

# Future climate of the Carpathians: climate change hot-spots and implications for ecosystems

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**Abstract** The Carpathians are the largest European mountain range and harbour exceptional biodiversity. However, recent and anticipated changes in climate along with rapid social and economic development suggest that the region's values may not be sustained. We strived to identify the main regional climate change hot-spots and evaluate the distribution of climatically exposed land-use types and ecosystems. The analysis was based on 10 climate models driven by the emission scenario A1B. To identify the hot-spots, we adopted a methodology based on

change trajectories in a multidimensional climate space. Three hot-spots were in the Western Carpathians (Czech Republic, Slovakia, and Hungary), two were in Ukraine, and three were in the Romanian and Serbian Carpathians. Regions with the highest aggregate climate exposure (i.e. above 70 % of the regional range) were mostly covered by broadleaved forests (39 %), agricultural land (30 %), and pastures and woodlands (15 %). These regions also contained 15 % of protected areas and 36 % of the total human population in the Carpathians. While growing season length was the main factor affecting hot-spot magnitude in the north-west, precipitation-related variables were the main factors in the east and south. Analysis of inter-climate model variability indicated that the level of confidence in hot-spot position and magnitude differed among hot-spots. In addition to identifying a large-scale regional pattern of climate change, we showed that there are sub-regions with remarkably high climate exposure. The hot-spot distribution in lower elevations suggests that Carpathian ecosystems in water-limited environment may be particularly exposed to climate change.

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## Introduction

The Carpathian Mountains form the largest European mountain range and pass through Austria, Czech Republic, Slovakia, Poland, Hungary, Ukraine, Romania, and Serbia (Ruffini et al. 2006). Adjacent populated areas are functionally linked to the mountains and rely on a wide range of ecosystem services (Gurung et al. 2009; Grêt-Regamey

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et al. 2012). Countries with transitional economies cover a substantial part of the Carpathians, and overexploitation of natural resources and other indicators of unsustainable management are evident across the region (Schulze 2002; Knorn et al. 2012). Such practices may cause some ecosystems and human communities to be particularly sensitive to climate change. At the same time, the socio-economic capacity to adapt to anticipated threats is inadequate because of the relatively low performance of regional economies and the generally low level of public awareness regarding the need to adapt to climate change (Grothmann and Patt 2005; Fischer et al. 2005; Hlásny et al. 2014).

Recent observations indicate changes in the long-term quasi-equilibrium of diverse physical and biological systems in the Carpathians (Gurung et al. 2009; Spinoni et al. 2015). The frequency of extreme hydrological events has been increasing over the last decades and likely reflects recent changes in the climate (Easterling et al. 2000; Gurung et al. 2009). The Carpathians face accelerated vegetation dynamics with potentially adverse effects on biodiversity (Mihai et al. 2007; Martazinova et al. 2011; Solár and Janiga 2013), including the undesired influx of alien species (Simpson and Prots 2013). Recent observations indicate a substantial increase in the rate of forest disturbances including windthrows, forest fires, and pest outbreaks (Hlásny and Sitková 2010; Temperli et al. 2013) that adversely affect the provision of numerous ecosystem goods and services. Such disturbances also act as positive feedback to climate change through episodic releases of large amounts of carbon (e.g. Kurz et al. 2008; Seidl et al. 2014).

Information on the spatial variability of anticipated changes in climate is requested for vulnerability assessment and spatially targeted adaptation planning (Baettig et al. 2007; de Sherbinin 2014). The identification of climate change hot-spots based on the integration of diverse climate projections and other data has been increasingly used to assess the patterns and magnitude of climate exposure or vulnerability of various regions (e.g. Giorgi 2006; Baettig et al. 2007; Diffenbaugh et al. 2008; Ericksen et al. 2011; Diffenbaugh and Giorgi 2012; Piontek et al. 2014). The increasing resolution of climate modelling output, which can currently describe small-scale atmospheric processes and regionally important climate–orographic patterns (Farda et al. 2010), has resulted in the initiation of a number of regional studies, including specific research on regional climate change hot-spots (e.g. Midgley et al. 2011; Hagenlocher et al. 2014). Recent research has also provided comprehensive evaluation of climate models performance (Flato et al. 2013) as well as options for narrowing the uncertainty of climate projections

(Hawkins and Sutton 2011), which might provide a useful support to climate change impact studies.

In this study, we provide new information on the magnitude, spatial trends, and variability of projected climate change in the Carpathians. So far, such information has been available mostly at a scale of countries extending into the Carpathians (e.g. Pongrácz et al. 2011, 2013; Bartholy et al. 2013; Micu et al. 2015), covering only a part of the region, or using a limited number of climate projections (Belda et al. 2015). Moreover, no hot-spot analyses have been conducted in the region. We adopt the methodology for global hot-spot identification that evaluates trajectories of change in a multidimensional climate space. We focus on climate exposure hot-spots (Giorgi 2006; Diffenbaugh and Giorgi 2012; Gu et al. 2014; Torres and Marengo 2014) rather than complex vulnerability hot-spots (Barnett et al. 2008; Piontek et al. 2014) or specific hot-spots related to human population migration (Samson et al. 2011) or other phenomena. We strive to identify the main land-use types and ecosystems of the Carpathians that are likely to experience high climate exposure in the future to encourage scientists and professionals to concentrate on these land-use types and ecosystems in climate change vulnerability assessment and adaptation planning. At the same time, we identify percentages of the human population in the Carpathians residing in climatically highly exposed regions; these human communities are likely to be directly affected by the declining provisioning of ecosystems goods and services as well as by the increasingly unfavourable climate. The importance of this research is underscored by numerous European or regional initiatives addressing the Carpathian region, including climate change vulnerability assessments, biodiversity and climate mapping, and adaptation (Turnock 2002; Gurung et al. 2009; Spinoni et al. 2015; Carpathian EcoRegion Initiative; Carpathian Convention; WWF Danube-Carpathian Programme, etc.).

