

The WRF model as a new tool for investigating climate change in the Carpathian region – Near-future projections of temperature and precipitation

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Abstract

This study presents the first application of the Weather Research and Forecasting (WRF) model for regional climate modelling in Hungary, specifically adapted for the Carpathian Basin. Simulations for the historical (1985–2010) and future (2020–2045) periods were conducted using WRF with a 10 km grid spacing, downscaling the MPI-ESM1-2-LR global climate model from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). The future simulation employs the high-emission SSP5-8.5 scenario. The CARPATCLIM observational dataset was used for model evaluation and bias correction. Expected changes in mean temperature and precipitation between the future and historical periods are assessed based on the bias-corrected WRF simulations. WRF projects a spatially averaged temperature increase of 1 °C in winter, 0.7 °C in summer, and 0.6 °C in spring and autumn over Hungary. Precipitation is projected to increase by 12 percent in winter, 31 percent in spring, and 21 percent in autumn, with no significant change in summer. While future climate change assessments should always be based on multiple model simulations, this study demonstrates the utility of WRF as a regional climate model for the Carpathian region.

Keywords: climate change, regional climate model, WRF model, temperature, precipitation

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Introduction

Regional climate models (RCMs) are widely used to study climate processes and analyse climate change at a fine-scale regional level (GIORGI, F. 2019). A wide range of RCM simulations is now available from internationally coordinated projects like the Coordinated Regional Climate Downscaling Experiment (CORDEX) for various regions, including Europe (VAUTARD, R. *et al.* 2021). However, adapting RCMs for specific countries is also justified. It allows for greater flexibility in model tuning and evaluation over the re-

gion of interest and enables adjustments to the model output based on its intended use (e.g., output frequency and variables). Internationally available RCM simulations, along with targeted national model runs, are essential for obtaining future climate information. They support adaptation and mitigation strategies and facilitate uncertainty assessment (RUMMUKAINEN, M. 2016; GUTOWSKI, W.J. *et al.* 2020).

In Hungary, four models have been adapted for regional climate modelling: REMO and ALADIN-Climate at the Hungarian Meteorological Service (HungaroMet) (CsIMA,

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G. and HORÁNYI, A. 2008; SZÉPSZÓ, G. and HORÁNYI, A. 2008; BÁN, B. *et al.* 2021; SUGA, R. *et al.* 2021; MEGYERI-KOROTAI, O.A. *et al.* 2023), and PRECIS and RegCM at the Department of Meteorology at Eötvös Loránd University (ELTE) (BARTHOLY, J. *et al.* 2009; TORMA, Cs.Zs. *et al.* 2011; PIECZKA, I. *et al.* 2017; KALMÁR, T. *et al.* 2021). These models have been extensively evaluated and applied to study various aspects of climate change. In addition to general assessments of temperature and precipitation changes (e.g. KRÜZSELYI, I. *et al.* 2011), they have been used to investigate specific phenomena such as heatwaves (GÖNDÖCS, J. *et al.* 2018), air quality (PIECZKA, I. *et al.* 2019), river runoff (KIS, A. *et al.* 2020), and urban climate (ALLAGA-ZSEBEHÁZI, G. 2021).

The Weather Research and Forecasting (WRF) model (SKAMAROCK, W.C. *et al.* 2019) has been widely used as a regional climate model globally (e.g. CALDWELL, P. *et al.* 2009; HEIKKILÄ, U. *et al.* 2011; MARTA-ALMEIDA, M. *et al.* 2016; SRIVASTAVA, A.K. *et al.* 2023). In Hungary, WRF has long been used for numerical weather prediction (HORVÁTH, Á. *et al.* 2015), but its application as an RCM is a novel approach in the country. We began the adaptation of WRF by conducting short-term sensitivity studies to evaluate the performance of different physical and dynamical settings (VARGA, Á.J. and BREUER, H. 2020). We then conducted an evaluation run for the 1985–2010 period, driven by the ERA5 reanalysis (HERSBACH, H. *et al.* 2020). The validation results, previously published for various meteorological variables such as convective environmental parameters, temperature, precipitation, global radiation, and snow depth, are available in VARGA, Á.J. and BREUER, H. (2022, 2023, 2024a).

This study presents results from WRF regional climate simulations for a historical period (1985–2010) and a future period (2020–2045). The simulations are driven by a general circulation model from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), marking the first time a CMIP6 model has been downscaled specifically for

the Carpathian region. The model is evaluated and bias-corrected using observational data from the CARPATCLIM dataset. Expected changes in monthly and seasonal mean temperature and precipitation are presented. The main goal is to demonstrate the suitability and initial applications of WRF as a regional climate model for the Carpathian region.

