IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 118, No. 4, October – December, 2014, pp. 305–321

Estimation of future precipitation conditions for Hungary with special focus on dry periods

Rita Pongrácz*, **Judit Bartholy,** and **Anna Kis**

Department of Meteorology, Eötvös Loránd University,
Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary

E-mail: prita@nimbus.elte.hu, bartholy@caesar.elte.hu,
kisanna@nimbus.elte.hu

**Corresponding author*

(Manuscript received in final form August 25, 2014)

Abstract—In this paper, estimated trends of precipitation- and drought-related climate indices and the return period of the daily precipitation amount are analyzed. For this purpose 11 regional climate model (RCM) simulations from the ENSEMBLES project with 25 km horizontal resolution for the emission scenario A1B are used after applying a bias-correction procedure. According to the results, the summer 10- and 20-year return periods will increase by a factor of 1.2–2 by the late 21st century relative to the 1961–1990 reference period. The projected changes are considerably smaller for the other three seasons compared to future summer changes. Furthermore, drought-related climate indices in summer are projected to increase significantly in Hungary as well as in Central/Eastern Europe by the end of the 21st century. Additionally, precipitation-related indices are projected to decrease in summer by 2071–2100 compared to 1961–1990.

Key-words: precipitation index, dry period, return period, bias correction, regional climate model simulation

1. Introduction

Climate change is most often referred as higher temperature values and more frequent heat waves (e.g., *Pongrácz et al.*, 2013). However, it usually involves more intense and more frequent extreme events related to excess or lack of precipitation (e.g., severe dry spells, heavy precipitation, intense thunderstorms), too (*IPCC*, 2012). This highlights the importance of climate research in quantifying the detected past and the projected future changes from global to local scales. Frequent hot weather in summer and overall increasingly warm climatic conditions are quite straightforward consequences of global warming. Global and regional warming induced effects on precipitation are not as clear as on temperature, because the higher spatial and temporal variabilities might hide any robust changing signal. Nevertheless, precipitation is one of the most important meteorological variables, since it considerably affects natural ecosystems and cultivated vegetation as well as most of human activities. Extreme precipitation events – both excessive, intense rainfalls and severe droughts – may result in several environmental, agricultural, economical, and natural disasters. The lack of precipitation for extended period and coincidental intense heat wave often lead severe drought events. For instance, in 2003 a long-lasting, devastating heat wave occurred throughout Europe (*Stott et al.*, 2004), causing death of hundreds of people (*Bouchama*, 2004). In Hungary, the year 2003 was generally dry with 17% less annual precipitation than the 1971–2000 average (*Schirokné Kriston*, 2004). The Europe-wide heat wave in the summer superposed to these overall dry conditions, resulting in severe drought. The estimated monetary damage in the Hungarian agriculture reached 50–55 billion HUF by the end of the year (*Faragó et al.*, 2010). Another hot and dry summer from the past decades occurred in 2007, this drought resulted in reduced harvest of maize in Hungary and caused at least 80 billion HUF loss (*Faragó et al.*, 2010). On the contrary, in May 2010, the total rainfall in Hungary largely exceeded the average monthly precipitation of the 1971–2000 baseperiod for May, namely, almost three times more precipitation occurred than usual (*Móring*, 2011). The excessive precipitation led to inland inundation and floods on Sajó, Hernád, Bodrog, and Bódva rivers resulting in more than 10 billion HUF of defence and recovery costs (*KSH*, 2011). Overall, the year 2010 became the wettest year in Hungary since 1901 with 959 mm annual precipitation amount exceeding the annual mean of the 1971–2000 period by 65% (*Móring*, 2011). Besides Hungary, a large majority of the Central/Eastern European region was hit at the same time by severe floods (*Bissolli et al.*, 2011; *WMO*, 2011). After the year of excessive precipitation, Hungary experienced the driest year in 2011 since 1901 with only 407 mm annual total precipitation amount, being only 72% of the annual average in the 1971–2000 period (*Móring*, 2012), which affected the agricultural production quite negatively. The very next year, 2012 was also dry in Hungary, the annual total precipitation was only 470 mm (*Horváth et al.*, 2012; *Rajhonáné Nagy*, 2013) resulting in more losses in agriculture than in 2011 (e.g., by 24% less harvested cereal and 20% less production of sunflower and grape) (*KSH*, 2013). Due to the large temporal variability of precipitation, after two consecutive very dry years, in late May and early June in 2013 large precipitation occurred again in Central Europe and resulted in extreme water levels, with record high peak levels on several Central European rivers, i.e., the Danube, the Elbe, and the Vltava (*BBC News*, 2013; *van der Schrier et al.*, 2013; *WMO*, 2014). Besides the great amount of precipitation, the large spatial extension and the strong intensity (exceeding 100 mm/24 hours) also contributed to this extreme event (*Horváth et al.*, 2013). Overall, this flood affected several countries in Central and Eastern Europe (e.g., Germany, Austria, Czech Republic, Hungary, Serbia) with 16 billion EUR losses and 22 deaths altogether (*Munich Re*, 2013).

