for the interpolation with the Meteorological Interpolation based on the Surface Homogenized Data Basis (MISH) method (Szentimrey, T. and Bihari, Z. 2007; Szentimrey, T. *et al.* 2010; Szentimrey, T. *et al.* 2012). Data are available on daily, monthly and yearly basis, we used monthly data in the analyses. We involved the monthly maximum temperature (TMAX), average temperature (TA), potential evapotranspiration (PET) and precipitation (PREC).

Topographic data

We applied the Shuttle Radar Topography Mission (SRTM) data with the void filled SRTM-Plus SRTM NASA V3 version (NASA Jet Propulsion Laboratory, 2013). The original data were retrieved in 2000 with a C-band and X-band radar interferometry sensor of the Space Shuttle Endeavour, SRTM Plus was released in 2013. It has 30 m geometric resolution and according to Szabó, G. *et al.* (2015) the mean vertical error is less than 5 m in Hungary.

Data pre-processing

We performed trend line fitting using regression analyses in each point of the time series of the CC-grid. As in 2009 and 2010 the amount of precipitation was unusually higher than during the previous years (Móring,

A. 2011; Spinoni, J. *et al.* 2015a,b), we excluded them from the analysis to decrease the bias rising from this temporal occurrence. The equation of the regression analysis consists of the intercept (β_0) where the fitted line intercepts the vertical axis, and the gradient of the fitted line (β_1) which is the multiplier of the independent variable. The general form of an equation is Eq. 1, where the model error (ε_i) is also presented (Field, A. *et al.* 2012).

$$Y_i = (\beta_0 + \beta_1 x_i) + \varepsilon_i \qquad (1)$$

Accordingly, β_1 reflects the change in the dependent variable (*Y*) against a unit change of the independent variable. In our case, we worked with the dataset as a time series, we analysed the changes along the time range between 1960 and 2010 (as independent variable), while the dependent variable was the given climatic variable (TMAX, TA, PET or PREC). We performed the trend line fitting on the annual data; furthermore, we repeated it with separating the months into seasonal groups: spring (March-May), summer (June-August), autumn (September-November) and winter (December-February). Thus, we were able to analyse both the annual (i.e. general) and seasonal (i.e. specific) changes.

The statistical modelling and the extraction of β_1 values were performed in R 3.5.2 environment (R Core Team, 2018) using the R language for scripting. The β_1 values served as input data for statistical analysis.

Statistical analysis

We summarized the resulting β_1 values with median and ranges with violin plots combined with boxplots. Violin plots show the kernel probability density at different values. For seasonal changes, differences were analysed with robust ANOVA with robust post hoc test using trimmed means (20%) combined with bootstrapping (599 replications) with the t1waybt() function, the same robust approach was applied for the post hoc pairwise comparisons with the mcpp20() function (Field, A. *et al.* 2012). The trimmed mean approach handles the outliers of the dataset, while bootstrapping, which is a resampling technique with replacement, i.e. random sampling from the whole dataset (usually 99-9999 times) helps to calculate the accuracy of the existing data by quantifying the variance of the mean, confidence intervals, prediction error, etc. As robust techniques these tests do not require normal distribution (Efron, B. and Tibshirani, R.1993).

The spatial trend was analysed with a factorial design: we separated the study area into four equal width regions from West to East, and four equal width regions from North to South (see *Figure 1*). Using these regions as ordered factors, the Kruskal-Wallis test was applied to reveal the statistical difference (H_0: β_1 values' medians were from the same distribution for all regions; H_1: β_1 values' medians differ at least for one region from the others). The trend was justified with the Jonckheere-Terpstra test (Ali, A. *et al.* 2015). Both the Kruskal-Wallis and the Jonckheere-Terpstra tests are non-parametric tests which do not require the normal distribution; furthermore, we applied permutation with 5,000 repetitions for better representation of the median of the statistical population. Two-way factorial ANOVA was applied to reveal whether there is a statistical interaction between the spatial trend from West to East and North to South. Statistical analysis was performed in R 3.5.2 (R Core Team, 2018) with the clinfun (Venkatraman, E.S. 2018) and the WRS2 (Mair, P. and Wilcox, R. 2018) packages.