## Data and methods

### Study region

This study used the Carpathian border designated by the Carpathian EcoRegion Initiative (CERI, <http://www.carpathes.org/>) and the Carpathians Environment Outlook (KEO 2007) (Supplementary material A, Fig. A1). The region, which has an area of 229,966 km<sup>2</sup>, contains the main Carpathian mountain range and adjacent foothills and lowlands; hence, the region includes a broad range of ecosystems and land uses. The current climate of the Carpathians (1961–1990), which was evaluated according

to geomorphologic sub-provinces (Kondracki 1989), is described in Supplementary material A.

### Climate data

Past climate data (1961–1990) used in this study are based on the daily data provided by the E-OBS database (Haylock et al. 2008) combined with the monthly CRU TS 1.2 (Mitchell et al. 2004) gridded data set. The future climate (2021–2050 and 2071–2100) was investigated based on 10 RCM–GCM (regional climate model–general circulation model) combinations provided by the ENSEMBLES FP6 project (van der Linden and Mitchell 2009). The models used were selected from the 32 models available in the ENSEMBLES database based on the following criteria: (1) spatial resolution of  $25 \times 25$  km and (2) continuous coverage from 1951–2100 (for additional details, see Dobor et al. 2015). All climate projections were driven by the A1B greenhouse gas emission scenario (Nakicenovic and Swart 2000).

Because the direct use of RCM data is limited by systematic errors in the simulated variables (Christensen et al. 2008, Dosio and Paruolo 2011), data used in this study were bias-corrected following Dobor et al. (2015).

Given its regional scale, the current study requires high-resolution climate maps capturing the regional orographic pattern in the Carpathians. To produce such maps, we used kriging with external drift, a spatial interpolation method that was previously found suitable for the interpolation of climate data (Hudson and Wackernagel 1994). We used a digital elevation model with spatial resolution of 250 m (Jarvis et al. 2008) as a supportive variable correlated with all climate variables used in the current study. The climate maps were produced with the geostatistical software ISA-TIS (Geovariances, France).

### Identification of climate change hot-spots

We modified the method proposed by Diffenbaugh and Giorgi (2012), which uses the standard Euclidean distance (SED) to quantify the aggregate climate change (ACC) in a multidimensional climate space between the present and future periods (Williams et al. 2007). The ACC is given as:

$$ACC = \sqrt{\left( \sum_{i=1}^n SED_v \right)}$$

where

$$SED_v = (\Delta_v / \max[\Delta_v])^2$$

$\Delta_v$  is the value of change in climate variable  $v$  at each grid point in the study area between two periods (1961–1990 and 2071–2100 in this study), and  $\max[\Delta_v]$  is a maximum

value of change in variable  $v$  over the entire study area between the two periods.

We recalculated ACC to represent a percentage of the maximum permissible change, which is defined as the square root of the number of variables used for hot-spot identification ( $n$ ):

$$ACC_{\%} = \frac{ACC}{\sqrt{n}} * 100$$

The identification of hot-spot positions is hampered by a large-scale north-west to south-east trend in the climate exposure of the Carpathians that causes the highest values of  $ACC_{\%}$  to occur in the south of the region. Hence, highly exposed locations with sub-regional importance (e.g. Western Carpathians) would not be identified. Therefore, we extracted a spatial trend from the  $ACC_{\%}$  surface and identified the hot-spots in positions where the residual  $ACC_{\%}$  (R- $ACC_{\%}$ ) is above the 95 % quantile. Because the magnitude of the R- $ACC_{\%}$  in hot-spots is more or less equal across the Carpathians, we used the original  $ACC_{\%}$  values (i.e. those containing trend) to evaluate hot-spot magnitude. The trend-containing data were also used to evaluate the relative contribution of the underlying climate variables to the  $ACC_{\%}$  for all hot-spots. Therefore, while hot-spot positions have sub-regional importance, their magnitude allows their comparison at a pan-Carpathian scale.

The variables used to calculate  $ACC_{\%}$  are precipitation totals during the growing season (April to September) (PTGS), growing season length (GSL), consecutive number of dry days (CDD), number of days with maximum air temperature exceeding 30 °C (T30), and the Ellenberg climate quotient (EQ) (for the justification of this selection, see Supplementary material B).

We calculated  $ACC_{\%}$  and R- $ACC_{\%}$  for all 10 RCMs (Supplementary material G); R- $ACC_{\%}$  based on the average climate projection was used for hot-spot identification. The uncertainty in hot-spot positions associated with inter-climate model differences was evaluated using the map of coefficient of variation (CV, ratio of standard deviation to mean climate projection in per cent). The CV was calculated for both  $ACC_{\%}$  and R- $ACC_{\%}$ .