Data and methods

CARPATCLIM observations

Observational temperature and precipitation data were obtained from the CARPATCLIM dataset (SZALAI, S. *et al.* 2013; SPINONI, J. *et al.* 2015). CARPATCLIM consists of quality-controlled, homogenized daily weather station observations interpolated to a 0.1° grid. It covers the period 1961–2010 and the region 44°–50°N, 17°–27°E, which also defines our study area. In this study, CARPATCLIM is used to evaluate the historical WRF simulation for the 1985–2010 period and serves as a reference for bias correction.

WRF model configuration

The Weather Research and Forecasting (WRF) model, originally developed in the United States, is a highly flexible, open-source meteorological model. It is particularly well-suited for mesoscale applications due to its non-hydrostatic dynamical core.

For the regional climate simulations in this study, the Advanced Research WRF (ARW) version 4.2 (SKAMAROCK, W.C. *et al.* 2019) was configured on a Lambert conformal conic projection with two one-way nested domains (Figure 1). The outer domain, covering the Med-CORDEX region (RUTI, P.M. *et al.* 2016), has a horizontal grid spacing of 50 km with 110×69 grid points. The inner domain has a 10 km grid spacing with 226×131 grid points. This study presents results only for the 10 km

runs, while the 50 km runs served as an intermediate step to downscale the relatively coarse (~200 km) general circulation model data. The 10 km grid spacing was selected as a compromise between regional-scale detail and the computational cost of multi-decadal climate simulations. At this resolution, deep convection is still parameterized, and the simulation is therefore not a convection-permitting simulation (PREIN, A.F. *et al.* 2015). Vertically, the model employs 61 hybrid sigma-pressure levels, with the top at 50 hPa.

The initial and boundary conditions for the WRF RCM were derived from the low-resolution (~200 km) version of the Max Planck Institute for Meteorology Earth System Model version 1.2 (MPI-ESM1-2-LR) (MAURITSSEN, T. *et al.* 2019), a participant in the sixth phase of the Coupled Model Intercomparison Project (CMIP6) (EYRING, V. *et al.* 2016). Lateral boundary conditions were updated every

six hours. The historical CMIP6 simulations reflect climate change conditions consistent with observed data. For the future period, the global model forcing is based on the high-emission SSP5-8.5 scenario, which represents a worst-case fossil-fuel-based development pathway for the 21st century (MEINSHAUSEN, M. *et al.* 2020).

The regional climate simulations for the historical period were initiated on 1 July 1984 at 00 UTC and ended on 1 January 2011 at 00 UTC. For the future period, the model integration started on 1 July 2019 at 00 UTC and ended on 1 January 2046 at 00 UTC. The future period was selected to focus on near-term climate change impacts, as extending the simulations to the end of the century would have substantially increased the computational requirements. The first six months of both periods served as a spin-up period and were excluded from the analysis.