In order to avoid or at least reduce the effects of these precipitation related hazards, national and local communities need to develop regional adaptation strategies (*IPCC*, 2012; *Motha*, 2009; *Sivakumar* and *Stefanski*, 2009; *Anwar et al.*, 2013), and then, act according to them. For this purpose, results of global climate model (GCM) simulations must be downscaled to regional and local scales, hence better serving end-users' needs. Downscaling of coarse resolution GCM simulation outputs is especially important in case of precipitation because of the large temporal and spatial variabilities, and consequently, since appropriate precipitation impact assessment studies require fine resolution information (e.g., *Marengo* and *Ambrizzi*, 2006; *Fowler et al.*, 2007; *Maurer et al.*, 2007; *Serinaldi* and *Kilsby*, 2014). From the agricultural point of view, especially potential dry conditions induce long-term planning, for which estimation of precipitation is evidently the key element.

Sheffield and *Wood* (2008) analyzed global and regional trends of drought using a moisture-based drought index for 1950–2000. According to their results, soil moisture has increased globally with regional differences. In Africa, a significant drying can be identified, whereas increasing trend is detected in North America. The annual precipitation sum in Hungary decreased in the 1901–2009 period; in Budapest the mean change is –20.5%, which is statistically significant (*Lakatos* and *Bihari*, 2011). Precipitation measurements in the Carpathian Basin suggest that both the overall intensity and frequency of extreme precipitation events – related to both excess and lack of precipitation – increased in the 20th century, whereas the mean climate became slightly drier (*Bartholy* and *Pongrácz*, 2005; *Lakatos et al.*, 2011). For the future, 50 km horizontal resolution regional climate model (RCM) experiments of the PRUDENCE project (*Christensen et al.*, 2007a) suggest that the annual distribution of precipitation will be totally restructured in Hungary both in case of A2 and B2 emission scenarios (*Nakicenovic* and *Swart*, 2000), namely, the wettest season (currently summer) will become the driest, and the driest season (currently winter) is likely to be the wettest by the end of the 21st century (*Bartholy et al.*, 2008). The projected changes for Central/Eastern Europe involve large uncertainity, therefore, further analysis is necessary. In order to successfully adapt to the changing climatic and environmental conditions, appropriate assessment of possible changes is essential.

In the current study, fine (25 km) resolution RCM experiments of the ENSEMBLES project are analyzed taking into account the A1B intermediate emission scenario for the entire 21st century. First, the data and the bias correction method applied to the raw RCM outputs are presented. Then, the precipitation-related characteristics, return period of daily precipitation, and various climate indices are defined. Section 3 discusses projected changes in the seasonal return period of daily precipitation, and estimated seasonal changes of climate indices with special focus on dry conditions. Finally, Section 4 summarizes the main conclusions.

2. Data and methods

2.1. Data used in the analyses

In this paper, simulations of 25 km horizontal resolution RCMs nested in coarse resolution GCMs are used to estimate the future precipitation- and drought-related climatic conditions in Central/Eastern Europe covering the region 43.625°–50.625°N, 13.875°–26.375°E. The assessment focuses on analysis of daily precipitation outputs of 11 RCM simulations (listed in *Table 1*) from the ENSEMBLES project (*van der Linden* and *Mitchell*, 2009). This European Union funded project aimed and successfully completed to run several climate models between 2004 and 2009 in order to improve the reliability of climate projections, measure uncertainty, and help decision-makers with reliable information. All of the RCM simulations selected for this study cover the entire 1951–2100 period and apply the intermediate A1B emission scenario, according to which the estimated CO_2 concentration level will be 532 ppm and 717 ppm by 2050 and 2100, respectively (*Nakicenovic* and *Swart*, 2000). The necessary initial and boundary conditions are provided by three different GCMs: ECHAM (*Roeckner et al.*, 2006) developed at the Max Planck Institute, HadCM (*Gordon et al.*, 2000) developed at the UK MetOffice, and ARPEGE (*Déqué et al.*, 1998) developed at Météo-France.

Table 1. List of the selected RCMs, their main references, their driving GCMs, and the responsible institutes used in this analysis.

