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RESEARCH ARTICLE

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Temperature characteristics over the Carpathian Basin-projected changes of climate indices at regional and local scale based on bias-adjusted CORDEX simulations

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Abstract

The present research focuses on temperature change signals over the Carpathian Basin with a special focus on selected lowland and mountainous subregions. High-resolution (0.11°) EURO- and Med-CORDEX regional climate model (RCM) simulations of near-surface air temperature are analysed based on raw and bias-adjusted data. The mini-ensemble consists of eight RCM simulations driven by five different general circulation models for the period 1976–2099 under the high-end RCP8.5 scenario. The high-resolution, homogenized and quality controlled CARPATCLIM was used as a reference dataset. The selected subregions cover eight municipalities located at diverse altitudes: Bratislava, Budapest, Brassov, Debrecen, Hoverla, Novi Sad, Pécs and Poprad. The following climate indices are assessed: summer days, ice days, frost days, tropical nights, the coldest day, the warmest day, the coldest night and the warmest night. In general, for the reference period (1976–2005) bias-adjusted RCM data showed almost perfect match with observations. Accordingly, no best performing RCM is found for all indices. The ensemble mean of the bias-adjusted RCM simulations projects an increase (decrease) of 32% and 112% (18% and 25%) in the annual number of summer days and tropical nights (frost days and ice days) for the period 2021–2050. For 2070–2099 we can expect more frequent tropical nights (about five times) with respect to the reference period and the frequency of frost days can be halved. Profound warming manifests in the increase of the warmest temperature of day of up to 2–3°C by the near future and of 5–7°C by the end of the 21st century, which means the absolute maximum temperature can reach 44–47°C for the period 2070–2099. Our results also highlight the need for bias-adjusted data adapted by different sectors (human health, agriculture, transport, disaster management, heritage conservation) under the national adaptation strategies.

KEYWORDS
CARPATCLIM, Carpathian Basin, climate change, EURO-CORDEX, Med-CORDEX, temperature-based climate indices

1 | INTRODUCTION

One of the greatest challenges we face today is climate change, which means not only higher mean temperatures, but also associated with changes in the intensity and frequency of extreme weather events—according to the IPCC (2021), these extreme events are expected to become more frequent in the future. Global and regional climate models (GCMs and RCMs, respectively) are key tools for climate research and for providing information on climate change (IPCC, 2013), but it is important to keep in mind that model simulations are subject to uncertainties from a variety of sources. The main sources of these uncertainties are the internal variability of climate, the greenhouse gas emission scenarios, the model dynamics, the different parametrization procedures and the systematic errors of model simulations (Giorgi, 2005). GCMs have a coarser horizontal resolution of 100–500 km and therefore cannot describe extremes in detail and resolve the different land forms that occur at regional scales. RCMs are used to downscale the GCM simulations, but they are applied to a selected limited area only, however, with a higher horizontal resolution (10–50 km); therefore, smaller-scale processes can be described which are not possible at the coarser resolution of GCMs (Farda et al., 2010). Many studies have already demonstrated the added value of regional projections, especially in regions with complex topography, such as mountainous and coastal areas (Ciarlo et al., 2021; Fantini et al., 2018; Rummukainen, 2016; Torma et al., 2015) and for extreme precipitation events and local wind systems (Evin et al., 2021). In addition, for RCM simulations, the model uncertainty combines the uncertainties of the driving GCM and the uncertainty of the RCM. Existing uncertainties can be quantified and reduced by evaluating the RCMs together, as members of an ensemble (Beniston et al., 2007).

CORDEX (COordinated Regional Downscaling EXperiment; Giorgi et al., 2009) is an ongoing initiative that provides a large number of RCM simulations for several domains of the world. EURO-CORDEX (Jacob et al., 2014) and Med-CORDEX (Ruti et al., 2016) are subprogrammes for the European branches of CORDEX, which provide regional climate projections at a horizontal grid resolution of 0.11° (about 12 km) and 0.44° (about 50 km) using the latest versions of RCMs and their driving GCMs—complementing the already established international projects such as PRUDENCE (Christensen & Christensen, 2007), ENSEMBLES (Hewitt & Griggs, 2004) or CECILIA (Halenka, 2007). However, it is important to take into account that RCM simulations are characterized by variable dependent biases compared to observations due to systematic errors. RCM simulations are prone to errors despite extensive testing and tuning (Giorgi, 2019); thus, the use of raw outputs can lead to unrealistic results and hinder their direct use. This can be eliminated by bias-correction procedures, which requires a reference dataset (preferably observation-based) of good quality. Many bias-correction methods have been developed (see, e.g., Casanueva et al., 2020; Räty et al., 2014) to overcome or reduce the large biases and adjust simulations to the present climate. According to previous studies bias-adjustment is required to improve RCM simulations (Fang et al., 2015; Halmstad et al., 2012; Ngai et al., 2016). It may be particularly important when climate model outputs are used for impact studies; however, bias-correction itself contributes to the overall uncertainty (e.g., Teutschbein & Siebert, 2012).

Previous studies have also looked at climate change signals in the Carpathian Region, and their results show that the annual mean temperature could increase by 1–4°C on a spatial average by the end of the 21st century (Dumitrescu et al., 2022; Probst & Mauer, 2023). Average values of annual frequency of climate indices related to maximum temperature are expected to increase in the future, however, cold extreme indices indicate lower values—the results indicate a warming in the region of interest. In the period 2071–2100, the annual number of summer days may reach 60 in the northern part, and more than 100 can occur in the southern part of the Carpathian Basin. The warmest day temperature is expected to increase by 3–5°C (Ciupertea et al., 2017; Skarbit et al., 2022).

The aim of this study is to provide information on temperature change signals over the Carpathian Region, with a special focus on selected subregions of different longitude and latitude and characterized by different geographical characteristics. We also aimed to demonstrate the role of complex topography in temperature change signals by selecting and analysing subregions within the Carpathian Basin. In previous work, the performance of nine RCMs at grid spacings of 0.44° and 0.11° (from the framework of the EURO-CORDEX and Med-CORDEX initiatives) driven by ERA-Interim (Dee et al., 2011;

perfect boundary conditions approach) was evaluated and reported in the work of Torma (2019). It should be noted that such simulations (driven by ERA-Interim) are not intended to assess climate change (as these simulations are integrated for the recent past, which is covered by observations), but for evaluation purposes. Based on the results reported for the period 1989–2008 in the work of Torma (2019), eight RCMs with a grid spacing of 0.11° were selected for further evaluation and bias adjustment of daily precipitation and temperature data derived from GCM-driven simulations. First, the bias-adjusted precipitation dataset was introduced (Torma et al., 2020), followed by the bias-adjusted temperature dataset obtained from the same GCM-driven RCM simulations (Torma & Kis, 2022). Present research is based on EURO-CORDEX and Med-CORDEX RCM projections for the future periods 2021–2050 and 2070–2099 with respect to the reference period 1976–2005. Both raw and bias-corrected RCM simulations are analysed. We used the bias-corrected RCM dataset documented in the work of Torma and Kis (2022), for which the CARPATCLIM database (Szalai et al., 2013) served as a reference dataset during the percentile-based quantile mapping method (Mezghani et al., 2017) as the bias-correction procedure. In summary, the aim of the present study is twofold. On the one hand, to report on the overall performance of the selected eight RCMs over the reference period (1976–2005) in representing temperature-based climate indices (threshold and absolute) characteristics at the regional scale (Carpathian Basin). On the other hand, to provide information on the expected changes during the 21st century (2021–2050 and 2070–2099, with respect to the reference period) in temperature-based climate indices from regional to local scales based on bias-corrected RCM data and to reveal possible orographic dependencies.

In section 2, the area of interest is presented first, followed by an introduction to the observational reference dataset, the selected RCM simulations and the chosen climate indices are introduced. Section 3 presents the evaluation results of the historical RCM simulations reproducing climate of the reference period 1976–2005. Then, section 4 presents the projected changes of the temperature-based climate indices over the Carpathian Region followed by a short summary and final considerations in section 5.

2 | DATA AND METHOD

2.1 | Study area: Selected cities

The region of interest, the Carpathian Basin is a region embraced by mountains and located in eastern-central Europe, between latitudes 44°N and 50°N, and longitudes 17°E and 27°E covering an area of about 500,000 km^2. The Carpathians and its surrounded territory together form the whole Carpathian Basin. Hence, it has a complex topography: the elevation lies between 75 m (which can be found in the Great Plain) and 2655 m (called Gerlachov Peak located in the northern Carpathians) above sea level (Figure 1). Note that the highest peak of the region is located in the northern flank of the Carpathians, but average altitude is greater in the southern Carpathians. The climate of the Carpathian Basin is influenced by continental, oceanic and Mediterranean effects, in addition, the weather and climate of the region is strongly governed by the mountain range: it has an influence on cloud formation and precipitation events through orographic effect and blocks cold air masses of Siberian origin. Based on the complex topography and various climatic effects, changes in the mean temperature characteristics are investigated not only for the entire region, but also for eight subregions with different orography and average altitude above sea level. Details of these subregions are listed in Table 1. During the selection, our aim was to choose lowland and mountainous areas as well from different latitudes and longitudes to cover the region of interest. Furthermore, one subregion was chosen from the region of the northern Carpathians, one from the eastern Carpathians and one from the southern Carpathians. Note that even though the chosen subregions are named after cities located in the given region, the urban effect is not investigated in this study.

