Projected values of thermal and precipitation climate indices for the broader Carpathian region based on EURO-CORDEX simulations

Nóra SKARBIT, János UNGER and Tamás GÁL[1]

Abstract

Since our climate is in a rapid changing phase, it is crucial to get information about the regional patterns of basic climatic parameters and indices. The EURO-CORDEX project provides high-quality regional climate model outputs, but these raw datasets are not convenient for the application in wider geoscience studies. According to the authors' knowledge, there is a lack of published spatial information about basic climate parameters and indices in Central Europe and especially in the broader Carpathian region therefore the basic aim of this study to fill this gap. The study presents the future trends in daily air temperature and precipitation and various climatic indices in the broader Carpathian Basin region during the 21st century. The indices are calculated using multi-model average temperature and precipitation data from EURO-CORDEX model simulations for the future time periods (2021–2050, 2071–2100) and emission scenarios (RCP4.5, RCP8.5). The indices present the future trends of the heat load, energy demand as well as extreme precipitation and drought characteristics. Based on the results the temperature increase is obvious and the heat load and energy demand quantifying indices follow the temperature trend. However, the trend is difficult to evaluate in the case of precipitation. The changes in the precipitation and the related indices can be considered small and appear within the regions. The future changes are the most considerable in the Carpathian Basin, but the entire examined region faces crucial changes in the following decades.

Keywords: climate change, 21st century, climate indices, Carpathian Basin, EURO-CORDEX model simulations

Received July 2022, accepted November 2022.

Introduction

Climate change, a very important environmental phenomenon on earth, has become one of the most important issues facing humanity today. In the first two decades of the 21st century, global average temperatures were 1 °C higher than between 1850 and 1900, and this difference could be between 3.3 °C and 5.7 °C by the end of the century, according to the worst-case scenario (IPCC 2021). Rising temperatures have complex environmental effects on a global, regional and local scale. As part of this process, we may experience an increase in the frequency of extreme weather events (such as summer heat waves) in our daily lives (Meehl, G.A. and Tebaldi, C. 2004; Pongrácz, R. *et al.* 2013). This could have far-reaching implications for society's health status and mortality rates (Baccini, M. *et al.* 2008; Kovats, R.S. and Hajat, S. 2008; McGregor, G.R. *et al.* 2015; Bartholy, J. and Pongrácz, R. 2018).

The most recent climate projections are based on the Representative Concentration Pathways (van Vuuren, D.P. *et al.* 2011). The most commonly used of these are the less (RCP4.5) and the highly pessimistic (RCP8.5) scenarios (IPCC 2013). Under these scenarios, global temperature increases of 2 °C and 4 °C, respectively, are expected by the end of the century, compared to the period 1986–2005, but the change at the regional level may be very different from these values (IPCC 2013).

[1] Department of Climatology and Landscape Ecology, University of Szeged. Egyetem u. 2. H-6722 Szeged, Hungary. E-mails: skarbitn@geo.u-szeged.hu, unger@geo.u-szeged.hu, tgal@geo.u-szeged.hu

To help assess future climate trends, in addition to the basic temperature and precipitation values, the use of so-called climate indices can further nuance and detail the picture of the change ahead. An example of such an index is when we count the days when the daily minimum temperature exceeds 20 °C (tropical night) in a given period. The number of these days shows well the annual duration of unfavourably warm weather conditions, as a high minimum temperature is also likely to mean a high daytime temperature (Pieczka, I. *et al.* 2018). There are several other similar indices, such as the number of summer days, hot days, heavy rainy days, and so on (see e.g., Dankers, R. and Hiederer, R. 2008; Sillmann, J. and Roecker, E. 2008). Analyses of the predicted values of these indices and their spatial patterns may be very useful for further detailed exploration of the characteristics of expected future climate change.

Going to a regional level, this paper deals with the region of the Carpathian Basin and its wider environment using climate projection outputs (related to the temperature and precipitation indicators) of the EURO-CORDEX regional models in case of RCP4.5 and RCP8.5 scenarios. Looking back on a few years, the earlier and similar modelling results based on the mentioned outputs to date, and at least in part related to the current study area, are as follows (grouped according to the extent to which their study areas differ from the domain of the present study):

– The study area covers a country, province or region (Štěpánek P. *et al.* 2016; Dalelane, C. *et al.* 2018; Pieczka, I. *et al.* 2018; Vuković, A. and Mandić, M.V. 2018; Kis, A. *et al.* 2020; Olefs, M. *et al.* 2021; Torma, C.Z. and Kis, A. 2022).

– The study area covers all or most of Europe (Jacob, D. *et al.* 2014; Kovats, R.S. *et al.* 2014; Rajczak, J. and Schär, C. 2017; Spinoni, J. *et al.* 2018; COACCH 2019; von Trentini, F. *et al.* 2019; Coppola, E. *et al.* 2021; Evin, G. *et al.* 2021; Badora, D. *et al.* 2022).

The importance of this topic is also highlighted by our previous studies: for many cities, we found a significant increase in the annual number of various thermal indices, so a strong warming trend is expected by the end of the century (Skarbit, N. and Gál, T. 2016; Bokwa, A. *et al.* 2019; Gál, T. *et al.* 2021). Information from regional climate projections on temperature- and precipitation-related climate indices is essential for the development and implementation of climate change mitigation and adaptation plans in this region.

According to our knowledge, published EURO-CORDEX model results are not available for the whole study area mentioned above, thus, information about the process of climate change based on this database is difficult to access for the broad scientific community. Therefore, the main aim of the study is to fill these gaps and contribute to obtain accurate spatial information about climate change. These results could also provide vital information for climate mitigation and adaptation plans, moreover it could serve as a starting point for other studies in smaller scale or in different disciplines.

The specific aims of the study are the following, (i) presenting the model averages of all available EURO-CORDEX outputs for basic climatic parameters (daily mean air temperature and daily precipitation), (ii) calculation of the most crucial climate indices in order to describe the different details of future climate, namely the heat load (warm and tropical nights, summer and hot days), energy demand (heating and cooling degree days) as well as extreme precipitation and drought characteristics (heavy and very heavy precipitation days and consecutive dry days).

Methods

Study area

This study would like to present the future conditions of the Carpathian Basin and surrounding areas of Central and Eastern Europe. The study area lies between longitudes 11° and 30°, and latitudes 43° and 51°.

This area covers southeast Germany, south Poland, Czech Republic, Slovakia, west Ukraine, almost the whole area of Austria, Hungary, Romania, Moldova, Slovenia, Croatia and the northern parts of Bosnia and Herzegovina and Serbia *(Figure 1).*

Applied model simulations

The study examines the future conditions through the average values of two periods: 2021–2050, and 2071–2100. For these periods the average of bias-corrected air temperature, daily

Fig. 1. Location in Europe marked by the red rectangle (a), and detailed map of the study area (b) with the mentioned regions in *Table 4. Source of the background map*: Elevation map of Europe (European Environment Agency – https://www.eea.europa.eu/data-and-maps/figures/elevation-map-of-europe).

maximum and minimum air temperature and precipitation data of different EURO-CORDEX model simulations with resolution 0.11° were used (Jacob, D. *et al*. 2014). All available model simulations that include these parameters for the study area, thus, the output of 13 simulations were applied for RCP4.5 and RCP8.5 scenarios (van Vuuren, D. P. *et al.* 2011) *(Table 1).*

Table 1. Details of the applied EURO-CORDEX model simulations

Nr	Institute	Global climate model	Regional climate model
1. 2. 3. 4.	CLMcom	CNRM-CM5 EC-EARTH HadGEM2 MPI-ESM-LR	CCLM4
5.	DMI	EC-EARTH	HIRHAM5
6. 7.	KNMI	EC-EARTH HadGEM2	RACMO22E
8.	MPI	MPI	REMO2009
9.	SMHI	CNRM-CM5	RCA4
10.		EC-EARTH	
11.		IPSL-CM5A-MR	
12.		HadGEM2	
13.		MPI-ESM-LR	

Applied indices

Besides the basic climatic parameters (temperature, precipitation), several climate indices were calculated to describe different aspects of the process of climate change *(Table 2).* Four indices were applied to examine the heat load change. The night heat load was analysed through the average number of warm and tropical nights, which indices are based on the daily minimum temperature. While the daytime heat load was determined with the change of the summer and hot days, using the daily maximum temperature.

In order to present the change of energy demand the heating degree days (*HDD*) and cooling degree days (*CDD*) were examined (see *Table 2*). Their calculation was based on Matzarakis, A. and Thomsen, F. (2009). The *HDD* and *CDD* give the heating and cooling energy demand of the buildings during the heating and cooling period, respectively. In case of the *HDD* the heating threshold of 15 °C was used. The index summons the difference of this value and the daily mean temperature when it does not reach this threshold. The *CDD* calculated in a similar way, in this case we applied the cooling threshold of 18 °C and the index summons the difference between the threshold and the daily mean temperature when it exceeds that. Selecting a suitable threshold for a larger area is inherently difficult because of the different regional climates, thus, studies for Europe or parts of Europe use several different thresholds (Cartalis, C. *et al*. 2001; Golombek, R. *et al*. 2012; Lindberg, F. *et al*. 2013; Moreci, E. *et al*. 2016; Chervenkov, H. *et al*. 2020). The focus of this analysis is mostly on the change in the

Table 2. The examined climate indices and their definition with the applied parameter

Nr.	Index	Definition	Applied parameter
1. 2.	Warm night (WN) Tropical night (TN)	$T_{min} \geq 17$ °C $T_{min} \geq 20$ °C	Daily minimum temperature (T_{min})
3. 4.	Summer day (SD) Hot day (HD)	$T_{max} \geq 25$ °C $T_{max} \geq 30$ °C	Daily maximum temperature (T_{max})
5. 6.	Heating degree day (HDD) Cooling degree day (CDD)	$\sum (15 - T_a)$ when $T_a < 15$ $\sum (T_a - 18)$ when $T_a > 18$	Daily mean temperature (T_a)
7.	Heavy precipitation day (HPD)	$R_d > 10$ mm	Daily precipitation sum (R_d)
8.	Very heavy precipitation day (VHPD)	$R_d > 20$ mm	
9.	Consecutive dry days (CD)	$R_d < 1$ mm (maximum number of consecutive days per time period)	

value of the indices, so the choice of thresholds was not considered relevant.