The sensitivity map was compiled using the ß₁-values of the climatic variables. We classified these values to binary variables considering the upper quartiles for TMAX, TA and PET and the lower quartile for PREC as threshold values. Thus, the new map layers reflected the areas where the risk of drought tendencies was the highest (representing the most dangerous 25 per cent of the total area). We then merged the map layers with a simple addition, which showed those areas where the number of risky climatic factors (increase in TMAX, TA and PET and

decrease in PREC) indicated the severity of the drought issue (from 0 to 4, i.e. 0: no risk, 4: all climatic factors' trends exceeded the threshold). Map operations were performed in QGIS 3.6 (QGIS Development Team, 2019).

Results

Annual and seasonal trends

According to the robust ANOVA, all the studied climatic variables showed significant seasonal differences ($p < 0.05$); i.e. all seasons differed from each other and all seasons' trend differed from the case when the trend was determined from the whole months of the years (annual) (*Figure 2*).

The rise of TMAX (*Figure 2*, a) was observed in all seasons except for autumn. In the case of autumn the decrease was more moderate than the rise in the rest of the seasons. The extent of the increase rate showed similarities in spring, summer and autumn but in winter it covered a larger interval.

Increase can be expected annually as well, and the steepness of rise had similar distribution to that in the first half year; however, it can be interpreted in a smaller range. Statements regarding TA (*Figure 2*, b) were similar with the difference that the variance was smaller in each season. It is worth noting that the distribution of the β_1 values had higher kurtosis in the summer compared to the rest. In the case of PREC (*Figure 2*, c), there were only small changes in spring and summer, while there was an increasing trend in autumn and a decreasing trend in winter. In the latter two cases, effects balance each other resulting in no significant changes in the distribution of annual precipitation just like in the case of spring and summer.

Regarding PET (*Figure 2*, d), a change typical for the mean and maximum temperatures can be observed, i.e. rise in spring, summer and winter, at more moderate rate in the latter case, and decrease in autumn with the difference that the extent of changes can be interpreted over a smaller interval and the magnitude of changes is one order greater.
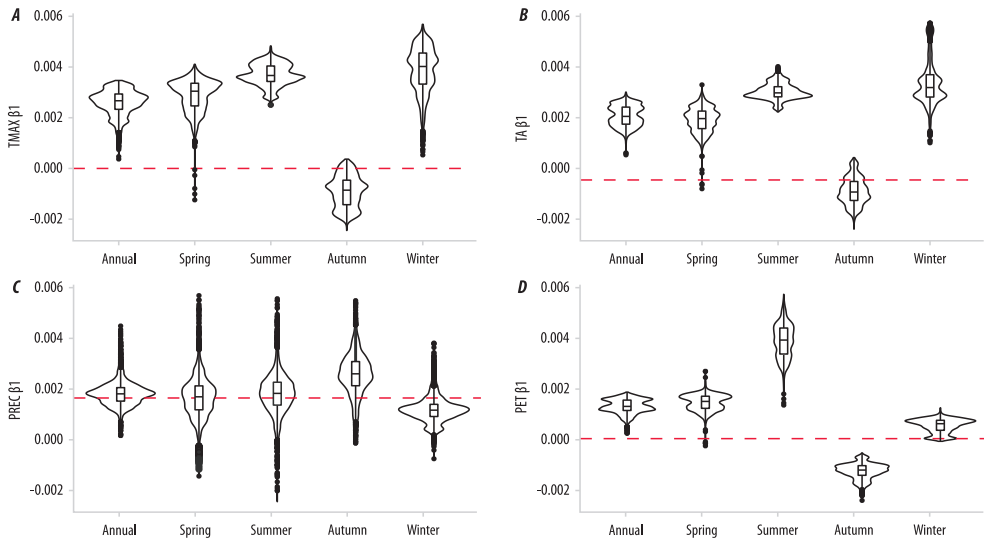

Fig. 2. Combined violin plot and boxplot diagrams of the climatic variables' regression β_1 values. – TMAX = monthly maximum temperature; TA = monthly average temperature; PREC = monthly precipitation; PET = potential evapotranspiration. Zero level indicating no change.