### Land-cover types, ecosystems, and population data

We used the Corine Land Cover data set (EEA 2006; CLC) to identify dominant land-cover categories in climatically highly exposed areas in the Carpathians (i.e. those areas with R- $ACC_{\%} > 70$  % quantile, Supplementary material H). Because the data set was not available for Ukraine, we classified the Landsat satellite imagery and derived a map consistent with the CLC (Supplementary material D).

Forest tree species composition was taken from the results of statistical mapping of forest tree species in Europe (Brus et al. 2011) and from the Forest Management Plans of Slovakia (National Forest Centre, internal data). The natural vegetation of the Carpathians was evaluated based on a map developed by Bohn et al. (2004). The indicative information on non-forest vegetation was taken from several data sources such as the Carpathian Biodiversity Information System (CBIS, Carpathian EcoRegion Initiative) or Carpathian Integrated Biodiversity System (CCI-BIS, WWF Danube-Carpathian Programme). The map of nature conservation areas in the Carpathians was produced based on a combination of national environmental databases and the maps of the Carpathian Network of Protected Areas (<http://www.carpathianparks.org>) and NATURA 2000 sites.

The population density grid of the European Union (Gallego 2010) was used to estimate the percentage of the human population living in highly exposed areas. Because this data set did not include Serbia and Ukraine, rougher data based on the local administrative units (LAU 1) were used instead (Ruffini et al. 2006).

## Results

### Spatial pattern of climate change

We present here future climate exposure of 14 geomorphologic units in the Carpathians based on 10 climate models for periods 2021–2050 and 2071–2100, compared to the period 1961–1990. The multi-model mean projection indicated an increase in the mean annual air temperature of 3.2–3.8 °C by the end of the century in the Carpathians, although some locations show an increase of up to 5.1 °C (details are given in the Supplementary material E).

While T30 in the Western and Eastern Carpathians was projected to increase by 18–30 days in the period 2071–2100, the projected increase in the Transylvanian Plateau, Serbian, and Western Romanian Carpathians was 33–48 days. The maximum change in T30, which was projected by HadRM3Q0–HadCM3Q0, was an increase of 65 days.

In the Western Carpathians, most models showed that PTGS in 2021–2050 would be more or less equal to PTGS in the reference period, but that PTGS would decrease by up to 10 % in 2071–2100. A mean decrease in precipitation of 15–27 % was projected for the rest of the Carpathians; however, the inter-model variability was high and ranged in the Serbian Carpathians, for example, from –7 to –47 %.

The pattern of change in CDD was mostly unclear, but an increase from the north-west to the south-east was

apparent. While CDD was projected to decrease by about 4 days (from 17 to 13) in the Outer Western Carpathians, CDD was projected to increase from 18 to 21 days in the Serbian Carpathians. The pattern of change was unclear for the rest of the region, and inter-model variability was high.

EQ values in the reference period ranged from 10 to 85. Most of the Carpathians had values up to 30, but a small area in the Transylvanian Plateau had extreme values. Future projections indicated that the climate will become drier from the Western Carpathians (by 5 units) towards the Eastern and Serbian Carpathians (by 13 units). Locally, an increase in EQ values of up to 27 units occurred by the end of the century.

GSL was projected to increase across the Carpathians relatively uniformly by 10–20 days in 2021–2050 and by 30–40 days in 2071–2100; the inter-model variability, however, was high.

### Climate change hot-spots

The magnitude of the original (i.e. not detrended)  $ACC_{\%}$  increased from the north-west towards the south-east of the Carpathians.  $ACC_{\%}$  in the Outer Western Carpathians was 51 to 53 % of the maximum permissible change in the Carpathians (all-model average  $ACC_{\%}$  in CZ<sub>HS</sub> and SK-PL<sub>HS</sub>), while  $ACC_{\%}$  in the Serbian Carpathian hot-spot (RS<sub>HS</sub>) was 76 % (Table 1).  $ACC_{\%}$  values were high in the main lowlands and intra-Carpathians valleys but lower on the main mountain crest. Inter-climate model variability of  $ACC_{\%}$  was nearly equal in most of the Carpathians (the CV ranged from 8 to 13 %), except at RS<sub>HS</sub>, where the CV was 17 % (Fig. 2a).

The extraction of a quadratic spatial trend from  $ACC_{\%}$  generated normally distributed residuals suitable for hot-spot identification for all 10 climate models (Supplementary material G). The classification of the all-model average R- $ACC_{\%}$  using the threshold of 95 % quantile produced eight spots with remarkably high climate exposure, and these were located mostly in the Carpathian lowlands and foothills (Fig. 1). The CV was substantially higher for R- $ACC_{\%}$  than for the original trend-containing values (Fig. 2b); the 25 and 75 % quantiles of CV were 43 and 149 % for R- $ACC_{\%}$ , and 9.4 and 13.6 % for  $ACC_{\%}$ . Four hot-spots (SK-HU<sub>HS</sub>, UA-North<sub>HS</sub>, UA-South<sub>HS</sub>, and RO-East<sub>HS</sub>) were in locations where the CV of R- $ACC_{\%}$  had relatively low values (22–56 %), while the remaining hot-spots were in locations with high inter-model variability (110–124 %).

