IDŐJÁRÁS

Evaluation of EURO-CORDEX and Med-CORDEX precipitation simulations for the Carpathian Region: Bias corrected data and projected changes

Csaba Zsolt Torma[*,1,2], **Anna Kis**[1,3], and **Rita Pongrácz**[1,3]

[1] *Department of Meteorology*
Eötvös Loránd University
Pázmány P. s. 1/A, H-1117, Budapest, Hungary

[2] *HAS Post-Doctoral Research Program*
Budapest, Hungary

[3] *Excellence Center, Faculty of Science*
Eötvös Loránd University
Brunszvik u. 2, H-2462, Martonvásár, Hungary

*Corresponding Author e-mail: tcsabi@caesar.elte.hu

(Manuscript received in final form March 5, 2019)

Abstract—This study aims to give a brief overview of an ensemble of regional climate model (RCM) simulations with and without bias correction for daily precipitation for the Carpathian Region located in Central/Eastern Europe. Within the international initiative called the Coordinated Regional Downscaling Experiment (CORDEX), EURO-CORDEX and Med-CORDEX provide RCM simulations targeting Europe as a whole or in a part at the grid resolutions of 0.44° (~50 km) and 0.11° (~12 km). The ensemble of RCMs provides a huge amount of data, which are, however, prone to biases compared to high-resolution observations. First, the bias correction of the daily precipitation output of EURO-CORDEX and Med-CORDEX RCM ensemble at a common $0.11^\circ \times 0.11^\circ$ horizontal grid resolution is performed based on the high-resolution, high-quality observational dataset CARPATCLIM. The region covered by the CARPATCLIM dataset can be considered as the Carpathian Region, for which the RCM ensemble (consisting of six members in total at 0.11° resolution) of a historical period (1976−2005) and under the Representative Concentration Pathway 8.5 (RCP8.5) over two future time slices (2021−2050 and 2070−2099) are assessed. Percentile-based bias correction method was used in order to adjust systematic biases in all simulated precipitation fields. The present study focuses on different precipitation climate indices derived from high-resolution RCM outputs over the entire Carpathian Region and specifically two sub-regions representing high- and lowlands

within the target region. The analyzed indices are as follows: the frequency of rainy days (RR1, days with a total rainfall of at least 1 mm), heavy precipitation days (RR10, days with a total rainfall of at least 10 mm), highest daily precipitation (RX1), maximum consecutive dry periods (CDD, the duration of the longest period with < 1 mm total daily precipitation), maximum consecutive wet periods (CWD, the duration of the longest period with > 1 mm total daily precipitation). Our results indicate that both the spatial distribution and magnitude of mean changes are similar to those found in previous works based on ENSEMBLES project simulations using a different greenhouse gas emission scenario. Furthermore, the present study also aims to introduce a high-resolution bias-corrected precipitation database, which can serve as input for climate change impact and adaptation studies to be carried out for the Carpathian Region and to provide important information to stakeholders and decision makers at local/regional/national levels.

Key-words: EURO-CORDEX, Med-CORDEX, CARPATCLIM, Carpathian Region, precipitation, bias correction, regional climate change, precipitation climate indices

1. Introduction

Information is of great value. One of the most crucial issues concerning climate change is: what impacts and changes will the changing climate have in the future? An important aspect of this question is that all precipitation projections come with a certain degree of uncertainty, which can have different sources. On the one hand, climate models can be useful tools for providing information on human induced climate change (*IPCC*, 2013), but on the other hand, the climatic parameters derived from climate model simulations are encumbered with high uncertainties. In fact, climate model simulations are characterized by biases compared to observations (*Torma et al.*, 2011; *Kotlarski et al.*, 2014). The main sources of uncertainties of global climate model (GCM) simulations can be attributed to (1) the internal climatic variability (in the absence of any external radiative forcing), (2) the implemented parameterization and model dynamics (model or response uncertainty), (3) the prescribed emission scenarios (scenario uncertainty), or (4) model systematic errors. Furthermore, RCM projections include additional uncertainties due to simulation configuration features as the choice of integration domain, resolution, lateral boundary conditions (LBCs), etc. Precipitation projections for the Carpathian Region, which is characterized by complex topography (with an altitude range between 27 m and 2655 m) and is located in Central Europe, where warmer Mediterranean climate meets the colder, continental northeastern European air masses, come with a certain degree of uncertainty (*IPCC*, 2013; *Gaál et al.*, 2014; *Fischer et al.*, 2015).

However, climate models may exhibit substantial systematic errors at different horizontal resolutions with distinct origins; valuable efforts can be done by adjusting or correcting those. In general, when bias correcting the raw climate simulation data, we can ensure the equal means between the observations and the bias-corrected climate simulation data (*Déqué et. al.*, 2007). More recent and sophisticated methods (*Berg et al.*, 2012; *Lafon et al.*, 2013) ensure to fit the whole

distribution of climate model simulation to observations for a given meteorological variable (e.g., precipitation). The non-parametric (any prior knowledge of the theoretical distribution of the assessed variable is not required) quantile mapping method is considered to be among the best methods in reproducing not only the means but also other statistical properties (standard deviation, quantiles, etc). In principle, the quantile mapping method is easy to implement, which makes this method attractive among the climate research community (e.g., *Gudmundsson et al*., 2012; *Fang et al*., 2015). Note that the method requires a reliable observational dataset serving as reference data. From this point of view, a high-resolution, quality controlled, and homogenized observational dataset is essential in the bias correcting process. The CARPATCLIM (*Szalai et al*., 2013) dataset served as reference in the present study since it is a high-resolution and high-quality observational dataset, thus optimal for such purposes. Additionally, the CARPATCLIM dataset covers the region of interest, which is the Carpathian Region in this study.

A few RCM-based high-resolution (25 km or finer grid spacing) climate change projects have been accomplished encompassing the entire domain of the Carpathian Region in the last two decades, namely, ENSEMBLES (Ensembles-Based Predictions of Climate Changes and Their Impacts, 2004−2009; *Hewitt* and *Griggs*, 2004), CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment, 2006−2009; *Halenka*, 2007), and CORDEX (The Coordinated Regional Downscaling Experiment, *Giorgi et al*., 2009), which is the most recent international initiative with the task of producing reliable regional climate simulations for several well-defined domains under the supervision of the World Climate Research Programme (WCRP). EURO-CORDEX (*Jacob et al*., 2014) and Med-CORDEX (*Ruti et al*., 2016) both target Europe with a more and a less extended modeling domain, respectively. More precisely, EURO-CORDEX covers the entire continent, whereas Med-CORDEX focuses on the Mediterranean region, i.e., the southern part of Europe up to the 50°N. As being parts of CORDEX, they provide RCM simulations targeting European regions at grid resolutions of 0.44° (~50 km, medium resolution) and of 0.11° (~12 km, high-resolution).

We post-processed and analyzed a 6-member RCM ensemble (*Table 1*) involving EURO-CORDEX and Med-CORDEX high-resolution RCM simulations under the high-end greenhouse gas scenario RCP8.5 (*Moss et al*., 2010). Following the work of *Mezghani et al*. (2017), the percentile-based quantile mapping method was used for bias correcting precipitation projections obtained from the high-resolution RCM simulations. The bias-corrected daily total precipitation data obtained from the aforementioned RCM ensemble is assessed for future periods 2021−2050 and 2070−2099 with respect to the reference period 1976−2005 (which is the last 30 years of processed historical simulations) over the Carpathian Region. Changes in mean seasonal precipitation characteristics are reported not only for the entire Carpathian Region, but also for

two sub-regions selected along the same latitude representing low- and highlands with low and high mean altitudes, respectively (*Fig. 1*). Precipitation climate indices are also involved in the assessment of future precipitation characteristic and summarized in detail in *Table 2*.

Table 1. Overview of global (a-d) and regional (e-j) climate models used in the present study. For the regional models the letter in parenthesis indicates the driving GCM (from CMIP5) and whether the run accomplished over the EURO-CORDEX (EC) or MED-CORDEX (MC) domain.