2.2 | Reference dataset

CARPATCLIM is used in this study as a reference dataset for evaluation studies and for bias correction which is available for the following 50 years: 1961–2010. Data are available on a daily basis, and freely accessible via http://www.carpatclim-eu.org. It covers the Carpathians and the whole Carpathian Basin at 0.1° × 0.1° horizontal grid spacing between latitudes 44°N and 50°N, and longitudes 17°E and 27°E (Szalai et al., 2013). Fifty-three variables, related derived indicators and indices are accessible, including minimum air temperature, maximum air temperature, mean air temperature and precipitation. This is a station-based, homogenized and quality-controlled database, which is provided by the Multiple Analysis of Series for Homogenized Database (MASH; Szentimrey, 2007) software. The method of Meteorological Interpolation based on Surface Homogenized Database (MISH; Szentimrey & Bihari, 2007) is used for gridding and interpolating the meteorological data.

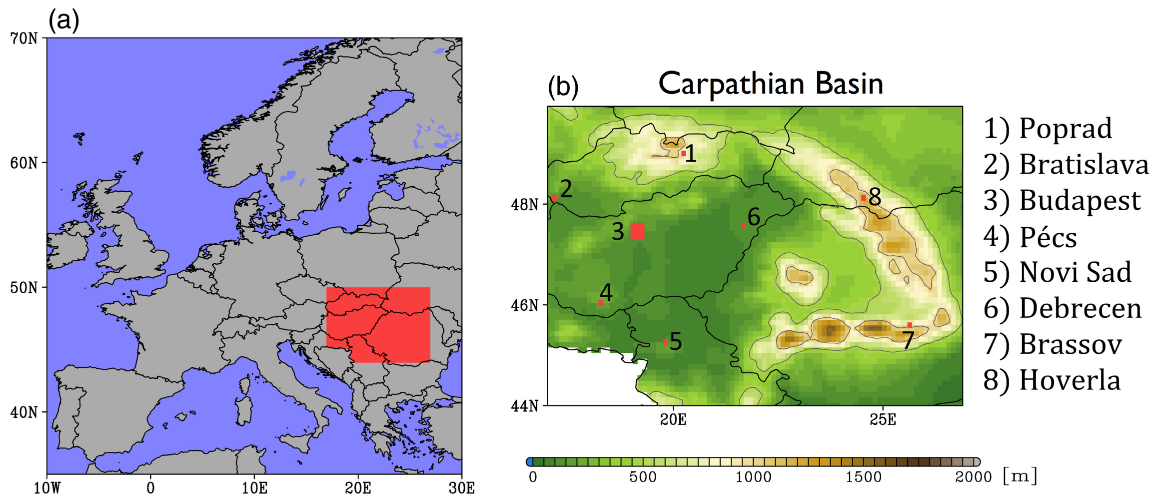

FIGURE 1 The region of interest. (a) Location of the Carpathian Basin in Europe (marked with a box). (b) The topography of the analysed area on a 0.11° × 0.11° horizontal grid. Subregions are shown by small boxes. Unit is given in meter [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary of the subregions investigated in this study

Name of subregion	Longitude; latitude (number of grid points)	Interval of height above sea level (multimodel average)
Budapest	18.98°–19.31°E; 47.3°–47.63°N (4 × 4)	85–338 m (150 m)
Brassov	25.58°–25.69°E; 45.54°–45.65°N (2 × 2)	603–1154 m (894 m)
Debrecen	21.62°–21.73°E; 47.52°–47.63°N (2 × 2)	119–148 m (129 m)
Hoverla	24.48°–24.59°E; 48.07°–48.18°N (2 × 2)	967–1422 m (1131 m)
Pécs	18.21°–18.32°E; 45.98°–46.09°N (2 × 2)	161–277 m (189 m)
Poprad	20.19°–20.3°E; 48.95°–49.06°N (2 × 2)	663–1190 m (898 m)
Bratislava	17.11°–17.22°E; 48.07°–48.18°N (2 × 2)	122–210 m (160 m)
Novi Sad	19.75°–19.86°E; 45.21°–45.32°N (2 × 2)	85–191 m (138 m)

Note: In the last column an interval of altitude is shown covered by the grid points for each subregion based on the GTOPO30 database. The altitude of the multimodel average for the subregions can be seen in parenthesis.

2.3 | Model simulations

Eight RCMs are investigated in this study from the framework of CORDEX—two of them are provided by the subprogram of Med-CORDEX (ALADIN and RegCM) and six by EURO-CORDEX (CCLM, HIRHAM, RACMO, RCA, REMO, WRF), both consist simulations at a horizontal grid resolution of 0.11° (~12.5 km). The evaluation of these models over the Carpathian Basin are provided in detail in the works of Torma (2019), Torma et al. (2020) and Torma and Kis (2022). Table 2 contains the details about RCMs and their driving global models used in this study. All simulations follow the GHGs-forcing scenario RCP8.5 (Moss et al., 2010) and cover the period 1976–2099. Three time slices were chosen as follows: 1976–2005 representing the recent past and served as a reference period, and two time slices representing the near and the far future: 2021–2050 and 2070–2099, respectively. Two variables were used for this work: daily minimum- and daily maximum near-surface air temperature. Our study focuses on projections for the future periods (based on raw and bias-corrected data) with respect to the 1976–2005 reference period. Since CARPATCLIM is available on a different horizontal grid (0.1°) than the RCMs, all data were interpolated onto a common 0.11° × 0.11° grid. The method of nearest neighbour remapping was used for interpolating data to the same horizontal grid, which process was carried out with the help of CDO (Climate Data Operators; https://code.mpimet.mpg.de/projects/cdo/) software. Following the previous work focusing on the same region of interest (Torma & Kis, 2022), percentile-based quantile mapping method (Mezghani et al., 2017) was applied to achieve bias-correction of the RCM data.

TABLE 2 Overview of the applied regional climate models and their driving global climate models

RCM	Driving GCM	Modelling group
ALADIN52 (Colin et al., 2010)	CNRM-CM5 (Voldoire et al., 2012)	Centre National de Recherches Meteorologiques, France
CCLM4-8-17 (Rockel et al., 2008)	MPI-M-MPI-ESM-LR (Jungclaus et al., 2010)	Climate Limited-area Modelling Community, Germany
HIRHAM5 (Christensen et al., 1998)	ICHEC-EC-EARTH (Hazeleger et al., 2010)	Danish Meteorological Institute, Denmark
RACMO22E (van Meijgaard et al., 2012)	ICHEC-EC-EARTH (Hazeleger et al., 2010)	Royal Netherlands Meteorological Institute, The Netherlands
RCA4 (Kupiainen et al., 2014)	MOHC-HadGEM2-ES (Collins et al., 2011)	Swedish Meteorological and Hydrological Institute, Rossby Centre, Sweden
RegCM4-3 (Giorgi et al., 2012)	MOHC-HadGEM2-ES (Collins et al., 2011)	International Centre for Theoretical Physics, Italy
REMO2009 (Jacob et al., 2012)	MPI-M-MPI-ESM-LR (Jungclaus et al., 2010)	Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology, Germany
WRF331F (Skamarock et al., 2008)	IPSL-IPSL-CM5A-MR (Dufresne et al. 2013)	Institut Pierre Simon Laplace and Institut National de l' Environnement industriel et des RISques, France

2.4 | Selected climate indices

A total of eight temperature-based climate indices were selected and analysed over the region of our interest which can be separated into two categories: (1) threshold indices, which count the number of days when a given temperature threshold is exceeded; these are summer days (SU), frost days (FD), ice days (ID) and tropical nights (TR); (2) absolute indices, which means the lowest or highest temperature of the year; such as the warmest day (TXx), the warmest night (TNx), the coldest day (TXn) and the coldest night (TNn). The set of the indices used in our study is summarized in Table 3.

3 | EVALUATION OF RCMS

First of all, we investigated how well the raw and bias-adjusted ensemble-mean of historical RCM simulations reproduce climate in the reference period 1976–2005 compared to CARPATCLIM, when all datasets interpolated onto the same 0.11° grid. The results for threshold and absolute indices applied to the entire Carpathian Basin are reported first, followed by the results for the selected subregions.

Figure 2 shows the spatial distribution of the annual number of summer days, ice days, frost days and tropical nights averaged over the reference period of 1976–2005. The multimodel ensemble mean of the bias-adjusted simulations is almost identical to CARPATCLIM for each climate index. The annual frequency of SU is the highest (80–100 days) in the central region of the domain, in the lowland areas (raw ensemble mean underestimated this by about 20 days). The number of ID is relatively homogeneous in the above-mentioned central parts of the Carpathian Basin (20–30 days per year), but in the Carpathians it reached 80–120 days. Spatial distribution of FD is similar to the previous ones, consistent with topography: 50–90 days occurred in the Great Plain, 100–120 days were detected in mid-mountains, while on the highest peaks this value reached 200 days or more. The annual number of TR was strongly overestimated by raw model simulations, especially over the Hungarian Great Plain and over the southern slopes of the Carpathians, while it was better reproduced by the bias-adjusted RCM simulations. Over areas characterized by relatively low altitudes of the region 2–8 tropical nights occurred per year, but in the mountain range no tropical nights were detected during the period of 1976–2005.