In the Western Carpathians, two hot-spots (CZ<sub>HS</sub> and SK-PL<sub>HS</sub>) of almost equal magnitude, i.e. with  $ACC_{\%}$  values near 50 %, were identified (Table 1). CZ<sub>HS</sub> is located in the lowland of Moravia (Czech Republic), while SK-PL<sub>HS</sub> is adjacent to the mountain range of High Tatras



**Table 1** Magnitude and inter-model variability of the aggregate climate change in hot-spots, magnitude and inter-model variability of change in underlying climate variables in hot-spots and relative contribution of five underlying climate variables to hot-spot magnitude

Code	Hotspot	Climate variable											
		ACC <sub>%</sub>		CDD		EQ		GSL		PTGS		T30	
		$\bar{x} \pm SD$	Range	$\bar{x} \pm SD$	REL	$\bar{x} \pm SD$	REL	$\bar{x} \pm SD$	REL	$\bar{x} \pm SD$	REL	$\bar{x} \pm SD$	REL
1	CZ <sub>HS</sub>	53 (±4)	42–60	-3 (±3)	16	+6 (±6)	6	+40 (±7)	59	-3 (±16)	8	+23 (±9)	12
2	SK-HU <sub>HS</sub>	59 (±5)	51–63	-2 (±4)	20	+10 (±8)	11	+34 (±6)	33	-13 (±13)	10	+37 (±11)	26
3	SK-PL <sub>HS</sub>	51 (±7)	37–62	-5 (±2)	34	+5 (±4)	4	+36 (±10)	48	-8 (±5)	9	+12 (±6)	4
4	UA-North <sub>HS</sub>	60 (±7)	53–63	-7 (±2)	42	+6 (±6)	5	+36 (±8)	37	-12 (±15)	12	+16 (±9)	4
5	UA-South <sub>HS</sub>	58 (±6)	53–61	-1 (±3)	6	+11 (±7)	15	+33 (±6)	33	-20 (±9)	19	+37 (±10)	26
6	Trans <sub>HS</sub>	58 (±7)	48–66	-4 (±2)	24	+9 (±7)	9	+30 (±7)	27	-17 (±14)	15	+36 (±10)	25
7	RO-East <sub>HS</sub>	72 (±7)	64–80	+1 (±4)	10	+19 (±11)	27	+30 (±8)	17	-27 (±14)	21	+46 (±10)	25
8	RS <sub>HS</sub>	76 (±13)	71–80	+4 (±3)	12	+17 (±8)	25	+30 (±7)	15	-22 (±11)	18	+53 (±11)	30

ACC<sub>%</sub> aggregate climate change in terms of the percentage of the maximum permissible change in the Carpathians,  $\bar{x} \pm SD$  all-model average and inter-model standard deviation, Range inter-model range of ACC<sub>%</sub> in hot-spot positions, REL relative importance of a climate variable with respect to ACC<sub>%</sub> values in hot-spot positions (%), CDD cumulative dry days, EQ Ellenberg quotient, GSL growing season length, PTGS precipitation total during growing season, T30 number of days with maximum daily air temperature exceeding 30 °C

Mts. at the Slovak–Polish border. At both hot-spots, GSL had the main effect on the ACC<sub>%</sub>, i.e. 59 % in CZ<sub>HS</sub> and 48 % in SK-PL<sub>HS</sub> (Table 1). At SK-PL<sub>HS</sub>, also CDD had substantial effect on ACC<sub>%</sub> (34 %). The CV of R-ACC<sub>%</sub> in both hot-spots was relatively high (110 and 124 %, respectively), suggesting uncertainty in these hot-spot positions.

The third hot-spot in the Western Carpathians (SK-HU<sub>HS</sub>) is in the Pannonian Lowland at the border of Slovakia and Hungary. Its magnitude of 59 % was mainly affected by GSL (33 %), T30 (26 %), and CDD (20 %) (Table 1). CV of R-ACC<sub>%</sub> of 56 % indicates relatively high agreement of climate models used.

Two hot-spots adjacent to the range of Carpathians are in Ukraine and reach 60 % (UA-North<sub>HS</sub>) and 58 % (UA-South<sub>HS</sub>) of the maximum permissible change. Among the eight hot-spots identified in this study, CDD had the largest influence at UA-North<sub>HS</sub> (42 %), followed by GSL (37 %). For UA-South<sub>HS</sub>, the magnitude of ACC<sub>%</sub> reflected the combined influence of GSL (33 %), T30 (26 %), PTGS (19 %), and EQ (15 %). The CV of R-ACC<sub>%</sub> was relatively small in both hot-spots (31 and 53 %, respectively).