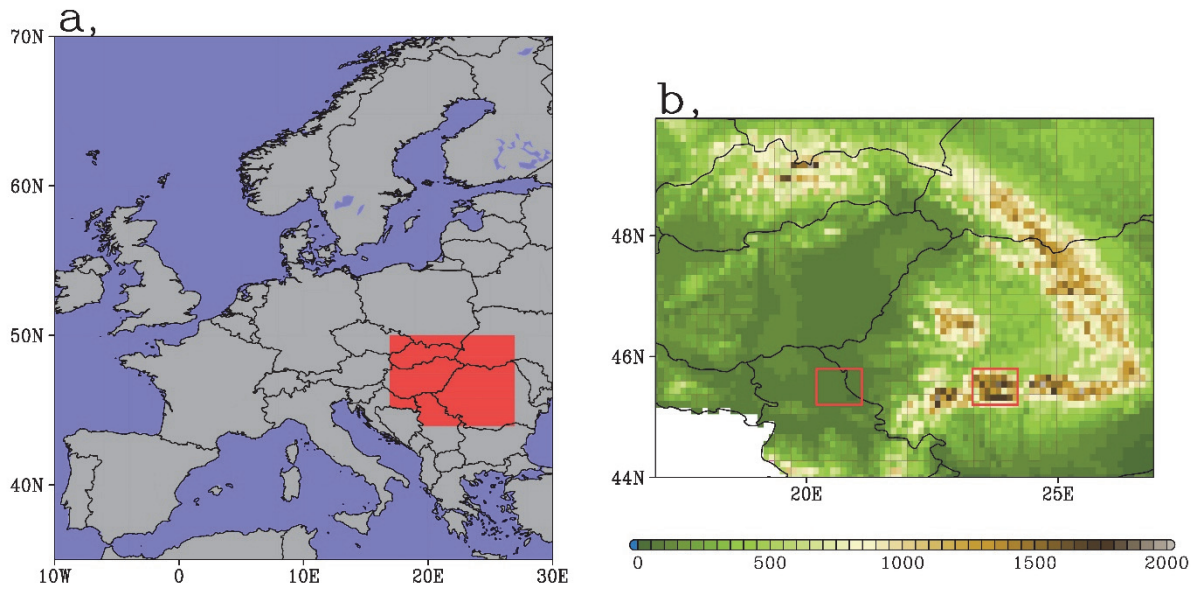| Model	Modelling group	Horizontal resolution	Convection scheme
a, CNRM-CM5 (*Voldoire et al.*, 2012)	Centre National de Recherches Meteorologiques and Centre Europeen de Recherches et de Formation Avancee en Calcul Scientifique, France	1.40625°	*Bougeault* (1985) with a *Kuo* (1965) type closure
b, EC-EARTH (*Hazeleger et al.,* 2010)	Irish Centre for High-End Computing, Ireland	1.125°	*Bechtold et al.* (2008)
c, HadGEM2-ES (Collins et al., 2011)	Met Office Hadley Centre, UK	1.875°(lon) × 1.2413°(lat)	*Derbyshire et al.* (2004)
d, MPI-ESM-LR (Jungclaus et al., 2010)	Max Planck Institute for Meteorology, Germany	1.875°	*Tiedtke* (1989)
e, ALADIN (a-MC) (Colin et al., 2010)	Centre National de Recherches Meteorologiques, France	0.11°	*Bougeault* (1985) with a *Kuo* (1965) type closure
f, CCLM (d-EC) (Rockel et al., 2008)	Climate Limited-area Modelling Community, Germany	0.11°	*Tiedtke* (1989)
g, RCA4 (c-EC) (Kupiainen et al., 2014)	Swedish Meteorological and Hydrological Institute, Rossby Centre, Sweden	0.11°	*Kain* and *Fritsch* (1993)
h, RACMO (b-EC) (Meijgaard van et al., 2012)	Royal Netherlands Meteorological Institute, The Netherlands	0.11°	*Tiedtke* (1989), *Nordeng* (1994), *Neggers et al.* (2009)
i, REMO (d-EC) (Jacob et al., 2001)	Max-Planck-Institut für Meteorologie, Germany	0.11°	*Tiedtke* (1989), *Nordeng* (1994), *Pfeifer* (2006)
j, RegCM4 (c-MC) (*Giorgi et al.*, 2012)	International Centre for Theoretical Physics, Italy	0.11°	*Grell* (1993), *Emanuel* (1991)

Fig. 1. Analysis region and topography (on a common 0.11° grid) over the Carpathian Region. a) Location of the analysis region within the European domain (red area); b) topography based on the GTOPO30 database. Sub-regions within red boxes are for representing low- and highlands in the region of interest. Units in b) are m.

Table 2. Description of analyzed precipitation indices.

Abbreviation of index	Definition	Unit
CDD	Maximum number of consecutive dry days with daily precipitation sum < 1 mm	day
CWD	Maximum number of consecutive wet days with daily precipitation sum > 1 mm	day
RR1	Number of wet days (daily precipitation sum > 1 mm)	day
RR10	Number of days with heavy precipitation (daily precipitation sum ≥ 10 mm)	day
RX1	Highest total daily precipitation	mm

The present study follows the work of *Mezghani et al.* (2017), which introduces a publicly available bias-corrected dataset consisting projected daily precipitation totals along with near surface air temperature (minimum, maximum, and mean) for the region of Poland. Here we present the initial steps towards

creating similar dataset for the Carpathian Region with special focus on precipitation. One of the main objectives of the present work is to introduce a publicly available high-resolution RCM based, bias-corrected precipitation dataset, which can serve as a fundamental input for application to regional risk assessment or impact studies for the Carpathian Region. We also aim to provide a brief summary on the assessment of the possible future climatic precipitation characteristics over the Carpathian Region based on such dataset. The introduced dataset will be publicly available shortly after publication, upon request.

2. Data and methods

2.1. The CARPATCLIM gridded observational dataset

The CARPATCLIM dataset provides 16 daily meteorological variables (including daily total precipitation) and related derived indicators for the period of 1961−2010 encompassing the Carpathian Region at $0.1° \times 0.1°$ horizontal grid resolution (*Szalai et al.*, 2013). This climatic database is station-based, state-of-the-art quality controlled, covers the Carpathian Mountains and the whole Carpathian Basin (approximately 500 000 km^2), and freely available for scientific purposes through the following link: http://www.carpatclim-eu.org. From a network of meteorological weather stations covering the region of interest 904 stations were used in collecting daily total precipitation data (*Spinoni et al.*, 2015). The technique of Multiple Analysis of Series for Homogenized Database (MASH; *Szentimrey,* 2007) is used for homogenization and checking data quality, while the Meteorological Interpolation based on Surface Homogenized Database (MISH; *Szentimrey* and *Bihari*, 2006) method is applied for gridding and interpolating within the CARPATCLIM database. Thus, the CARPATCLIM is the ideal and best currently publicly available high-resolution climatological dataset, which includes daily total precipitation that can serve as reference for bias correction studies over the Carpathian Region with special focus on precipitation.

2.2. RCM simulations

Several RCM experiments have been accomplished over each of the 14 different sub-regions of the globe in the framework of CORDEX. The European continent is targeted by two different sub-programs of CORDEX: EURO-CORDEX and Med-CORDEX, both provide RCM simulations for Europe (Med-CORDEX is focusing on the Mediterranean region, between the latitudes of 30°N and 50°N) at grid resolutions of 0.44° and 0.11°. As both initiatives provide data encompassing the whole Carpathian Region, they are ideal for investigating RCM simulations obtained from the EURO- and Med-CORDEX programs. We used an ensemble of RCM simulations consisting six RCM simulations driven by four different GCMs (*Table 1*). All RCM simulations involved in the present study

follow the high-end RCP8.5 scenario (*Moss et al.*, 2010) and were obtained from the EURO-CORDEX and the Med-CORDEX initiatives. Although some RCMs are available with multiple simulations (different driving GCMs, different realizations, etc.) within the CORDEX project, our selected ensemble includes only one simulation from each individual RCM in the interest of any of the RCMs that should not dominate the selected ensemble. Our study focuses on present climatic conditions (1976−2005), and on projections for the future periods 2021−2050 (near future) and 2070−2099 (far future) with respect to the reference period 1976−2005 (the last 30 years of historic runs within CORDEX).

Since the RCM simulations and the CARPATCLIM dataset are available on different horizontal grids, all simulation data and observational data were interpolated onto a common grid by following the previous work of *Torma et al.* (2015). The Climate Data Operators software (CDO, https://code.mpimet. mpg.de/projects/cdo) was used during the interpolation processes. More specifically, the distance-weighted average remapping method was used in order to all data share the same grid. However, several different interpolation methods are available in the framework of CDO, such as bicubic, bilinear, distance weighted, or field conserving, the distance-weighted method was found to be the most spatial pattern consistent between different horizontal resolutions over regions with complex topography (*Torma et al.*, 2015). All data reported in the present study are represented on the common 0.11° grid.