If we turn our attention to the absolute climate indices and their spatial distribution (Figure 3), it can be seen that raw outputs of RCM simulations overestimated especially TXx and TNx in the central part of the region of up to about 1–4°C. In the case of TNn overestimation with 1–3°C is also observed in the aforementioned area. In the Carpathians TNn and TXn are strongly (by 2–6°C) underestimated by the raw RCM simulations. After the bias-correction procedure, the multimodel ensemble mean performed better for TNx and TXn with negligible differences compared to CARPATCLIM (especially in the

TABLE 3 Set of the temperature-based climate indices used in this study

Label	Index name	Index category	Index description	Unit
SU	Summer days	Threshold	Let TX be the daily maximum temperature on day *i* in period *j*. Count the number of days where $TX_{ij} > 25°C$	days
ID	Ice days	Threshold	Let TX be the daily maximum temperature on day *i* in period *j*. Count the number of days where $TX_{ij} < 0°C$	days
FD	Frost days	Threshold	Let TN be the daily minimum temperature on day *i* in period *j*. Count the number of days where $TN_{ij} < 0°C$	days
TR	Tropical nights	Threshold	Let TN be the daily minimum temperature on day *i* in period *j*. Count the number of days where $TN_{ij} > 20°C$	days
TXn	The coldest day	Absolute	Let TXn be the daily maximum temperature in month *k*, period *j*. The minimum daily maximum temperature each month is then: $TXn_{kj} = \min(TXn_{kj})$	°C
TXx	The warmest day	Absolute	Let TXx be the daily maximum temperature in month *k*, period *j*. The maximum daily maximum temperature each month is then: $TXx_{kj} = \max(TXx_{kj})$	°C
TNn	The coldest night	Absolute	Let TNn be the daily minimum temperature in month k, period j. The minimum daily minimum temperature each month is then: $TNn_{kj} = \min(TNn_{kj})$	°C
TNx	The warmest night	Absolute	Let TNx be the daily minimum temperature in month *k*, period *j*. The maximum daily minimum temperature each month is then: $TNx_{kj} = \max(TNx_{kj})$	°C

mountainous regions). In addition, overestimation of up to 1–2°C for TXx in the central part of the Carpathian Basin, and for TNn in the Carpathians is also present in the bias-corrected RCM ensemble.

Figure 4 reports the simulated climate indices based on the individual RCMs without and with bias correction for the eight subregions in comparison with the CARPATCLIM database. Threshold indices were analysed first. In general, we cannot highlight any model, which performed best for all indices, so we analysed them individually. The bias for most of the RCMs was the greatest in the case of FD, which was substantially underestimated by 22–70 days by CCLM and REMO, and overestimation was the most pronounced by RACMO and ALADIN with absolute bias of up to 30–60 days. For TR the performance of the models was the best at higher altitudes (Brassov, Poprad, Hoverla). In subregions with lower average elevation WRF and RegCM substantially overestimated the annual frequency of TR. Turning our attention to ID, RCMs performed better at lowlands such as Budapest, Debrecen, Bratislava and Novi Sad with a bias of less than ±10 days. In the case of SU, both underestimation (ALADIN, HIRHAM, RACMO, CCLM) and overestimation (RCA, REMO) occurred for raw RCM simulations.

In terms of absolute indices related to the minimum (TNn, TXn), bias of the raw RCM simulations is greater (±12°C), but those which refer to the maximum (TXx, TNx), bias is half as high. Taking into account every model, TXn is underestimated the most by WRF, while TNn is overestimated the most (underestimated) by CCLM (REMO). For TXx and TNx the RACMO model performed best at low altitudes (Budapest, Debrecen, Novi Sad, Pécs), where the bias varied between 0.1 and 0.5°C, but in case of higher latitudes, such as Brassov, Poprad and Hoverla, RCA showed better results with +(0.3–0.9) °C of bias. Considering absolute indices related to the maximum, the greatest differences compared to the CARPATCLIM occurred for the RegCM model with an overestimation of 2–6°C. The bias of the annual absolute minimum temperature (TNn) was mostly pronounced by CCLM and REMO models especially at high latitudes, but these RCMs performed among the most accurate for TXn. WRF produced substantial underestimations by 2–10°C for both TNn and TXn.

After bias-adjustment, negligible differences remained between the RCM simulations and the CARPATCLIM reference dataset. One exception can be seen in the case of Brassov, where the bias-corrected RCM simulations underestimated the annual number of FD by about 20 days.

4 | FUTURE PROJECTIONS FOR 2021–2050 AND 2070–2099 WITH RESPECT TO 1976–2005

After evaluating the raw and bias-adjusted historical RCM simulations for the reference period 1976–2005, in

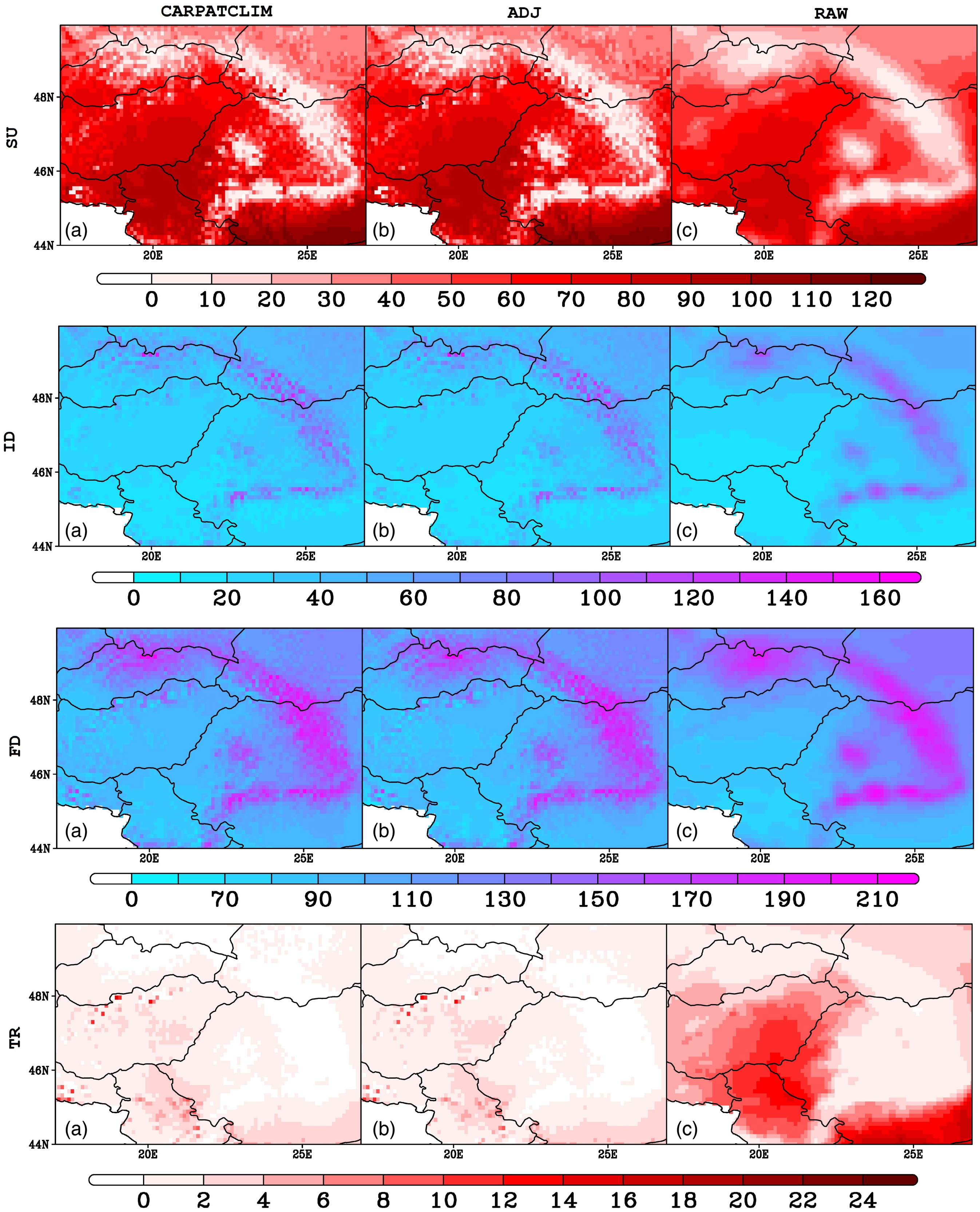

FIGURE 2 Threshold climate indices (SU, ID, FD, TR) over the Carpathian Basin based on the multimodel averages of bias-adjusted and raw RCM simulations (middle and right panels, respectively) compared to the CARPATCLIM reference database (left panels) for the period 1976–2005. The results are given in days·year^{-1} [Colour figure can be viewed at wileyonlinelibrary.com]