The extreme precipitation characteristics were investigated through two indices, the heavy and very heavy precipitation days when the daily precipitation sum exceeds 10 mm and 20 mm, respectively (see *Table 2*). While the change of drought circumstances was studied through consecutive dry days. In case of this index the maximum number of consecutive dry days per time period was determined, when the daily precipitation did not reach 1 mm. While the other applied indices are average values for the 30 periods, this index shows the maximum number for the whole periods.

Results

Basic climatic parameters

Temperature

In the period of 2021–2050, the daily average (T_a) temperature in the northern part of the study area is mostly between 8 °C and 10 °C (*Figure 2*, a and b). It is over 10 °C in the lower areas in Germany, Czech Republic and Poland, which covers a larger area in scenario RCP8.5 (see *Figure 2*, b). In the Carpathians the values are between 4 °C and 8 °C, lower values appear in the eastern part. Similar values appear in the Alps. In the Carpathian Basin, T_a is higher than 10 °C in almost the whole area. In the southern part, the temperature exceeds 12 °C. The greatest difference between the two scenarios occurs in this area. In case of scenario RCP8.5, the values over 12 °C appear over a larger area, especially in the southern and central part of Hungary and in the Little Hungarian Plain. In the Romanian Plain, the values are over 12 °C in most of the area. In the Dinaric Alps, T_a will be between 6 and 10 °C. On the coast of the Adriatic Sea T_a exceeds 14–16 °C.

In 2071–2100, under RCP4.5, values over 10 °C can be typical in the north areas of the study area (*Figure 2*, c). In the Carpathians and the Alps, T_a can be over 6 and 8 °C in more area, values under 4 °C almost disappear. In almost the whole Carpathian Basin and the Romanian Plain, T_a will be above 12 °C, and in Serbia in a small area over 14 °C. The values will exceed 10 °C in several areas of the Dinaric Alps, while on the coast of the Adriatic Sea there is not relevant change.

According to scenario RCP8.5 major changes will occur. Apart from the mountains and higher areas, T_a will be over 12 °C (*Figure 2*, d). T_a in the Carpathians and Alps will be above 8 °C. The typical values in the Carpathian Basin and the Romanian Plain will be over 14 °C, in the Dinaric Alps 16 °C. In the Mediterranean, the temperature will exceed 16 °C or even 18 °C in a large area.

Precipitation

In 2021–2050, the annual precipitation (P) will be between 600 mm and 800 mm in the most northern parts of the study area (*Figure 3*, a and b). In the Carpathians, Alps and Dinaric Alps the values are typically over 800 and 1,000 mm and in many areas exceed 2,000 mm. In the Carpathian Basin, P will be between 600 and 800 mm, but in the central and southern part it is lower than 600 mm. The pattern of P does not depend on the scenario in this period. Values close to 400 mm will appear in the southern and south-eastern parts of the study area.

In 2071–2100, there are no remarkable changes compared to the previous period under any of the scenarios (*Figure 3*, c and d). The only major change will appear in the area of the Carpathian Basin where P will be over 600 mm in a large area. This change is more pronounced in scenario RCP8.5 (see *Figure 3*, d).

Minimum temperature-based indices

Warm nights

The warm nights (WN) in 2021–2050 will be between 10 and 20 in the northern areas and under 10 in the higher areas (*Figure 4*, a and b). In the Carpathian Basin, WN are over 30 and exceed 40 in the central and southern

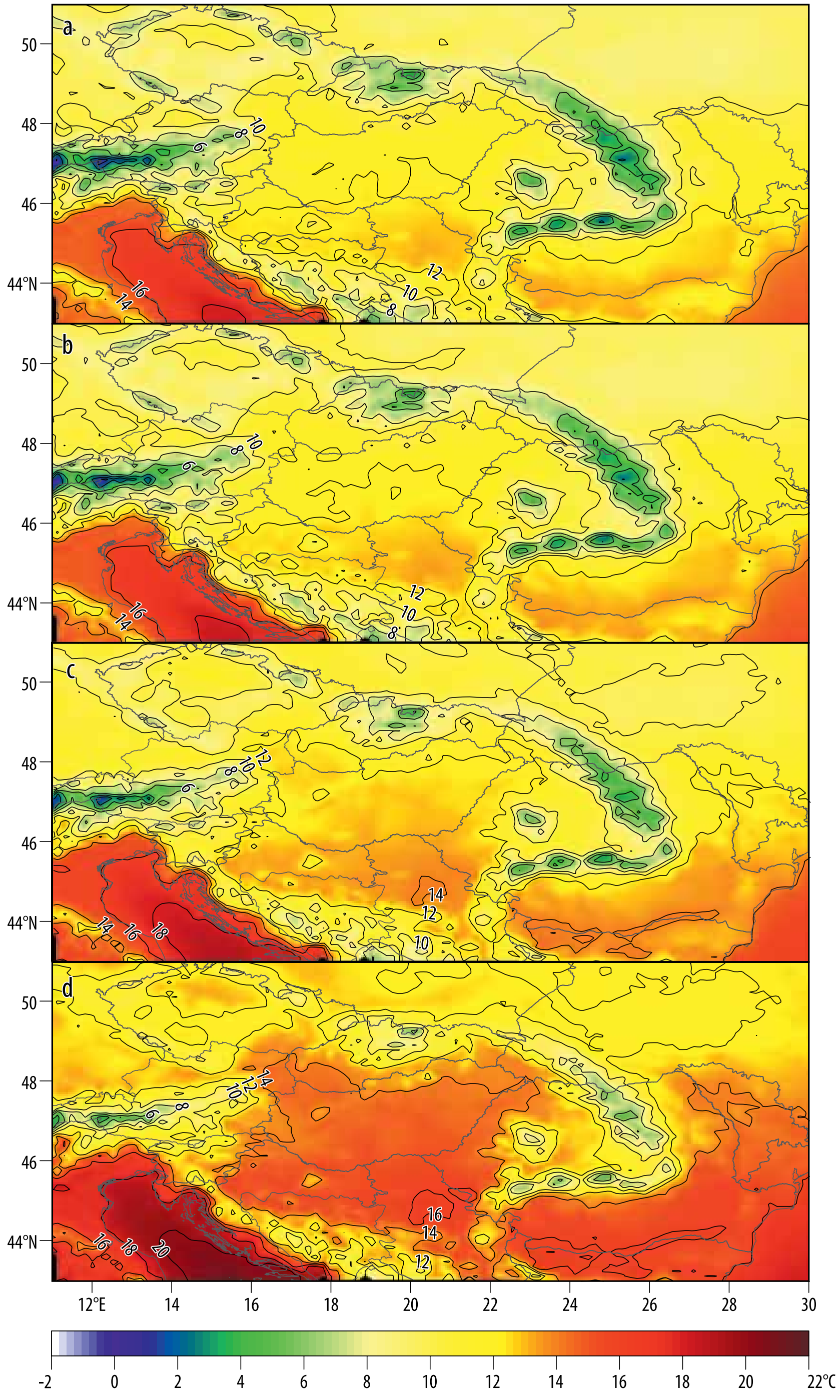

Fig. 2. Daily average mean temperature in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

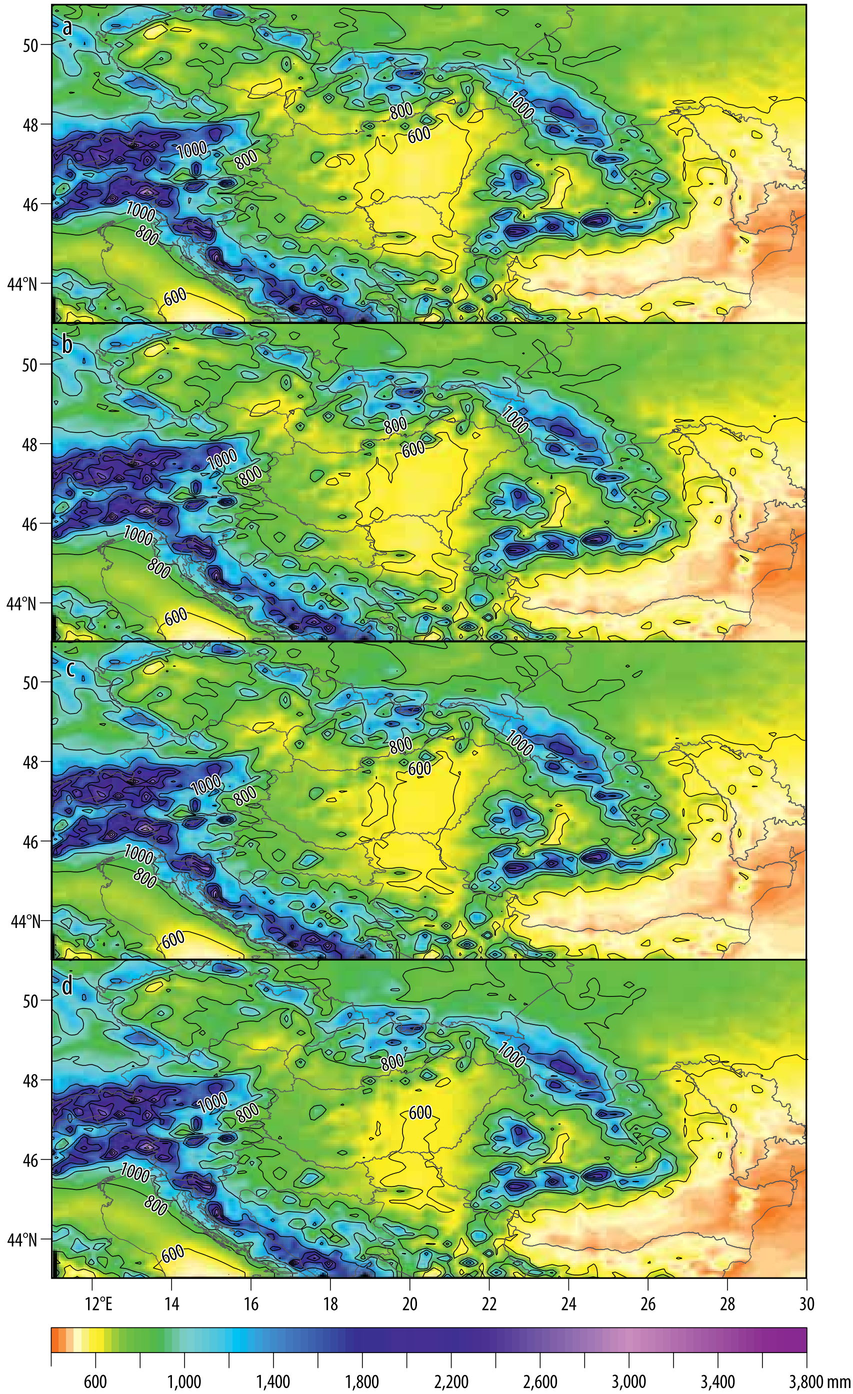

Fig. 3. Average annual precipitation in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