2.3. Bias correction method

Either of available bias correction methods is used, one has to keep in mind, that bias correction is a mere statistical post-processing tool, which cannot be expected to overcome the fundamental shortcomings of any climate model (*Maraun*, 2016). To correct the systematic biases present in our RCM ensemble, we used a percentile-based bias correction method (or quantile mapping; *Wang et al.*, 2016). The percentile-based bias correction technique is considered to be flexible and to be a prominent representative of the most frequently used bias correction techniques by the climate research community (e.g., *Teutschbein* and *Seibert*, 2013; *Rajczak et al.*, 2016; *Kis et al.*, 2017). In general, the quantile mapping method employs a quantile-based transformation of distributions in order to adjust the variance of simulated distribution to better match the variance obtained from the observations. It is also important to note that the quantile mapping has a few limitations, which must be taken into consideration. The method is considered to be sensitive to the length and quality of the calibration or reference dataset (*Fowler* and *Kilsby*, 2007). Regarding the aforementioned facts, under different climatic conditions, unobserved values may not present in the calibration dataset in that given time period (*Themeßl et al.*, 2010). Following the work of *Mezghani et al.* (2017), the adjustment of all simulated daily precipitation to the observations was performed for each grid cell after interpolating all data onto the common

0.11° grid. In addition, an adjustment for rainy day frequencies was applied with a given threshold of 0 mm day^{-1}. In order to compute the threshold, the probability of rainy days was first determined based on observations, and then all modeled data below that threshold were set to zero. Accordingly, all modeled data were fitted to the portion of the distributions of observed rainy days. The present study represents data derived from simulations bias-corrected by the quantile mapping technique, where the number of quantiles was set to 1000. Additionally, the quantile mapping method was used on seasonal scale in order to take into account the seasonal behavior of biases (e.g., correction factors were computed for each season for each grid cell). Finally, the quantiles of the RCM simulations for the analyzed periods were mapped onto the corresponding quantiles derived from observations using the entire available period of CARPATCLIM (1961−2010). This was done in order to minimize the sensitivity to the choice of the calibration time period, when some unobserved values may lie outside the range, if too short time period is considered as calibration period.

2.4. Precipitation climate indices

Based on the bias-corrected high-resolution RCM simulation ensemble, in total, 5 precipitation climate indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI, e.g., *Sillmann et al.*, 2013) are calculated and analyzed over the region of interest. The analyzed indices are as follows: frequency of rainy days (RR1), heavy precipitation days (RR10), highest daily precipitation sum (RX1), maximum consecutive dry periods (CDD), and maximum consecutive wet periods (CWD). Indices selected from ETCCDI are analyzed for the following reasons: RR1 and CWD represent wet conditions, while CDD represents dry spells. RX1 represents precipitation intensity and RR10 represents extreme precipitation events. All indices are reported in detail in *Table 2*.

3. Results

3.1. Evaluating raw and bias-corrected RCM-simulated precipitation against CARPATCLIM (1976–2005)

The period 1976−2005 served as reference for which the historical RCM simulations were evaluated first. Model errors usually show spatial and temporal dependence. More specifically, wet and dry regions vary depending on the season across the region of interest. The biases of simulated seasonal and annual precipitation fields compared to CARPATCLIM show their maxima over mountainous regions, which can also be attributed to the low station network density over those regions. As the thorough comparison of analyzed RCMs before and after bias-correction are out of the scope of the present work, here we report only a representative example of RCM performance on representing precipitation

in the form of spatial plot in *Fig. 2*. For this purpose, we show as an example of the high-resolution run of RCM named as KNMI-RACMO22E (hereafter RACMO) driven by EC-EARTH validation against CARPATCLIM before and after bias correcting the daily precipitation sums. *Fig. 2* depicts not only the negative or positive bias of simulated precipitation, but in the form of root mean square error (RMSE) given on each panel, it also gives information on the magnitude of overall deviation between simulated and observed precipitation taking into account all the grid cells over the entire Carpathian Region. In case of RACMO, the raw data holds high seasonal RMSE, especially in winter and summer (16.28 mm month^{-1} and 16.43 mm month^{-1}, respectively), while for the transition seasons, slightly more modest RMSE values were found (12.09 mm month^{-1} for spring, and 12.22 mm month^{-1} for autumn). Relatively smaller RMSE was found on annual scale (10.23 mm month^{-1}). The highest biases occurred along the chains of the Carpathian Mountains, especially over the southern flanks of the Southern Carpathians, where a positive bias can exceed 100 mm month^{-1}. The RMSEs obtained from the bias-corrected simulation found to be much lower compared to those derived from the raw simulation and were close to 2 mm month^{-1} for annual and seasonal means, except for summer (4.01 mm month^{-1}). After bias correction, the annual and seasonal precipitation biases on individual grid cells were found to be between –20 and +20 mm month^{-1}.
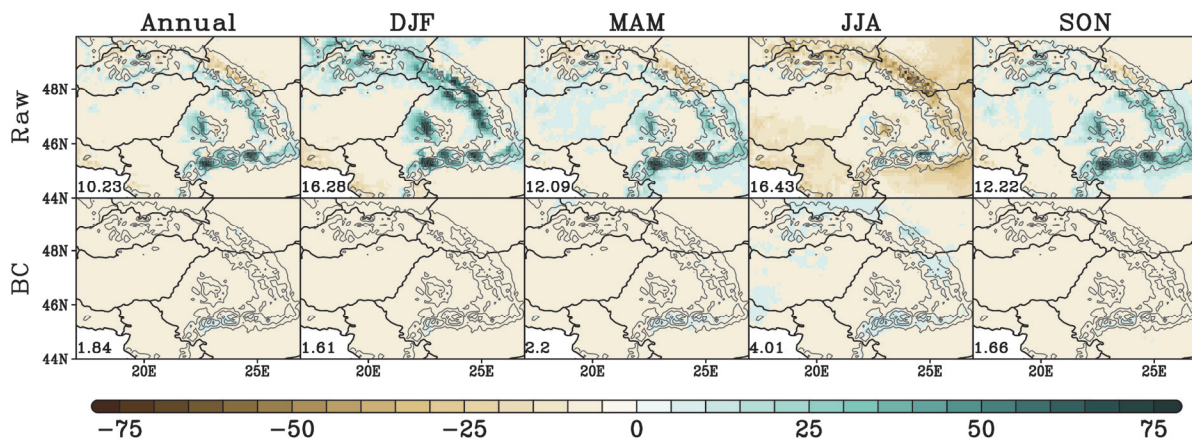

Fig. 2. Annual and seasonal precipitation bias with (labeled as "BC" maps in the lower panels) and without (labeled as "Raw" maps in the upper panels) bias correction for the RACMO model simulation (see *Table 1*), for the period 1976–2005. The root-mean-squared error (RMSE) is averaged for the whole domain and is given in mm/month in the lower left corner of each panel.

Next, the RCM simulations were assessed for the reference period over the two selected sub-regions along the same latitude (*Figs. 3* and *4*), as an additional

measure on their performance across the Carpathian Region. *Fig. 3* reports the individual RCMs simulated seasonal precipitation totals for both sub-regions with and without bias correction. In general, over the mountainous sub-region, the seasonal precipitation positive bias is more pronounced compared to the sub-region with low average elevation. Taking into account all simulations, the relative bias varies between –49% and 53% (–37% and 159%) in the case of lowland (mountainous region). On the one hand, over the mountainous sub-region, the exaggerated simulated seasonal precipitation totals (compared to CARPATCLIM) can indicate the relatively sparse station network density. On the other hand, it can also allude to the fact, that how challenging the simulation of precipitation over mountainous region can be. *Fig. 3* also shows that seasonal precipitation is overestimated by most of the models over both sub-regions in all seasons, except for summer (JJA). Note that only the ALADIN model overestimated the seasonal total precipitation regardless of the season and sub-region with a somehow exaggerated summer maximum. The latter may be attributed to the sensitivity of the applied convective parameterization. After the quantile mapping bias correction, the biases present in the raw simulated seasonal precipitation totals were almost eliminated, leading to negligible differences between RCMs and observational seasonal precipitation totals. In the case of lowland (mountainous region), the relative bias is between –4% and 4% (–1% and 8%), which is substantially less than in the case of raw simulations. The remaining slight discrepancy is due to the fact that the calibration period (1961–2010) embeds the reference period (1976–2005) used in our study and they are not identical.