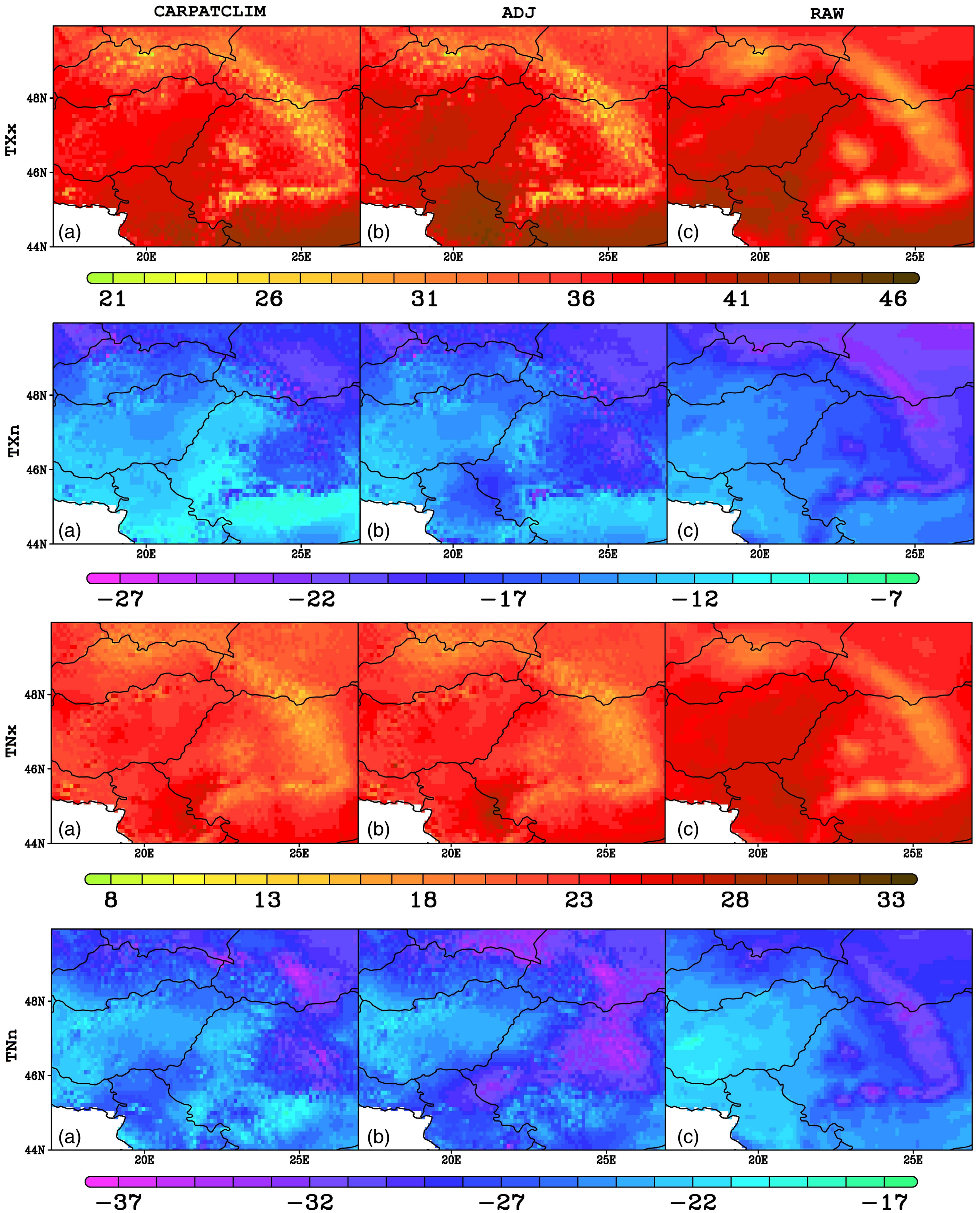

FIGURE 3 The same as in Figure 2, but for absolute climate indices. The results are given in °C [Colour figure can be viewed at wileyonlinelibrary.com]

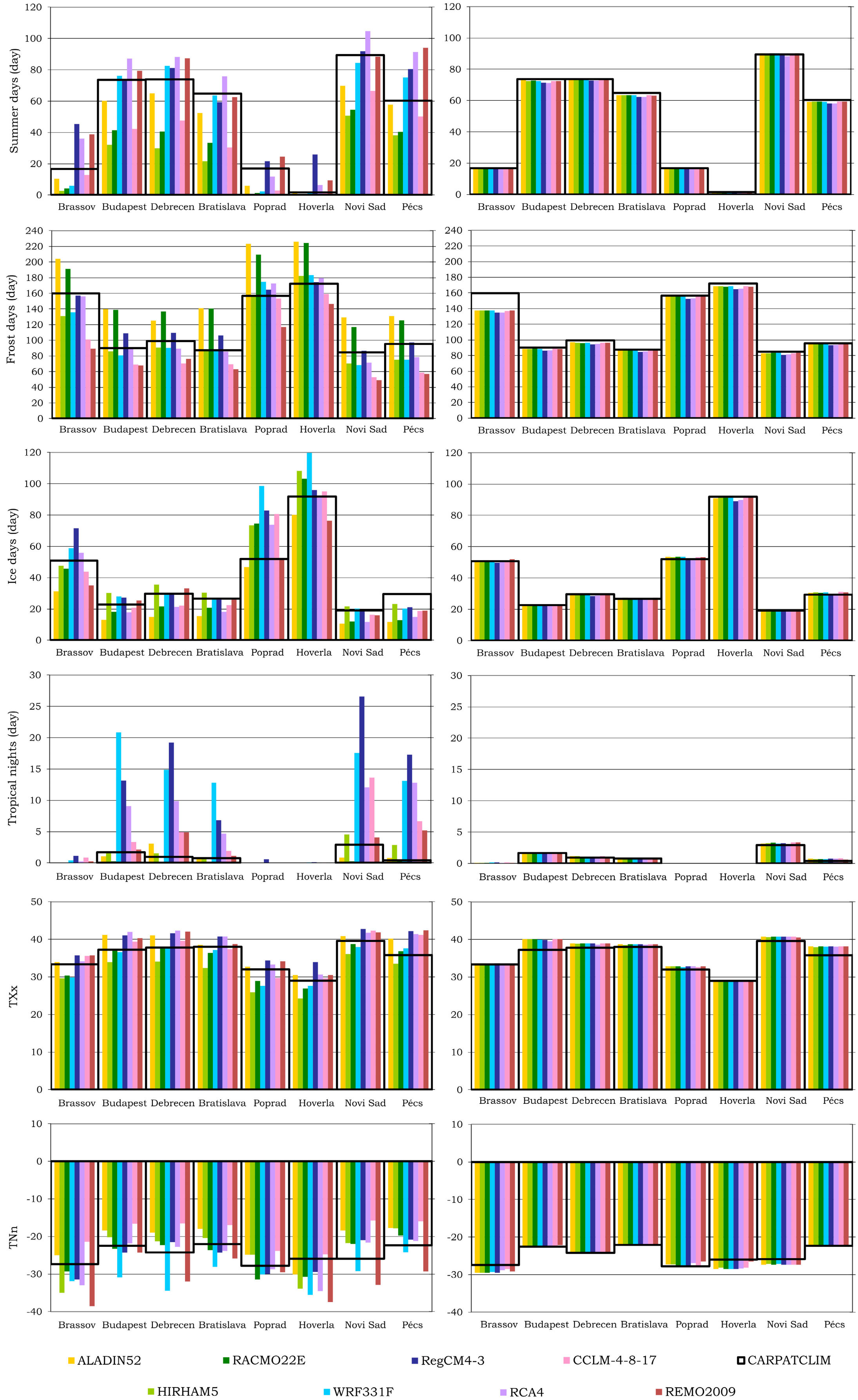

FIGURE 4 Legend on next page.

this section we turn our attention to the changes that are projected for the two future time slices (2021–2050 and 2070–2099) with respect to the aforementioned historical period. The raw and bias-corrected multimodel ensemble mean of eight RCM simulations were examined first for the entire Carpathian Basin, followed by the results for the selected subregions.

Figure 5 shows the projected changes in threshold indices related to both raw (first and third rows) and bias-adjusted (second and fourth rows, marked with "Adj") results and for both future time slices across the whole region. Figure 6 refers to absolute indices with the same notations. In general, bias-corrected RCM simulations show an increase (decrease) in the annual number of threshold indices related to warm (cold) weather. In terms of changes in the values of the absolute indices, all of them are likely to increase according to the RCM simulations.

By the near future (2021–2050), the annual number of ID across the Carpathian Basin will decrease by 6–15 days according to the multimodel ensemble mean, while by the end of the 21st century models project 20–40 days fewer ID compared to the reference period—the greatest decrease is expected in the mountainous regions. The change in FD is more pronounced than for ID with a decrease of 40–60 days per year in the far future (2070–2099). The annual frequency of SU is expected to increase throughout the region, with the largest extent (45–58 days) in the southern foothills of the southern Carpathians and the eastern third of the lowlands surrounded by the mountain range by the end of the 21st century. Increase of SU shows its minimum on the highest peaks. A similar tendency is shown by the RCM simulations in the annual number of TR: an increase by 6–12 days in the near future and by 36–50 days in the far future with respect to the reference period.

Turning our attention to the change in absolute climate indices, it can be said that an increasing tendency is expected for each index. The projected spatial patterns are similar in the cases of TNn and TXx with a relatively homogenous increase across the Carpathian Basin, with 2–3°C for the period of 2021–2050 and 5–7°C by the end of the 21st century. For the results of TXn and TNx a noticeable difference occurred between the raw and bias-corrected simulations. Multimodel ensemble mean of raw RCM simulations showed a weak decrease in mountainous areas, but it has been eliminated after bias-correction. TNx will increase by 2–5°C in the near future (2021–2050) and by up to 6–13°C in the far future (2070–2099) according to the bias-corrected multimodel ensemble mean. The rate of the change of TXn is smaller than for TNx, but spatial patterns are similar with the greatest increase in the middle and the eastern third of the lowlands surrounded by the Carpathians. Spatial multimodel averages of projected changes in climate indices in the Carpathian Basin summarized in Table 4 for 2021–2050 and 2070–2099 based on the bias-adjusted data with respect to 1976–2005.

