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RESEARCH ARTICLE

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Projected changes in Feddema climate characteristics in the Larger Carpathian Region by the end of the 21st century

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Abstract

Climate change in the Larger Carpathian Region (LCR) by the end of the century has been analysed using the Feddema climate classification. Temperature (T) and precipitation (P) data for the reference period 1971–2000 were taken from the CarpatClim dataset and projected data for the period 2069–2098 were taken from the EURO-CORDEX dataset. The delta-corrected simulated data with EUR-11 and EUR-44 resolutions are based on the RCP4.5 and 8.5 scenarios. Results obtained with the RCA4-EC-EARTH model pair are presented. Climate indices calculated from T and P describe annual heat and water availability, define the magnitude of seasonal variation and attribute seasonality to the variation of T or P. Changes in spatial coverage of climate types and seasonality types, and spatial shifts in each of the variables are presented. The analysis is performed for the total area and separately for lowlands, hills, low-, mid- and high-altitude mountain regions. There is a shift indicating warming for every climate type and the climate types indicating water deficiency are to become dryer while climate types with water surplus are to become wetter by the end of the 21st century. In most cases seasonality attributed to T is becoming dominant together with increasing magnitude of seasonality. According to RCP4.5, climate type change will affect 26.2% and seasonality type change will affect 23.2% of the study area. In case of RCP8.5 climate type change is projected on 64.4% and seasonality type change is projected on 48.5% of the study area, respectively. Changes in climate types and seasonality types are more significant in every subregion and altitudinal region of the LCR for RCP8.5 compared to RCP4.5. Climate change projections suggest not only warming but significant changes in moisture availability and seasonality, especially the magnitude of seasonality in mountainous areas.

KEYWORDS

CarpatClim, climate change, EURO-CORDEX, Feddema climate classification, Larger Carpathian Region, moisture characteristics, seasonality characteristics, thermal characteristics

† deceased.

1 | INTRODUCTION

Many analyses of climate change impacts focus on changes in temperature and precipitation, but in many ways these analyses constitute an incomplete analysis of climate change and its potential impact on communities. A more holistic description of climate is required to identify the impact of climate change and potential adaptation strategies. Climate classification schemes set out to better define climate parameters to interpret climate for both research and educational purposes and, therefore, will offer an excellent mechanism for identifying a more complete analysis of climate change impacts. It is essential to know the expected extent of climate change regionally to enable sufficient adaptation to the unavoidable change already under way (IPCC, 2018). In the case of Central Europe, including the Larger Carpathian Region, temperatures have been increasing at a higher rate than the global average and are projected to increase by over 4.5°C in winter, and by over 3.6°C in summer, while precipitation is projected to increase in winter by about 20% and decrease by summer by about 7% by the end of the century with respect to the reference period 1981–2010 according to the EURO-CORDEX simulations based on RCP8.5 (Coppola *et al.*, 2021). Changes to climate variables associated with anthropogenic global warming, such as temperature or precipitation, can result in geographical shifts of climatic zones (Jylhä *et al.*, 2010). The investigation of global or regional changes in climate using climate classification schemes can provide additional benefits, because they can be understood not only by the scientific community but also by the general public (Szabó *et al.*, 2019). According to Rohli and Vega (2018), climate classification approaches may be exact or empirical. Exact schemes estimate the variability and classify the climatic elements using eigenvector analysis and clusters, while empirical schemes calculate climate types according to predetermined class boundaries using only a few variables. In this study a generic empirical method is used to indicate the projected changes in the Larger Carpathian Region. Generic climate classifications use criteria systems based on thresholds defined according to the climatological variables, such as temperature and precipitation, that determine the climate of a region. There are methods based on the correspondence between climatological variables and vegetation communities, such as the Köppen (1900) method, and more physical based approaches using the concept of water balance of an area, such as Thornthwaite's (1948) classifications. A number of studies have used generic climate classification schemes to analyse climate-type-related changes in the Larger Carpathian Region, however, only as a part of larger European analyses (Castro *et al.*, 2007; Jylhä *et al.*, 2010; Hanf *et al.*, 2012; Gallardo *et al.*, 2013; Skarbit *et al.*, 2017; Breuer *et al.*, 2018) and separately for its subregions (Melo *et al.*, 2013; Mihailović *et al.*, 2015; Breuer *et al.*, 2017; Rubel *et al.*, 2017; Skalák *et al.*, 2018; Szelepcsényi *et al.*, 2018). Numerous studies on climate change have been performed using historical data for the 20th century and climate projections for the 21st century. Most of these analyses were performed based on Köppen's original (1900) or modified methodology (Köppen, 1936). Melo *et al.* (2013) studied climate change during the 20th century in the Slovakian Carpathians using the Köppen climate classification method and the classification scheme of Konček based on station data of the Slovak Hydrometeorological Institute. Results showed climate types shifts to the north and to higher altitudes. Skalák *et al.* (2018) introduced the Köppen–Geiger climate type shifts in central Europe, including Slovakia and the Czech Republic, on simulations from the CECILIA project using the A1B emissions scenario of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES) (Nakicenovic *et al.*, 2000). This research project showed significant changes in the region's climate type distribution with the vanishing of boreal and colder climate types by the end of the 21st century and assumed lower crop production in rain-fed agricultural areas. Mihailović *et al.* (2015) analysed the effect of climate change on Serbian crop yields and Köppen climate zone distributions using the SRES A1B and A2 scenarios. The study showed shifts towards warmer and drier climate types and projected increased crop yields. Köppen–Geiger climate zone shifts in Austria were shown in Rubel *et al.* (2017) over a 300-year period starting from 1800 using the HISTALP historical observation dataset and the Rossby Centre regional atmospheric model under the 2.6 and 4.5 scenarios of the Representative Concentration Pathways (RCP; Moss *et al.*, 2010). This study showed changes in forest, tree and snow lines over the three analysed centuries. Changes of Köppen climate types in Hungary between 1971 and 2060 were studied in Fábián and Matyasovszky (2010) using four SRES emission scenarios (A1FI, A2, B1, B2). The study also showed strengthening in climate extremes and an increasing frequency of the appearance of the steppe climate type. For this study, Köppen's method was extended with two additional classes because in some cases where the monthly mean temperature greatly exceeded the threshold representing summer warmth, the original Köppen classification was unable to identify the projected warming trend. The Holdridge classification has been used by Szelepcsényi *et al.* (2018) to project changes in the Carpathian Region based on ENSEMBLE project model simulations (van der Linden and Mitchell, 2009) using the A1B SRES scenario.

Climate change in Hungary according to Feddema's scheme (Feddema, 2005) was analysed in Breuer *et al.* (2017) to quantify and visualize the 20th century's climate. The main process was drying and 23.3% of the study area experienced changes in climate according to the Feddema classification. In the Breuer *et al.* (2018) and Skarbit *et al.* (2017) studies focusing on Europe, the SRES A1B scenario was used from the 3rd and 4th IPCC Assessment Report (IPCC, 2001; 2007) based on different socio-economic and climate system-related scenarios, but these are unable to consider changes in national policies. RCPs (Moss *et al.*, 2010) were introduced in the fifth IPCC Assessment Report (AR5; IPCC, 2014) representing radiative forcing changes as the result of various greenhouse gas emission reduction strategies. To date Feddema's scheme has not been applied for showing climate change by the end of the 21st century in the Larger Carpathian Region using RCPs.