Other metrics are also known to evaluate the performance of climate models in simulating present climatic conditions (*Zhao et al.*, 2013). Besides computing the mean bias and RMSE (e.g., *Fig. 2*), the degree of statistical similarity between the simulated and observational fields can be concisely quantified and displayed in the form of Taylor diagrams (*Taylor*, 2001). *Fig. 4* summarizes the performance of each RCM over the sub-regions with respect to CARPATCLIM over the period 1976−2005 in the form of Taylor diagrams. More specifically, the azimuthal position of symbols present in *Fig. 4* refers to the correlation coefficient between the RCM simulations and the CARPATCLIM, the radial distance from the reference point (marked with black dot) to each symbol indicate the centered RMSE, while the distance from point 0 shows the ratio of standard deviation derived from the RCM simulations against the observations. In *Fig. 4*, all RCM simulations are represented by symbols filled with different colors. More precisely, color refers to the RCM, while the raw and bias-corrected simulated precipitation is denoted by different symbols (square and circle, respectively). Among others, *Fig. 4* reports the imperfection of the raw RCM simulations, which is partly due to biases inherited by the driving fields provided by GCMs. Regardless the sub-region, the raw RCM simulations are characterized by very low (or even negative) and high (in case of ALADIN) spatial correlation

coefficients, varying between –0.3 and 0.93, while after bias correcting the RCM simulated precipitation fields, the spatial correlation coefficients are found to be within the range of 0.65 and 0.94 (so the low and negative values disappear). Regarding the centered RMSE and the standard deviation, both metrics show the clear signal of the bias correction on RCM precipitation fields by tending towards them to the observations over both sub-regions. It is also interesting to note that RACMO with and without bias correction is among the best performing RCMs over both sub-regions. In summary, over both sub-regions the application of the bias correction method leads to the substantial improvement of the simulated precipitation distributions with respect to CARPATCLIM.

Fig. 3. Seasonal precipitation bias over the sub-regions with (on the right) and without (on the left) bias correction for all RCMs (see Table 1), for the period 1976–2005.
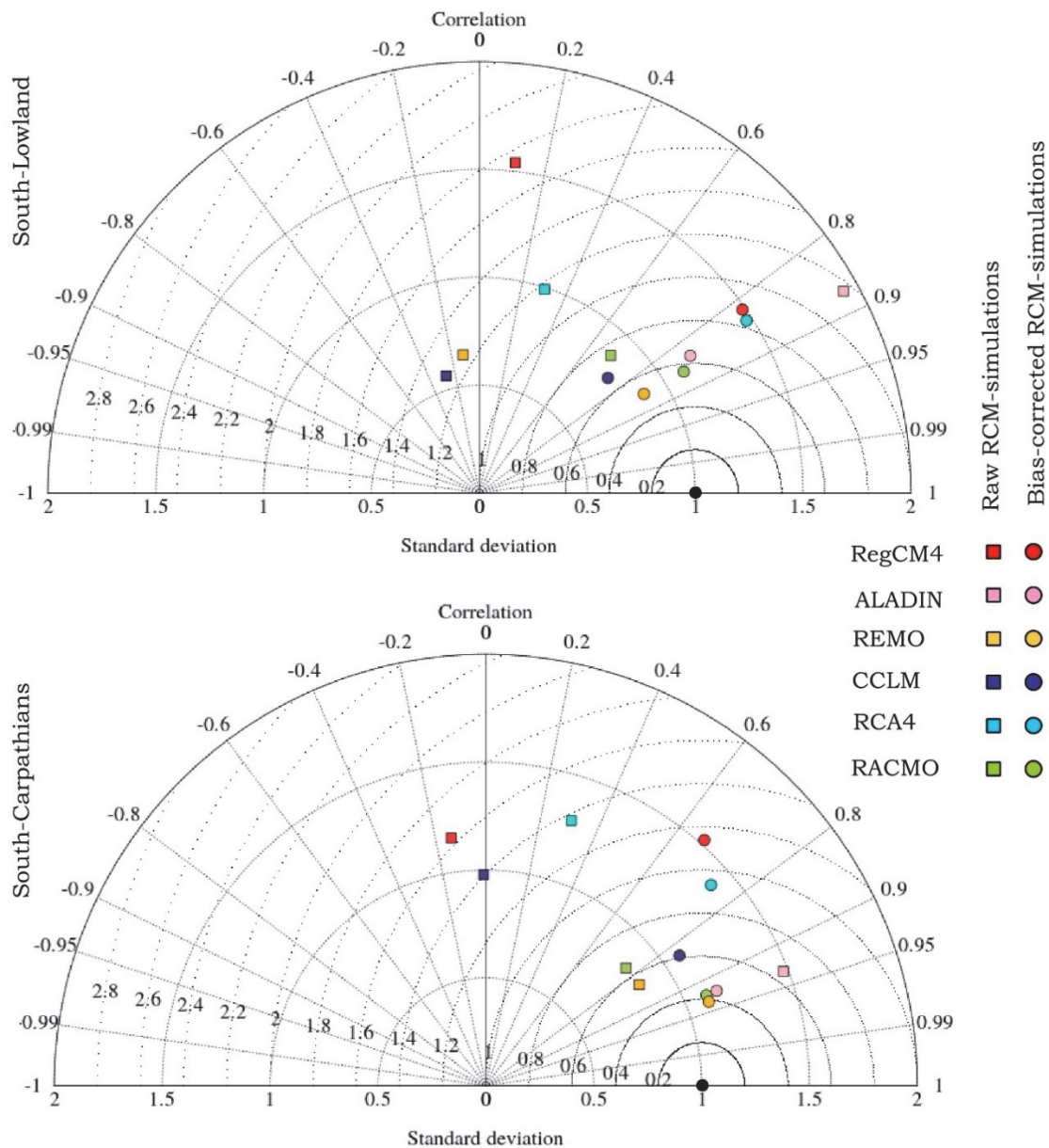
Fig. 4. Taylor diagrams for summarizing the statistical characteristics of simulation data and the effect of bias correction for the two selected sub-regions, for the period 1976–2005.

3.2. Seasonal mean precipitation projections

After having assessed the RCM simulations with and without bias correction for the historical period 1976−2005, now we turn our attention to the projected precipitation changes. Toward this purpose, we analyzed the six-member high-resolution bias-corrected RCM ensemble including projections following