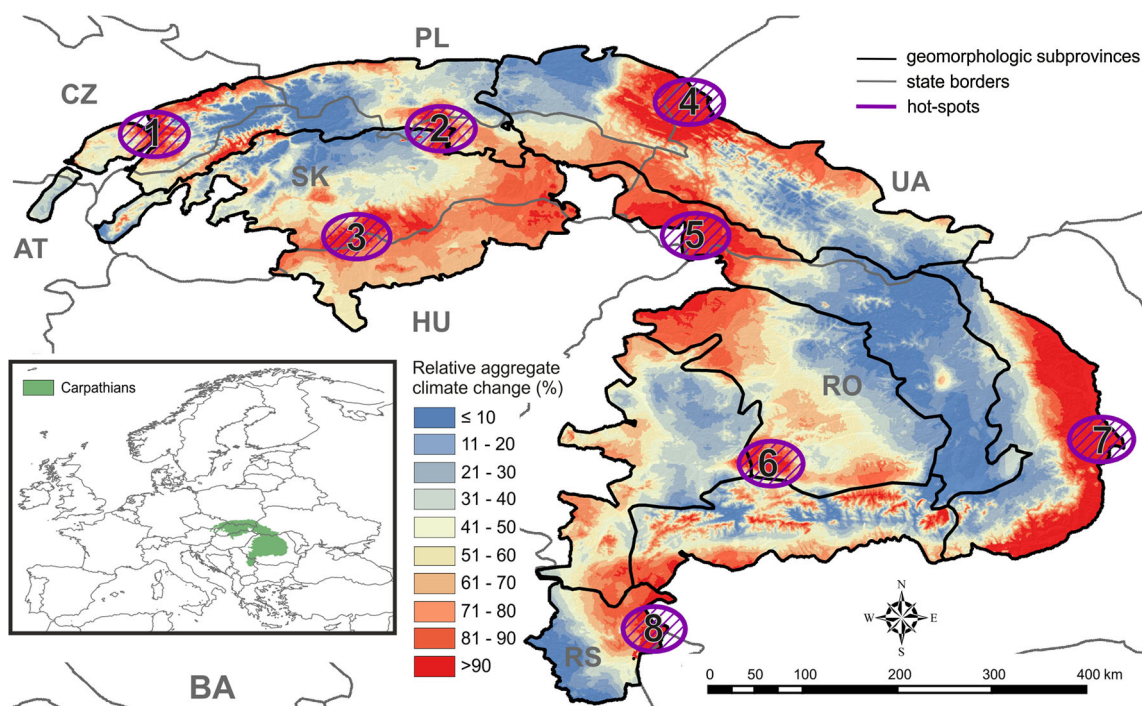
Two hot-spots were identified in Romania: one in the Transylvanian Plateau (Trans<sub>HS</sub>) with a magnitude of 58 % and one in the Outer Eastern Carpathians (RO-East<sub>HS</sub>) with a magnitude of 72 %. Trans<sub>HS</sub> reflected the combined influence of GSL (27 %), T30 (25 %), CDD (24 %), and PTGS (15 %). RO-East<sub>HS</sub> was influenced by EQ (27 %), T30 (25 %), PTGS (21 %), and GSL (17 %). The main difference between the Romanian hot-spots was that while Trans<sub>HS</sub> was significantly affected by CDD (24 %), this variable had little effect in RO-East<sub>HS</sub>. Although the CV of R-ACC<sub>%</sub> was small in RO-East<sub>HS</sub> (22 %), the CV in Trans<sub>HS</sub> was high (109 %), suggesting uncertainty in the identification of the latter hot-spot.

The Serbian Carpathian hot-spot (RS<sub>HS</sub>) had the highest ACC<sub>%</sub> (76 %) and was affected by T30 (30 %), EQ (25 %), and PTGS (18 %), followed by GSL (15 %) and CDD (12 %). CV of R-ACC<sub>%</sub> was large (108 %).

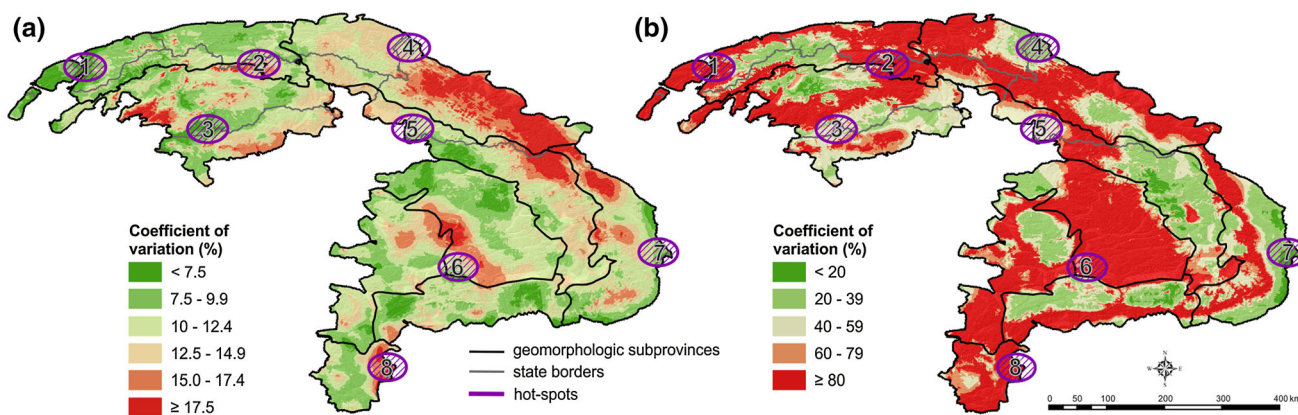
### Land cover, ecosystems, and population distribution

The areas with high climate exposure, which are those with the R-ACC<sub>%</sub> > 70 % (Supplementary material H), are mostly covered by broadleaved forests (39 %), agriculture land (30 %) and pastures and woodlands (15 %) (Supplementary material I).