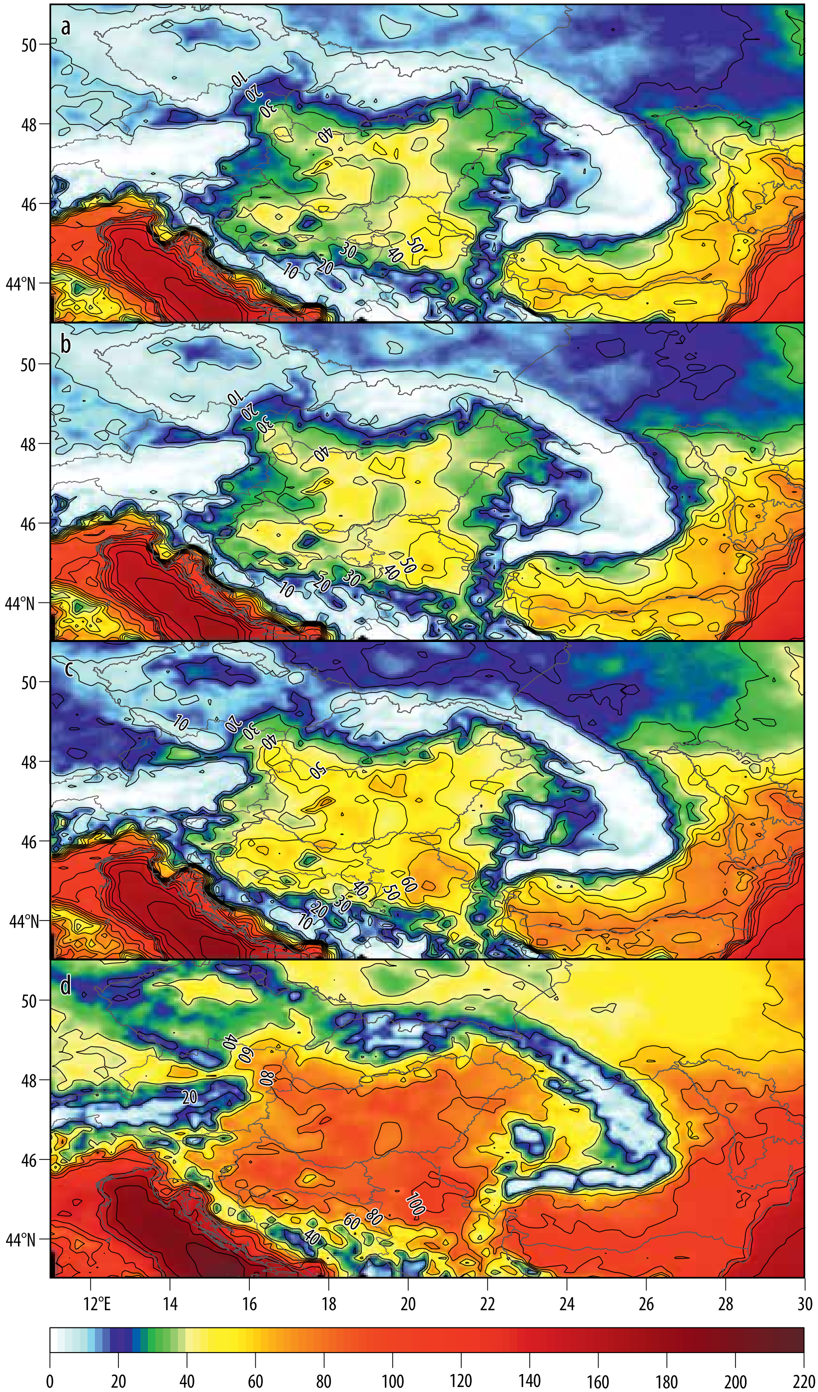

Fig. 4. Average number of warm nights in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

parts. Higher values appear in the Romanian Plain where *WN* exceed 40 or even 60. There are higher (over 80) values on the Adriatic coast. There is minimal difference between the scenarios. The only spectacular difference appears in the Carpathian Basin, the Romanian Plain and on the seacoast.

In 2071–2100, under scenario RCP4.5, *WN* will exceed 20 in the northern and north-eastern parts of the study area *(Figure 4*, c*)*. Furthermore, fewer areas in the mountains have values below 10. The values are over 40 and 60 in almost every part of the Carpathian Basin and in the central and southern part and in the main part of the Romanian Plain, respectively. On the coast of the Adriatic Sea, *WN* will exceed 80 or even 100.

According to scenario RCP8.5, major changes will take place at the end of the century *(Figure 4*, d*)*. In the mountains *WN* will be below 20 in only a few areas and between 40 and 60 in the northern and north-eastern areas. In the Carpathian Basin they exceed 60, and in most of the areas 80 and in Serbia even 100. In case of the Romanian Plain, values over 80 and 100 will be typical. On the Adriatic coast *WN* will be over 120–140.

Tropical nights

In 2021–2050, the number of tropical nights (*TN*) is low, except the Carpathian Basin and Romanian Plain, it will not reach 5 *(Figure 5*, a and b*)*. It will exceed 10 in the central and southern part of the Carpathian Basin and 20 the eastern and southern parts of the Romanian Plain. On the coast of the Adriatic Sea, the values will be higher than 40 or even 60. There are hardly noticeable differences between the scenarios.

Under the RCP4.5 scenario, *TN* will be higher than 10 in the whole area of the Carpathian Basin and 20 in its central and southern parts *(Figure 5*, c*)*. In the Romanian Plain it exceeds 20 and 30 in its central and eastern parts. On the seashore, *TN* will reach 40 or even 60.

There will be a huge change for 2071–2100 according to scenario RCP8.5 *(Figure 5*, d*)*. Values below 10 will occur only in the mountains. The number of *TN* will be higher than 20 in the entire area of the Carpathian Basin and in most parts it can exceed 40 and in some southern parts 50. Higher values will be in the Romanian Plain where *TN* exceed 60 and in some eastern part 70. On the shores of the Adriatic Sea, the values can be over 80–100.

Maximum temperature-based indices

Summer days

In 2021–2050 the number of summer days (*SD*) is between 20 and 40 in the northern part of the study area *(Figure 6*, a and b*)*. In most parts of the mountains the values are under 20. In the Carpathian Basin *SD* are over 80 and 100 in its southern part. In almost the entire area of the Romanian Plain the values are over 80 and 100 in the inner parts. Similar values can appear on the Adriatic coast where the typical values are over 80 and 100. The difference between the scenarios is minimal.

For the period of 2071–2100, the *SD* is higher than 60 in the northern parts of the study area according to RCP4.5 *(Figure 6*, c*)*. Furthermore, more areas in the mountains can have *SD* over 40. In the Carpathian Basin, the number of *SD* is above 100 in a larger area and values over 120 can appear in the southern part. In the Romanian Plain *SD* is over 120 in almost the entire area. Values are also above 120 on the Adriatic coast where they can be over 140 too.

Under scenario RCP8.5, *SD* is above 80 and 40 in most parts of the north of the study and in the mountains, respectively *(Figure 6*, d*)*. In the entire Carpathian Basin, the values are over 100, but it can be 120 in most areas and 140 in the south. *SD* can exceed 140 in almost the whole Romanian Plain. On the Adriatic coast, *SD* above 140 are typical, but values above 160 also appear.