the high-end RCP8.5 greenhouse gas concentration for the future time periods: 2021−2050 and 2070−2099, with respect to the historical period. *Fig. 5* shows the change in ensemble mean seasonal precipitation over the region of interest for both future time slices. Dotting indicates regions where at least 4 out of 6 RCMs agree on that seasonal precipitation change is statistically significant at the 90% confidence level using two-sided t-test. Thus, findings are considered robust over regions highlighted by dots. According to *Fig. 5,* it is evident that during the 21st century, the region of interest is likely to experience a general increase in precipitation during all seasons, except for summer. On the one hand, the mean seasonal precipitation changes found to be similar for both future time periods (regarding the sign and spatial pattern), but on the other hand, these changes found to be more prominent and robust by the end of the 21st century (2070−2099) than by the mid-century. For this reason, hereafter in this section, we focus on changes by the end of the century. The bias-corrected RCM simulations show a maximum winter (DJF) precipitation increase in the western part of the region (mostly covering the territory of Hungary) and surrounding the mountain chains of the Carpathians exceeding 30%. The latter one can indicate the sign of the topographically induced precipitation change. Regarding the sign and spatial distribution, very similar but less pronounced changes were found for spring (MAM) within the range of 0%–30%. It is also interesting to note that precipitation increase in DJF and MAM tends to be more moderate towards the south over the Southern Carpathians, while the precipitation change signal is the opposite over the northern and southern parts of the Southern Carpathians (-15%−0%, but being mostly not significant) in autumn (SON). Obviously, the orientation of the southern flanks of the Carpathians plays a key role in this process (precipitation shadowing effect) along with the prevailing wind flow change (*Zappa et al.*, 2013). The models project significant precipitation decrease in the summer season (JJA) over the selected domain, reaching a maximum of -25% − -30% over the southern regions of the Carpathian Basin. This raises a major concern on future fresh water availability (e.g., irrigation), since the precipitation maximum occurs in the summer season. In summary, our findings on seasonal precipitation change confirm previous studies reporting general winter precipitation increase and decrease in summer over the region of interest (e.g., *Jacob et al.*, 2014; *Kis et al.*, 2017).
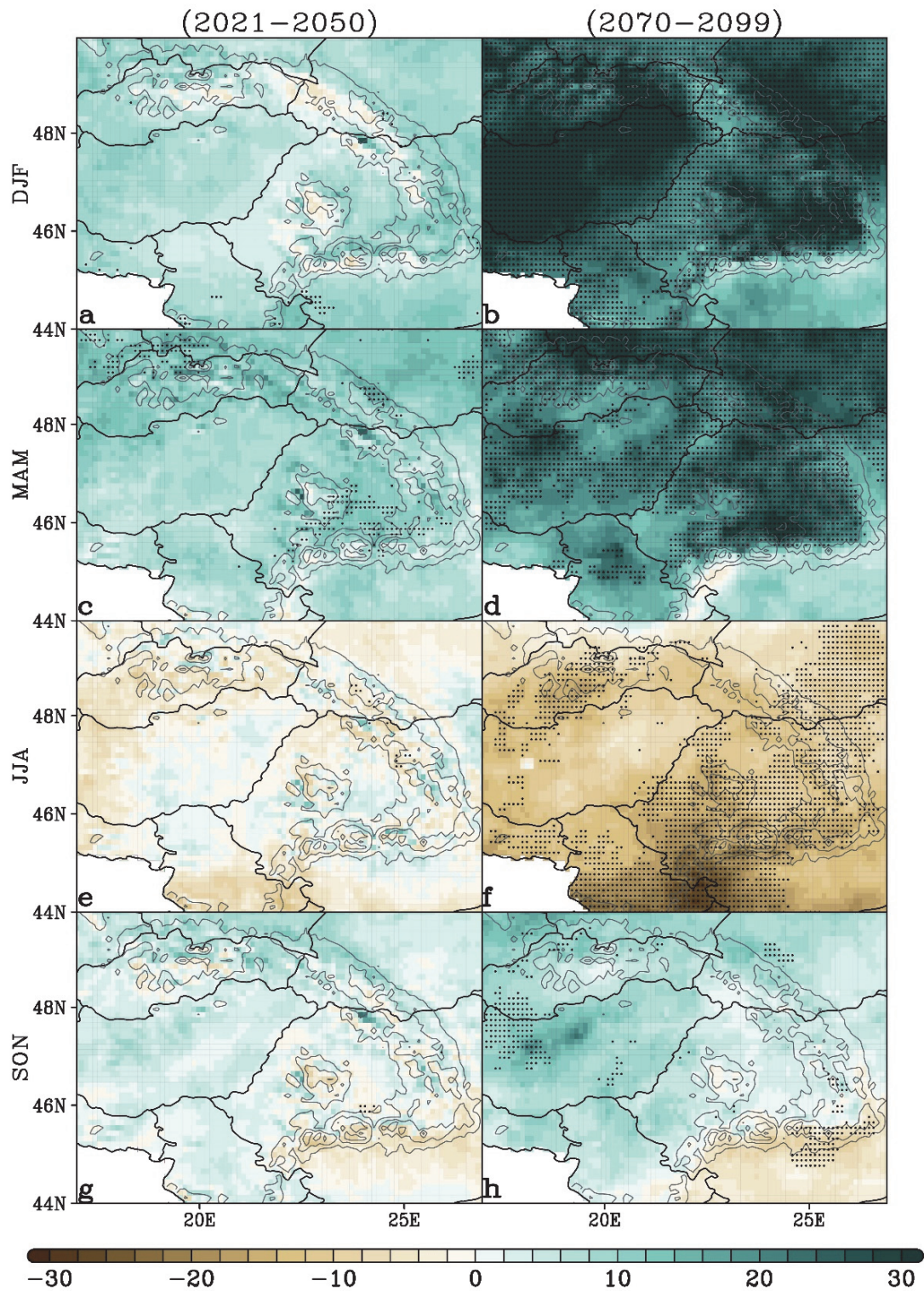
Fig. 5. Ensemble average of the projected seasonal precipitation change over the Carpathian Region. The changes are presented for two different future time slices compared with the reference period 1976–2005, derived from the RCM ensemble (see *Table 1*; units of percentage of reference period values) for 2021–2050: DJF (a), MAM (c), JJA (e), and SON (g). For far future (2070–2099): DJF (b), MAM (d), JJA (f), and SON (h). Dotting indicates areas where at least 4 out of 6 RCMs agree on that precipitation change is statistically significant at the 90% confidence level. Thin contour lines represent topography with the intervals of 500 m. Thick black lines show country borders.

3.3. Estimated changes of precipitation climate indices

As discussed in the previous Section (3.2) the assessed RCM ensemble projects robust precipitation change only by the end of the 21st century, therefore climate index changes are analyzed and reported only for this later future period in *Fig. 6.* More specifically, Figure 6 summarizes the spatial distribution of the aforementioned climate indices' winter and summer changes projected by 2070−2099 with respect to 1976−2005 over the Carpathian Region. Noting that, indices which take into account several days (CDD and CWD) and based on bias corrected model data are not expected to perfectly match with observations due to some residual bias. Whilst one-day indices based on bias corrected data expected to be really close to observations. The estimated changes of CWD and CDD are not found significant in DJF. Whilst, the maximum length of dry periods in JJA is projected to be significantly extended over most part of the region with a maximum increase of 7 days. Note that the maximum increase of CDD is projected over the same region where the maximum summer precipitation decrease is estimated to occur. CWD does not show robust change with any particular topographical feature. Estimated change of RR1 shows similar seasonal and spatial patterns to CDD changes. More specifically, the absolute increase of RR1 is robust in winter and estimated to increase by 2–3 days per season in the northern regions of the Carpathian Mountains. While in summer, the projected decrease of RR1 is found to be significant technically all over the region of interest. It is also interesting to note the evidence of the topographical modulation of the Carpathians on the spatial distribution in the summer change of RR1, where the estimated decrease can reach 7– 8 days per season over the mountain peaks. The more abundant future winter precipitation reported in Section 3.2. is associated with more intense daily precipitation totals: RX1 relative change is estimated to reach a maximum of 50% over the Northeastern Carpathians. A moderate increase of RX1 is simulated for summer over most part of the Carpathian Region, but with a slight decrease (~10%) over the western part of the Southern Carpathians. In terms of the sign and spatial distribution, the increase of RR10 is found to be in line with the winter precipitation change, even the changes are robust only for the interior of the chains of Carpathians reaching 2–3 days more per season. In the meanwhile, RR10 in summer is estimated to decrease with the same magnitude over the peaks of the Carpathians, the region of Croatia, and the southern parts of Serbia covered by the CARPATCLIM dataset.

In summary, the number of days with precipitation total exceeding 1 mm is estimated to decrease; also the intensity of rainy events is estimated to decrease over the western part of the Southern Carpathians, leading the climate of that region considerably drier. In addition, the overall winter and summer precipitation changes are fostered by the projected robust changes found for RX1 and RR1, respectively.
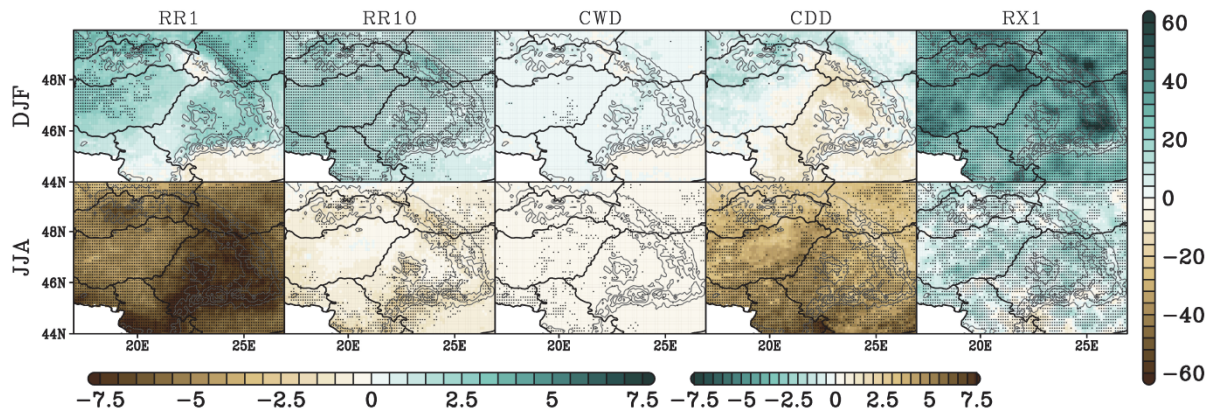
Fig. 6. Ensemble average of the projected winter (DJF) and summer (JJA) change of precipitation climate indices for the far future (2070–2099). Dotting indicates areas where at least 4 out of 6 RCMs agree on that precipitation change is statistically significant at the 90% confidence level. Thin contour lines represent topography with the intervals of 500 m. Units are day season^{-1}, while changes are given in % for RX1. Thick black lines show country borders.