The exposed forests contain diverse species of oak (*Quercus* spp.), European beech (*Fagus sylvatica* L.), pines (*Pinus* spp.), and hornbeam (*Carpinus betulus* L.), plus other less important species. The natural vegetation in exposed regions is dominated by pre-Carpathian beech forests, Carpathian fir-beech and spruce-fir-beech forests,



**Fig. 1** Aggregate climate change in the Carpathians and climate change hot-spots (indicated by *numbers*) identified based on multi-model mean projection. Hot-spot codes are explained in Table 1



**Fig. 2** Coefficient of variation of the aggregate climate change (a) and of the residual aggregate climate change (b). The coefficient indicates the degree of uncertainty related to differences in the 10

climate models used for the analysis. Also indicated are the positions of eight climate change hot-spots identified based on the mean climate projection

Pannonian-pre-Carpathian sessile oak-bitter oak forests, and Pannonian-pre-Carpathian hardwood alluvial forests (Bohn et al. 2004). Some vegetation types of the Carpathians occur exclusively in the exposed regions (Supplementary material J).

The exposed regions comprise a variety of primary and secondary thermo- and xerophilous communities of the class *Festuco-Brometea* Br.-Bl. et Tüxen ex Soó 1947, and communities of the secondary mesic and wet meadows and pastures on nutrient-rich soils of the class *Molinio-Arrhenatheretea* Tüxen 1937. The meadow vegetation

contains mainly the mesic meadows of lower altitudes (alliance *Arrhenatherion elatioris* Luquet 1926) and manured pastures of lower altitudes (alliance *Cynosurion cristati* Tüxen 1947 nom. cons. propos.) (Janišová et al. 2007). Most of the grasslands have been traditionally grazed, but some types in more productive habitats have also been mown (Chytrý 2007).

Of the total area of nature conservation areas (i.e. national parks, protected landscape areas, and nature reserves) in the Carpathians, 23 % is distributed in the exposed regions (Supplementary material K). Parts of the

most important Carpathian nature conservation areas, such as the Bükki National Park and the Duna-Ipoly National Park in Hungary, and the Djerdap National Park on the border of Romania and Serbia, lie in the exposed regions. Twenty-three percentage of the NATURA 2000 sites (under both bird and habitat directive) is in the exposed regions as well, with the highest share in the Outer Eastern Carpathians North (47 % of NATURA sites in the geomorphologic unit).

Approximately 36 % of the total human population in the Carpathians live in the exposed regions (Supplementary material K).

## Discussion

In this study, we have explored how climate in the Carpathians is likely to develop in the future and whether the spatial pattern of “aggregate climate change” includes regions that are particularly exposed to climate change and should be chiefly considered in complex vulnerability assessment and adaptation planning. This study adds to the recent research efforts addressing the regional patterns of climate exposure or of complex vulnerability (e.g. Midgley et al. 2011; Gu et al. 2014; Hagenlocher et al. 2014), which are meant to support the targeted allocation of resources for climate change adaptation. Indeed, the drawbacks and deficiencies in these assessments, which concern both the analytical aspects of hot-spot identification (Freudenberg 2003; Diffenbaugh and Giorgi 2012) and the use of hot-spots in decision- and policy-making (Barnett et al. 2008; de Sherbinin 2014), have been repeatedly stressed.

## Methodological aspects

The application of global hot-spot mapping methodology based on the studies of Giorgi (2006), Williams et al. (2007), and Diffenbaugh and Giorgi (2012) at a regional scale raises several questions concerning the proper interpretation of the regional hot-spot patterns. That the maximum change in the underlying climate variables used for the  $ACC_{\%}$  calculation was identified in the Carpathians rather than on the global scale obviously indicates that the identified hot-spot patterns are strictly specific to the Carpathian region. For this reason, for example national assessments should avoid interpreting the identified hot-spots as hot-spots of national importance. Assessing the maximum change parameters within the Carpathian territory also suggests that values of  $ACC_{\%}$  higher than those in the hot-spots (i.e. above 100 %) may be distributed in areas surrounding the investigated region or elsewhere; for example,  $ACC_{\%}$  values above 100 % occur south of the Carpathians in Hungary and Romania, suggesting that

these areas are likely to experience higher climate exposure than the Carpathians themselves.

The use of spatially detrended  $ACC_{\%}$  for hot-spot identification represents a substantial modification of the original procedure. Such a modification was necessary to be applied to cope with the presence of the north-west to south-east gradient in the projected climate exposure that was present in all climate variables used for  $ACC_{\%}$  calculation, and consequently, in the  $ACC_{\%}$  itself. Trend extraction from the original  $ACC_{\%}$  values allowed us to identify the hot-spots by setting a unique threshold in the  $R-ACC_{\%}$  (i.e. the 95 % quantile) for the entire Carpathians and prevented hot-spot accumulation in the south of the Carpathians, as would be the case with the original trend-containing  $ACC_{\%}$ . The latter pattern would provide information of questionable value for most of the region. It follows that hot-spots identified using the  $R-ACC_{\%}$  should be thought of as having sub-regional rather than pan-Carpathian relevance; however, such a sub-regional scale can be more useful for regional vulnerability assessment and adaptation planning. Regardless, we also preserved the information on the  $ACC_{\%}$  magnitude in hot-spot positions based on the original trend-containing data, which can be valuable for specific pan-Carpathian evaluations.