In this study Feddema's method is applied since it is able to reproduce the large climate heterogeneity of the region (Breuer *et al.*, 2017; Szabó *et al.*, 2021) and because it is not a nominal classification and can provide insight on climate variation within climate classes as opposed to changes in boundary locations in most traditional methods. Feddema's method, which is a simplified Thornthwaite method, has been more successful in regional applications (Grundstein, 2008; Elguindi and Grundstein, 2013; Breuer *et al.*, 2017; Rahimi *et al.*, 2019) compared to other well-known climate classifications, such as Köppen (Szabó *et al.*, 2021). This method has also been successfully used for global-scale climate change analysis and can be applied worldwide at the regional scale (Elguindi *et al.*, 2014; Bonfils *et al.*, 2020).

The aim of this study is to analyse the projected annual and seasonal changes of the Larger Carpathian Region's climate based on the Feddema climate characteristics in the region using observed data taken from the CarpatClim dataset (Szalai *et al.*, 2013), which is a gridded observational dataset providing the best open access high-resolution climatological data for the region and simulated climate data from the stabilization RCP4.5 climate projection scenario and the pessimistic business-as-usual RCP8.5. Improvements in both observation data and regional climate simulations lead to a more accurate and up-to-date understanding of the possible climate change in the study area. In addition to introducing the climate change research on the Larger Carpathian Region, we also present an improvement of Feddema's seasonality representation according to Feddema's proposal for a further improvement of the scheme (see section 3). Altitude has a strong role in how climate change affects areas (Spinoni *et al.*, 2015; Ács, 2017; Rubel *et al.*, 2017). Shifting climate zones may have a significant impact on ecosystems via the alteration of habitats (Li *et al.*, 2018), and the rate of vulnerability may vary with altitude. Lakatos *et al.* (2013) showed that growing season shifts may have greater impacts in lower altitudinal regions of the Larger Carpathian Region. Hence the changes in climate characteristic categories are shown separately for lowlands, hills, low-, mid- and high-altitude mountain regions.

The paper is structured as follows: Region and data are presented in section 2. Feddema's method is introduced in section 3. Results are presented in section 4 and discussed in section 5. Concluding remarks are made in section 6.

2 | REGION AND DATA

The Larger Carpathian Region (LCR; Figure 1), including the Carpathian Mountains and the Carpathian Basin, experiences a variety of different climates (Domonkos, 2003; Bartholy *et al.*, 2009; Antofie *et al.*, 2015). This climate heterogeneity is caused not only by the differences in latitude, longitude and continentality, but also by the almost closed geophysical structure of the Carpathians (PannEx White Book, 2019). The region's climate is influenced by the Atlantic marine, Baltic and continental climate from the west, north and from the east, respectively (Nistor *et al.*, 2016). While vegetation and water sheds have little effect on the climate heterogeneity of the LCR, the complex orography with a variety of relief forms, such as lowlands and hills, leads to disturbances in the temperate continental climate (Cheval *et al.*, 2014). Annual mean temperatures for the 1971–2000 period within the region vary from −1.1 to 12.6°C (CarpatClim, 2021; carpatclim-eu.org), with the lowest temperatures in the North-western Carpathians and highest in Vojvodina and the Wallachian Plain, all temperatures being highly correlated with elevation (Spinoni *et al.*, 2015). Annual total precipitation has a spatial range from 487 to 1710 mm and is higher in the high-altitude mountain regions (annual average >1200 mm) compared to the lower altitudes existing in the southern and eastern areas of Hungary (Cheval *et al.*, 2014).

A good climate classification should be able to detect these differences and provide logical transitions within its variables to explain these features. For example, the energy and moisture gradients created by these features should be readily apparent in mapping climate classification indices, and there should be the potential to create climate subclasses that are useful for local and regional scale analyses.

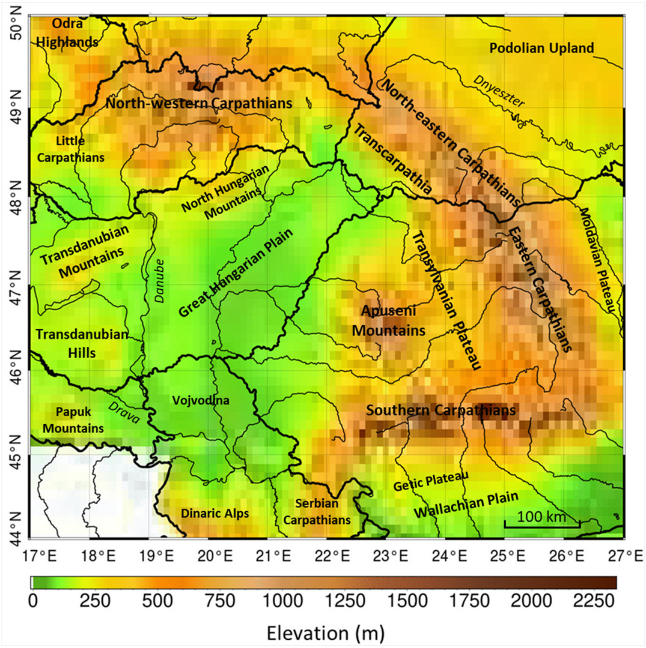

FIGURE 1 Elevation data of the Larger Carpathian Region (LCR) (Bosnia-Herzegovina in white is not included, data: CarpatClim, Szalai *et al.*, 2013) [Colour figure can be viewed at wileyonlinelibrary.com]

2.1 | CarpatClim dataset

Temperature and precipitation data were taken from CarpatClim (Szalai *et al.*, 2013) for the reference period 1971–2000. The CarpatClim dataset is the joint product of 10 scientific institutions from Hungary, Austria, Croatia, Czech Republic, Poland, Romania, Serbia, Slovakia and Ukraine, and is one of the latest climate databases in the Larger Carpathian Region (LCR; CarpatClim, 2021; carpatclim-eu.org). The domain lies between 44°N and 50°N and 17°E and 27°E and includes 2 m daily mean air temperature data from 288 stations with approximately one station per 41×41 km^2. Daily accumulated precipitation data from 1961 to 2010 come from 643 stations with approximately one station per 27.4×27.4 km^2. All data are processed into a gridded dataset with a $0.1° \times 0.1°$ spatial resolution (CarpatClim, 2021; carpatclim-eu.org). Bosnia-Herzegovina is not included in the CarpatClim dataset, hence it not included in this research (Figure 1).

Studies of climate change in the region based on CarpatClim show high correlation with altitude and a significant increase in mean and maximum temperature in the LCR during the 20th century (Lakatos *et al.*, 2013; Spinoni *et al.*, 2015). Lakatos *et al.* (2013) showed a significant decrease of wet days in the northwestern Carpathians. The largest increase in hot days occurs on plateaus in the southern and eastern Carpathians basins with a higher rate in Hungary than in the Transylvanian part of the region. The number of wet days increases significantly in the Ukrainian part of the northeastern Carpathians and in the Apuseni Mountains.

The data have been upscaled to the resolution of the climate model domains introduced in section 2.2. CDO (Schulzweida, 2019) has been used to perform bilinear interpolation of temperature data and first order conservative remapping of precipitation data.