Hot days

The number of hot days (*HD*) in the period 2021–2050 is under 10 in the Alps, Carpathians

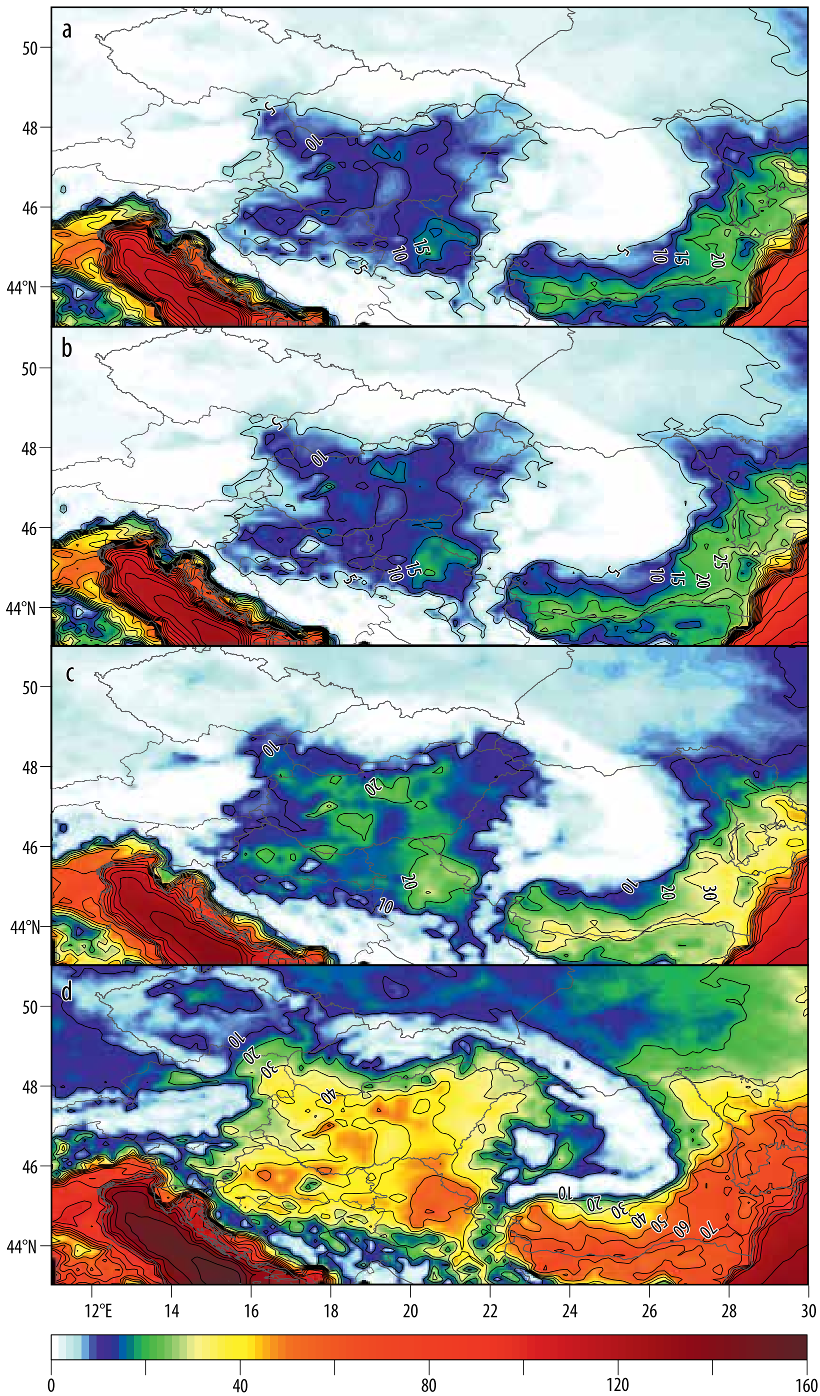

Fig. 5. Average number of tropical nights in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

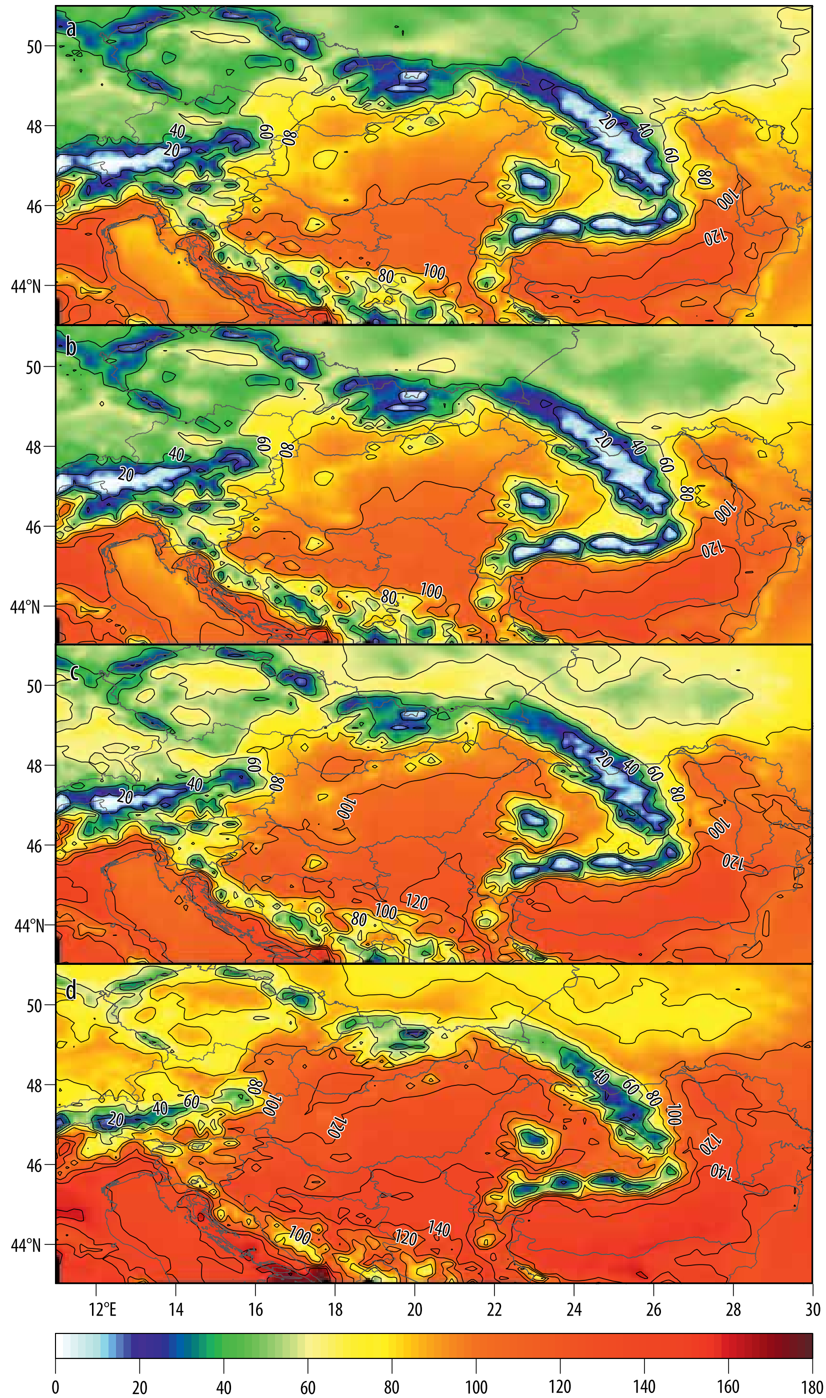

Fig. 6. Average number of summer days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

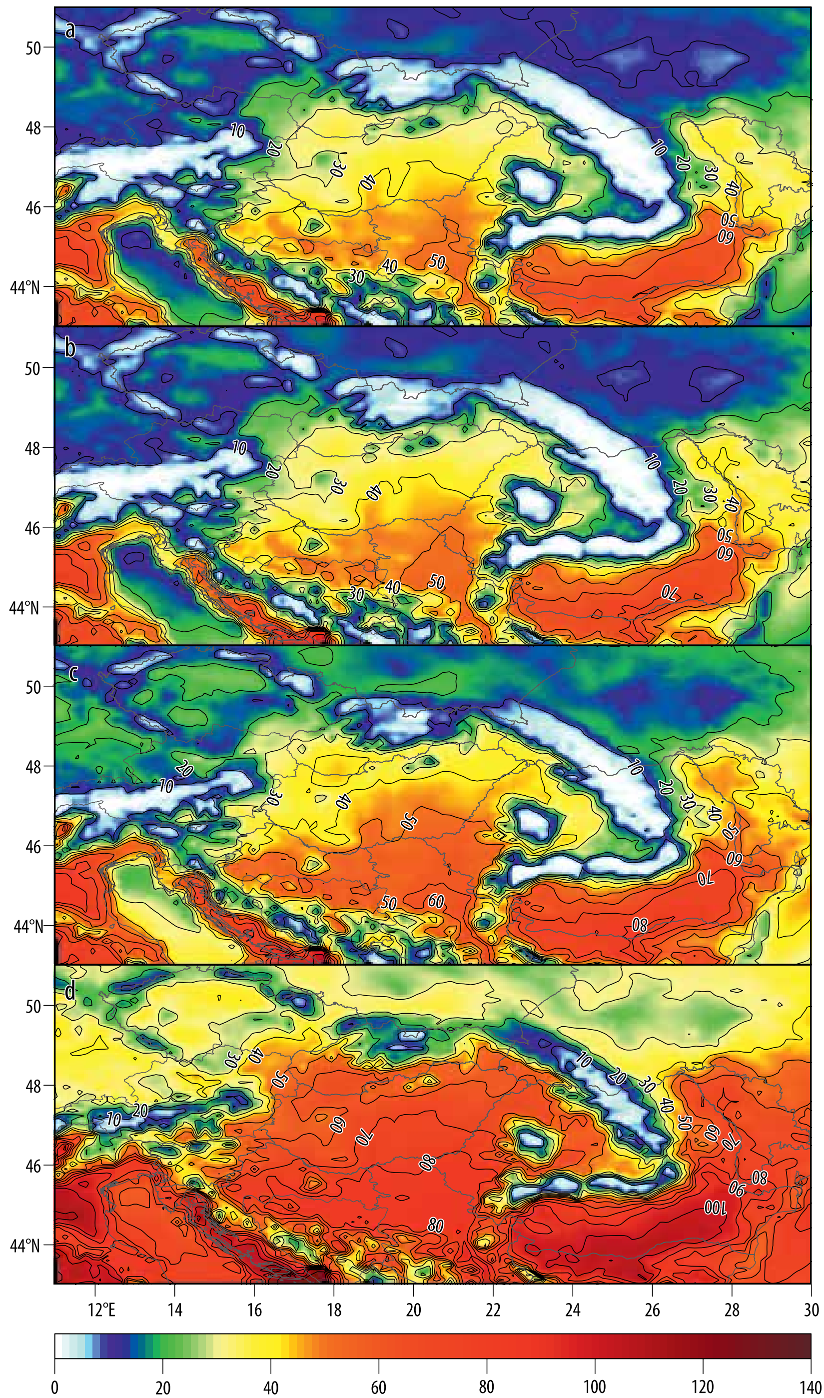

Fig. 7. Average number of hot days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

and higher altitudes in the north, however, it is between 10 and 20 in the lower parts of the northern areas *(Figure 7*, a and b*)*. In the largest area of the Carpathian Basin the *HD* is over 30 and in the southern part, 40 or even 50. In most of the Romanian Plain the values are over 60 and in a smaller area 70. On the shores of the Adriatic Sea *HD* is over 50–60. There are minimal differences between the scenarios; the values differ only in some smaller areas.