Spatial trends

We also studied whether the changes had a spatial trend regarding the main directions of the wind rose. We identified significant increasing trends both in case of the West–East and the North–South directions (see *Figure 1*). Kruskal-Wallis statistics revealed that there were significant changes when we split the dataset by regions, but did not point on the ones having those significant (p < 0.05) differences between the regions of #1-#4 or #A-#D (according to *Figure 1*).

Concerning the West–East direction, in the cases of TMAX, TA and PET medians decreased to the line of Eastern Carpathians for each climatic variable, but beyond this line (Region #D) it was true only for summer and winter. For spring and autumn Region #D had significantly larger values than the neighbouring Region #C, and its ß_1-values were comparable (but not higher) than the most western Region #A. PREC, similar to the previous observations, had the opposite pattern with increasing trend, but this was not a strict rule: while it was only a slight increase in spring and summer, it was definitely high in the autumn and there was a decreasing trend in the winter. Nevertheless, Region #D had significantly lower values (p < 0.05) except summer when it was significantly higher (p < 0.05). Each of the climatic variables had significant trends according to the Jonckheere-Terpstra test considering the direction from West to East (*Table 1*).

Analysing the regions from North to South, the TMAX medians had the largest values in the northern region (Region #1) and then the trend started to decrease to south up to the line of the Southern Carpathians, where significantly higher (p < 0.05) medians occur in spring, summer and winter. For autumn the trend is continuous, without any deviations. TA had almost a similar pattern but in this case, winter had also a continuously decreasing trend such as autumn; furthermore, Region #1 had larger variance, and larger median values related to any of the climatic variables or seasons. In this direc-

Table 1. Differences of the trends from West to East based on the Kruskal-Wallis (K-W) and the Jonckheere-Terpstra (J-T) test

Climatic variable	Direction: West–East Significance: p < 0.001	
	K-W test	J-T test
TMAX	2,463.40	3,057,100
TMAX spring	1,661.30	3,780,100
TMAX summer	2,099.60	2,572,100
TMAX autumn	3,665.00	1,509,900
TMAX winter	850.94	4,935,800
TA	1,797.90	3,596,600
TA spring	1,550.60	3,837,900
TA summer	2,271.20	2,709,000
TA autumn	3,802.90	1,539,300
TA winter	831.57	4,740,300
PET	2,500.60	2,520,200
PET spring	1,963.80	3,110,500
PET summer	1,129.30	3,543,300
PET autumn	2,342.70	2,980,900
PET winter	838.32	3,934,300
PREC	282.61	6,438,500
PREC spring	324.21	5,482,100
PREC summer	460.42	6,424,800
PREC autumn	651.70	7,273,000
PREC winter	510.33	4,600,900

Notes: ß_1 values of monthly temperature maximums (TMAX), of monthly mean temperatures (TA), of monthly mean precipitations (PREC), of monthly mean evapotranspiration (PET).

Table 2. Differences of the trends from North to South based on the Kruskal-Wallis (K-W) and the Jonckheere-Terpstra (J-T) test

Climatic variable	Direction: North–South Significance: p < 0.001	
	K-W test	J-T test
TMAX	543.05	5,202,400
TMAX spring	866.77	4,859,200
TMAX summer	707.57	7,413,700
TMAX autumn	1,058.40	3,673,500
TMAX winter	578.91	5,718,700
TA	1,664.30	3,363,500
TA spring	1,307.50	3,768,900
TA summer	411.83	6,766,500
TA autumn	665.74	4,062,300
TA winter	1,642.10	3,460,500
PET	429.81	6,931,400
PET spring	587.91	4,564,700
PET summer	1,839.90	8,715,000
PET autumn	1,725.60	2,983,200
PET winter	879.06	7,603,700
PREC	1,155.00	3,502,000
PREC spring	2,727.50	2,168,200
PREC summer	203.03	5,481,300
PREC autumn	206.65	6,246,700
PREC winter	2,285.70	2,569,500

Notes: TMAX, TA, PET and PREC = for explanation see *Table 1*.

tion PET's pattern was different as it had a decrease in the trend in spring and autumn, and an increasing trend in summer and winter. PREC had a definite and continuously decreasing trend from North to South in the spring and winter and had a slight decrease in summer and autumn. Each climatic variable had significant trends according to the Jonckheere-Terpstra test considering the direction of North to South (*Table 2*).