2.2 | EURO-CORDEX data

Temperature and precipitation projections for 2069–2098 were taken from the EURO-CORDEX ensemble (Jacob *et al.*, 2014; 2020). EURO-CORDEX is a subprogram of the World Climate Research Program (WCRP) providing internationally coordinated and improved regional climate projections. In this study EURO-CORDEX simulations with EUR-44 (0.44° corresponding to an approximately 50-km grid spacing) and EUR-11 (0.11° corresponding to an approximately 12.5-km grid spacing) resolutions are used. Projections for the stabilization (RCP4.5) and business-as-usual (RCP8.5) scenarios are used. RCP4.5 assumes that the radiative forcing will stabilize at 4.5 W·m^{-2} by the end of the century while RCP8.5 assumes a steady rise in radiative forcing in the 21st century, reaching 8.5 W·m^{-2} by 2100 (Moss *et al.*, 2010).

For this study, the delta-change method for correcting (Déqué, 2007) 19 model outputs is used to adjust climate projections relative to the CarpatClim data to reduce biases and ensure homogeneity between the observation and modelled climate periods (Hanf *et al.*, 2012). The list of the postprocessed GCM-RCM model pairs can be found as Table S1, Supporting Information.

3 | FEDDEMA'S METHOD

Feddema's method (2005) was developed based on the Thornthwaite climate classification. The development process is described in detail in Feddema (2005). The method can be used to provide synthesized, easily interpretable information about both climate and seasonality type and climate change process type. In most climate classification schemes only the boundary shifts are readily discernible. Feddema's method introduces even intervals on continuous variables for categorisation, thus providing the opportunity to subdivide or redefine climatic boundaries to better describe local conditions or to present not only the discrete climate type changes but also the continuous shifts in annual and seasonal characteristics.

Climate types defined by annual and seasonal heat and water availability characteristics are determined based on thermal and moisture indices. Criteria are presented for categories that occur in the LCR. The thermal state is calculated from potential evapotranspiration (PET). PET is calculated from air temperature (T) and daylight length considering latitude according to Thornthwaite's (1948) formula. On the global scale, the annual sums of monthly PET values are divided into even intervals to determine thermal regime categories (Table 1). The moisture state is defined according to Willmott and Feddema's (1992) moisture index (I_m), which is calculated from PET and precipitation (P) as follows:

$$I_m = \begin{cases} 1 - \frac{\mathrm{PET}}{P}, \text{if } P > \mathrm{PET} \\ 0, \text{if } P = \mathrm{PET} = 0 \\ \frac{P}{\mathrm{PET}} - 1, \text{if } P \leq \mathrm{PET} \end{cases}.$$

Global moisture regime categories are related to even intervals of annual I_m values. Positive numbers indicate an excess of water supply while water demand is represented with negative values (Table 2).

The treatment of seasonality is a departure from traditional metrics of seasonal variation in T or P used in most climate classification methods. Instead, the method makes use of two metrics that describe seasonality and its attribution to T or P variation. The first metric, magnitude of seasonal variation (I_s) is represented by the monthly range of moisture index values. I_s values are used to express how intense seasonality is (Table 3). Small changes in the index result in low seasonal changes and a high range of I_m assumes high seasonality.

The second metric (A_s) attributes seasonality to either T variation or P variation, or a combination of both. Feddema's scheme defines the attribution (A_s) calculated via the ratio of PET range and P range. In this paper the calculation of the original Feddema index determining which climatic element possessed seasonality introduced in Feddema (2005) has been modified to obtain more interpretable values and category boundaries. The new formula is constructed similar to the calculation of I_m:

$$A_s = \begin{cases} 1 - \frac{\mathrm{PET}_{\mathrm{range}}}{P_{\mathrm{range}}}, \text{if } P_{\mathrm{range}} > \mathrm{PET}_{\mathrm{range}} \\ 0, \text{if } P_{\mathrm{range}} = \mathrm{PET}_{\mathrm{range}} = 0 \\ \frac{P_{\mathrm{range}}}{\mathrm{PET}_{\mathrm{range}}} - 1, \text{if } P_{\mathrm{range}} \leq \mathrm{PET}_{\mathrm{range}} \end{cases}.$$

For global classification purposes, values around zero (from −0.5 to 0.5) represent the seasonality possessed by both P and T. Positive values above 0.5 show that seasonality is primarily attributed to intra-annual variation in P and negative values below −0.5 represent seasonality attributed to intra-annual T changes (Table 4).

4 | RESULTS

Thermal and moisture regime category pairs each define a "climate type." Seasonality magnitude and attribution category pairs of the LCR define the "seasonality type" of a climate. The climate types and their seasonality types are presented in this section for the reference period (1971–2000) and for the end of the century (2069–2098) according to the RCP4.5 and the RCP8.5 scenarios for the EUR-11 resolution. All the figures presented in this paper are created using the R programming language (R Core Team, 2019).

The coverage changes in terms of percentage of the climate types and seasonality types across the LCR for both scenarios and resolutions according to the 19 climate model pairs can be found as Figures S1–S8. For the sake of providing background on ensemble uncertainty, the multi-model statistics on the changes of climate type and

TABLE 1 Feddema (2005) thermal regime categories found in the Larger Carpathian Region

Thermal regime category	PET (mm·year^{-1})
Warm	900–1200
Cool	600–900
Cold	300–600

TABLE 2 Feddema (2005) moisture regime categories found in the Larger Carpathian Region

Moisture regime category	Annual I_m
Saturated	0.66–1.00
Wet	0.33–0.66
Moist	0.00–0.33
Dry	−0.33 to 0.00
Semiarid	−0.66 to −0.33

TABLE 3 Feddema (2005) criteria to determine seasonality magnitude categories found in the Larger Carpathian Region

Seasonality magnitude category	I_s
Low	0.0–0.5
Medium	0.5–1.0
High	1.0–1.5
Extreme	1.5–2.0

seasonality type coverage can be found in Table 5 and Tables S2–S4. The greatest ensemble median response is an increase in the cool-moist type area with 14 and 12.9% and a decrease in the cold-moist type area with 13.8 and 15.1% according to RCP4.5 for the EUR-11 and EUR-44 resolutions, respectively. RCP8.5 shows the greatest median increase of cool-dry area (49.5%) for the EUR-11 resolution and of cool-moist area (8.9%) for the EUR-44 resolution. The warm climate type is projected to appear in the LCR according to the RCP8.5 projection. While there is a 0.3% ensemble median area change in the warm-moist and warm-dry climate types in the EUR-11 simulations, there is much uncertainty in this projection. There is a 14% range across ensemble members in the warm-dry climate type, mainly caused by the RCA-4-HadGEM2-ES and RCA-4-IPS-CM5A-MR model pairs (Table 5 and Figure S3). At the EUR-44 resolution according to the RCP8.5 scenario, RCA-4-CanESM2 and RACMO-HadGEM2-ES result in an increase in the area of warm-semiarid and warm-dry climate types in the range of 17.8 and 17%, respectively (Table S2 and Figure S4).