In the period 2071–2100, according to RCP4.5, the values exceed 20 in the northern part of the study area *(Figure 7*, c*)*. There can be fewer areas in the mountains where the values do not exceed 10. *HD* can be over 30 in the entire Carpathian Basin, 40 in most parts of it and 50–60 in the southern parts. In most parts of the Romanian Plain the values can exceed 70 and in a smaller area 80. On the Adriatic coast, *HD* can be 70–80.

Under scenario RCP8.5, the values can be over 30 in most parts of the northern areas and 10 or even 20 in the mountains in 2071–2100 *(Figure 7*, d*)*. *HD* can be over 50–60 in the entire Carpathian Basin, while 70–80 in the southern parts of it. Higher values can appear in the Romanian Plain and the Adriatic coast, since in these areas *HD* can exceed 90–100.

Measures of energy demand

Heating degree days

The heating degree days (*HDD*) in 2021–2050 will be between 2,000–3,000 in the northern parts of the study area *(Figure 8*, a and b*)*. In the mountains, the values will be higher than 3,000 and in most parts they exceed 4,000. In the northern Carpathian Basin *HDD* will be between 2,000 and 2,500 while in the southern parts under 2,000. In large parts of the Romanian Plain *HDD* will be between 1,500 and 2,000. The lowest values, under 1,500 *HDD*, will appear near to the Adriatic Sea. The differences between the scenarios are minimal.

In 2071–2100, according to RCP4.5, the *HDD* will not exceed 2,500 in the north, higher values will appear only in the mountains *(Figure 8*, c*)*. In some smaller northern areas, the *HDD* will not reach 2,000. While in the Carpathian Basin and the Romanian Plain the values will be between 1,500 and 2,000.

Under scenario RCP8.5, *HDD* will exceed 2,000 only in the mountains and in some higher areas in the Czech Republic and Ukraine *(Figure 8*, d*)*. In the Carpathian Basin and Romanian Plain the values will be between 1,000 and 1,500, as well as between 500 and 1,000 on the Adriatic coast.

Cooling degree days

The cooling degree days (*CDD*) in 2021–2050 will be under 100 in the mountains, and they exceed 100 in most and 200 in some minor northern areas *(Figure 9*, a and b*)*. In the Carpathian Basin *CDD* will be over 300 in north and 400–500 in the southern part. In almost the entire Romanian Plain the values will be over 500. The highest number of *CDD*, over 600–700 will appear on the coast of the Adriatic Sea. There are some minor differences between the scenarios, but they are not remarkable.

In 2071–2100, under scenario RCP4.5, the values will be higher than 200 in almost the entire northern part of the study area *(Figure 9*, c*)*. *CDD* will be under 100 only in the mountains. In almost the entire part of the Carpathian Basin *CDD* will be over 400–500 and 600–700 in the south. In the Romanian Plain, *CDD* will exceed 700–800 and 900–1,000 on the Adriatic coast.

According to scenario RCP8.5, *CDD* will be over 300–400 in 2071–2100 in the northern parts *(Figure 9*, d*)*. In the mountains, there are very few areas where the *CDD* will not reach 100. In almost the whole Carpathian Basin, *CDD* will exceed 700 and in the southern parts 800–1,000. In most parts of the Romanian Plain, the values will be over 1,000–1,200 and 1,400–1,600 on the coast of the Adriatic Sea.

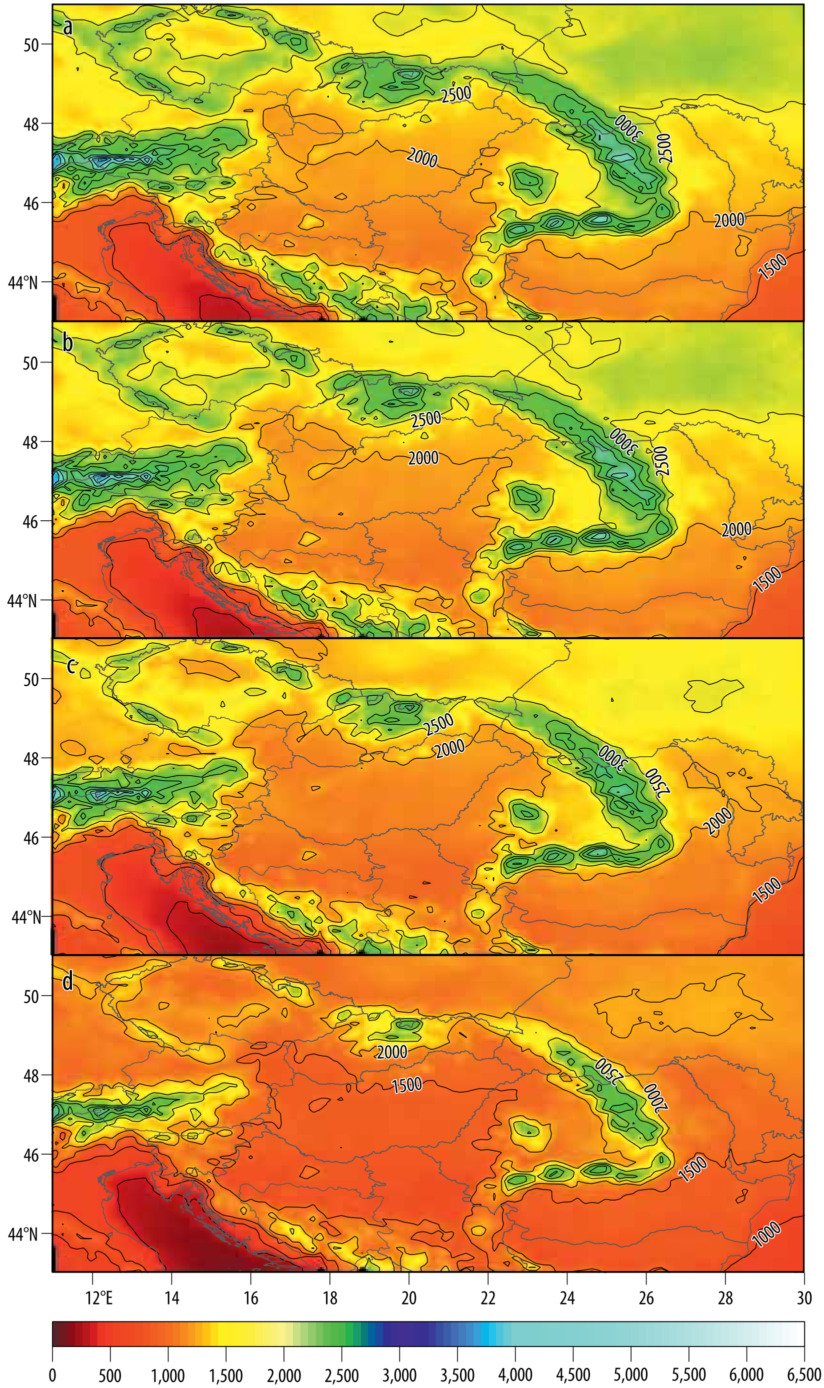

Fig. 8. Average heating degree days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

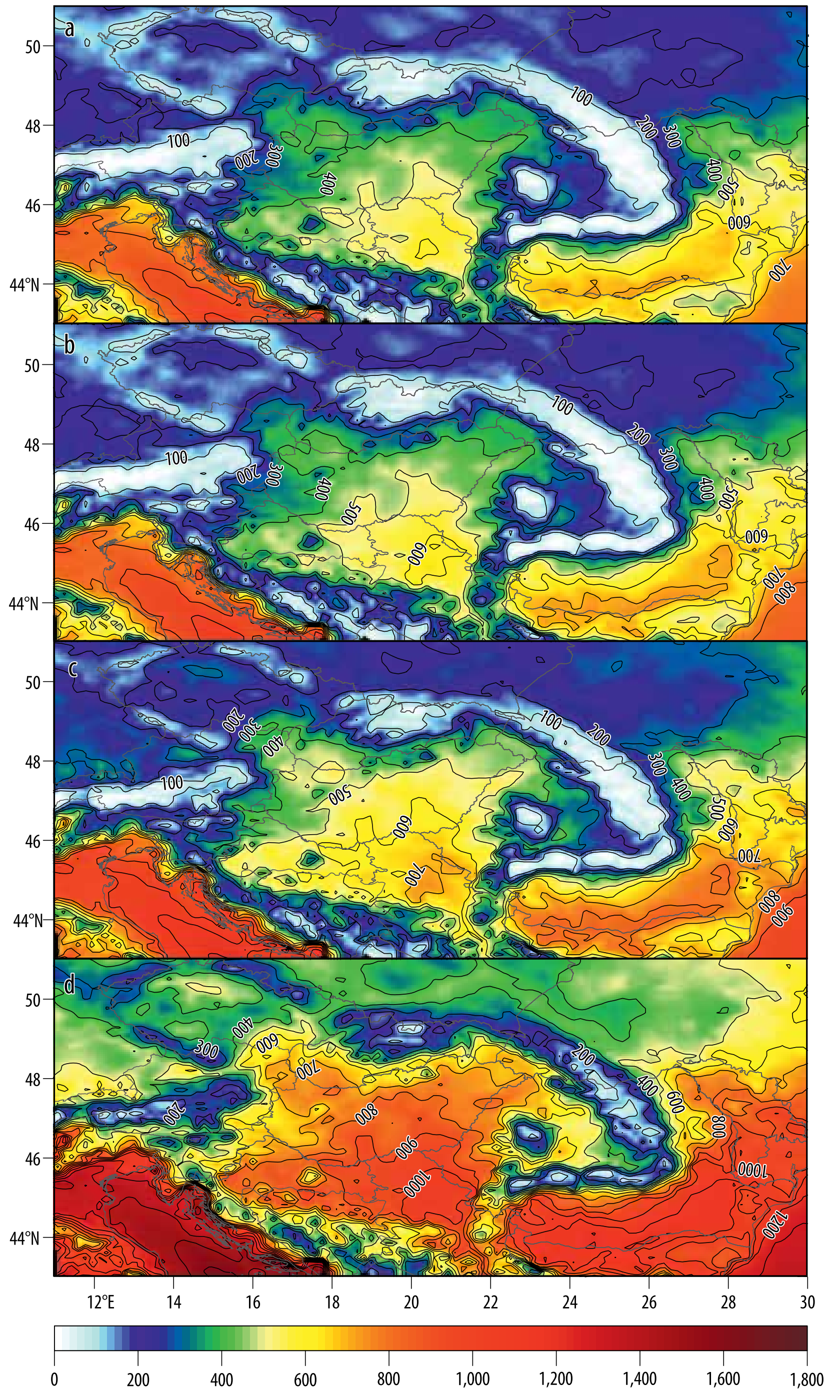

Fig. 9. Average cooling degree days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