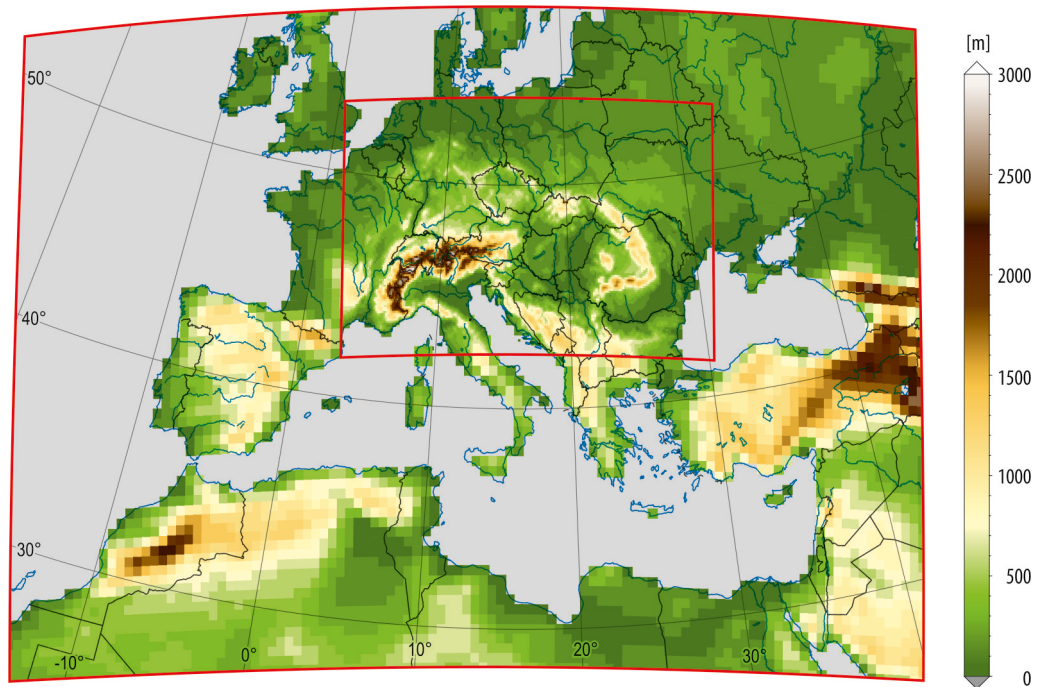


Fig. 1. Geographical coverage and topography of the WRF regional climate model domains.

Source: Authors' own elaboration.

The WRF physical parameterizations include the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) for radiative transfer (IACONO, M.J. *et al.* 2008), the Kain-Fritsch scheme for deep convection (KAIN, J.S. 2004), the Thompson scheme for microphysics (THOMPSON, G. *et al.* 2008), and the Mellor-Yamada-Janjić (MYJ) parameterization for the planetary boundary layer (JANJIĆ, Z.I. 1994). The surface layer uses the Eta model's similarity scheme, while the Noah-Multiparameterization Land Surface Model (Noah-MP) is employed for land surface processes (Niu, G.Y. *et al.* 2011). The model configuration was informed by previous sensitivity experiments conducted during the adaptation of WRF for the Carpathian region, including those presented by VARGA, Á.J. and BREUER, H. (2020). These experiments showed that model performance depends strongly on the selected physics schemes and that no single configuration performed best for all evaluated variables and seasons. Therefore, the final configuration was selected based on the broader experience gained during the adaptation process rather than by directly adopting a single best-performing setup from the sensitivity experiments.

Three-hourly temperature and precipitation values from WRF were interpolated from the native Lambert conformal projection to a regular 0.1° grid using bilinear interpolation ("remapbil" in Climate Data Operators (CDO); SCHULZWEIDA, U. 2023) to facilitate comparison with CARPATCLIM observations and the bias correction procedure. Daily mean surface (2 m) temperature and total daily precipitation were then calculated from the three-hourly output.

Bias correction and climate change assessment

Bias correction was applied to daily temperature and precipitation fields using quantile mapping (the "QuantileMapping" function in the *ibicus* Python package; SPULER, F.R. *et al.* 2024). Quantile mapping adjusts

the distribution of model-simulated data to better match observed data by aligning the cumulative distribution function (CDF) of the model with that of the observations (CANNON, A.J. *et al.* 2015), thereby correcting systematic biases. However, the method assumes that model biases remain constant over time. To account for seasonality, a 31-day running window was used during the correction process. The correction function was calibrated using CARPATCLIM observations and the historical WRF simulation (1985–2010) and subsequently applied to both the historical and future WRF simulations. In the following, WRF_RAW refers to the WRF output before bias correction, while WRF_BC refers to the corresponding bias-corrected WRF output. Finally, monthly and seasonal climate averages were computed from the bias-corrected data for the historical (1985–2010) and future (2020–2045) periods.

Climate change is assessed using bias-corrected data by comparing mean temperature change (°C) and relative precipitation change (%) between the historical and future periods. The study area corresponds to the CARPATCLIM region. Spatial distributions of model errors and temperature and precipitation changes are shown for the entire region, while spatially averaged monthly means are presented for Hungary.

Results and discussion

Evaluation of the historical (1985–2010) simulation

Figure 2 shows the observed and WRF-simulated annual cycles of temperature and precipitation for the historical (1985–2010) period, highlighting both the raw model biases and the effects of bias correction. The raw WRF simulation underestimates the spatially averaged monthly mean temperature over Hungary by 1.9–2.1 °C in winter and by 0.9–1.4 °C in spring, compared to the CARPATCLIM observations. This cold bias

is attributed to the inadequate treatment of snow cover, specifically the overestimation of snow depth and snow albedo in winter and early spring (GARCÍA-DÍEZ, M. *et al.* 2015; VARGA, Á.J. and BREUER, H. 2024b). In summer, slight warm biases ($< 1\text{ }^{\circ}\text{C}$) are observed. Precipitation is overestimated by 33–50 per-

cent in spring, and by 68 percent in January, while dry biases of 12–36 percent appear in summer and September. The figure also demonstrates that biases in the mean and median values are effectively corrected by the quantile mapping method for both temperature and precipitation.