Unlike our study, most other studies have identified hot-spots based on the visual evaluation of some type of the aggregate climate change map or other indicator (e.g. Giorgi 2006; Baettig et al. 2007; Gu et al. 2014). For example, Giorgi (2006) argues against the importance of setting a unique threshold that would allow for hot-spot identification, because hot-spot analysis primarily compares regions with each other and does not provide an absolute measure of change. We argue that an approach based on classification of a residual map, as was done in the current study, is more rigorous than one based on visual investigation and that the classification of a residual map can be particularly useful when large-scale trends might obscure regionally important hot-spot patterns. In most cases, however, both approaches are likely to produce similar results.

The selection of climate variables used for  $ACC_{\%}$  calculation was based on expert decision and was justified based on the importance of the selected variables for regional ecosystem dynamics (Supplementary material B). For example, Diffenbaugh and Giorgi (2012) and Gu et al. (2014) used seven climate variables for each of four seasons, yielding a 28-dimensional climate space; Giorgi (2006) and Torres and Marengo (2014) used four variables for two seasons to calculate a Regional Climate Change Index (RCCI); and Baettig et al. (2007) used nine combinations of climate elements and seasons to calculate a Climate Change Index (CCI). We argue that such analyses were likely to be affected by an inter-variable correlation



(for example, when the same variable is evaluated for several seasons), which could result in the overestimation of the effects of some variables. Therefore, we suggest that some degree of control of inter-variable correlation, as performed in the current study, should be applied.

The inter-model range of the underlying climate variables was high (Supplementary material F), even though the used models were driven by only a single emission scenario. The latter fact raises the question as to whether the used ensemble of climate models represents an adequate portion of the uncertainty in future climate development. In this regard, Hawkins and Sutton (2011) suggested that uncertainty in precipitation related to the difference in emission scenarios is relatively small by the end of the twenty-first century in Europe, while uncertainty in precipitation related to the difference in climate models driven by the same radiative forcing is substantial. However, this is not the case for temperature. On this basis, we argue that the ensemble of climate change scenarios used in our study contained a substantial part of the uncertainty related to future climate development, although temperature-related uncertainty was probably underestimated. Moreover, a quality-controlled and bias-corrected climate data set driven by an emission scenario other than that used in the current study (Dobor et al. 2015) is not currently available for the region.

As our investigation used present-day data on ecosystems, land use, nature conservation, and human population distribution, one may question whether it is appropriate to evaluate future climate exposure for these present-day systems. Moreover, numerous studies have provided scenarios on how ecosystems, land use, and human population distributions are likely to develop in the future (e.g. Rounsevell et al. 2006), and these kinds of information could also be used in the investigated region. We argue, however, that the concurrent use of a number of scenario-based modelling outputs (i.e. outputs for climate, ecosystems, and human populations) would likely generate uncertain information with limited applicability. Therefore, we opted to assume a baseline scenario, which can inform vulnerability assessment studies about the type of climate exposure of ecosystems and other features provided no changes in their distribution occur. In fact, sensitivity and adaptive capacity variables used in vulnerability studies often represent current rather than future state, which needs to be considered in the interpretation of such studies (Preston et al. 2011; de Sherbinin 2014).

### Ecological and environmental inferences

The identified hot-spots are mainly located in lowland and foothill areas adjacent to the main mountain range of the Carpathians. At the same time, the magnitude of the

aggregate change (in terms of the trend-containing  $ACC_{\%}$ ) increased towards the south; the magnitude of  $ACC_{\%}$  was ca. 25 % higher for the Romanian–Serbian hot-spot ( $RS_{HS}$ ) than for the  $CZ_{HS}$  and  $PL_{HS}$  located in the Western Carpathians (76 vs. 51–53 % of the maximum permissible change). Such findings indicate that the areas that are most likely to experience excessive climate exposure are those that currently contain semi-arid ecosystems (forest steppe or open woodland), which act as important barriers to landscape aridification (Sun and Liu 2013), the climate-sensitive lower distributional limit of closed forests (Mátyás 2010; Mátyás and Sun 2014), as well as commercially and ecologically valuable broadleaved forests in the foothills of the main mountain crest. Interestingly, Mátyás (2010) suggested that the climate vulnerability of such ecosystems has been largely unexplored until very recently as compared with, for example, mountain ecosystems.