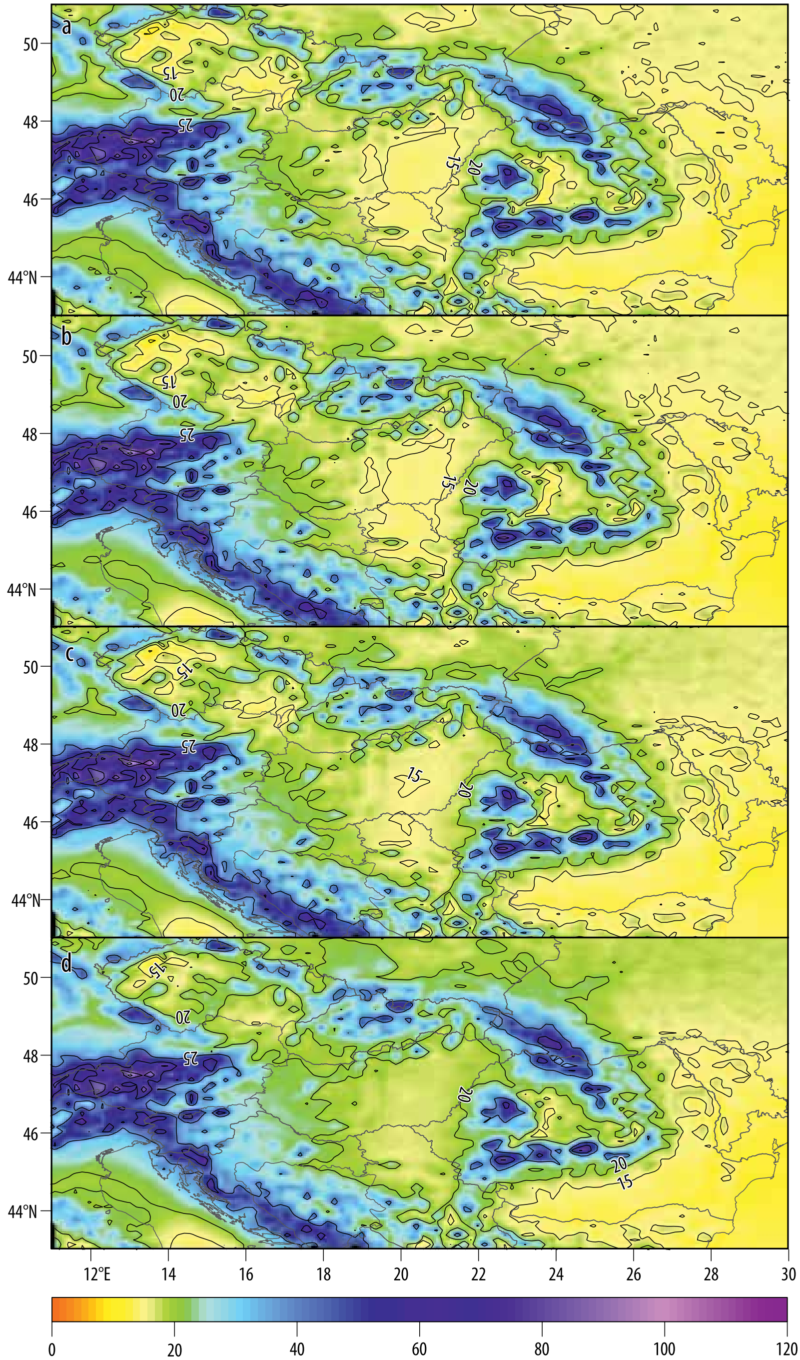

Fig. 10. Average number of heavy precipitation days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d). (The scale of the isolines is 5 and 20 under and above 20, respectively.)

Precipitation-based indices

Heavy precipitation days

The heavy precipitation days (*HPD*) in 2021–2050 will be under 20 in the Czech Republic, the northern and eastern part of the study area and in the Carpathian Basin *(Figure 10*, a and b*)*. In most of these areas, the values will be under 15, especially in the Carpathian Basin and Romanian Plain. Around the mountains, western and southern parts of the study area, *HPD* will be over 20–30. In the mountains, values are over 40 and in some smaller areas even 60–80. There is not relevant difference between the scenarios.

For the period of 2071–2100, *HPD* increase in especially lower lying regions. Under scenario RCP4.5, the size of the areas, where the value of *HPD* is under 15, decreases *(Figure 10*, c*)*. This process is the most remarkable in the Carpathian Basin, but it is also noticeable in the Czech Republic and in the northeast region. In these regions, *HPD* values above 20 will appear in some areas.

In case of scenario RCP8.5, the tendency is similar and larger changes will occur *(Figure 10*, d*)*. The affected areas are the same to the previous scenario. According to RCP8.5, *HPD* will be over 15 in the entire Carpathian Basin and 20 in its northern and western parts.

Very heavy precipitation days

In 2021–2050, the very heavy precipitation days (*VHPD*) will be under 5 in most parts of the study area, while values over five will appear around the mountains and south-eastern region *(Figure 11*, a and b*)*. In mountainous areas, the values will be above ten and in some parts, especially in the Alps, over 20–30. The difference between the scenarios are minimal.

For 2071–2100, the values increase and the number of *VHPD* exceed 5 in case of RCP4.5 in the west of the Carpathian Basin *(Figure 11*, c*)*. Under scenario RCP8.5, the change is more remarkable *(Figure 11*, d*)*. The affected areas are the northern and western parts of the Carpathian Basin, the areas north from the Carpathians and north-western part of the study area.

Consecutive dry days

The consecutive dry days (*CD*) in 2021–2050 will be under 40 in the north-western part of the study area and in the mountains *(Figure 12*, a and b*)*. In the Alps, *CD* will be under 30 in a larger area, while in most areas of the Carpathians and Dinaric Alps they will exceed 50. In almost the entire Carpathian Basin *CD* will be over 50 and 60 in some scattered areas, which are larger in the case of scenario RCP8.5 (see *Figure 12*, b). In the Romanian Plain, values will exceed 70 and in a smaller area 80, which are also larger under RCP8.5. On the Adriatic coast, the values will be over 50–60.

For 2071–2100, minor changes will occur compared to the previous period *(Figure 12*, c and d*)*. In the Carpathians, values higher than 40 and 50 will appear in several areas. In the Carpathian Basin, the *CD* will be over 60, especially in its eastern and southern parts. In the Romanian Plain, values over 80 will occur, particularly under scenario RCP8.5 (see *Figure 12*, d). In the case of this scenario, values over 60 will appear on the Adriatic coast.

Conclusions

In order to summarize our results, the range of the examined climatic parameters and indices are presented in the main regions of the study area *(Table 3)*. In the last part of the century the temperature increase is obvious, but the trend is difficult to evaluate in the case of precipitation. The heat load and energy demand quantifying indices follow the temperature trend. Examining the changes of precipitation and the related indices, the changes can be considered small, and these changes appear more within the regions. Noticeable changes will appear in the Carpathian Basin, where *P* will decrease, while *HPD*, *VHPD* and *CD* will increase.