In the next part of this section the projected number of threshold climate indices in the subregions are analysed on a seasonal scale. Boxplots of the results are presented here for SU in Figure 7, for the other indices see Figures S1–S3. In general, seasonal frequency of indices related to warm (cold) weather is likely to increase (decrease) according to the RCM simulations—these results are consistent with the results related to the whole region and shown above in Figures 5 and 6. In summer, the most pronounced increase in the number of SU occurred at higher altitudes (Brassov, Hoverla, Poprad); in addition, SUs also appear in the future periods more often in spring and autumn—during these seasons their number increases the most at subregions with lower altitudes (Budapest, Pécs, Novi Sad). Estimated changes of TR show similar spatial patterns to SU. According to the bias-corrected models TR will occur only in the far future (2070–2099) in the cases of Hoverla and Poprad with less than 5 days per summer. In the other subregions number of TR by the end of the 21st century can be double as it was in the historical period (1976–2005). A decrease in FD is expected in all seasons (except for summer when FD does not occur), for example in winter the projected decrease is 40–60 days for the period 2070–2099 with respect to 1976–2005, with the greatest change in Poprad and Brassov. ID occurs in all time slices of our study only in winter, except for higher altitudes, where it occurs also in autumn and spring, but the tendency of change is the same as for FD. Note that in the case of Pécs raw RCM simulations underestimated the seasonal (winter) number of ID in comparison with bias-adjusted simulations in all time slices. In Table 5 we give the summary of the multimodel mean of the projected changes by 2021–2050 and 2070–2099 for SU, FD, absolute minimum and absolute maximum temperature for each subregion with respect to a present-day baseline 1976–2005. In summary,

FIGURE 4 Bias of climate indices for the period 1976–2005 over the subregions without (on the left) and with (on the right) bias-correction based on the RCMs compared to the CARPATCLIM reference dataset. Open black boxes depict the results based on CARPATCLIM. Dimension of TXx and TNn is °C [Colour figure can be viewed at wileyonlinelibrary.com]

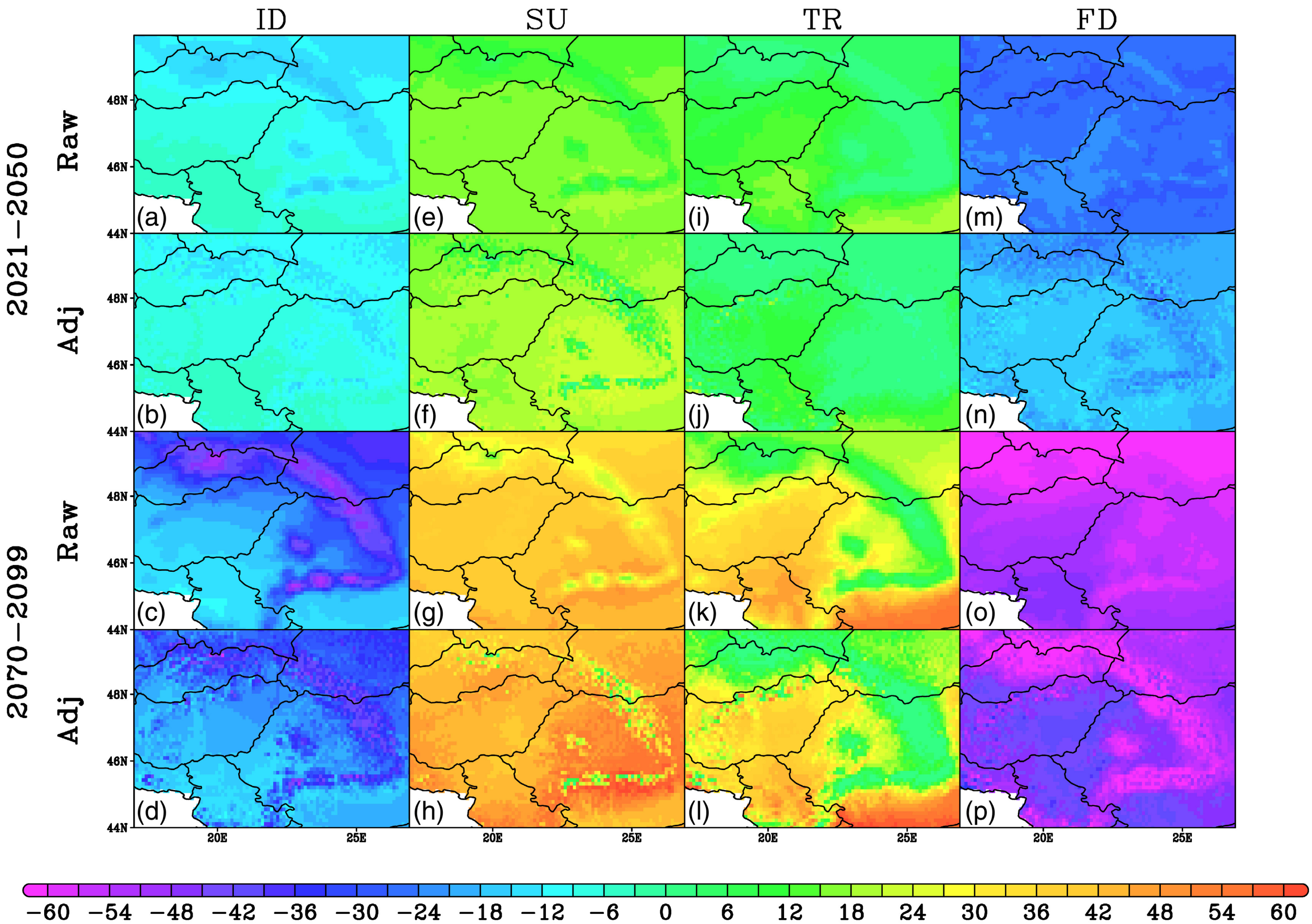

FIGURE 5 Projected changes (expressed in days per year) in threshold climate indices based on raw and bias-adjusted multimodel average of RCMs for 2021–2050 and 2070–2099 (reference period: 1976–2005) [Colour figure can be viewed at wileyonlinelibrary.com]

occurrence of events related to cold conditions (e.g., FD) are likely to decrease in the future, while those related to warm weather (e.g., SU) will probably increase in the Carpathian Basin according to the RCM simulations.

In general, more pronounced changes are expected by the end of the century (2070–2099) than by the near future (2021–2050) based on the bias-corrected RCM ensemble. The greatest changes are mainly projected over the mountainous regions (3 out of 4 indices). Which demonstrates the vulnerability of mountainous regions to climate change (Adler et al., 2022). More specifically, the maximum change in SU (Brassov), in FD (Poprad) and in TXx (Hoverla) are detected over subregions with relatively high altitude, only the largest change in TNn is projected for Novi Sad by the period 2070–2099 with respect to 1976–2005. In addition to the bias-adjusted RCM results, it is also interesting to see that indices associated with daily minimum temperature in general show more pronounced increase by the end of the century, than indices based on daily maximum temperature (see also Figure 6). This signal for TNn is somewhat modulated by the orography: highest increases are detected over subregions characterized by low altitudes (Table 5). Furthermore, a north–south difference can be also recognized, that is, SU is projected to increase the most in Brassov and Pécs, while the smallest increase is simulated for Hoverla, Poprad and Bratislava. Even though Bratislava and Hoverla are located at similar latitudes, there is a difference in topographies (see Table 1), this may cause considerable differences in results related to the changes in climate indices. These results demonstrate that orography plays an important role in the evolution of temperature characteristics within a region characterized by complex topography.

5 | SUMMARY AND FINAL CONSIDERATIONS

In the present study, eight RCMs are investigated from the framework of EURO-CORDEX and Med-CORDEX at a horizontal grid resolution of 0.11° (∼12.5 km). The