Minimum and maximum percentage change in seasonality types show significant uncertainty across models in the direction of change. Models suggesting a reduced change of extreme seasonality attributed to T include PROMES-EC-EARTH, RCA4-CNRM-CM5 and HIRHAM5-EC-EARHT for RCP8.5 at both resolutions (Tables S3 and S4 and Figures S7 and S8). Models displaying an increasing in the extent of extreme seasonality include ALADIN-CM5, RCA-4-HadGEM2-ES with the EUR-11 resolution, and COSMO-HadGEM2-ES with the EUR-44 resolution for RCP4.5, and RCA-4-HadGEM2-ES and RCA-4-ESM-LR with the EUR-11 resolution, and RCA-4-CanESM2 with the EUR-44 resolution for RCP8.5 (Figures S5–S8).

Since the aim of this study is to introduce the projected change in the LCR from the annual and seasonal point of view, the Rossby Centre regional atmospheric model RCA-4 driven by the global EC-EARTH model was selected to represent a representative median projected future scenario outcome. This model pair does not specifically under or overestimate present day T or P in the LCR (Strandberg *et al.*, 2014) and resulted in average PET values for both scenarios and domains in comparison with the other simulations. Analysis of changes in Feddema indices and climate and seasonality type is performed not only for the total area but also separately for the lowlands (elevation <200 m), hills (elevation between 200 and 500 m above sea level), low-altitude mountain areas (elevation between 500 and 1,000 m above sea level) and mid- and high-altitude mountain areas (elevation >1,000 m) (Meybeck *et al.*, 2001).

TABLE 4 Improved criteria to determine seasonality attribution categories found in the Larger Carpathian Region

Seasonality attribution category	A_s
Temperature	lower than −0.5
Temperature and precipitation	−0.5 to 0.5
Precipitation	greater than 0.5

4.1 | Projected changes in climate and seasonality characteristics

To assess the potential change in climate and seasonality characteristics, potential changes in thermal and moisture characteristics, and also in seasonality and magnitude of seasonality have been considered.

4.1.1 | Change in climate type characteristics

Figure 2 shows shifts in thermal and moisture characteristics and changes in the coverage of various climate types. Even if there is no shift from one category to another, tending towards higher or lower annual PET or I_m values means warming and wetting or cooling and drying, respectively. Mean annual PET and I_m values related to climate types are projected to shift due to warming by the end of the century for all locations and initial climate states for both RCP4.5 and RCP8.5 scenarios, except for the cold-saturated climate type which is projected to disappear. The strongest warming occurs in cool-dry and cool-moist areas. Strong shifts in the moisture regime towards drying occur in the RCP8.5 scenario, while the RCP4.5 scenario has similar shifts, but of much lower magnitude. Moist climate types, with mean annual I_m values above zero during the reference period, get wetter according to the simulations, and areas with a water demand during the reference period, that is, with I_m values below zero, get dryer by the end of the century.

Changes in coverage are estimated for all climate types in both scenarios. Cold areas shrink by 21.2% and by 27.1% for RCP4.5 and RCP8.5, respectively, by the end of the century; these are replaced with cool climate types. In the case of RCP8.5 the following new types are projected to appear: warm-semiarid, warm-dry and cool-semiarid. The new warm thermal regime category will cover 4.6% of the LCR, while the cold-dry climate will vanish in both scenarios. Saturated climate types will disappear and in the case of RCP8.5 the coverage of wet and moist climates is estimated to decrease by roughly 7 and 17%, respectively. Dry areas will expand by at least 3%, and in the RCP8.5 scenario semiarid areas, which are not

TABLE 5 Percentage changes of Feddema climate types in the period 2069–2098 according to the RCP4.5 and RCP8.5 scenarios based on multimodel results of the EUR-11 simulations

	RCP4.5				RCP8.5			
Climate type	**Median**	**Min**	**Max**	**Range**	**Median**	**Min**	**Max**	**Range**
Warm-semiarid					4.3	0.7	10.7	10.0
Warm-dry					0.3	0.1	14.2	14.0
Warm-moist					0.3	0.3	0.3	0.0
Cool-semiarid	0.6	0.1	1.5	1.4	3.1	0.3	12.9	12.6
Cool-dry	0.3	−4.0	3.5	7.5	49.5	44.0	60.1	16.2
Cool-moist	14.0	11.8	16.3	4.5	10.2	−3.6	12.9	16.4
Cool-wet	4.6	3.3	7.3	4.0	5.6	3.4	10.3	7.0
Cool-saturated					2.8	0.1	12.9	12.8
Cold-dry								
Cold-moist	−13.8	−14.9	−12.6	2.2	−15.8	−16.13	−14.5	1.6
Cold-wet	−6.1	−8.8	−3.8	5.1	−9.6	−11.4	−8.8	2.6
Cold-saturated	−0.1	−0.2	0.0	0.2	−0.2	−0.2	0.2	0.4

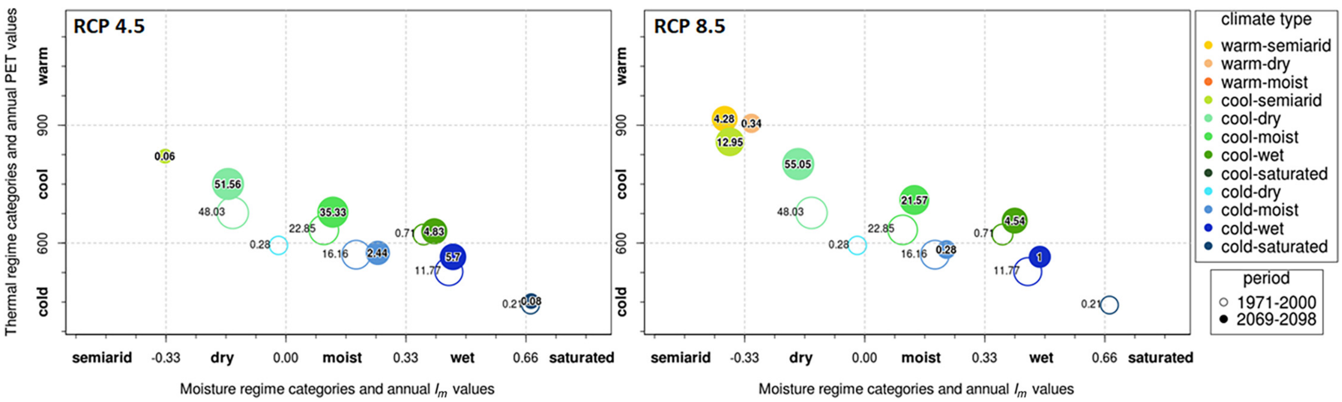

FIGURE 2 Shifts in thermal and moisture characteristics and changes in climate type represented by circles with radius size proportional to log10 of the covered area. The values in the circles show the coverage relative to the total area in percentage. The centre of circles represents the mean annual PET and I_m of the area covered by the climate type. Empty circles represent climate types in the period 1971–2000 based on CarpatClim observation data. Filled circles represent climate types in the period 2069–2098 according to the RCP4.5 and RCP8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations [Colour figure can be viewed at wileyonlinelibrary.com]

present in the reference period, occur across 17.2% of the LCR.

To further assess subregional impacts, the analysis has also been carried out for areas separated by elevation intervals. The greatest difference between RCP4.5 and 8.5 scenarios in terms of shifts of PET and I_m values occurs in the lowlands (elevation <200 m), which include 38.5% of the study area (Figure 3). Warming is the strongest for the present day cool-dry and cool-moist climate types. RCP8.5 projects 88% of lowlands would shift towards the border of the cool-warm category, with 12% of the lowlands changing from cool to warm climate types and 44% of the lowlands would also shift into the semiarid moisture regime, which is a climate type not found during the reference period.