Combined effects of the spatial and seasonal factors

We combined the effect of the spatial features and found that there was a significant interaction effect of the two directions in case of each climatic variable (*Table 3, Figure 3*) according to the 2-way factorial ANOVA.

The analysis of the spatial trends of TMAX, regarding the β_1-values, revealed that the Regions #1 and #4 had almost the same character in maximum temperature change: steepness decreases from the western part of the area (*Figure 3*, a; #A) then a quasi-stagnating state (#B, #C) can be observed with a minimal rise (#D). The trends of the two central regions (#2 and #3) were also similar to the differences that there was no decreasing tendency in the steepness of the trend in the eastern half of Region #2 (in contrast to #3).

Regarding TA (*Figure 3*, b), the slope of the trend decreased from West to East in all regions, but only the Region #3 had straight trend in each location. Three regions (#1, #2, #4) had decreasing trends up to the line of Carpathian Mountains, from where an increase began.

Trends observed in case of PET (*Figure 3*, c) had similar structures as TMAX with the difference that the location of Region #1 and #4 was the opposite: trend values of #1 were smaller in the West and decreased towards the East. The starting value of #A of #4 can be ignored as no data are available from more than 75 per cent of the cell area; therefore, it cannot be compared with the others.

Precipitation increase (*Figure 3*, d) was observed in the foreland of the high mountains (on the western side of the Carpathians – #C) and a decrease on the eastern slopes of the mountains. Region #4 is an exception as the Southern Carpathians and the Romanian Plain can be found in its cells #C and #D with the lack of precipitation in the latter.

We also analysed the grid points from geospatial perspective and revealed the most sensitive areas (*Figure 4*). The largest part (42.0%) was outside of the set threshold, i.e. of the upper quartiles. This class included Northeast and Southeast Hungary, Bánság (Banat), the Transylvanian Basin, certain parts of the Partium (Westernmost Romania), Slovakia and Transcarpathia (*Figure 4*, a).

31.6 per cent of the investigated area is characterized by the fact that only one climatic variable was above the threshold, altogether with the non-sensitive parts, almost the 75 per cent of the study area is a relatively stable region. The area where two climatic variables exceeded the threshold was 14.3 per cent, and the percentage was 7.5 for the areas where three of the climatic variables exceeded the quartiles. A relatively small area belonged to the riskiest class (4.6%) mostly in Western Hungary and in Eastern Croatia.

Table 3. Differences between the regions regarding the directions of West to East (WE) and North to South (NS) and their statistical interaction (WE:NS) based on the Two-way factorial ANOVA

β_1 values	Mean square			F value		
	WE	NS	WE:NS	WE	NS	WE:NS
TMAX	4.001×10^{-4}	5.9×10^{-6}	3.8×10^{-6}	2,382.0	35.00	23.00
TA	1.313×10^{-4}	1.492×10^{-4}	3.866×10^{-5}	1,585.6	1,801.80	466.80
PET	3.544×10^{-3}	6.18×10^{-4}	2.8×10^{-5}	3,826.7	667.52	30.46
PREC	5.86×10^{-3}	8.644×10^{-2}	4.442×10^{-2}	106.6	1,573.30	808.40