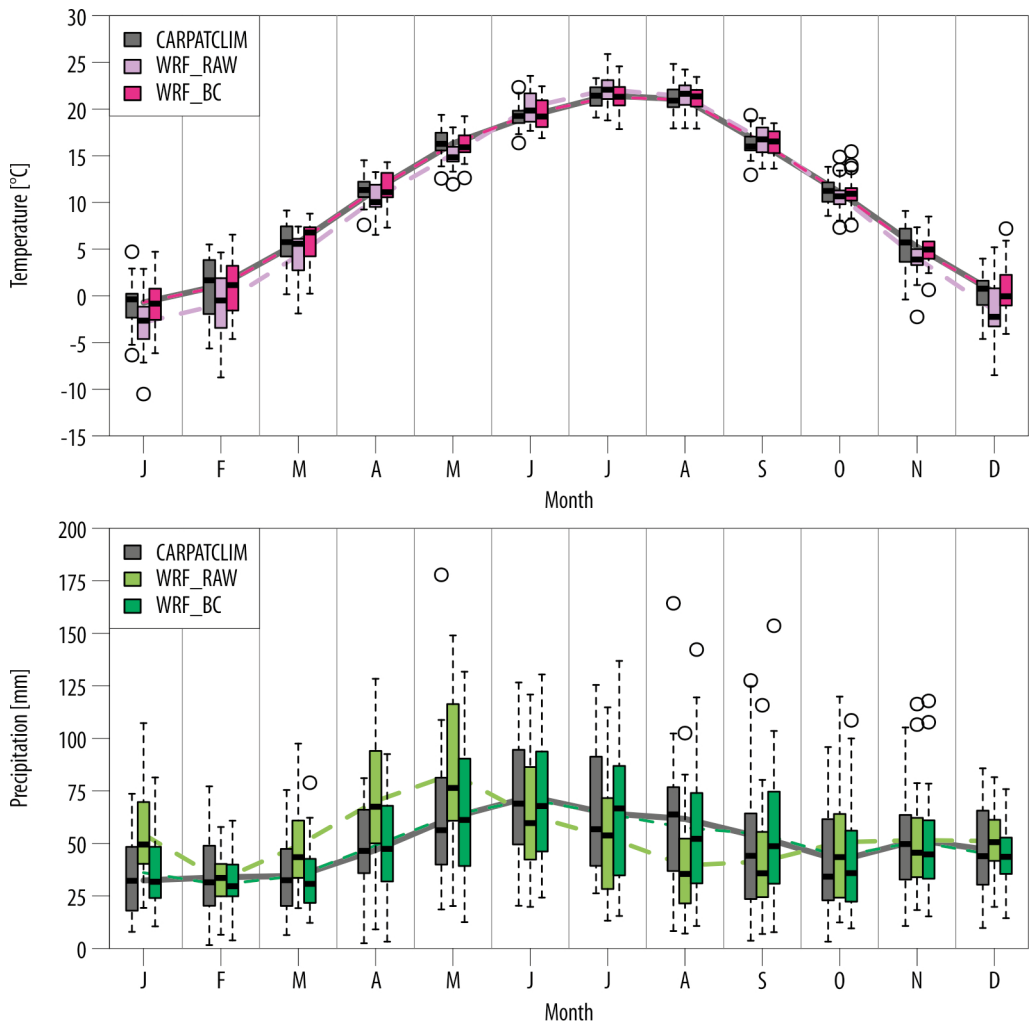


Fig. 2. Annual cycle of monthly mean temperature (top) and precipitation (bottom) from the CARPATCLIM observations, as well as the raw (WRF_RAW) and bias-corrected (WRF_BC) WRF simulations for the 1985–2010 period, spatially averaged over Hungary. The solid line represents mean values for observations, while the dashed lines represent the mean values for the raw and bias-corrected WRF simulations.

Source: Authors' own elaboration.