RCM (Reference)	**Driving GCM**	**Institute**
HadRM3Q0 (*Jones et al.*, 1995; 2004)	HadCM3Q	HC (Hadley Centre), United Kingdom
RCA3 (*Samuelsson et al.*, 2011)	HadCM3Q (high sensitivity version)	C4I (Community Climate Change Consortium for Ireland), Ireland
CLM (*Böhm et al.*, 2006)	HadCM3Q	ETHZ (Eidgenössische Technische Hochschule Zürich), Switzerland
RCA3 (*Samuelsson et al.*, 2011)	HadCM3Q (low sensitivity version) ECHAM5	SMHI (Swedish Meteorological and Hydrological Institute), Sweden
RACMO (*van Meijgaard et al.*, 2008)	ECHAM5	KNMI (Koninklijk Nederlands Meteorologisch Instituut), Netherlands
REMO (*Jacob* and *Podzun*, 1997)	ECHAM5	MPI (Max Planck Institut), Germany
RegCM (*Giorgi* and *Bi*, 2000)	ECHAM5	ICTP (International Centre for Theoretical Physics), Italy
HIRHAM (*Christensen et al.*, 2007b)	ECHAM5 ARPEGE	DMI (Danmarks Meteorologiske Institut), Denmark
ALADIN (*Radu et al.*, 2008)	ARPEGE	CNRM (Centre National de Recherches Météorologiques), France

2.2. Bias correction of RCM outputs

The evaluation of raw precipitation outputs of RCMs for 1961–1990 suggests that simulated values usually significantly overestimate the observations in Central/Eastern Europe, except in summer when mostly underestimations were found (*Pongrácz et al.*, 2011). In case of precipitation indices associated with specific thresholds, it is particularly important to use the most accurate simulations, as close to measurements as possible. For this purpose, before the analyses, a bias correction method should be applied to the raw simulated data. The biases of the raw RCM outputs are corrected using quantile matching technique. This is based on the assumption that two datasets are considered similar if their distributions are close to each other (and the closer is the more similar), therefore, the monthly empirical distribution functions of daily precipitation at each grid cell should be fitted (*Formayer* and *Haas*, 2010) to the observed distribution represented by the gridded E-OBS (*Haylock et al.*, 2008) data for a baseperiod, i.e., 1951–2000 in this study. These fitting procedures provide the multiplicative bias-correcting factors for each month, for each grid cell. Then, these calculated factors are applied to the raw daily outputs of RCM experiments both for the past (1951–2000) and the target (2000–2100) period.

Fig. 1 illustrates the successful fitting of the bias-correction for January for a selected grid cell, where the percentile values of the raw and bias-corrected simulations are compared to the percentiles of E-OBS data. The Q-Q plot clearly shows that after the correction, the distribution of the simulated precipitation fits perfectly to the distribution of the reference data (i.e., all the percentile value pairs are located along the y = x line).

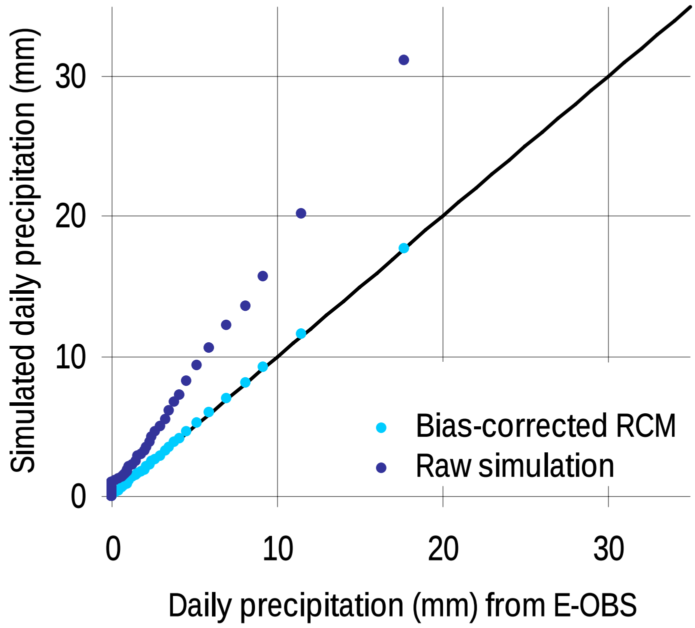

Fig. 1. Q-Q plot for raw and bias corrected simulation data, 1951–2000. Results for January daily data from the grid cell located at 47.625°N, 19.125°E using the ARPEGE-driven HIRHAM experiment are shown.