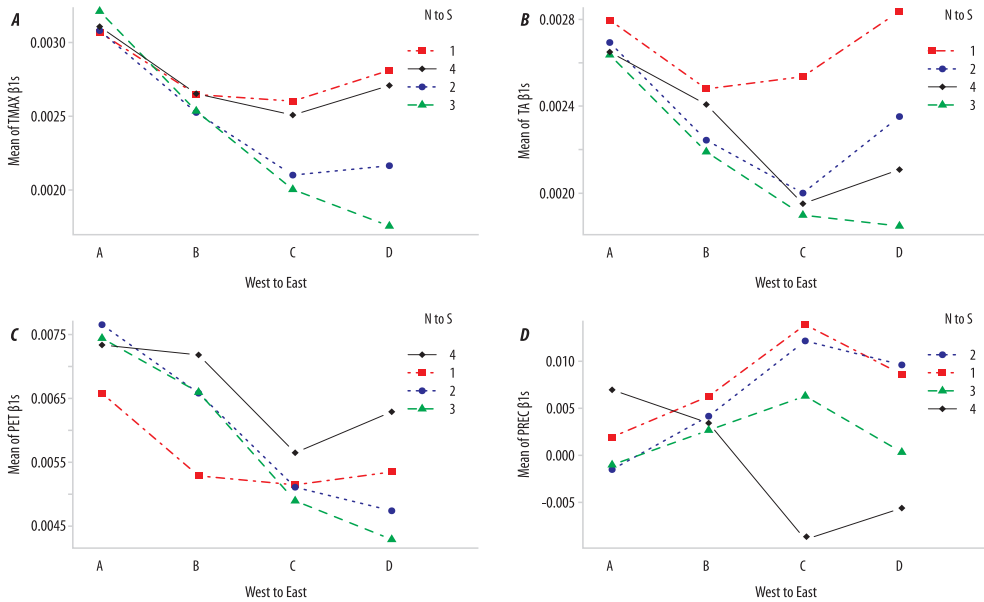Notes: TMAX, TA, PET and PREC = for explanation see *Table 1.* Significance: p < 0.001.

Fig. 3. Interaction plots of climatic variables by spatial features (region codes correspond with *Fig. 1*)

Unique features of the climatic variables showed that, generally, the eastern part of the Carpathian Basin and the Carpathian Mountains were rather consistently stable, while the western and southeastern areas were sensitive. Regarding TMAX, the areas West of the Danube fell in the most sensitive areas (*Figure 4*, b). TA had the same pattern with the difference that the coverage of the southwestern part of Hungary was more mosaic-like and that of the Ukraine beyond the Carpathians was homogeneous (*Figure 4*, c). Considering PET, the coverage of sensitive areas was mosaic-like in the areas West of a NNW–SSE striking line. In Hungary this meant the whole area West of the Danube, and 1/3 of the area West of the Tisza river (*Figure 4*, d). The precipitation coverage showed the greatest spatial dispersion. The areas West of a NE–SW striking line were mosaic-like. In Romania this can be observed on the western side of Apuseni Mountains and in the Eastern and Southern Carpathians (*Figure 4*, e).

Discussion

Seasonal variations of maximum (TMAX) and mean temperatures (TA) were synchronous with each other in both seasonal and annual comparisons. The explanation can be found in the data providing the basis of variables as both values are obtained from hourly maximum and mean temperature data. Comparing TMAX and TA, the probability of maximum values was higher suggesting an increase in periods of heat waves. This was also supported by the diagram showing mean temperatures (see *Figure 2*) and the findings of GÖNDÖCS, J. *et al.* (2018). The probability of precipitation increase occurred only in autumn, in an order of magnitude greater than in the case of temperature parameters. The even distribution of autumn excess precipitation could explain the decrease of mean and maximum temperatures.