4.1.2 | Change in climate seasonality characteristics

Figure 4 shows shifts in seasonality characteristics and changes in coverage of seasonality types for the entire LCR. While there may not be major shifts from one category to another, there are still distinct shifts in seasonality trends based on changes in the mean I_s and A_s values across the region. During the reference period, the magnitude of seasonality (I_s) is categorized as high in 56.9% of the LCR. RCP4.5 assumes only minor increases in I_s overall. However, RCP8.5 shows significant increases in seasonality with the extreme category expanding from 37% to 59.3%, while the area of moderate seasonality is nearly eliminated from the initial value of 6.09% of the area to 0.67%. Overall, the coverage of areas where seasonality is attributed to variation in both T and P (A_s values between −0.5 and 0.5) is projected to drop from 45.9 to 37.5% for RCP4.5, and significantly to 15.7% for RCP8.5. Overall, seasonality attribution is projected to be more T driven, meaning a reduction in precipitation variation over the year, or an increase in seasonal energy differences.

The greatest difference between the result of the RCP4.5 and 8.5 scenarios in terms of shifts of I_s and A_s values occurs in mid- and high-altitude mountains (elevation >1,000 m), which includes 6% of the study area. The changes in seasonality characteristics in these mountain regions can be seen in Figure 5. Shifts appear in the direction of more intense seasonality and in an increased role for temperature, or, alternatively, a decreased role for precipitation in determining seasonal variability in both RCP scenarios. The greatest shift in I_s and A_s is related to seasonality attributed to T and P variation together with high seasonality magnitude, where A_s moves to lower values, which means the increasing dominance of T variation, and I_s moves towards higher seasonality magnitude.

4.2 | Changes by altitude region

Analyses of climate type (Table 6) and seasonality type (Table 7) change are performed separately for different elevation intervals, while also indicating the percentage of the different altitudinal zones that are experiencing change.

By the end of the century, the LCR is more likely to experience an increase in the heterogeneity of climate type considering the total area. Changes in climate type are the greatest in the case of the lowlands, where the RCP8.5 scenario results in more than double the number of climate types. Increasing homogeneity of climate type is likely for the hills and low-altitude mountain regions. Low-altitude mountain regions will be distinguished by 5 (RCP4.5) or 4 (RCP8.5) types instead of six climate types currently. Both scenarios result in increasing heterogeneity of climate type at the same rate of change in the mid- and high-altitude mountain regions. Higher percentage of area experiencing climate type change occurs for RCP8.5, where on average 72% of the areas are altered to a new climate type, compared to 30% of the areas for RCP4.5. According to the business-as-usual scenario more than 50% of every altitudinal region undergoes a change in climate type. The most significant change is projected for the low-altitude mountain regions with the climate types projected to alter in 68.3 and 93.8% of the area for RCP4.5 and RCP8.5, respectively. The lowlands are projected to change the least according to RCP4.5, with 3.2% of the area changing climate type, while RCP8.5 projects that 54.3% of lowlands will experience a change in climate type.

The number of seasonality types remains the same in the lowlands, hills, and decreases in the mid- and high-altitude mountain regions in the RCP4.5 scenario.

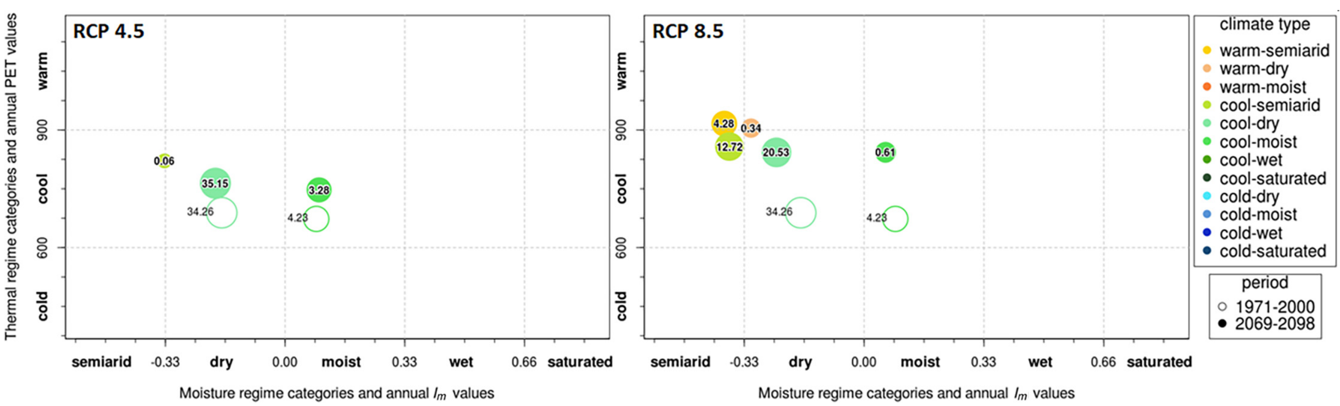

FIGURE 3 Shifts in thermal and moisture characteristics and changes in climate type in lowlands (elevation <200 m) represented by circles with radius size proportional to log10 of the covered area. The values in the circles show the coverage relative to the total area in percentage. The centre of circles represents the mean annual PET and I_m of the area covered by the climate type. Empty circles represent climate types in the period 1971–2000 based on CarpatClim observation data. Filled circles represent climate types in the period 2069–2098 according to the RCP4.5 and RCP8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations [Colour figure can be viewed at wileyonlinelibrary.com]

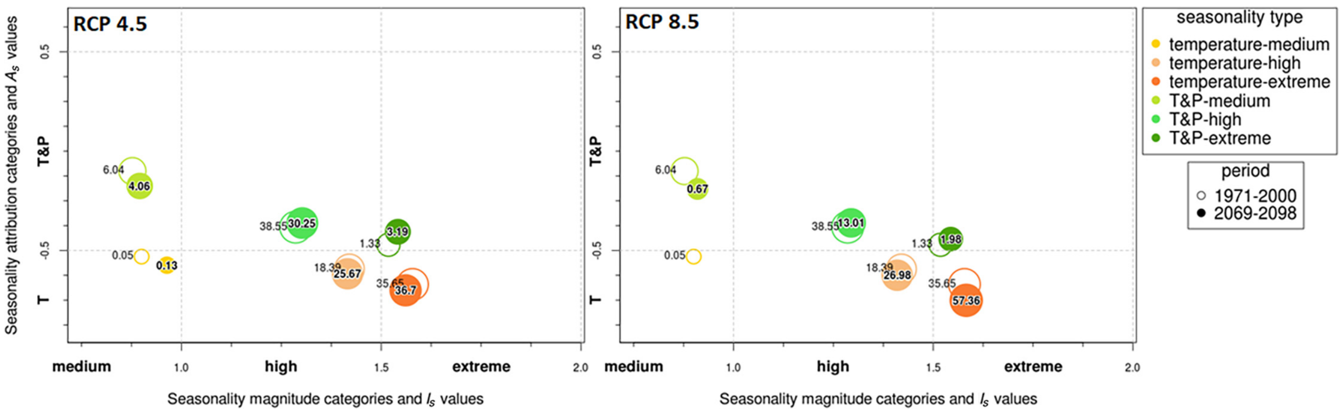

FIGURE 4 Shifts in seasonality characteristics and changes in seasonality type represented by circles with radius size proportional to log10 of the covered area. The values in the circles show the coverage relative to the total area in percentage. The centre of circles represents seasonality magnitude (I_s), and seasonality attribute (A_s) indices of the area covered by the seasonality type. Empty circles represent seasonality types in the period 1971–2000 based on CarpatClim observation data. Filled circles represent seasonality types in the period 2069–2098 according to the RCP4.5 and RCP8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations [Colour figure can be viewed at wileyonlinelibrary.com]