The spatial distribution of seasonal mean biases in the raw WRF model also reflects the extensive precipitation overestimation in winter and spring, and the underestimation in summer (Figure 3). Errors are smallest in autumn. Precipitation overestimation is most pronounced on the windward side of the Carpathian Mountains. However, the bias correction effectively reduces model errors across all seasons and the entire study area. Accordingly, although the assumption that model biases remain constant over time must be acknowledged, the bias-corrected model is expected to provide an improved representation of future climate conditions. Based on the good performance of the bias adjustment, as demonstrated in Figure 2 and 3, temperature and precipitation projections for the future period are presented only for the bias-corrected fields.

Future (2020–2045) projections of temperature and precipitation

The bias-corrected WRF model projects a spatially averaged temperature increase of

0.7 °C in Hungary between the near-future (2020–2045) and historical (1985–2010) periods. The largest seasonal increase is projected in winter (1 °C), followed by summer (0.7 °C), and spring and autumn (0.6 °C) (Figure 4). This projected warming is lower than the approximately 1.4 °C annual increase reported by Torma, Cs.Zs. and Kis, A. (2022) for the Carpathian region in 2021–2050 relative to 1976–2005. Part of this difference can be explained by the different reference and projection periods used in the two studies. Over Hungary, the mean temperature difference between the 1976–2005 and 1985–2010 reference periods in the CARPATCLIM dataset is 0.3 °C. Additional factors may include differences in the analysed domain (Hungary versus the entire Carpathian region) and the use of a single simulation rather than a multi-model ensemble. Since Torma, Cs.Zs. and Kis, A. (2022) identified CCLM4 as one of the best-performing regional climate models in their evaluation, we additionally analysed a bias-corrected EURO-CORDEX CCLM4 simulation driven by MPI-ESM-LR (Vautard, R. et al. 2013; Jacob, D. et al. 2014). This yielded a mean annual warming of 0.73 °C in Hungary

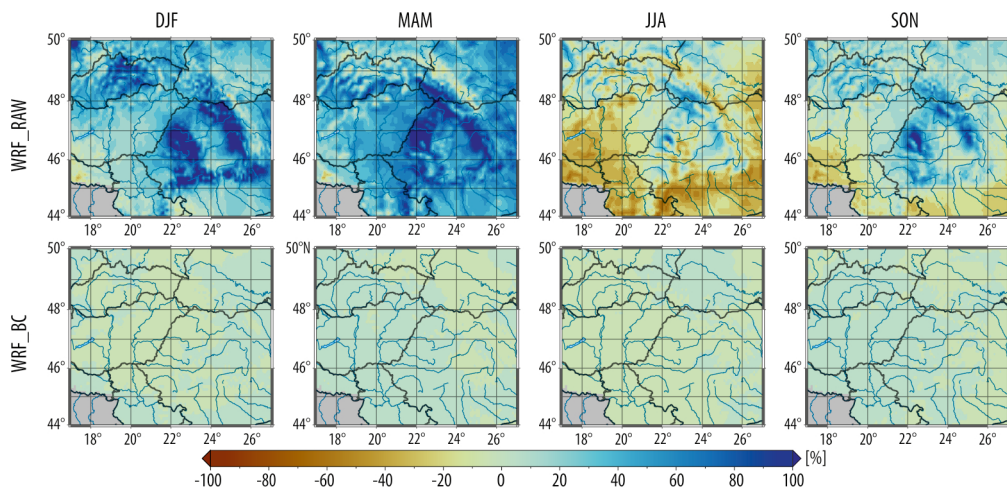


Fig. 3. Relative error of seasonal mean precipitation from the raw (WRF_RAW) and bias-corrected (WRF_BC) WRF simulations during the 1985–2010 period, with respect to the CARPATCLIM observations (DJF = winter, MAM = spring, JJA = summer, SON = autumn). Source: Authors' own elaboration.