ZHAO, W. and KHALIL, M.A.K. (1993) also found similar correlations between temperature and precipitation in the United States in summer, in the cases of Central and Southern
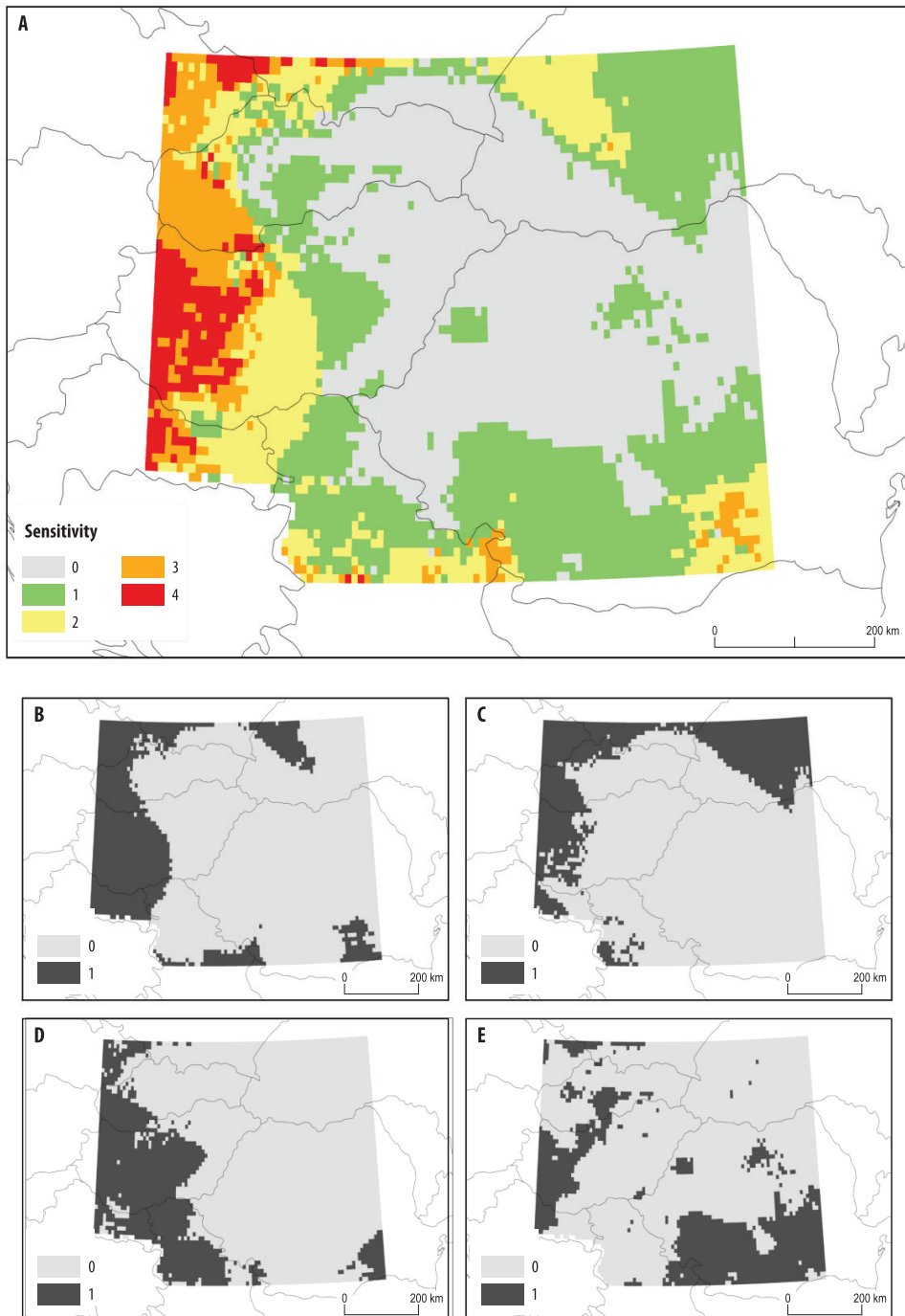
Fig. 4. Sensitive areas based on the observed highest trends (β_1 values) for the climatic variables using the threshold value of upper quartiles. – a = sum of climatic variables where all maps were added (the higher the value, the more climatic variables exceeded the threshold); b = TMAX; c = TA; d = PET; e = PREC

Great Plains (Hungary, #B2 and #B3); it is important to note that the topography of these areas is similar to our study area. Ferrari, E. *et al.* (2018) also found a negative trend in the time series in Southern Italy, and also pointed to the fact that although the evidences of general warming were confirmed, seasonal changes can vary and can be contradicting. Milošević, D. *et al.* (2015) obtained similar results as in this study for precipitation and temperature trends in Vojvodina region of Serbia (regions #B3 and #B4) suggesting significant precipitation increase in autumn months while mean and maximum temperature decreased only in autumn for the period 1949–2013. The sign and distribution of PET and temperature parameters followed a similar characteristic with the difference that PET values were one order of a magnitude greater. The reason of this similarity can be found in temperature correlations as higher temperature generates greater evaporation and transpiration (Helfer, F. *et al.* 2012).