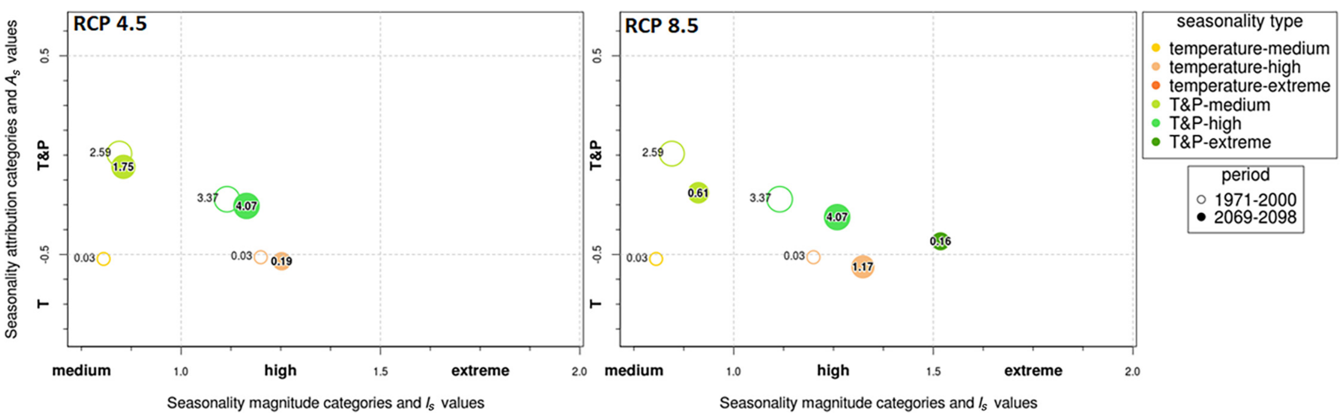

FIGURE 5 Shifts in seasonality characteristics and changes in seasonality type in mid- and high-altitude mountain regions (elevation >1,000 m) represented by circles with radius size proportional to log10 of the covered area. The values in the circles show the coverage relative to the total area in percentage. The centre of circles represents the mean seasonality magnitude (I_s), and seasonality attribute (A_s) indices of the area covered by the seasonality type. Empty circles represent seasonality types in the period 1971–2000 based on CarpatClim observation data. Filled circles represent seasonality types in the period 2069–2098 according to the RCP4.5 and RCP8.5 scenario based on the RCA4–EC-EARTH model pair in the EUR-11 simulations [Colour figure can be viewed at wileyonlinelibrary.com]

The RCP8.5 results in no change in the number of distinguished seasonality types in low-altitude mountain regions and mid- and high-altitude mountain regions. However, seasonality type change is projected on average 23% of the areas in each elevation zone in RCP4.5 compared to an average of 53% of the areas in RCP8.5. The RCP8.5 results in a seasonality type change in more than 50% of hills and mountainous areas. RCP4.5 results in the most significant seasonality type change occurring in the hills with 31.4% of its area altered, while RCP8.5 results in most change taking place in the low-altitude mountain regions with 71% of its area altered.

4.3 | Spatial distribution changes

Spatial distribution maps are created to display changes in climate type and seasonality type by subregion. Spatial distribution maps of climate type and seasonality type for the reference period and for the simulated period can be seen in Figures S9 and S10.

4.3.1 | Climate type changes

The projected spatial distribution of climate type changes by the end of the century are shown in

Figure 6. Both RCP scenarios project changes of heat and water availability in every country of the LCR. According to the RCP4.5 scenario the main driver of change is warming, which occurs mostly in mountainous areas, such as the Papuk Mountains, the Serbian Carpathians, the Apuseni Mountains, along the southern-, eastern-, and North-western Carpathians, the Podolian Upland, and the eastern part of the Transdanubian Mountains. Drying alone can be found in the Transdanubian Mountains and Hills, the Serbian Carpathians, the Getic Plateau, Transcarpathia, in the southeast part of the North-western Carpathians, and in the Polish part of the North-western Carpathians. The process of warming and drying together can be found in the eastern part of the Southern Carpathians, the eastern part of Transcarpathia and in a few grid points along the eastern-, and northwestern Carpathians. Areas characterized by wetting can be found south of the Podolian Upland and in the southern part of Transylvania, where warming and wetting can be found as well. In the case of RCP8.5, warming is simulated in major parts of the mountainous areas, while changes in moisture availability are the main driver of change in the lowlands, hills, and low-altitude mountain areas. Drying alone occurs in the Transdanubian Mountains and Hills, the Dinaric Alps, the Serbian Carpathians, Vojvodina, the Great Hungarian Plain, the southern part of the Apuseni Mountains, the Getic Plateau, the southern part of the Transylvanian Plateau, Transcarpathia, south of the Podolian Upland, and in the southern part of the Slovakian part of the Carpathians. Warming and drying together occur mainly in the Wallachian Plain, the Podolian Upland, the Apuseni Mountains and at multiple locations along the Carpathians. Wetting and warming together or wetting alone do not occur in the RCP 8.5 scenario.

TABLE 6 Number of climate types and percentage of areas experiencing change in climate type

			Number of climate types and percentage of areas experiencing climate type change				
			Total area	Lowlands (elevation < 200 m)	Hills (200 m < elevation < 500 m)	Low-altitude mountain regions (500 m < elevation <1,000 m)	Mid- and high-altitude mountain regions (elevation > 1,000 m)
1971–2000		Number of climate types	7	2	5	6	3
2069–2098	RCP4.5	Climate type change (%)	26.2	3.2	29.4	68.3	19.2
		Number of climate types	7	3	3	5	5
	RCP8.5	Climate type change (%)	64.4	54.3	56.3	93.8	84.9
		Number of category pairs	8	5	4	4	5

Note: Results are shown for the total area and separately for lowlands, hills, low-altitude mountain regions and mid- and high-altitude mountain regions for the observation period (1971–2000) based on the CarpatClim dataset and by end of the century (2069–2098) according to the RCP4.5 and 8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations.