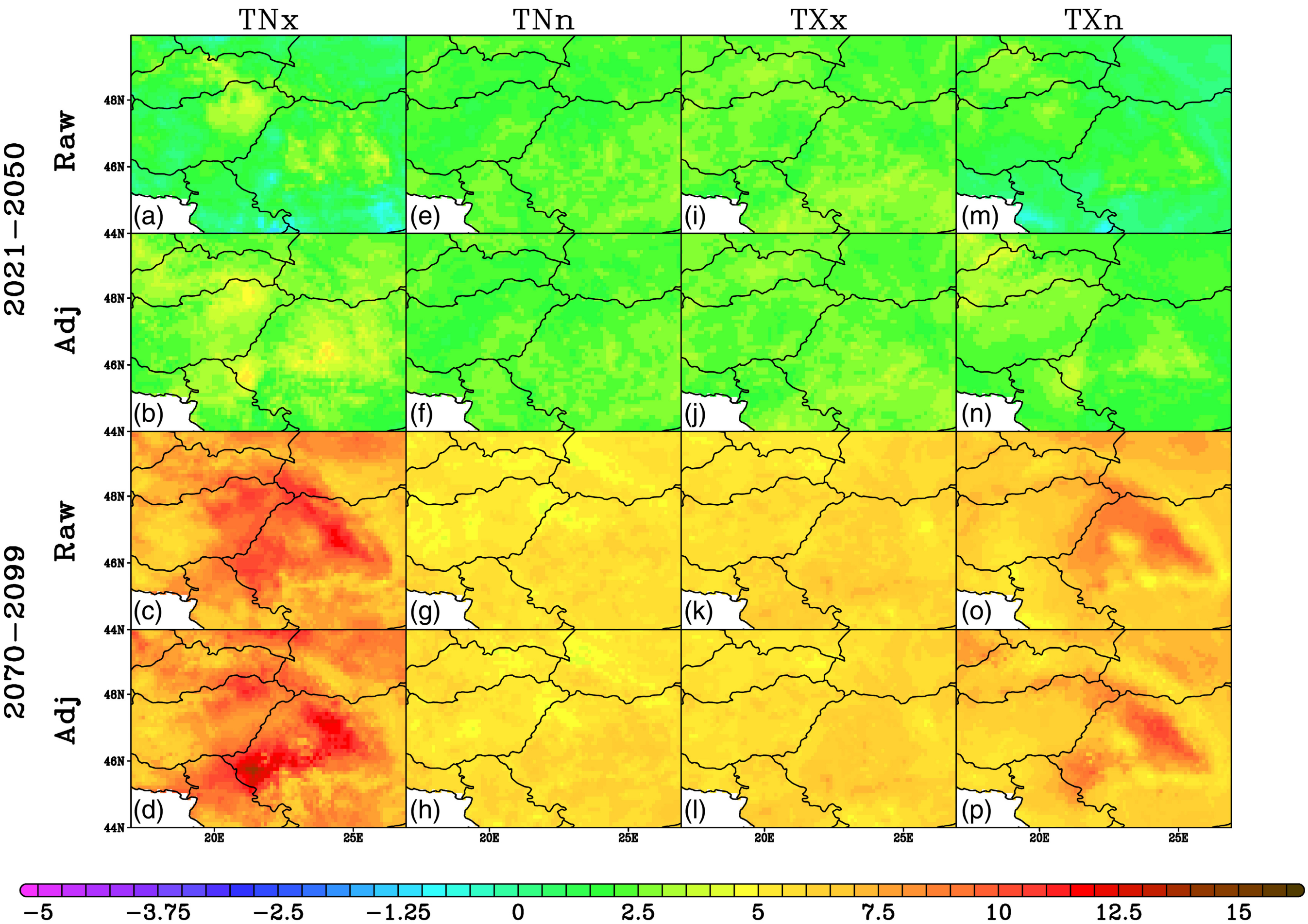

FIGURE 6 Same as in Figure 5, but for the absolute climate indices change. The results are given in °C [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Thirty-year spatial multimodel averages of projected changes in climate indices with respect to a present-day baseline (1976–2005) in the Carpathian Basin for 2021–2050 and 2070–2099

	2021–2050	2070–2099
SU	+18.3 (0.01–26.11)	+44.6 (0.45–65.04)
ID	−8.5 (−20.12–[−2.34])	−24.5 (−56.82–[−7.9])
FD	−20.5 (−31.03–[−10.53])	−52.2 (−82.55–[−31.53])
TR	+4.5 (0–21.4)	+24 (0.02–62.1)
TNn	+1.3 (−5.68–[+5])	+6.8 (0.84–11.26)
TNx	+2.6 (1.32–4.94)	+5.8 (4.55–8.48)
TXn	+1.1 (−5–[+4.56])	+5.5 (0.48–8.56)
TXx	+3.4 (1.49–6.35)	+6.8 (4.95–9.81)

Note: The minimum and maximum values of changes across the Carpathian Basin are shown in parenthesis. For threshold indices results are given in days·year^{-1}, while in the case of absolute indices unit is °C. These results are based on the bias-adjusted dataset.

CARPATCLIM observation-based dataset served as a reference dataset for evaluating the models and bias-correcting the RCM simulations using the percentile-based quantile mapping method (Mezghani et al., 2017). All RCM simulations follow the high-emission greenhouse gas scenario (RCP8.5) and provide daily minimum and maximum temperature. Two future time slices (2021–2050 and 2070–2099) were assessed with respect to the reference period 1976–2005. Two groups of temperature based climate indices were assessed: threshold climate indices: summer days (SU), tropical nights (TR), ice days (ID) and frost days (FD); and absolute climate indices: the warmest day (TXx), the warmest night (TNx), the coldest day (TXn) and the coldest night (TNn). Our study also focused on the projected changes of climate indices over the whole Carpathian Region with special focus on eight subregions with different topography.

In the reference period the bias-adjusted multimodel ensemble mean was well approximated CARPATCLIM for each climate index in the region of interest. On the other hand, the absolute minimum temperature of days and nights were overestimated by the raw simulations by 1–4°C in the central part of the region, but an underestimation was found in the Carpathians.

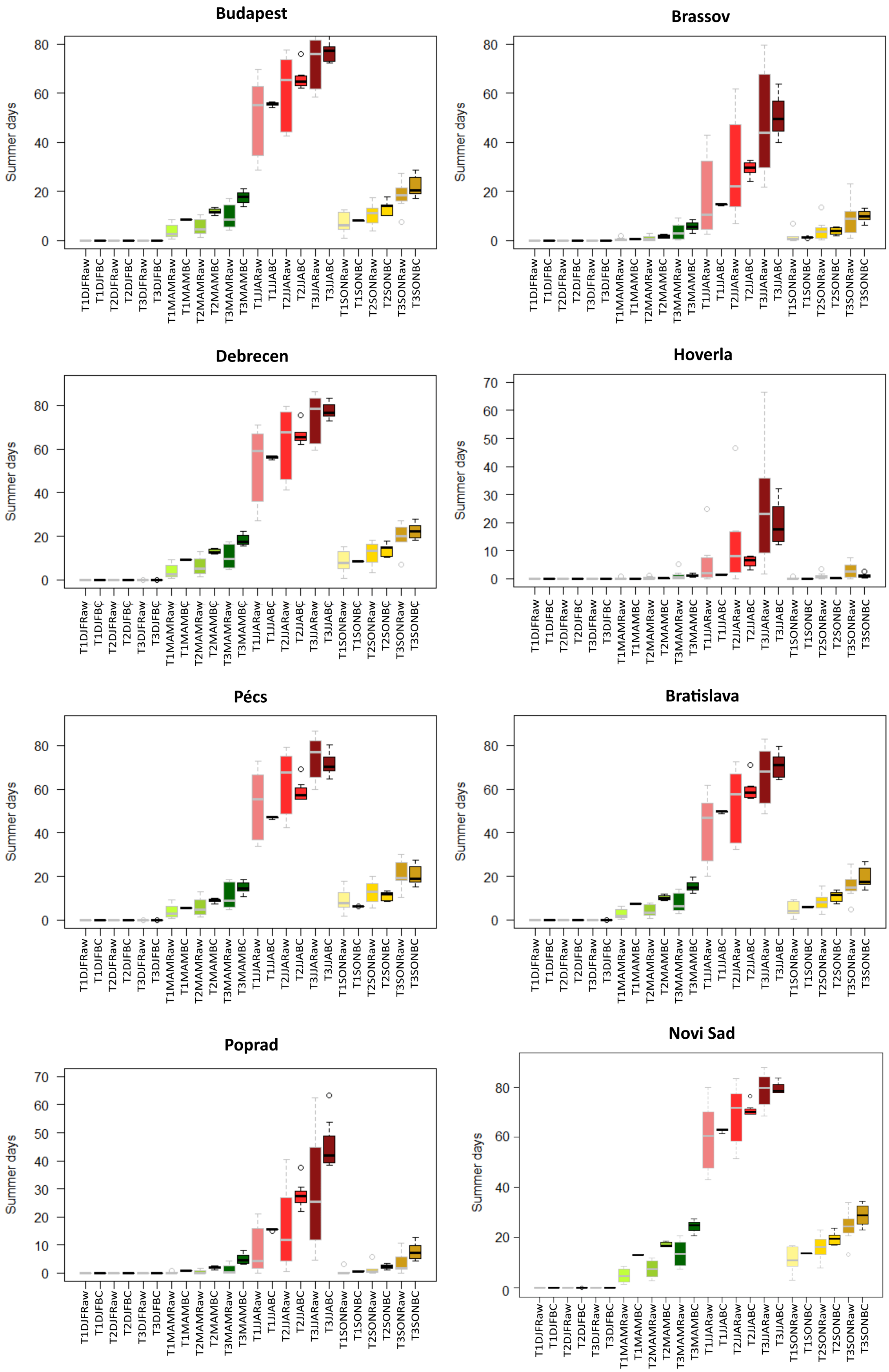

FIGURE 7 Legend on next page.

There are more studies focusing on the changes of climate indices in the Central European region. For example, Skarbit et al. (2022) analysed summer days and tropical nights in the Carpathian Basin too, based on 13 bias-corrected EURO-CORDEX simulations, also at a resolution of 0.11°, considering the RCP4.5 and RCP8.5 scenarios. They found that the indices are likely to increase in the future: in 2021–2050 there are no remarkable differences between the two scenarios, but by the end of the 21st century, RCP8.5 shows greater changes. However, they used a different database for the calculation, the projected number of tropical nights is in line with our results, namely, in the lowland areas of Hungary it can reach about 30 days by 2071–2100. Ciupertea et al. (2017) also calculated climate indices (including the indices which are investigated in the present study) based on bias-corrected (quantile mapping method) EURO-CORDEX simulations for both RCP4.5 and RCP8.5 scenarios at a horizontal resolution of 0.1°, but they only considered Cluj-Napoca (Romania). They concluded that calculations based on bias-corrected data are almost identical with the reference, while raw simulations underestimated the minimum and maximum temperatures. Frost days will be less than 80 and 50 days by the end of the 21st century according to the mean of the simulations (in the case RCP4.5 and RCP8.5, respectively). Summer days are likely to be 82 on average by 2071–2100 in the case of RCP4.5, while simulations considering RCP8.5 present 107 days. Our study also concluded that more than 100 summer days can occur in the southern part of the Carpathian Basin. Ten bias-corrected EURO-CORDEX simulations with spatial resolution of 0.11° were also investigated by Dumitrescu et al. (2022) for RCP4.5 and RCP8.5, but their target domain was Romania, not the entire Carpathian Basin. For the bias-correction the ROCADA gridded dataset was used. They did not calculate indices, but the minimum-, mean- and maximum temperatures and found a substantial temperature increase in the case of both scenarios: if RCP8.5 was applied, the projected change by 2100 exceeds 4°C (in the case of RCP4.5 it is between 1 and 3°C). Overall, our results for future periods are consistent with these previous studies, even though we analyse slightly different target regions, model simulations, reference databases for the bias-correction, scenarios and indices.