The geospatial structure of the spatial variation of maximum temperature showed an increase from West to East. The most important finding is that the increase was greater in the areas where the climate was cooler in a spatial average due to orographic conditions (major areas in the North-western [#A1 and #B1], North-eastern [#D2 and #D3] and Southern Carpathians [#C4 and #D4]; Regions #1 to #4, and in the western part of Hungary), in accordance with Szabó, S. *et al.* (2019). Blanka, V. *et al.* (2013) and Mezősi, G. *et al.* (2016) predicted the largest changes in the Great Hungarian Plain (#B2 and #B3). This may seem to be a contradiction with our results, but some conditions are different: we analysed the trend and not the temperature change; i.e. a further increase of temperature can occur in the plains, too, but those areas are more affected where the temperature is currently cooler. The further, even a smaller increase of average and maximum temperature values can cause severe problems; thus, both land managers and urban planners have to be conscious of possible negative effects (e.g. water shortage, heat waves).

The Carpathians appeared to be a climatic boundary in this geospatial comparison: this phenomenon was reflected in Regions #C and #D in cells #2 and #3 with a greater decrease of the increasing tendency. This can be explained by the effect of orography (Kohler, T. *et al.* 2014). Kohler *et al.* also indicated that the change in the number of days per year with over 20 mm precipitation was usually a positive value in the Carpathians between 1960 and 2010, there were several areas in the mountains with decreasing tendencies, too. The number of intensive rainfalls and the decrease of total days of precipitation can result in an unbalanced water regime, flash floods and intensive erosion (Pirkhoffer, E. *et al.* 2009; Czigány, Sz. *et al.* 2010, 2013; Szabó, J. *et al.* 2015; Jakab, G. *et al.* 2019). Regions of higher temperature and evapotranspiration and lower precipitation are endangered by wind erosion. Although wind erosion is common in dry areas, this issue will arise in regions where previously the vegetation and soil moisture protected the soils (Pásztor, L. *et al.* 2016; Négyesi, G. 2018).

PET showed a decreasing tendency from West to East in all regions; however, Region #1 and #4 (similarly to TMAX) showed stagnating (1) and increasing (4) tendencies respectively, proving earlier statements regarding the correlation between temperature and evaporation/transpiration in a geospatial perspective as well. Precipitation increased gradually up to Region #C then decreased in #1, #2 and #3 corresponding to the arriving moist air masses from the Atlantic Ocean and the orographic precipitation excess of the western slopes of the Carpathians (Kohler, T. *et al.* 2014). An exception was the southernmost Region #4, which can be explained by the lack of enough data in cell #A4 and by Mediterranean effects (Panthou, G. *et al.* 2018).

The spatial distribution of maximum and mean temperatures and PET above the upper quartile differed only in the considerably more mosaic-like map in the case of TA (see *Figure 4*, c), while PET represented a greater area compared to the maximum temperature. Areas below the lower quartile of

precipitation had the greatest spatial heterogeneity. It is worth noting that an area outside the category can be observed in the region of Turnu Roşu Pass (Hungarian: Vöröstorony Pass; #C4). The analysis of precipitation data revealed that monthly precipitation amounts showed major differences in this area in the 50-year average. In a distance of 30–40 km differences of even 50–100 mm rain can be found among the grids within this distance.

Conclusions

CarpatClim ensured a detailed analysis of the time series in almost 500,000 km². We aimed to involve the climatic trends into a detailed geospatial analysis.

We revealed that monthly average temperature, maximum temperature, evapotranspiration had positive trends except in autumn; precipitation did not follow this pattern, it had a negative trend in winter. The intensity of the changes in precipitation and evapotranspiration was one order of magnitude larger related to maximum and average temperature. There was a spatial trend from West to East, but the Carpathian Mountains had a relevant effect on it and changed the increasing values. There was a spatial trend from North to South and the Southern Carpathian Mountains also had a relevant effect in the southernmost region of the study area.

There was a significant statistical interaction between the directions (i.e. E–W and N–S). Assigning the upper quartiles (in case of precipitation the lower quartile) as threshold helped to identify the regions most affected by the changing climate. Summing up the climatic variables identified those regions where the threshold exceeded more than one climatic variable; accordingly, the western part of Hungary and the eastern part of Croatia are the most sensitive regions for the predicted climatic changes. An important result is that largest changes can be expected in those regions where the climate is currently cooler related the warmest area of the Great Hungarian Plain.

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