2.3. The return period and the selected climate indices

After the bias-correction, both the 10- and 20-year return periods of the daily precipitation amount are analyzed. The return period (τ) is defined as the inverse of the expected average number of occurrences (P) in a year (τ=1/P). *Fig. 2* shows an example for how to determine the change of the 10-year return period. First, the 90th percentile of the daily precipitation ($P_{0.9}$(1961–1990)) is calculated for the reference period (1961–1990) in each grid cell. Then, this daily precipitation amount should be compared to the future (2071–2100) percentile values, and that one (P_X(2071–2100)) is selected, which equals to this $P_{0.9}$(1961–1990) daily precipitation. In the example of *Fig. 2*, X = 0.94 since the 94th percentile value of the future period equals to $P_{0.9}$(1961–1990). So $\tau_{10\text{years, 1961–1990}}$ = 100/(100–94) = 16.67 years, which implies a substantial increase of the return period, and hence, drier climatic conditions.

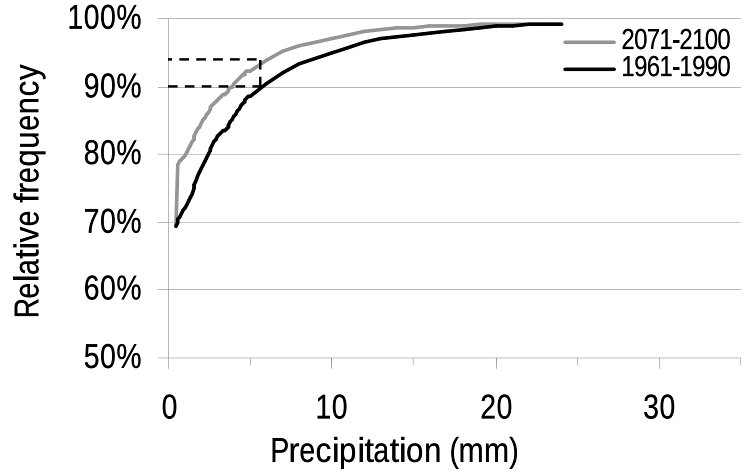

Fig. 2. Calculation of the projected value of the 10-year return period ($\tau_{10years,\ 1961–1990}$). Empirical distributions of summer daily data from the grid cell located at 47.625°N, 19.125°E using the ARPEGE-driven HIRHAM experiment are shown.

In order to assess future climate tendencies in the Central/Eastern European region, several precipitation-related indices are also analyzed on seasonal scales. *Table 2* lists the names, definitions, and units of the selected climate indices. Three indices are directly related to drought (DD, MDS, CDD), the other three indices refer to wet conditions using small precipitation thresholds (RR1, RR5, MWS). The grid cell values of all the six indices are calculated from the bias-corrected simulated precipitation data sets for the entire selected domain covering the latitude 43.625°–50.625°N and longitude 13.875°–26.375°E for the whole simulation period (1951–2100) using all the 11 RCM experiments. Overall projected seasonal changes by 2021–2050 and 2071–2100 periods relative to the 1961–1990 reference period are also calculated. Furthermore, spatial average changes for Hungary represented by the grid cells located within the country border are estimated for all the seasons both for mid to late 21st century.

Table 2. Drought- and precipitation-related climate indices used in the current analysis

Index	**Definition**	**Unit**
DD	Number of dry days ($R_{day} < 1$ mm)	day
MDS	Mean length of dry spell ($R_{day} < 1$ mm)	day
CDD	Maximum length of dry spell, i.e., maximum number of consecutive dry days ($R_{day} < 1$ mm)	day
RR1	Number of precipitation days exceeding 1 mm ($R_{day} \geq 1$ mm)	day
RR5	Number of precipitation days exceeding 5 mm ($R_{day} \geq 5$ mm)	day
MWS	Mean length of wet spell ($R_{day} \geq 1$ mm)	day

3. *Results and discussion*

First, we focus on the 10-year and 20-year return periods of the daily precipitation amount. The projected seasonal changes generally show similar patterns for the whole selected domain. According to our results, a slight decrease of the return period is likely to occur in winter, namely, the 10-year return period may change to 8–9 years by the end of the 21st century (*Fig. 3*). This implies wetter climatic conditions for winter. In spring and autumn, individual RCM experiments suggest slightly more diverse changes than in winter, which results in larger uncertainty but very small changes overall. In case of summer, the results for the 2071–2100 period clearly suggest that the return period of daily precipitation occurred once in a decade on average in the recent past is very likely to increase by a factor of 1.2–2, so drier climatic conditions are projected. Larger increase of the 10-year return period is estimated in the southern parts (exceeding 8 years) of the selected domain than in the northern subregions (less than 4 years).