Stagl et al. (2015) suggested that information on climate exposure might be critical for climate-influenced decision-making in protected areas. That 23 % of the Carpathians' nature conservation areas lie in climatically exposed regions generates concern about the effects of climate change on the regional biodiversity (Turnock 2002). Such effects are generally expected to be adverse (Thuiller et al. 2005, 2007; Bellard et al. 2012), what is particularly relevant for Carpathians, which represent a unique reservoir of many endemic plant and animal species of the European importance (Grodzińska et al. 2004; Kueimmerle et al. 2010). Differences in climate sensitivity among the main ecosystem types in the Carpathians may result in differences in the responses of biodiversity to climate change. For example, climate change might induce habitat destruction in Carpathian forests that are located near their xeric distributional limit and that have high climate sensitivity (Lakatos and Molnár 2009; Mátyás et al. 2010; Hlásny et al. 2014). On the other hand, Carpathian grasslands, 24 % of which are distributed in the highly exposed areas, can be resilient to drought in the face of climate change and can help maintain ecosystem functioning even under increasing climate exposure (Craine et al. 2012).

Our assessment showed that the Carpathians include extensive, mostly mountainous areas with lower  $ACC_{\%}$  values than the rest of the region. This finding might seem surprising because some studies have suggested that the warming rate is greater at mountains than at lower elevations (e.g. Pepin et al. 2015). The evidence for this difference in warming rate has been questioned, however, based on methodological and other concerns (e.g. Rangwala and Miller 2012). Moreover, the aggregate climate exposure evaluated in this study was based on some climate variables that show geographic and topographic patterns different from that of the air temperature; hence, the specific pattern of  $ACC_{\%}$  was found in our research.



The identified high climate exposure of Carpathian lowlands and foothills should not be misinterpreted to mean that the mountain areas have a low vulnerability to climate change. The vulnerability of mountain ecosystems to climate change is generally high (Briner et al. 2013), mainly because of the high climate sensitivity of these ecosystems resulting from, for example, the limited options for species to migrate (Jump et al. 2009). Our research, however, indicates that lowland and foothill Carpathian ecosystems are likely to experience substantial climate exposure. That the climate sensitivity of these ecosystems has not been well studied (Mátyás 2010) might generate concerns about our capacity to understand region's vulnerabilities and to take appropriate actions. Therefore, we suggest that future research should focus on the climate-related vegetation dynamics in climatically exposed semi-arid regions, which represent large areas in the Carpathian region, and such research might be critical for effective adaptation.

Finally, we determined that 36 % of the human population of the Carpathians resides in the exposed regions, a finding that highlights the importance of potential declines in ecosystem services such as air and water quality maintenance, or climate regulation (Patz et al. 2005; McMichael et al. 2006) as well as of a direct effect of increasingly unfavourable climate on humans.

### Socio-economic and management perspectives

Five of the eight hot-spots identified in this study are distributed in the Ukrainian, Romanian, and Serbian part of the Carpathians, where social and economic indicators are much lower than in the Western Carpathian countries (Czech Republic, Slovakia, Poland, and Hungary); moreover, the magnitude of ACC% was as much as 25 % higher in the former than in the latter region. The gross domestic product per capita in the period 2009–2011 in the Ukraine, Romania, and Serbia was only 35.8 % of that in the Western Carpathian countries (<http://data.worldbank.org>), which indicates a much lower adaptive capacity in the Ukraine, Romania, and Serbia. The low adaptive capacity of countries with transitional economies along with the high climate exposure of the south-eastern region of the Carpathians underscores the urgent need for increasing our understanding of this region's vulnerability and for exploring options for adaptation.

Although identification of climatically exposed regions and vulnerable social, physical, or biological systems helps set priorities for research and resource management, there is little evidence that hot-spot maps developed for various regions and sectors have influenced investment, research, or adaptation (de Sherbinin 2014). Despite the promotion of knowledge-based and data-driven decision-making (e.g.

Vacik et al. 2013; Marušák and Kašpar 2015), there are factors in the region that hamper the use of vulnerability assessments in resource management. For example, none of the Carpathian countries has effective legislation regarding climate change adaptation, except for non-binding strategies (Merganičová et al. 2013), and this lack of legislation significantly reduces the transfer of knowledge gained from research to decision-making. The international scope of our study and of the identified hot-spots makes the transfer of knowledge even more difficult. In this regard, de Sherbinin (2014) suggested that national decision-makers often tend to distrust regional or international assessments because such decision-makers lack confidence in data not obtained under the supervision of national agencies. Indeed, there are reasons to question the quality of global or regional data, including those used in the current study (e.g. Trombik and Hlásny 2013), as well as relevance of inferences based on such data for decision-making at the national level. Still, researchers have repeatedly emphasized that natural resource management and conservation should be coordinated at a scale of bioregions (Turnock 2002; Chester 2006). Obviously, management at a regional scale (across the Carpathians, for example) will require global or regional assessment such as that presented in the current study.

### Conclusions

Our study confirmed that the investigation of spatial variability of climate projections can help identify sub-regions that are particularly exposed to climate change. Using a novel methodology proposed in this study, we found out that, in addition to a large-scale north-to-south trend of climate warming and drying in the Carpathians, there are sub-regions with remarkably high climate exposure. Such highly exposed sub-regions were distributed mainly in the lowland to foothill areas, which suggests that Carpathian ecosystems located in water-limited environment can be particularly exposed to climate change. Hence, understanding drought effects and improving water-friendly landscape management may be central to adapting to climate change in extensive parts of the Carpathian region. These facts can help to set future research priorities and decide upon adaptation actions. Unfortunately, the dynamics of semi-arid ecosystems and their responses to climate change in the study region are insufficiently understood to enable effective adaptation.

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