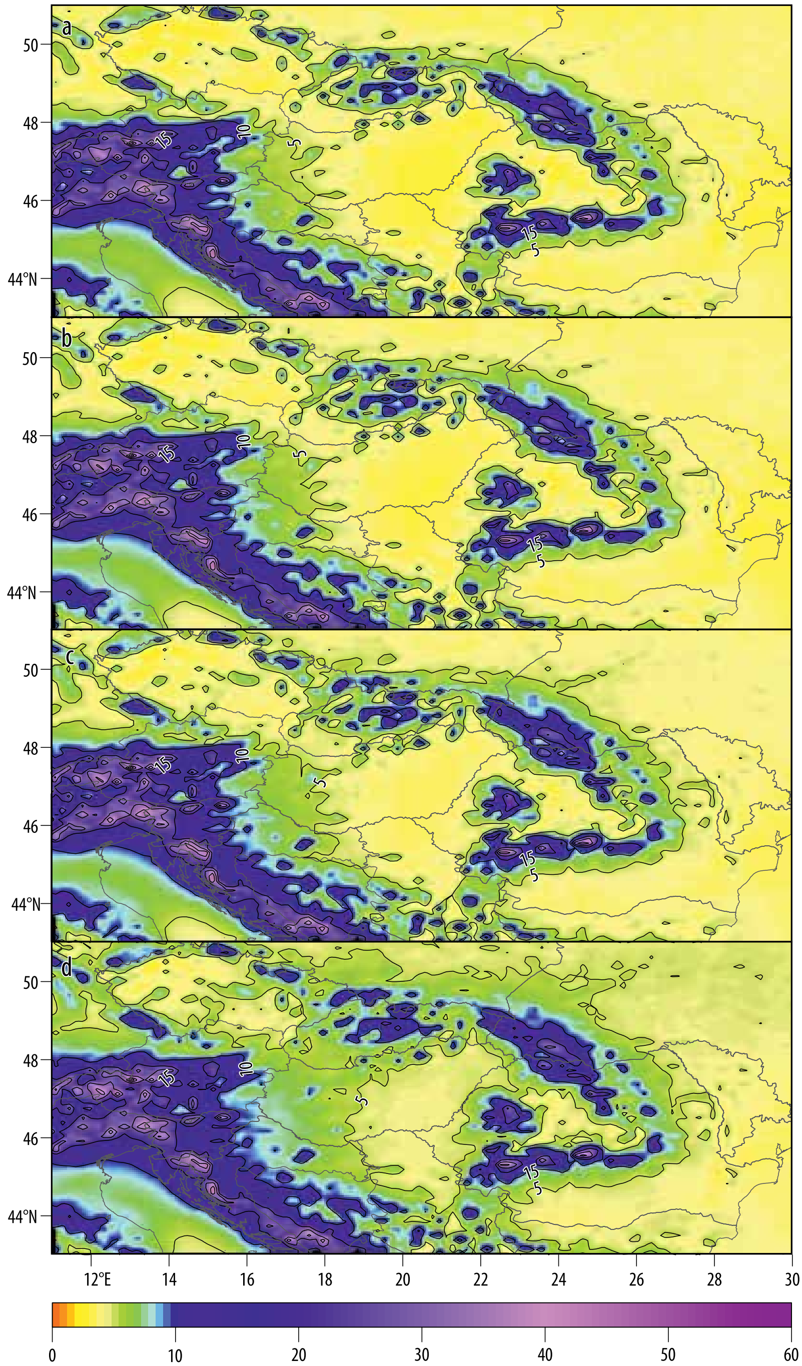

Fig. 11. Average number of very heavy precipitation days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d). (The scale of the isolines is 5 and 10 under and above 10, respectively.)

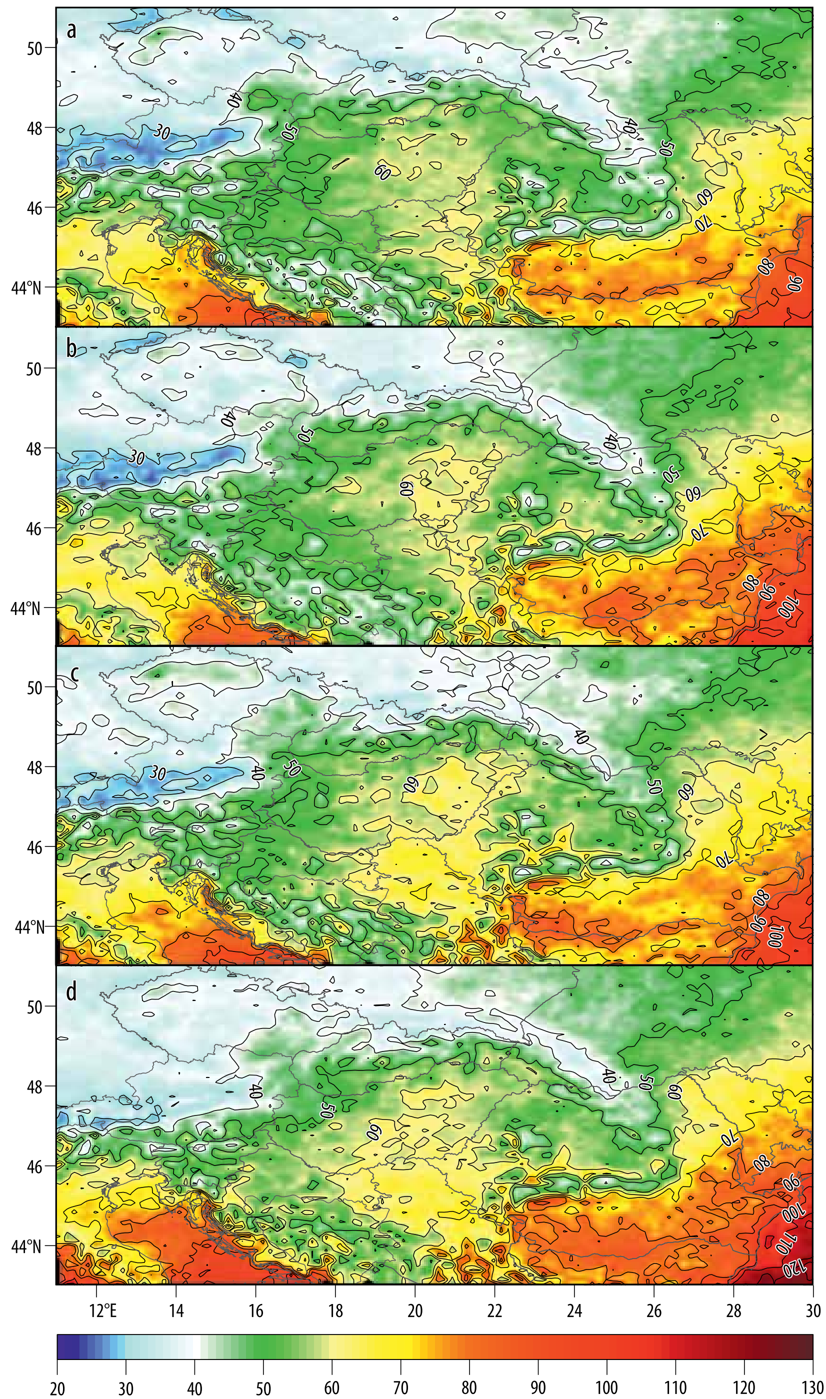

Fig. 12. Maximal number of consecutive dry days in 2021–2050 by RCP4.5 (a), in 2021–2050 by RCP8.5 (b), in 2071–2100 by RCP4.5 (c) and in 2071–2100 by RCP8.5 (d).

Table 3. *The range of the basic climatic parameters and indices in the main regions of the study area*

Index	Period, scenario	Region					
		Alps	Carpathians	Dinaric Alps	Carpathian Basin	Romanian Plain	Adriatic coast
T	21–50	2–8	4–10	6–10	10–14	10–14	12–18
	71–00, 4.5	0–10	6–10	8–12	12–16	12–16	16–20
	71–00, 8.5	4–12	6–12	8–14	14–18	14–18	18–22
P	21–50						
	71–00, 4.5	1,000–3,600	800–3,000	800–3,000	400–800	400–800	600–1,000
	71–00, 8.5						
WN	21–50	0–10	0–10	0–20	30–50	40–60	50–70
	71–00, 4.5	0–10	0–20	0–20	40–60	50–70	80–100
	71–00, 8.5	10–20	10–20	20–60	60–100	80–100	120–140
TN	21–50	0–5	0–5	0–5	5–15	10–20	30–40
	71–00, 4.5	0–5	0–5	0–5	10–25	15–30	40–60
	71–00, 8.5	0–10	0–10	10–20	30–50	30–60	80–100
SD	21–50	0–40	0–40	40–60	80–120	100–140	100–140
	71–00, 4.5	0–60	0–60	60–80	80–140	100–140	120–160
	71–00, 8.5	20–80	20–80	80–120	100–160	120–160	140–180
HD	21–50	0–10	0–10	0–20	20–60	40–80	40–90
	71–00, 4.5	0–20	0–20	0–30	30–70	60–90	60–90
	71–00, 8.5	0–30	0–30	30–50	50–90	80–110	80–120
HDD	21–50	3,500–6,500	3,000–5,000	2,500–4,000	2,000–2,500	2,000–2,500	1,000–2,000
	71–00, 4.5	3,000–5,500	2,500–4,500	2,000–3,000	1,500–2,000	1,500–2,000	1,000–1,500
	71–00, 8.5	2,000–4,000	2,000–3,500	1,500–2,500	1,000–1,500	1,000–1,500	500–1,000
CDD	21–50	0–100	0–100	0–300	300–700	400–800	700–1,000
	71–00, 4.5	0–200	0–200	100–300	400–800	600–900	800–1,100
	71–00, 8.5	100–400	100–400	200–500	600–1,000	900–1,200	1,000–1,300
HPD	21–50			40–80	0–20		
	71–00, 4.5	40–100	20–80	40–80	10–20	0–20	20–40
	71–00, 8.5			40–60	15–20		
VHPD	21–50		5–40	5–40			
	71–00, 4.5	10–60	5–50	5–50	0–10	0–10	5–20
	71–00, 8.5		5–50	5–50			
CD	21–50	20–40		30–50	50–70	70–90	50–70
	71–00, 4.5	20–40	30–60	40–50	50–80	70–90	50–70
	71–00, 8.5	30–40		60–60	50–80	70–100	60–80

It is important to mention that in case of precipitation there are no relevant changes in any region, however, based on the precipitation-related indices (*HPD*, *VHPD*, *CD*) the Dinaric Alps and the Carpathian Basin regions are facing considerable changes in the rest of the century (see *Table 3*). The highest temperature change occurs in the mountainous regions, especially in the Alps, however in case of temperature-related indices the spatial differences of the future change are more complex. In case of warm nights, tropical nights, summer days and hot days in the Carpathian Basin, Romanian Plain and Adriatic coast the changes are more severe. The trend in the heating degree days predict decreasing energy demand in all regions. In some areas in Carpathian Basin and Romanian Plain, as well as in almost the entire Adriatic coast, the energy demand for cooling will be more important than for heating.

Based on the results it is obvious that the entire region will face crucial changes in the following decades, therefore all the effort of climate mitigation and adaptation initiatives should be prioritized. These results may help to draw attention to these changes and hopefully it will help other climate change studies, climate strategies and climate adaptation plans.

Acknowledgements: The study was supported by the Hungarian Scientific Research Fund (OTKA K-137801, PD-143378) and by the Ministry of Human Capacities, Hungary grant 20391-3/2018/ FEKUSTRAT. The regional climate model simulations were provided by the EURO-CORDEX project.