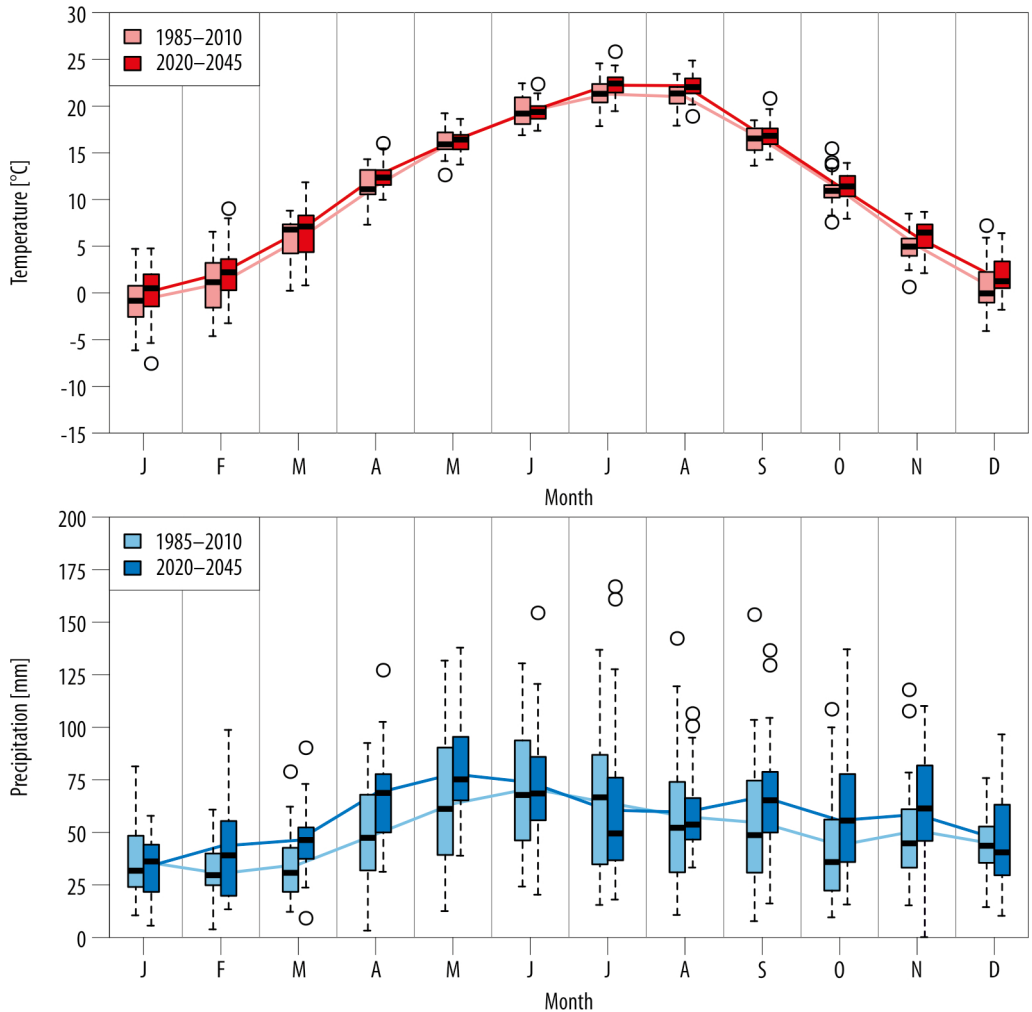


Fig. 4. Annual cycle of monthly mean temperature (top) and precipitation (bottom) from the bias-corrected WRF simulations for the historical (1985–2010) and future (2020–2045) periods, spatially averaged over Hungary. The lines represent the mean values. *Source:* Authors' own elaboration.

between 1985–2010 and 2021–2045, which is consistent with the 0.7 °C warming projected by our WRF simulation.

For precipitation, the WRF model projects a spatially averaged increase of 16 percent over Hungary for the entire 26-year period. However, this change is not evenly distributed across the seasons: winter precipitation is expected to increase by 12 percent, spring by 31 percent, and autumn by 21 percent, while

summer precipitation is projected to remain nearly unchanged, with only a 1 percent increase. A preliminary analysis of the number of days with daily precipitation exceeding specific thresholds indicates that changes between future and historical periods are negligible below the 5 mm/day threshold but exceed 30 percent for thresholds above 15 mm/day (not shown). This suggests an increase in the occurrence of extreme pre-

cipitation. This finding is consistent with previous studies for the Carpathian region and Europe, which project increasing heavy precipitation intensity and frequency under climate change (RAJCZAK, J. and SCHÄR, C. 2017; TORMA, Cs.Zs. et al. 2020). However, a more comprehensive analysis of extremes will be conducted in future research.