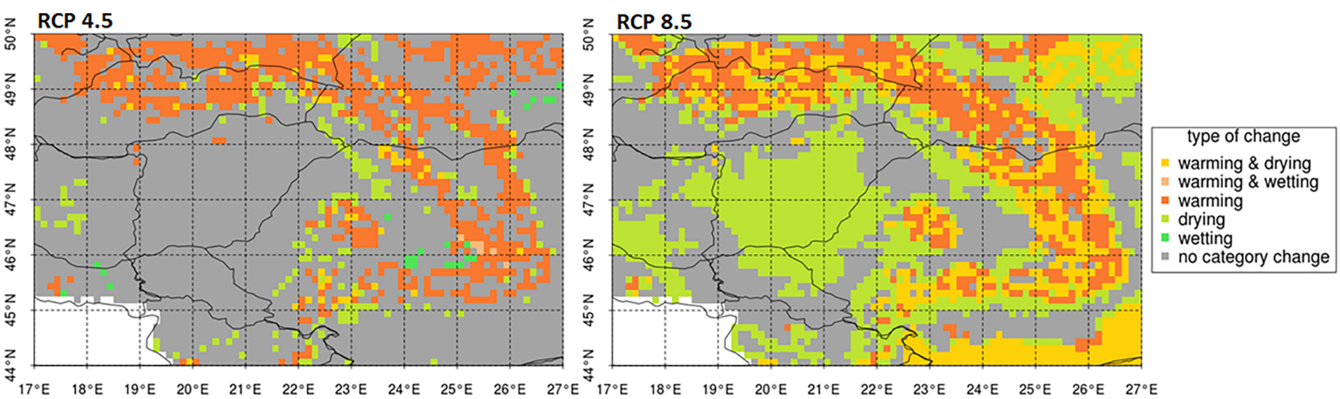

FIGURE 6 Spatial distribution of changes in climate type in the Larger Carpathian Region from the period 1971–2000, based on CarpatClim observation data, to the period 2069–2098 according to the RCP4.5 and RCP8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 7 Number of seasonality types and percentage of areas experiencing change in seasonality type

			Number of seasonality types and percentage of areas experiencing seasonality type change				
			Total area	Lowlands (elevation < 200 m)	Hills (200 m < elevation < 500 m)	Low-altitude mountain regions (500 m < elevation < 1,000 m)	Mid- and high-altitude mountain regions (elevation > 1,000 m)
1971–2000		Number of seasonality types	6	4	5	5	4
2069–2098	RCP4.5	Seasonality type change (%)	23.2	14.5	31.4	26.2	18.7
		Number of seasonality types	6	4	5	5	3
	RCP8.5	Seasonality type change (%)	48.5	18.6	67	71	53.9
		Number of category pairs	5	3	4	5	4

Note: Results are shown for the total area and separately for lowlands, hills, low-altitude mountain regions and mid- and high-altitude mountain regions for the observation period (1971–200) based on the CarpatClim dataset and by end of the century (2069–2098) according to the RCP4.5 and 8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations.

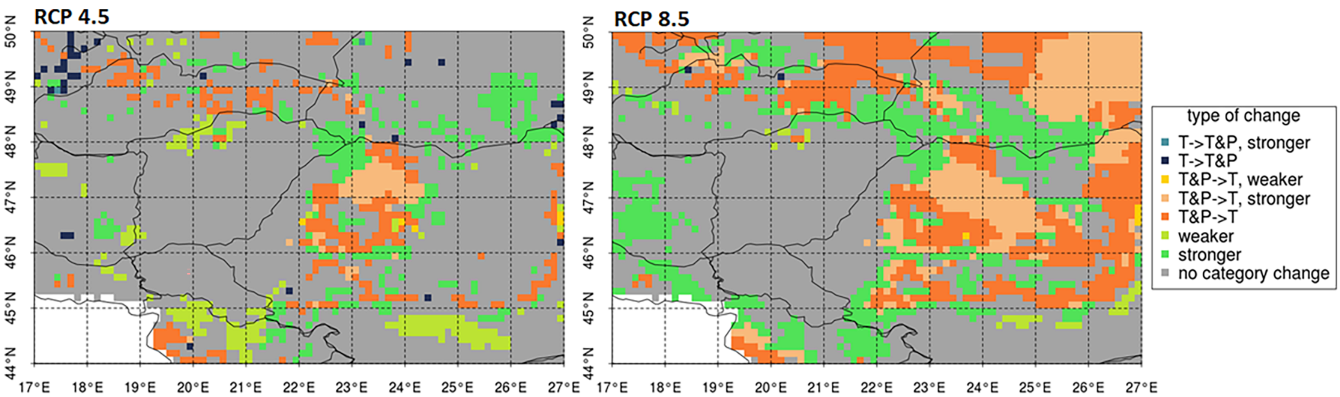

FIGURE 7 Spatial distribution of changes in type of seasonality in the Larger Carpathian Region from the period 1971–2000, based on CarpatClim observation data, to the period 2069–2098 according to the RCP4.5 and RCP8.5 scenarios based on the RCA4–EC-EARTH model pair in the EUR-11 simulations [Colour figure can be viewed at wileyonlinelibrary.com]

4.3.2 | Seasonality type changes

The spatial distribution of projected seasonality type changes by the end of the century are presented in Figure 7. Seasonality-related changes are simulated in every country of the LCR. Transition from intra-annual variation primarily attributed to T to seasonality attributed to a combination of variation in T and P is hereinafter referred to as $T \rightarrow T\&P$ and from T and P variation to T as $T\&P \rightarrow T$ transition. In the RCP4.5 scenario, seasonality magnitude becomes stronger with an accompanying change in attribution from $T\&P \rightarrow T$ in the Transylvanian Plateau and in some smaller regions, such as parts of the Apuseni Mountains. Decreasing seasonality magnitudes with the $T\&P \rightarrow T$ transition can be found in a few parts of the Apuseni Mountains and east from the Eastern Carpathians. $T\&P \rightarrow T$ transitions are simulated in the Papuk Mountain, the Dinaric Alps, south and west of the Apuseni Mountains and along the Carpathians. Changes in seasonality attribution in the form of $T \rightarrow T\&P$ transitions appear only on a few grids in the Transdanubian Hills and in the Carpathians and the Odra Highlands. Seasonality magnitude decreases in the Croatian area of the Drava River, the Wallachian Plain, and the North Hungarian Mountains, while seasonality magnitude becomes stronger in the western part of the Transdanubian Hills, in the area of the River Danube near the Serbian Romanian border, in the area of the

Dnyeszter River and in the Carpathians. For RCP8.5, major parts of the mountainous areas could experience changes in seasonality characteristics. Increasing seasonality in combination with the $T\&P \rightarrow T$ transition in seasonality attribution occurs in the Dinaric Alps, the southern part of the Apuseni Mountains, the Transylvanian Plateau, in the northern part of Moldavian Plateau, in the Podolian Upland, in the northern part of the North-eastern Carpathians, in the Czech and Slovakian part of the North-western Carpathians. The $T\&P \rightarrow T$ transition in seasonality attribution is simulated in the Papuk Mountain, the Dinaric Alps, the Apuseni Mountains, the Southern Carpathians, east of the Eastern Carpathians, in the western part of the Podolian Upland, in the eastern part of the North-western Carpathians. Seasonality magnitude increases in the Transdanubian Hills and Mountains, east of the Papuk Mountains, in the Dinaric Alps, in the northern part of the Serbian Carpathians, in the Southern and North-eastern Carpathians, in Transcarpathia, in the eastern part of Northern Carpathians, and in the Little Carpathians. Seasonality magnitude decreases in only a few parts of the study area: in the eastern part of Wallachian Plain, and in the eastern part of the North Hungarian Mountains. The $T \rightarrow T\&P$ transition can only be found on two grid points in the northwestern Carpathians based on the RCP8.5 projection. Overall, the dominant change in type of seasonality is the $T\&P \rightarrow T$ transition alone or together with the process of increasing seasonality magnitude.