In order to assess the possible role of orography on the projected changes in precipitation and the analyzed climate indices, further assessments are needed. Toward this purpose, the estimated changes of the precipitation indices over the two specific sub-regions within the Carpathian Region for time slices 2021−2050 and 2070−2099 compared to the reference period 1976−2005 were computed and are reported in *Fig. 7*. The bars with different colors depict the arithmetic mean of the climate index derived from the RCM simulations (2021−2050 is represented by dark, while 2070−2099 period is represented by light colors), while the vertical black line displayed over each bar indicates the minimum and maximum values (the entire spread of the six-member RCM ensemble). According to the sign and magnitude of the estimated changes of climate indices, slight differences were found between the analyzed sub-regions. In general, most climate indices show a more pronounced change in the far future (2070−2099) compared to the earlier time slice (2021−2050). No substantial changes were found for the frequency of rainy days (RR1) in DJF and MAM, while it is projected to decrease in JJA and SON by ~10−20% on average, with the maximum in JJA. Slight differences can be seen over the sub-regions in the estimated seasonal changes of RR10. More specifically, days with precipitation sum exceeding 10 mm are projected to become more frequent in DJF and MAM (by ~30−50% and by 20−35%, respectively). It is interesting to note that a more pronounced increase in RR10 is found over the sub-region with lower mean elevation. By the end of the 21st century, about 15% less RR10 is projected in JJA over both sub-regions, whilst small decrease (~5%) along with a more robust increase (~15%) is estimated in SON over the low elevation and the mountainous sub-regions, respectively. Thus, the estimated changes of RR1 and

RR10 envision the modulation of the annual precipitation cycle over the analyzed sub-regions. RX1 shows very similar increase in all seasons over both sub-regions (~10–20% in DJF, ~10–30% in MAM, and ~5–15% in JJA), except for SON, when over the mountainous sub-region, the increase of RX1 is more modest (~10%) compared to the other sub-region at lower elevation (~35%). According to the assessed precipitation climate indices, longer wet periods (CWD) are projected in DJF and MAM (~10%), whereas shorter wet periods in JJA and in SON (5–15%). Along with this, longer dry periods (CDD) are projected over both sub-regions by ~10–30% in JJA and SON by the end of the 21st century. Note that only negligible changes are estimated in CDD for DJF and MAM, regardless of the sub-region.
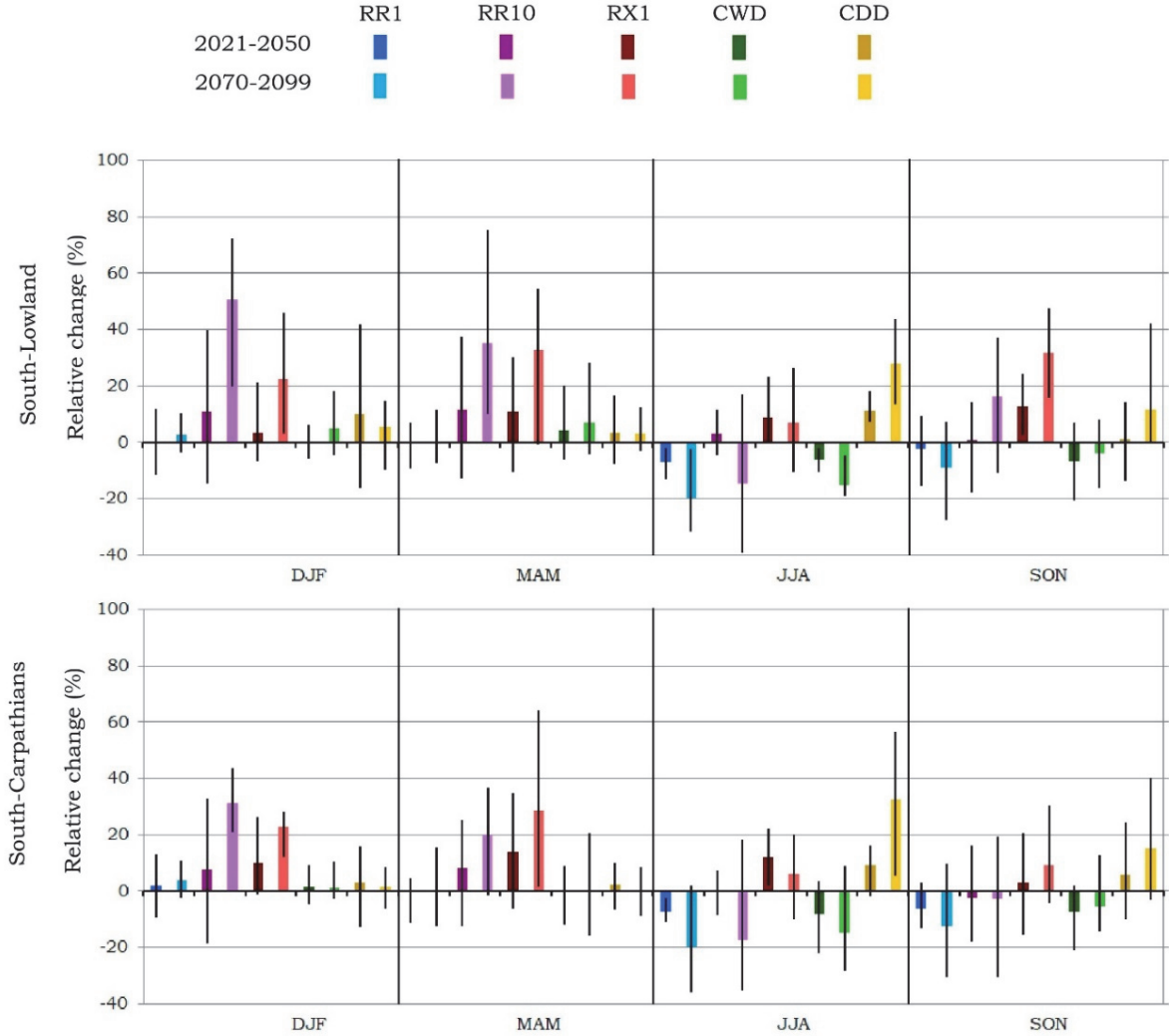

Fig. 7. Relative changes of precipitation climate indices for the two sub-regions for 2021–2050 and 2070–2099 with respect to 1976–2005. Changes are given in %. Color bars represent the ensemble mean, while the vertical black lines are drawn from the smallest to the greatest projected changes.

Different processes and different underlying mechanisms may be responsible for the seasonal precipitation change patterns projected for these sub-regions and for the entire Carpathian Region, which is in fact exciting and also challenging to be addressed, but the detailed investigation of it is out of the scope of the present study. It will be investigated in a future work.

4. Conclusions

The high-resolution, high-quality observational dataset, CARPATCLIM served as long-term reference dataset for the Carpathian Region to correct for systematic bias in daily precipitation simulated by six EURO-CORDEX and Med-CORDEX simulations. Following the work of *Mezghani et al*. (2017), the quantile mapping method was used in order to eliminate biases present in the ensemble of RCM simulations. The six-member high-resolution (~12 km) RCM ensemble assuming the high-emission greenhouse gas scenario (RCP8.5) was assessed for future time slices 2021–2050 and 2070–2099 with respect to the reference period 1976–2005. Based on the ensemble mean of bias-corrected RCM simulations, more robust changes are projected by the end of the 21st century than for the near future time slice. The present study also reported on the projected changes of precipitation climate indices over the entire Carpathian Region and with special focus on two sub-regions representing high- and lowlands within the target region. The sub-regions were selected in favor of the quest of the role of topography on precipitation change. The analyzed climate indices are: frequency of rainy days (RR1, days with a total rainfall of at least 1 mm), heavy precipitation days (RR10, days with a total rainfall of at least 10 mm), highest daily total precipitation (RX1), maximum consecutive dry days (CDD, duration of the longest period with < 1 mm total daily precipitation), maximum consecutive wet periods (CWD, duration of the longest period with > 1 mm total daily precipitation).