According to the ensemble mean of the bias-corrected RCM simulations, a clear decrease in the annual frequency of indices related to minimum temperature is expected throughout the 21st century, especially in the mountainous areas. The annual number of nights, when freezing occurs (when daily minimum temperature drops below 0°C) is likely to decrease for 2021–2050 by an average of 20 days and for 2070–2099 by half as many were detected in the reference period (1976–2005). In comparison, a greater decrease is projected in the case of such days when maximum temperature stays below 0°C with an amount of −25% for the near future and with −67% for the far future on a spatial average. The annual frequency of days when maximum temperature exceeds 25°C is expected to increase by a regional average of 32% in the middle of the 21st century. The greatest increase in summer is likely to occur in regions with higher elevation, while the increase in spring and autumn is higher at lower altitudes. The changes are more pronounced by the end of the 21st century, which means that with an annual number of 45–58 more summer days (an increase of +78% on regional average) will occur in the Carpathian Basin than in 1976–2005. According to the ensemble mean of the bias-corrected RCM simulations, in the period 2021–2050 the annual number of nights with minimum temperature above 20°C can be more than doubled (an increase by +112%) in lower parts of the region in comparison with the reference period. By the end of the 21st century, the annual number of tropical nights can be five times higher with respect to 1976–2005. In Poprad and Hoverla there were no such nights detected in the reference period, but these are projected to appear throughout the century. The values of all absolute climate indices are expected to increase across the Carpathian Basin, for the warmest (coldest) temperature of day (night) this means an increase of up to 2–3°C by the near future and of 5–7°C by the end of the 21st century, which in turn to the fact, that the absolute maximum temperature can reach 44–47°C for the period 2070–2099, especially in the lowlands of the Carpathian Basin. The signal of the projected changes for the absolute minimum temperature of nights shows its maximum over subregions characterized by low altitudes, which may indicate an orographical origin. Taking into account the individual RCMs, we could not highlight any model, which performed well for all indices. In terms of the subregions, mountainous regions are mainly affected by the greatest changes. Specifically, the values of the maximum change are detected in Hoverla (the highest temperature

FIGURE 7 Projected seasonal number of SU in the subregions for the periods 1976–2005 ("T1"), 2021–2050 ("T2") and 2070–2099 ("T3") based on the multimodel ensemble mean of raw (boxes with grey outlines, marked with "Raw") and bias-corrected RCM simulations (boxes with black outlines, marked with "BC") [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Thirty-year multimodel averages of the projected changes by 2021–2050 and 2070–2099 of climate indices for the selected cities with respect to a present-day baseline 1976–2005

	SU		FD		TNn		TXx	
	2021–2050	2070–2099	2021–2050	2070–2099	2021–2050	2070–2099	2021–2050	2070–2099
Brassov	+18.35	**+50.1**	**−23.12**	−58.76	+2.97	+7.54	**+3.05**	+5.83
Budapest	+18.72	+44.05	*−15.11*	*−42.73*	+2.8	+7.68	+2.54	+5.73
Debrecen	+19.49	+44.4	−16.05	−43.16	**+3.17**	+8.35	+2.65	+5.62
Hoverla	*+4.96*	*+20.34*	−16.82	−52.54	+2.6	+6.42	+2.34	**+6.21**
Pécs	**+19.91**	+47.94	−15.97	−44.66	*+2.2*	+6.58	+2.31	+5.66
Poprad	+15.05	+40.85	−22.17	**−62.86**	+2.49	*+5.93*	+2.86	*+5.25*
Bratislava	+17.43	+42.6	−15.78	−43.45	+2.75	+6.05	+2.83	+5.94
Novi Sad	+17.94	+43.33	−16.04	−43.76	+3.03	**+9.97**	*+1.85*	+5.85

Note: Values highlighted with Bold (Italic) type show the greatest (smallest) change in each climate index. For threshold indices result are given in days·year^{-1}, while in the case of absolute indices unit is °C. These results are based on the bias-adjusted dataset.

of day), Brassov (annual frequency of days when the maximum temperature exceeds 25°C), Poprad (annual number of nights, when freezing occurs)—over subregions with relatively high altitudes. The only exception is the absolute minimum temperature of nights, which is somehow modulated by the orography: the highest increases are detected over subregions characterized by low altitudes, and the greatest change was projected for Novi Sad by the end of the 21st century with respect to 1976–2005. Furthermore, a north–south difference was also found (e.g., this can be clearly seen in the case of summer days). In general, according to bias-adjusted RCM data, climate indices based on minimum temperature show a more pronounced increase by the period 2070–2099, than indices associated with maximum temperature.

The very first results, including projections at local scales, are reported here based on the recently released publicly available bias-adjusted daily temperature dataset derived from eight GCM-driven RCM simulations (available at https://doi.org/10.5281/zenodo.6393784). As a final conclusion, it can be said that the climate in the Carpathian Basin will shift towards generally warmer conditions, and frost and cold events are expected to become less frequent in the future according to the bias-corrected RCM projections. Our results also highlight the vulnerability of mountain environments to climate change and the need for bias-adjusted RCM data from regional to local scales in a region characterized by complex orography such as the Carpathian Basin. The added value of this paper is the quantification of the expected changes in temperature-based climate indices at the local scale and their possible orographic dependence. Accordingly, the projected changes are derived from a bias-corrected RCM database using the most reliable observational dataset currently available for the Carpathian Basin as a reference data. These projected changes may have a significant impact on human health, agriculture and ecosystems, so it is very important to mitigate climate change and create adaptation strategies. Accordingly, the potential benefits of the present research and the investigated bias-corrected RCM dataset are enormous in terms of adaptation measures to climate change. Our results can be adapted in line with the national adaptation strategies in other areas as follows: human health, agriculture, transport, tourism, disaster management, natural conservation or heritage conservation.

AUTHOR CONTRIBUTIONS

Csilla Simon: Writing – original draft; conceptualization; data curation; investigation; formal analysis; validation. **Anna Kis:** Writing – review and editing; conceptualization; visualization; supervision; validation. **Csaba Zsolt Torma:** Writing – review and editing; funding acquisition; conceptualization; visualization; supervision; methodology; validation.

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medcordex.php, CARPATCLIM: http://www.carpatclim-eu.org/pages/download/.

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REFERENCES

Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G.E., Morecroft, M.D. et al. (2022) Cross-chapter paper 5: mountains. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A. et al. (Eds.) *Climate change 2022: impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge and New York, NY: Cambridge University Press, pp. 2273–2318. Available from: https://doi.org/10.1017/9781009325844.022

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S. et al. (2007) Future extreme events in European climate: an exploration of regional climate model projections. *Climate Change*, 81, 71–95. Available from: https://doi.org/10.1007/s10584-006-9226-z

Casanueva, A., Herrera, S., Iturbide, M., Lange, S., Jury, M., Dosio, A. et al. (2020) Testing bias adjustment methods for regional climate change applications under observational uncertainty and resolution mismatch. *Atmospheric Science Letters*, 21(21), e978. Available from: https://doi.org/10.1002/asl.978

Christensen, J.H. & Christensen, O.B. (2007) A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Climatic Change*, 81, 7–30. Available from: https://doi.org/10.1007/s10584-006-9210-7

Christensen, O.B., Christensen, J.H., Machenhauer, B. & Botzet, M. (1998) Very high resolution regional climate simulations over Scandinavia—present climate. *Journal of Climate*, 11, 3204–3229.

Ciarlo, J.M., Coppola, E., Fantini, A., Giorgi, F., Gao, X.J., Tong, Y. et al. (2021) A new spatially distributed added value index for regional climate models: the EURO-CORDEX and the CORDEX-CORE highest resolution ensembles. *Climate Dynamics*, 57, 1403–1424. Available from: https://doi.org/10.1007/s00382-020-05400-5

Ciupertea, A., Piticar, A., Djurdjevic, V., Croitoru, A.E. & Bartok, B. (2017) *Future changes in extreme temperature indices in Cluj-Napoca, Romania*. Presented at the conference of air and water components of the environment, Cluj-Napoca, Romania.