5 | DISCUSSION

Feddema's (2005) scheme defines climate and seasonality types, including the thermal and moisture regime variables, and seasonality magnitude and attribution variables globally. For this exploratory study classes are distinguished by even intervals designed for global applications. Creation and choice of classes limits aspects of the analysis, much like Köppen's nominal classification categories, because changes within classes are not identified and because changes in climate characteristics are not linear. However, the classification easily allows for the application of user defined intervals by fine-tuning the method and selecting more meaningful category boundaries (Breuer *et al*., 2017). As pointed out in Breuer *et al*. (2018), grid boxes with values near climatic borders can shift to another climate type interval without significant change in climatic variables and, similarly, a major change need not necessarily result in a change in climate type. This said, Feddema's method also allows representation of climate change not only by showing discrete changes in annual and seasonal climate categories but also as shifts in continuous Feddema climate indices. The former approach is hereinafter referred to as Feddema-discrete and the latter as Feddema-continuous change detection. Using the continuous classes makes it less important to focus on the specific categories and simplifies the use of the indices for climate change analysis.

Annual climate type changes and changes in seasonality type in the Larger Carpathian Region using the Feddema-discrete method have been previously analysed in Breuer *et al*. (2018), but only as a part of an analysis focused on Europe using the SRES A1B scenario. This study offers a more targeted approach and projects the following three thermal and moisture type changes in the LCR: warming, drying, warming and drying together by the end of the century. Seasonality type changes are also simulated: $T\&P \rightarrow T$ transition together with increasing seasonality magnitude, $T\&P \rightarrow T$ transition alone and increasing seasonality magnitude alone. Our study results project the occurrence of greater heterogeneity of climate type and seasonality change in the region.

The reduction in the area where seasonality is attributed from a combination of T and P to seasonality dominated by T does not mean there is a significant increase in thermal variability. In many instances this change can be attributed to a change in seasonality associated with intra-annual P variability and a decreasing range of P over the year. This is typically caused by decreasing summer P (annual maximum) and increasing (annual minimum) winter P. In the case of increasing magnitude of seasonality, without a seasonality attribution transition, the change in variation results from increasing intra-annual variability of P and the shift of maximum P from summer to autumn or spring.

Our results differ from past work because of the updated scenarios and model projections, and because of the higher resolution and improved representation of orography and slightly modified methodology. Note that the projected changes introduced in this study are based on results of climate simulations using varying parametrizations, model configurations and include limitations, such as scenario uncertainty, representation of internal climate variability and also the assumption of the stationarity of statistical relationships in the present climate (Benestad, 2021). The spatial distribution of the climate types and seasonality types in Europe has been presented in Skarbit *et al*. (2017) using the SRES A1B scenario. They simulate the occurrence of a new semiarid climate type in the LCR, which is not present during the reference period. Skarbit *et al*. (2017) do not project any new thermal regime category by the end of the century, while our study showed the occurrence of the new warm climate type.

Note that climate change using the Feddema-continuous approach has only been applied on the global scale by Elguindi *et al.* (2014). They presented shifts in mean annual PET and I_m values of the climate types by the end of the century using the RCP4.5 and 8.5 scenarios. The shift in seasonality type was not presented. In this study, beside presenting climate change type using the Feddema-discrete approach a new formulation of seasonality attribution was introduced, and the Feddema-continuous method is used to show shifts not only in mean thermal and moisture indices but also in seasonality indices. The Feddema-continuous results provide significantly more information about expected climate change in the region compared to only using a discrete approach, the default when using, for example, the Köppen classification. Our results show that warming is related to shifts in every climate type across the region, something that cannot be seen using the Feddema-discrete method or, similarly, with the discrete application of other climate classification approaches (e.g., Köppen's method).

Global climate change results not only in regional changes in climate type, but also in the intra-annual alteration of T and P distribution. The future projection of these processes is a required part of the adaptation to the changes, hence treatment of seasonality is an important feature of Feddema's method to assist in this assessment process. The method obtains more information about seasonality than the most widely used Köppen (1936) scheme (Szabó *et al.*, 2021). The Feddema-discrete method shows six seasonality types during the reference period, and six and five seasonality types by the end of the century according to the RCP4.5 and RCP8.5 scenarios, respectively. The Feddema-continuous method also shows shifts towards increasing dominance of T variation, in part because of reductions in P variability, and increasing seasonality magnitude regardless of change in discrete seasonality type. Also noteworthy is that none of the above-mentioned studies analysed climate change separately for different elevation intervals. The use of the Feddema-continuous methodology in this study made it possible to show that in the lowlands the main climate change process is warming and drying, while in mid- and high-altitude mountain regions the main changes can be seen in seasonality characteristics.

To the best of our knowledge the continuous approach for the indication of climate change has not been applied for the most widely used generic empirical climate classifications, such as the Köppen (1936) or the Holdridge (1947, 1967) schemes.

6 | CONCLUSION

The Feddema (2005) climate classification has been applied to study climate change in the Larger Carpathian Region (LCR) under the following conditions and data: CarpatClim reference data, and EURO-CODEX RCP4.5 and 8.5 scenario simulations at the EUR-11 and EUR-44 resolutions. Results have been presented using the RCA4-EC-EARTH model pair. Climate change is shown via the alteration of annual and seasonal thermal and moisture categories and by the direction and magnitude of change in climate and seasonality characteristics. Analysis is performed for the total area and separately for lowlands, hills, low-altitude mountain areas and mid- and high-altitude mountain areas.

The greatest difference between scenarios in terms of shifts of thermal and moisture characteristics occurs in the lowlands with alternations towards warmer and drier conditions. Climate type heterogeneity is projected to increase together with the occurrence of new warm thermal and semiarid moisture regime categories according to RCP8.5. Climate type changes are also noteworthy when considered by altitude region and are much more extreme for RCP8.5, where on average 72% of the areas are altered to a new climate type, compared to 30% of the areas for RCP4.5. The main projected climate type change is warming, and increased seasonality characteristics, occurring mostly in the mid- and high-mountain regions. RCP4.5 assumes only minor increases in I_s while RCP8.5 shows significant increases in seasonality with the extreme category expanding from 37 to 59.3%. Significant changes in seasonality type are projected on average in 23% of the areas in each elevation zone in RCP4.5 compared to an average of 53% of the areas in RCP8.5. Most of the seasonality changes relate to decreased change in intra-annual range of P resulting in a more thermally controlled seasonality. Overall, the climate and seasonality type changes are very likely to have significant ramification for hydrology as P characteristics with potential impacts on snowpack and growing season characteristics.

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AUTHOR CONTRIBUTIONS

Amanda Imola Szabó: Conceptualization; formal analysis; investigation; software; visualization; writing – original draft. **Hajnalka Breuer:** Conceptualization; formal analysis; software; supervision; visualization; writing – review and editing. **Ferenc Ács:** Conceptualization; supervision; writing – review and editing. **Michal Belda:** Data curation; formal analysis; software; writing – review and editing. **Johannes J. Feddema:** Conceptualization; methodology; software; writing – review and editing.

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