The spatial distribution of seasonal mean temperature changes in the near future, relative to the historical period, shows positive values across the study area, with the greatest warming occurring in winter (Figure 5). Winter warming is most pronounced in the northern and eastern parts of the region, exceeding 1.5 °C east of the Carpathian Mountains. This southwest-northeast gradient in projected winter warming, also observed in

spring, is consistent with previous studies using the ensemble mean of eight CORDEX regional climate simulations for the Carpathian region (TORMA, Cs.Zs. and KÍS, A. 2022), as well as the large EURO-CORDEX ensemble (COPPOLA, E. et al. 2021). The amplified winter and spring warming in northern and eastern Europe is attributed to reduced snow cover, which leads to greater solar radiation absorption and enhances warming via the snow albedo feedback. In summer and autumn, no significant spatial patterns of temperature change are observed, except for slight increases over the mountain ranges of the Southern Carpathians. This contrasts with CORDEX simulations, which show a more marked north–south gradient in summer, with stronger warming in the southern

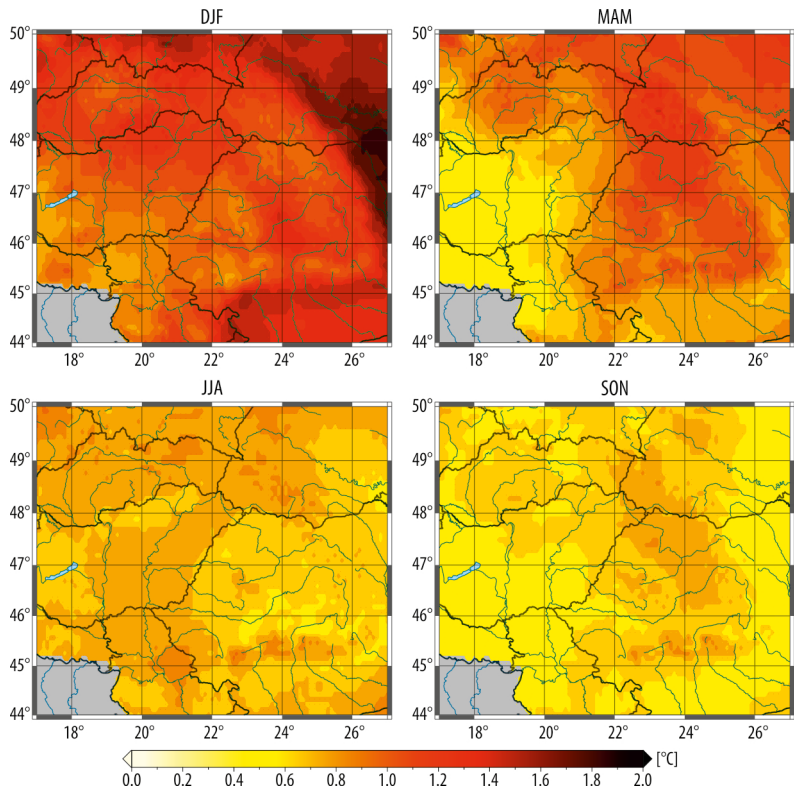


Fig.5. Projected seasonal mean temperature change (2020–2045 relative to 1985–2010) based on the bias-corrected WRF simulations (DJF = winter, MAM = spring, JJA = summer, SON = autumn). Source: Authors' own elaboration.