By and large, the key findings of the present study are as follows: (1) the influence of orography on seasonal precipitation change is evident throughout the analyzed periods, (2) the estimated precipitation change holds an unequivocal seasonality as most models project significant winter (DJF) precipitation increase (~30%), while in general drier (~20%) summers (JJA) are projected over the most part of the Carpathian Region by the end of the 21st century, (3) RR10 shows a clear signal of increase over the sub-regions in all seasons (10–50%), except for summer (~ -15%), while RX1 shows increase in all seasons.

The present study also introduces a high-resolution bias-corrected precipitation database, which can serve as input for further climate change impact and adaptation studies to be carried out for the Carpathian Region at local/regional/national levels. Furthermore, the present work draws attention to the important role that a high-resolution, quality controlled observational dataset may play not only in validation studies, but also in creating bias-corrected RCM simulation-based dataset for further scientific purposes.

References

Bechtold, P., Köhler, M., Jung, T., Doblas-Reyes, F., Leutbecher, M., Rodwell, M.J., Vitart, F., and *Balsamo, G.*, 2008: Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time-scales. *Q. J. Roy. Meteor. Soc., 134*, 1337–1351. https://doi.org/10.1002/qj.289

Berg, P., Feldmann, H., and *Panitz, H.J.*, 2012: Bias correction of high resolution regional climate model data. *J. Hydrol. 448–449*, 80–92. https://doi.org/10.1016/j.jhydrol.2012.04.026

Bougeault, P., 1985: A Simple Parameterization of the Large-Scale Effects of Cumulus Convection. *Mon. Weather Rev. 113*, 2108–2121. https://doi.org/10.1175/1520-0493(1985)113<2108:ASPOTL>2.0.CO;2

Colin, J., Déqué, M., Radu, R., and *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. 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., Hughes, J., Jones, C.D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and *Woodward, S.,* 2011: Development and evaluation of an Earth System model, HADGEM2. *Geosci. Model Dev. 4*, 1051–1075. https://doi.org/10.5194/gmd-4-1051-2011

Derbyshire, S.H., Beau, I., Bechtold, P., Grandpeix, J.-Y., Piriou, J.-M., Redelsperger, J.-L., and *Soares, P.M.M.*, 2004: Sensitivity of moist convection to environmental humidity. *Q. J. Roy. Meteor. Soc. 130*, 3055–3079. https://doi.org/10.1256/qj.03.130

Déqué, M., Rowell, D. P., Lüthi, D., Giorgi, F., Christensen, J. H., Rockel, B., Jacob, D., Kjellström, E., de Castro, M., and *van den Hurk, B.*, 2007: An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections, *Climatic Change 81*, 53–70. https://doi.org/10.1007/s10584-006-9228-x

Emanuel, K.A., 1991: A scheme for representing cumulus convection in large-scale models. *J. Atmos. Sci. 48*, 2313–2335. https://doi.org/10.1175/1520-0469(1991)048<2313:ASFRCC>2.0.CO;2

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

Fischer, A.M., Keller, D.E., Liniger, M.A., Rajczak, J, Schär, C., and *Appenzeller, C.*, 2015: Projected changes in precipitation intensity and frequency in Switzerland: a multi-model perspective. *Int. J. Climatol. 35*, 3204–3219. https://doi.org/10.1002/joc.4162

Fowler, H.J. and *Kilsby, C.G.*, 2007: Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change 80*, 337–367. https://doi.org/10.1007/s10584-006-9117-3

Gaál, L., Beranová, R., Hlavcová, K., and *Kysely, J.*, 2014: Climate Change Scenarios of Precipitation Extremes in the Carpathian Region Based on an Ensemble of Regional Climate Models. *Adv. Meteor.* ID 943487, 14p. https://doi.org/10.1155/2014/943487

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

Giorgi, F., Coppola, E., Solmon. F., Mariotti, L., Sylla, M.B., Bi, X., Elguindi, N., Diro, G.T., Nair, V., Giuliani, G., Turuncoglu, U.U., Cozzini, S., Güttler, I., O'Brien, T.A., Tawfik, A.B., Shalaby, A., Zakey, A.S., Steiner, A.L., Stordal, F., Sloan, L.C., and Brankovic, C., 2012: RegCM4: model description and preliminary results over multiple CORDEX domains. Clim. Res. 52, 7–29. https://doi.org/10.3354/cr01018

Grell, G., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. Mon. Weather Rev. 121, 764–787. https://doi.org/10.1175/1520-0493(1993)121<0764:PEOAUB>2.0.CO;2

Gudmundsson, L., Bremnes, J.B., Haugen, J.E., and Engen-Skaugen, T., 2012: Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations - a comparison of methods. Hydrol. Earth Sys. Sci. 16, 3383–3390. https://doi.org/10.5194/hess-16-3383-2012

Halenka, T., 2007: On the Assessment of Climate Change Impacts in Central and Eastern Europe - EC FP6 Project CECILIA. Geophys. Res. Abstr. 9, 10545.

Hazeleger,W., Severijns, C., Semmler, T., Stefanescu, S., Yang, S., Wang, X., Wyser, K., Dutra, E., Baldasano, J.M., Bintanja, R., Bougeault, P., Caballero, R., Ekman, A.M.L., Christensen, J.H., van den Hurk, B., Jimenez, P., Jones, C., Kållberg, P., Koenigk, T., McGrath, R., Miranda, P., van Noije, T., Palmer, T., Parodi, J.A., Schmith, T., Selten, F., Storelvmo, T., Sterl, A., Tapamo, H., Vancoppenolle, M., Viterbo, P., and Willén, U., 2010: EC-EARTH: a seamless Earth system prediction approach in action. Bull. Am. Meteorol. Soc. 91, 1357–1375. https://doi.org/10.1175/2010BAMS2877.1

Hewitt, C.D., and Griggs, D., 2004: Ensembles-Based Predictions of Climate Changes and Their Impacts. Eos Trans. AGU 85(52), 566–567. https://doi.org/10.1029/2004EO520005

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 [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/CBO9781107415324

Jacob, D., van den Hurk, B., Andræ, U., Elgered, G., Fortelius, C., Graham, L. P., Jackson, S. D., Karstens, U., Kopken, C., Lindau, R., Podzun, R., Rockel, B., Rubel, F., Sass, B.H., Smith, R.N.B., and Yang, X., 2001: A comprehensive model intercomparison study investigating the water budget during the BALTEX-PIDCAP period. Meteorol. Atmos. Phys. 77, 19–43. https://doi.org/10.1007/s007030170015

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., 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., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevel, 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. Reg. Environ. Change 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2

Jungclaus, J.H., Lorenz, S.J., Timmreck, C., Reick, C.H., Brovkin, V., Six, K., Segschneider, J., Giorgetta, M.A., Crowley, T.J., Pongratz, J., Krivova, N.A., Vieira, L.E., Solanki, S.K., Klocke, D., Botzet, M., Esch, M., Gayler, V., Haak, H., Raddatz, T.J., Roeckner, E., Schnur, R., Widmann, H., Claussen, M., Stevens, B., and Marotzke, J., 2010: Climate and carbon cycle variability over the last millennium. Clim. Past 6, 723–737. https://doi.org/10.5194/cp-6-723-2010

Kain, J.S., and Fritsch, J.M., 1993: Convective parameterization for mesoscale models: the Kain-Fritsch scheme. The representation of cumulus convection in numerical models. Meteorol. Monogr. 24, 165–170. https://doi.org/10.1007/978-1-935704-13-3_16

Kis, A., Pongrácz, R., and Bartholy, J., 2017: Multi-model analysis of regional dry and wet conditions for the Carpathian Region. Int. J. Climatol. 37, 4543–4560. https://doi.org/10.1002/joc.5104

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., and Wulfmeyer, V., 2014: Regional climate modeling on European scales: A joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci. Model Dev. 7, 1297–1333. https://doi.org/10.5194/gmd-7-1297-2014

Kuo, H.L., 1965: On Formation and Intensification of Tropical Cyclones Through Latent Heat Release by Cumulus Convection. *J. Atmos. Sci. 22*, 40–63.
https://doi.org/10.1175/1520-0469(1965)022<0040:OFAIOT>2.0.CO;2

Kupiainen, M., Jansson, C., Samuelsson, P., Jones, C., Willén, U., Hansson, U., Ullerstig, A., Wang, S., and *Döscher, R.,* 2014: Rossby Centre regional atmospheric model, RCA4, Rossby Center News Letter, Rossby Centre regional atmospheric model, RCA4

Lafon, T., Dadson, S., Buys, G., and *Prudhomme, C.,* 2013: Bias correction of daily precipitation simulated by a regional climate model: a comparison of methods, *Int. J. Climatol. 33*, 1367–1381.
https://doi.org/10.1002/joc.3518

Maraun, D., 2016: Bias correcting climate change simulations – a critical review. *Curr. Clim. Change Rep., 2*, 211–220. https://doi.org/10.1007/s40641-016-0050-x

van Meijgaard, E., van Ulft, L.H., Lenderink, G., de Roode, S.R., Wipfler, L., Boers, R., and *Timmermans, R.M.A.,* 2012: Refinement and application of a regional atmospheric model for climate scenario calculations of Western Europe. *Climate Scenarios*. KvR 054/12, 44p.