REFERENCES

Baccini, M., Biggeri, A., Accetta, G., Kosatsky, T., Katsouyanni, K., Analitis, A., Anderson, H.R., Bisanti, L., D'Ippoliti, D., Danova, J., Forsberg, B., Medina, S., Paldy, A., Rabczenko, D., Schindler, C. and Michelozzi, P. 2008. Heat effects on mortality in 15 European cities. *Epidemiology* 19. 711–719. Doi: 10.1097/EDE.0b013e318176bfcd

Badora, D., Wawer, R., Nierobca, A., Krol-Badziak, A., Kozyra, J., Jurga, B. and Nowocien, E. 2022. Modelling the hydrology of an upland catchment of Bystra River in 2050 climate using RCP 4.5 and RCP 8.5 emission scenario forecasts. *Agriculture* 12. 403. Doi: 10.3390/agriculture12030403

Bartholy, J. and Pongrácz, R. 2018. A brief review of health-related issues occurring in urban areas related to global warming of 1.5 °C. *Current Opinion in Environmental Sustainability* 30. 123–132. Doi: 10.1016/j.cosust.2018.05.014

Bokwa, A., Dobrovolný, P., Gál, T., Geletič, J., Gulyás, Á., Hajto, M.J., Holec, J., Hollósi, B., Kielar, R., Lehnert, M., Skarbit, N., Šťastný, P., Švec, M., Unger, J., Walawender, J.P. and Žuvela-Aloise, M. 2018. Urban climate in Central European cities and global climate change. *Acta Climatologica* 51–52. 7–35. Doi: 10.14232/acta.clim.2018.52.1

Cartalis, C., Synodinou, A., Proedrou, M., Tsangrassoulis, A. and Santamouris, M. 2001. Modifications in energy demand in urban areas as a result of climate changes: An assessment for the southeast Mediterranean region. *Energy Conversion and Management* 42. 1647–1656. Doi: 10.1016/S0196-8904(00)00156-4

Chervenkov, H., Ivanov, V., Gadzhev, G., Ganev, K. and Melas, D. 2020. Degree-day climatology over Central and Southeast Europe for the period 1961–2018. Evaluation in high resolution. *Cybernetics and Information Technologies* 20. 166–174. Doi: 10.2478/cait-2020-0070

COACCH 2019. *The Economic Cost of Climate Change in Europe: Synthesis Report on Interim Results.* Policy brief by the COACCH project. Eds.: Watkiss, P., Troeltzsch, J., McGlade, K. and Watkiss, M., Rome, Fondazione CMCC. Available at https://www.coacch.eu/wp-content/uploads/2019/11/COACCH-Sector-Impact-Economic-Cost-Results-22-Nov-2019-Web.pdf

Coppola, E., Nogherotto, R., Ciarlo, J.M., Giorgi, F., van Meijgaard, E., Kadygrov, N. Iles, C., Corre, L., Sandstad, M., Somot, S., Nabat, P., Vautard, R., Levavasseur, G., Schwingshackl, C., Sillmann, J., Kjellström, E., Nikulin, G., Aalbers, E., Lenderink, G., Christensen, O.B., Boberg, F., Sorland, S.L., Demory, M.-E., Bülow, K., Teichmann, C., Warrach-Sagi, K. and Wulfmeyer, V. 2021. Assessment of the European climate projections as simulated by the large EUROCORDEX regional and global climate model ensemble. *Journal of Geophysical Research: Atmospheres* 126. Doi: 10.1029/2019JD032356

Dankers. R. and Hiederer, R. 2008. *Extreme Temperatures and Precipitation in Europe: Analysis of a High-Resolution Climate Change Scenario*. JRC Scientific and Technical Reports. European Commission. Available at https://publications.jrc.ec.europa.eu/repository/handle/JRC44124

Dalelane, C., Früh, B., Steger, C. and Walter, A. 2018. A pragmatic approach to build reduced regional climate projection ensembles for Germany using the EURO-CORDEX 8.5 ensemble. *Journal* *of Applied Meteorology and Climatology* 57. 477–491. Doi: 10.1175/JAMC-D-17-0141.1

Evin, G., Somot, S. and Hingray, B. 2021. Balanced estimate and uncertainty assessment of European climate change using the large EURO-CORDEX regional climate model ensemble. *Earth System Dynamics* 12. 1543–1569. Doi: 10.5194/esd-12-1543-2021

Gál, T., Skarbit, N., Molnár, G. and Unger, J. 2021. Projections of the urban and intra-urban scale thermal effects of climate change in the 21st century for cities in the Carpathian Basin. *Hungarian Geographical Bulletin* 70. (1): 19–33. Doi: 10.15201/hungeobull.70.1.2

Golombek, R., Kittelsen, S.A. and Haddeland, I. 2012. Climate change: impacts on electricity markets in Western Europe. *Climatic Change* 113. Doi: 10.1007/s10584-011-0348-6

IPCC 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Eds.: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. Cambridge UK and New York, Cambridge University Press. Available at https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf

IPCC 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Eds.: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B., Cambridge UK and New York, Cambridge University Press. Available at https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. and Yiou, P. 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change* 14. 563–578. Doi: 10.1007/s10113-013-0499-2

Kis, A., Pongrácz, R., Bartholy, J., Gocic, M., Milanovic, M. and Trajkovic, S. 2020. Multi-scenario and multi-model ensemble of regional climate change projections for the plain areas of the Pannonian Basin. *Időjárás / Quarterly Journal of the Hungarian Meteorological Service* 124. 157–190. Doi: 10.28974/idojaras.2020.2.2

Kovats, R.S. and Hajat, S. 2008. Heat stress and public health: A critical review. *Annual Review Public Health* 29. 41–55. Doi: 10.1146/annurev.publhealth.29.020907.090843

Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F. 2014. Europe. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Eds.: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L., Cambridge UK and New York, Cambridge University Press, 1267–1326. Doi: 10.1017/CBO9781107415386.003

Lindberg, F., Grimmond, C.S.B., Yogeswaran, N., Kotthaus, S. and Allen, L. 2013. Impact of city changes and weather on anthropogenic heat flux in Europe 1995–2015. *Urban Climate* 4. 1–15. Doi: 10.1016/j.uclim.2013.03.002

Matzarakis, A. and Thomsen, F. 2009. Heating and cooling degree days as an indicator of climate change in Freiburg. In *89th American Meteorological Society Annual Meeting: Fourth Symposium on Policy and Socio-Economic Research.* Phoenix, 339–344. Available at https://www.urbanclimate.net/matzarakis/papers/BMIUF_18_2009_Thomsen_Matzarakis.pdf

McGregor, G.R., Bessemoulin, P., Ebi, K. and Menne, B. (eds.) 2015. *Heatwaves and Health: Guidance on Warning-System Development.* WMO-No. 1142. Geneva, World Meteorological Organization – World Health Organization. Available at https://library.wmo.int/doc_num.php?explnum_id=3371

Meehl, G.A. and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305. 994–997. Available at http://dx.doi.org/10.1126/science.1098704

Moreci, E., Ciulla, G. and Brano, V.L. 2016. Annual heating energy requirements of office buildings in a European climate. *Sustainable Cities and Society* 20. 81–95. Available at https://doi.org/10.1016/j.scs.2015.10.005

Olefs, M., Formayer, H., Gobiet, A., Marke, T., Schöner, W. and Revesz, M. 2021. Past and future changes of the Austrian climate – Importance for tourism. *Journal of Outdoor Recreation and Tourism* 34. Doi: 10.1016/j.jort.2021.100395

Pieczka, I., Pongrácz, R., Bartholy, J. and Szabóné André, K. 2018. Future temperature projections for Hungary based on RegCM4.3 simulations using new Representative Concentration Pathways scenarios. *International Journal of Global Warming* 15. 277–292. Available at https://doi.org/10.1504/IJGW.2018.093121

Pongrácz, R., Bartholy, J. and Bartha, E.B. 2013. Analysis of projected changes in the occurrence of heat waves in Hungary. *Advances in Geosciences* 35. 115–122. Available at https://doi.org/10.5194/adgeo-35-115-2013

Rajczak, J. and Schär, C. 2017. Projections of future precipitation extremes over Europe: A multi-model assessment of climate simulations. *Journal of Geophysical Research: Atmospheres* 122. Doi: 10.1002/2017JD027176

Sillmann, J. and Roecker, E. 2008. Indices for extreme events in projections of anthropogenic climate change. *Climate Change* 86. 83–104. Doi: 10.1007/s10584-007-9308-6

Skarbit, N. and Gál, T. 2016. Projection of intra-urban modification of nighttime climate indices during the 21st century. *Hungarian Geographical Bulletin* 65. (2): 181–193. Doi: 10.15201/hungeobull.65.2.8

Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P. and Dosio, A. 2018. Will drought events become more frequent and severe in Europe? *International Journal of Climatology* 38. 1718–1736. Doi: 10.1002/joc.5291

Štěpánek, P., Zahradníček, P., Farda, A., Skalák, P., Trnka, M., Meitner, J. and Rajdl, K. 2016. Projection of drought-inducing climate conditions in the Czech Republic according to Euro-CORDEX models. *Climate Research* 70. 179–193. Doi: 10.3354/cr01424

Torma, C.Z. and Kis, A. 2022. Bias-adjustment of high-resolution temperature CORDEX data over the Carpathian region: Expected changes including the number of summer and frost days. *International Journal of Climatology* 2022. 1–16. Doi: 10.1002/joc.7654

Vuković, A. and Mandić, M.V. 2018. *Study on Climate Change in the Western Balkans Region.* Sarajevo, Bosnia and Herzegovina, Regional Cooperation Council Secretariat.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. 2011. The representative concentration pathways: an overview. *Climatic Change* 109. 5–31. Doi: 10.1007/s10584-011-0148-z

Von Trentini, F., Leduc, M. and Ludwig, R. 2019. Assessing natural variability in RCM signals: comparison of a multi model EURO-CORDEX ensemble with a 50-member single model large ensemble. *Climate Dynamics* 53. 1963–1979. Available at https://link.springer.com/article/10.1007/s00382-019-04755-8

Web source: Elevation map of Europe. Available at https://www.eea.europa.eu/data-and-maps/figures/elevation-map-of-europe