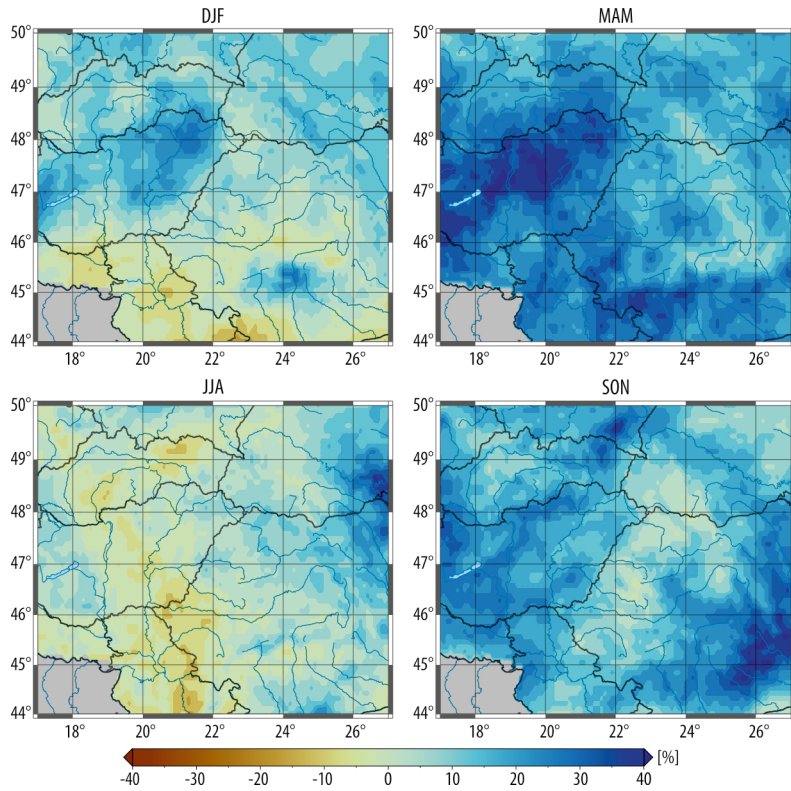


Fig. 6. Projected seasonal mean precipitation change (2020–2045 relative to 1985–2010) based on the bias-corrected WRF simulations (DJF = winter, MAM = spring, JJA = summer, SON = autumn). *Source:* Authors' own elaboration.

parts (COPPOLA, E. *et al.* 2021; TORMA, Cs.Zs. and KIS, A. 2022). Additionally, the ensemble mean of eight CORDEX models analysed by TORMA, Cs.Zs. and KIS, A. (2022) projects the largest warming in summer (2021–2050 relative to 1976–2005) for the Carpathian region, whereas our WRF simulations project stronger winter warming. These discrepancies may arise from the specific features of the MPI-ESM1-2-LR model used to drive our WRF simulations. Additionally, while the CORDEX models were run at similar grid spacing (~ 10 km or 0.11°) and applied a high-end emission scenario (RCP8.5), their boundary conditions were derived from general circulation models based on the CMIP5 protocol, the predecessor of CMIP6, which

was used in our WRF simulations. COPPOLA, E. *et al.* (2021) demonstrated that the CMIP6 ensemble projects stronger warming over Europe in both winter and summer compared to CMIP5, indicating that differences in forcing data may influence the climate change signals of the RCMs. Variations in the temporal coverage and bias correction methods across the studies prevent direct quantitative comparison.

The analysis of the spatial distribution of seasonal mean precipitation change between the near-future and historical periods (Figure 6) shows the largest increases in spring and autumn. The most significant relative increases across the Carpathian region occur over Hungary in both winter

and spring. Precipitation change also exhibits an orographic effect, with larger increases on the eastern (leeward) side of the Carpathian Mountains compared to the western (windward) side. Our results align well with the ensemble mean of six bias-corrected RCMs analysed for the Carpathian region, which also project increasing precipitation in winter, spring, and autumn during the near-future period (TORMA, Cs.Zs. et al. 2020). However, while their ensemble projects decreasing summer precipitation, our WRF simulations indicate a more heterogeneous summer response, with both drying and wetting regions and only a 1 percent increase in the spatially averaged precipitation. Furthermore, the pronounced differences across the Carpathian Mountains are consistent with the strong influence of orography on precipitation change identified by TORMA, Cs.Zs. et al. (2020). However, it should be noted that summer precipitation is primarily convective in nature, making it highly variable spatially and temporally. Its simulation is strongly influenced by model physics and dynamics, leading to high uncertainty in future projections of mean summer precipitation (RAJCZAK, J. and SCHÄR, C. 2017).

Conclusions

The adaptation and application of the WRF model as a regional climate model for the Carpathian region are demonstrated through near-future (2020–2045) projections of temperature and precipitation. WRF was run with a 10 km horizontal grid spacing, driven by the MPI-ESM1-2-LR model from the CMIP6 protocol at the outer boundaries, using the SSP5-8.5 emission scenario. The model was validated and bias-corrected against the CARPATCLIM observational dataset for the historical period (1985–2010). The bias-corrected model was then used to estimate future changes in monthly and seasonal mean temperature and precipitation in the region.

According to the bias-corrected projections, the spatially averaged seasonal mean temperature over Hungary is expected to increase by 1 °C in winter, 0.7 °C in summer, and 0.6 °C in both spring and autumn, relative to the historical period. Precipitation is projected to increase by 12 percent in winter, 31 percent in spring, and 21 percent in autumn, with no noticeable change in summer.

While similarities with previous studies on projected temperature and precipitation changes, based on the state-of-the-art ensemble of CORDEX regional climate simulations, were found, a few discrepancies also emerged. This highlights the importance of using an ensemble framework to obtain robust and reliable climate projections. Individual simulations, such as the one presented here, should be interpreted with caution. Nevertheless, the utility of WRF as a regional climate model for the Carpathian region has been demonstrated, providing a basis for further WRF-based applications in the region, including future kilometre-scale, convection-permitting simulations.

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