Mezghani, A., Dobler, A., Haugen, J.E., Benestad, R.E., Parding, K.M., Piniewski, M., Kardel, I., and *Kundzewicz, Z.W.*, 2017: CHASE-PL Climate Projection dataset over Poland – bias adjustment of EURO-CORDEX simulations. *Earth Syst. Sci. Data 9*, 905–925.
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., Carter, T.E., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., and *Wilbanks, T.J.,* 2010. The next generation of scenarios for climate change research and assessment. *Nature 463*, 747–756.
https://doi.org/10.1038/nature08823

Neggers, R.A.J., Köhler, M., and *Beljaars, A.C.M.,* 2009: A dual mass flux framework for boundary layer convection, Part I: Transport. *J. Atmos. Sci. 66*, 1465–1487.
https://doi.org/10.1175/2008JAS2635.1

Nordeng, T.E., 1994: Extended versions of the convection parametrization scheme at ECMWF and their impact upon the mean climate and transient activity of the model in the tropics. *ECMWF Tech. Memo. No. 206.*

Pfeifer, S., 2006: Modeling cold cloud processes with the regional climate model REMO. MPI for Meteorology, Hamburg, *Reports on Earth System Science No. 23*.

Rajczak, J., Kotlarski, S., and *Schär, C.*, 2016: Does quantile mapping of simulated precipitation correct for biases in transition probabilities and spell lengths? *J. Climate 29*, 1605–1615.
https://doi.org/10.1175/JCLI-D-15-0162.1

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

Ruti, S.M., Somot, S., Giorgi, F., Dubois, C., Flaounas, E., Obermann, A., Dell'Aquila, A., Pisacane, G., Harzallah, A., Lombardi, E., Ahrens, B., Akhtar, N., Alias, A., Arsouze, T., Aznar, R., Bastin, S., Bartholy, J., Béranger, K., Beuvier, J., Bouffies-Cloché, S., Brauch, J., Cabos, W., Calmanti, S., Calvet, J-C., Carillo, A., Conte, D., Coppola, E., Djurdjevic, V., Drobinski, P., Elizalde-Arellano, A., Gaertner, M., Galàn, P., Gallardo, C., Gualdi, S., Goncalves, M., Jorba, O., Jordà, G., L'Heveder, B., Lebeaupin-Brossier, C., Li, L., Liguori, G., Lionello, P., Maciàs, D., Nabat, P., Önol, B., Raikovic, B., Ramage, K., Sevault, F., Sannino, G., Struglia, M.V., Sanna, A., Torma, Cs., and *Vervatis, V.,* 2016: MED-CORDEX initiative for Mediterranean Climate studies. *Bull. Amer. Meteor. Soc. online*, https://doi.org/10.1175/BAMS-D-14-00176.1

Sillmann, J., Kharin, V.V., Zwiers, F.W., Zhang, X., and *Bronaugh, D.,* 2013: Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *J. Geophys. Res. Atmos. 118*, 2473–2493. https://doi.org/10.1002/jgrd.50188

Spinoni, J., Szalai, S., Szentimrey, T., Lakatos, M., Bihari, Z., Nagy, A., Németh, Á., Kovács, T., Mihic, D., Dacic, M., Petrovic, P., Kržic, A., Hiebl, J., Auer, I., Milkovic, J., Štepánek, P., Zahradnícek, P., Kilar, P., Limanowka, D., Pyrc, R., Cheval, S., Birsan, M.-V., Dumitrescu, A., Deak, G., Matei, M., Antolovic, I., Nejedlík, P., Štastn´y, P., Kajaba, P., Bochnícek, O., Galo, D., Mikulová, K., Nabyvanets, Y., Skrynyk, O., Krakovska, S., Gnatiuk, N., Tolasz, R., Antofie, T., and *Vogt, J.,* 2015: Climate of the Carpathian region in the period 1961–2010: Climatologies and trends of 10 variables. *Int. J. Climatol. 35*, 1322–1341. https://doi.org/10.1002/joc.4059

Szalai, S., Auer, I., Hiebl, J., Milkovich, J., Radim, T.. Stepanek, P., Zahradnicek, P., Bihari, Z., Lakatos, M., Szentimrey, T., Limanowka, D., Kilar, P., Cheval, S., Deak, Gy., Mihic, D., Antolovic, I., Mihajlovic, V., Nejedlik, P., Stastny, P., 738 Mikulova, K., Nabyvanets, I., Skyryk, O., Krakovskaya, S.,Vogt, J., Antofie, T., and *Spinoni, J.,* 2013: Climate of the Greater Carpathian Region. Final 740 Technical Report. http://www.carpatclim-eu.org.

Szentimrey, T., and *Bihari, Z.,* 2006: MISH (Meteorological Interpolation based on Surface Homogenized Data Basis). In: (Eds: *O.E.Tveito, M.Wegehenkel, F. van der Wel and H. Dobesch*) COST Action 719 Final Report, The use of GIS in climatology and meteorology, 54-56.

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

Taylor, K.E., 2001: Summarizing multiple aspects of model performance in a single diagram. *J Geophys Res, 106(D7)*, 7183–7192. https://doi.org/10.1029/2000JD900719

Teutschbein, C., and *Seibert, J.,* 2013: Is bias correction of regional model (RCM) simulations possible for non-stationary conditions? *Hydrol. Earth Syst. Sci. 17*, 5061–5077.
https://doi.org/10.5194/hess-17-5061-2013

Themeßl, M. J., Gobiet, A., and *Leuprecht, A.,* 2010: Empirical-statistical downscaling and error correction of daily precipitation from regional climate models, *Int. J. Climatol. 31*, 1530–1544.
https://doi.org/10.1002/joc.2168

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Weather Rev. 117*, 1779–1799.
https://doi.org/10.1175/1520-0493(1989)117<1779:ACMFSF>2.0.CO;2

Torma, Cs., Coppola, E., Giorgi, F., Bartholy, J., and *Pongrácz, R.,* 2011: Validation of a high resolution version of the regional climate model RegCM3 over the Carpathian Basin. *J. Hydrometeorol. 12,* 84–100. https://doi.org/10.1175/2010JHM1234.1

Torma, Cs., Giorgi, F., and *Coppola, E.,* 2015: Added value of regional climate modeling over areas characterized by complex terrain-Precipitation over the Alps. *J. Geophys. Res. Atmos. 120*, 3957–3972. https://doi.org/10.1002/2014JD022781

Voldoire, A., Sanchez-Gomez, E., Salas y Mélia, D., Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., Déqué, M., Deshayes, J., Douville, H., Fernandez, E., Madec, G., Maisonnave, E., Moine, M.-P., Planton, S., Saint-Martin, D., Szopa, S., Tyteca, S., Alkama, R., Belamari, S., Braun, A., Coquart, L., and *Chauvin, F.,* 2012: The CNRM-CM5.1 global climate model: description and basic evaluation. *Clim. Dyn. 40*, 2091–2121.
https://doi.org/10.1007/s00382-011-1259-y

Wang, L., Ranasinghe, R., Maskey, S., van Gelder, P.H.A.J.M., and *Vrijling, K.,* 2016: Comparison of empirical statistical methods for downscaling daily climate projections from CMIP5 GCMs: a case study of the Huai River Basin, China. *Int. J. Climatol.* 36, 145–164.
https://doi.org/10.1002/joc.4334

Zappa, G., Shaffrey, L.C., Hodges, K.I., Sansom, P.G., and *Stephenson, D.B.,* 2013: A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. *J. Climate* 26, 5846–5862. https://doi.org/10.1175/JCLI-D-12-00573.1

Zhao, Z.-C., Luo, Y., and *Huang, J.-B.,* 2013: A review on evaluation methods of climate modeling. *Adv. Clim. Change Res. 4*, 137–144. https://doi.org/10.3724/SP.J.1248.2013.137