Colin, J., Déqué, M., Radu, R. & Somot, S. (2010) Sensitivity studies of heavy precipitations in limited area model climate simulation: influence of the size of the domain and the use of the spectral nudging technique. *Tellus A*, 62, 591–604. Available from: https://doi.org/10.1111/j.1600-0870.2010.00467.x

Collins, W.J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T. et al. (2011) Development and evaluation of an Earth system model, HADGEM2. *Geoscientific Model Development*, 4, 1051–1075. Available from: https://doi.org/10.5194/gmd-4-1051-2011

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S. et al. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137, 553–597. Available from: https://doi.org/10.1002/qj.828

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O. et al. (2013) Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Climate Dynamics*, 40, 2123–2165. Available from: https://doi.org/10.1007/s00382-012-1636-1

Dumitrescu, A., Amihaesei, V.-A. & Cheval, S. (2022) RoCliB—bias-corrected CORDEX RCM dataset over Romania. *Geoscience Data Journal*, 1–14. Available from: https://doi.org/10.1002/gdj3.161

Evin, G., Somot, S. & Hingray, B. (2021) Balanced estimate and uncertainty assessment of European climate change using the large EURO-CORDEX regional climate model ensemble. *Earth System Dynamics, Discussion*, 12, 1543–1569. Available from: https://doi.org/10.5194/esd-2021-8

Fang, G.H., Yang, J., Chen, Y.N. & Zammit, C. (2015) Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, 19, 2547–2559. Available from: https://doi.org/10.5194/hess-19-2547-2015

Fantini, A., Raffaele, F., Torma, C., Bacer, S., Coppola, E., Giorgi, F. et al. (2018) Assessment of multiple daily precipitation statistics in ERA-Interim driven Med-CORDEX and EURO-CORDEX experiments against high resolution observations. *Climate Dynamics*, 51, 877–900. Available from: https://doi.org/10.1007/s00382-016-3453-4

Farda, A., Déqué, M., Somot, S., Horányi, A., Spiridonov, V. & Tóth, H. (2010) Model ALADIN as regional climate model for central and eastern Europe. *Studia Geophysica et Geodaetica*, 54, 313–332.

Giorgi, F. (2005) Climate change prediction. *Climatic Change*, 73, 239–265.

Giorgi, F. (2019) Thirty years of regional climate modeling: where are we and where are we going next? *Journal of Geophysical Research: Atmospheres*, 124, 5696–5723. Available from: https://doi.org/10.1029/2018JD030094

Giorgi, F., Coppola, E., Solmon, F., Mariotti, L., Sylla, M.B., Bi, X. et al. (2012) RegCM4: model description and preliminary results over multiple CORDEX domains. *Climate Research*, 52, 7–29. Available from: https://doi.org/10.3354/cr01018

Giorgi, F., Jones, C. & Asrar, G. (2009) Addressing climate information needs at the regional level: the CORDEX framework. *WMO Bulletin*, 58, 175–183.

Halenka, T. (2007) On the assessment of climate change impacts in central and Eastern Europe-EC FP6 project CECILIA. *Geophysical Research Abstracts*, 9, 10545.

Halmstad, A., Najafi, M.R. & Moradkhani, H. (2012) Analysis of precipitation extremes with the assessment of regional climate models over the Willamette River basin, USA. *Hydrological Processes*, 27(18), 2579–2590. Available from: https://doi.org/10.1002/hyp.9376

Hazeleger, W., Severijns, C., Semmler, T., Stefanescu, S., Yang, S., Wang, X. et al. (2010) EC-Earth: a seamless Earth-system prediction approach in action. *Bulletin of the American Meteorological Society*, 91(10), 1357–1364. Available from: https://doi.org/10.1175/2010BAMS2877.1

Hewitt, C.D. & Griggs, D. (2004) Ensembles-based predictions of climate changes and their impacts. *Eos, Transactions, American Geophysical Union*, 85(52), 566. Available from: https://doi.org/10.1029/2004EO520005

IPCC. (2013) In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. et al. (Eds.) *Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge and New York, NY: Cambridge University Press. Available from: https://doi.org/10.1017/CBO9781107415324

IPCC. (2021) In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S. et al. (Eds.) *Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge and New York, NY, 254 p: Cambridge University Press. Available from: https://doi.org/10.1017/9781009157896.013

Jacob, D., Elizalde, A., Haensler, A., Hagemann, S., Kumar, P., Podzun, R. et al. (2012) Assessing the transferability of the regional climate model REMO to different coordinated regional climate downscaling experiment (CORDEX) regions. *Atmosphere*, 3, 181–199. Available from: https://doi.org/10.3390/atmos3010181

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M. et al. (2014) EURO-CORDEX new high resolution climate change projections for European impact research. *Regional Environmental Change*, 14, 563–578. Available from: https://doi.org/10.1007/s10113-013-0499-2

Jungclaus, J.H., Lorenz, S.J., Timmreck, C., Reick, C.H., Brovkin, V., Six, K. et al. (2010) Climate and carbon cycle variability over the last millennium. *Climate of the Past*, 6, 723–737. Available from: https://doi.org/10.5194/cp-6-723-2010

Kupiainen, M., Jansson, C., Samuelsson, P., Jones, C., Willén, U., Hansson, U. et al. (2014) Rossby Centre regional atmospheric model, RCA4. *Rossby Center News Letter*.

Mezghani, A., Dobler, A., Haugen, J.E., Benestad, R.E., Parding, K. M., Piniewski, M. et al. (2017) CHASE-PL climate projection dataset over Poland—bias adjustment of EURO-CORDEX simulations. *Earth System Science Data*, 9, 905–925. Available from: https://doi.org/10.5194/essd-9-905-2017

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S. K., van Vuuren, D.P. et al. (2010) The next generation of scenarios for climate change research and assessment. *Nature*, 463, 747–756. Available from: https://doi.org/10.1038/nature08823

Ngai, S.T., Tangang, F. & Juneng, L. (2016) Bias correction of global and regional simulated daily precipitation and surface mean temperature over Southeast Asia using quantile mapping method. *Global and Planetary Change*, 149, 79–90. Available from: https://doi.org/10.1016/j.gloplacha.2016.12.009

Probst, E. & Mauer, W. (2023) Climate change impacts on water resources in the Danube River basin: a hydrological modelling study using EURO-CORDEX climate scenarios. *Water*, 15(1), 8. Available from: https://doi.org/10.3390/w15010008

Räty, O., Räisänen, J. & Ylhäisi, J.S. (2014) Evaluation of delta change and bias correction methods for future daily precipitation: intermodel cross-validation using ENSEMBLES simulations. *Climate Dynamics*, 42, 2287–2303. Available from: https://doi.org/10.1007/s00382-014-2130-8

Rockel, B., Will, A. & Hense, A. (2008) Special issue: regional climate modeling with COSMO-CLM (CCLM). *Meteorologische Zeitschrift*, 17, 347–348. Available from: https://doi.org/10.1127/0941-2948/2008/0309

Rummukainen, M. (2016) Added value in regional climate modeling. *WIREs Climate Change*, 7, 145–159. Available from: https://doi.org/10.1002/wcc.378

Ruti, P.M., Somot, S., Giorgi, F., Dubois, C., Flaounas, E., Obermann, A. et al. (2016) MED-CORDEX initiative for Mediterranean climate studies. *Bulletin of the American Meteorological Society*, 97, 1187–1208. Available from: https://doi.org/10.1175/BAMS-D-14-00176.1

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Duda, M.G., Huang, X.-Y. et al. (2008) *A description of the advanced research WRF version 3*. Boulder, CO: NCAR. NCAR technical note NCAR/TN-475+STR.

Skarbit, N., Unger, J. & Gál, T. (2022) Projected values of thermal and precipitation climate indices for the broader Carpathian region based on EURO-CORDEX simulations. *Hungarian Geographical Bulletin*, 71(4), 325–347. Available from: https://doi.org/10.15201/hungeobull.71.4.2

Szalai, S., Auer, I., Milkovich, J., Radim, T., Stepanek, P., Zahradnicek, P. et al. (2013) *Climate of the Greater Carpathian region*. Final 740 technical report. Available from: http://www.carpatclim-eu.org

Szentimrey, T. (2007) *Manual of homogenization software MASHv3.02*. Hungarian Meteorological Service, Budapest, 65 p.

Szentimrey, T., & Bihari, Z. (2007) Mathematical background of the spatial interpolation methods and the software MISH (Meteorological Interpolation based on Surface Homogenized Data Basis). In: Proceedings from the Conference on Spatial Interpolation in Climatology and Meteorology, Budapest, Hungary, 2004, COST Action 719, COST Office, 17–27.

Teutschbein, C. & Siebert, J. (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. *Journal of Hydrology*, 456–457, 12–29. Available from: https://doi.org/10.1016/j.jhydrol.2012.05.052

Torma, C., Giorgi, F. & Coppola, E. (2015) Added value of regional climate modeling over areas characterized by complex terrain—precipitation over the Alps. *Journal of Geophysical Research: Atmospheres*, 120, 3957–3972. Available from: https://doi.org/10.1002/2014JD022781

Torma, C.Z. & 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*, 42(12), 6631–6646. Available from: https://doi.org/10.1002/joc.7654

Torma, C. (2019) Detailed validation of EURO-CORDEX and Med-CORDEX regional climate model ensembles over the

Carpathian region. *Időjárás*, 123(2), 217–240. Available from: https://doi.org/10.28974/idojaras.2019.2.6

Torma, C., Kis, A. & Pongrácz, R. (2020) Evaluation of EURO-CORDEX and Med CORDEX precipitation simulations for the Carpathian region: bias corrected data and projected changes. *Időjárás*, 124(1), 25–46. Available from: https://doi.org/10.28974/idojaras.2020.1

van Meijgaard, E., van Ulft, L.H., Lenderink, G., de Roode, S.R., Wipfler, E.L., Boers, R. et al. (2012) *Refinement and application of a regional atmospheric model for climate scenario calculations of Western Europe*. Research report KVR 054/12, 44 p.

Voldoire, A., Sanchez-Gomez, E., Salas y Mélia, D., Decharme, B., Cassou, C., Sénési, S. et al. (2012) The CNRM-CM5.1 global climate model: description and basic evaluation. *Climate Dynamics*, 40, 2091–2121.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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