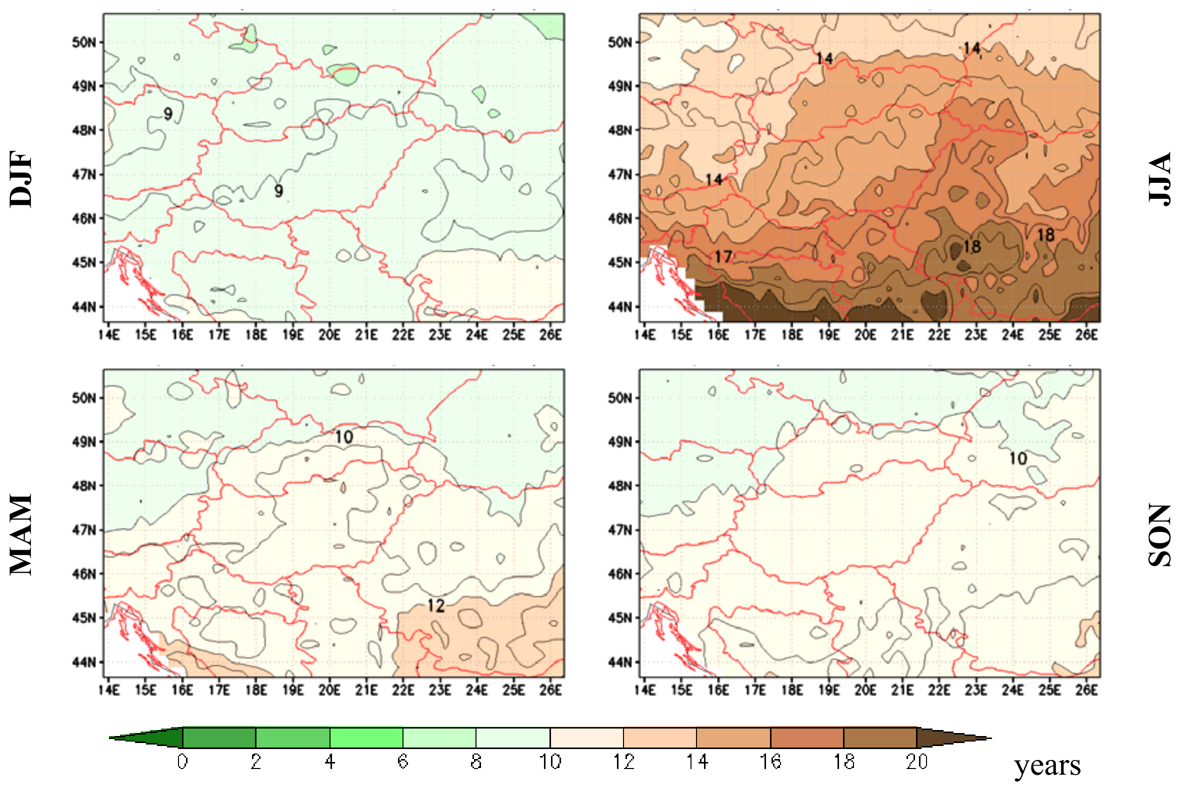

Fig. 3. Composite maps of 11 RCM simulations indicating the estimated seasonal mean changes of the 10-year return period by 2071–2100 relative to the reference period 1961–1990.

Besides the average return periods, the seasonal uncertainties for nine subregions are also determined (*Fig. 4*). Whisker-Box plot diagrams are used for indicating the highest (maximum) and the lowest (minimum) values, and the lower and upper quartiles, i.e., the 25th and 75th percentiles of the 10-year return period of daily precipitation amount for each subregion based on the 11 individual RCM simulations. According to these results, the return period increases in summer, thus implying an overall future drying trend by almost all of the RCM simulations in every subregion (only a few RCM simulations project slight decrease in the northwestern subregions). Although the projected tendency is clear, the RCM-based projections cover a wide range of return periods, thus, the uncertainty of the estimation is quite large. The estimated changes are clearly larger as proceeding from the northwestern to the southeastern part of the domain. In Hungary and Slovenia, the doubling of the return period is estimated by only a couple of RCM simulations (using CLM for instance), whereas in the southern subregions (Romania, Croatia, and northern Serbia) 25% of the RCM simulations suggest larger increase than by a factor of 2. In the other three seasons, the overall uncertainties of the projections are smaller than in summer, however, even the signs of the estimated changes are not identical, especially in spring and autumn. In winter, most of RCM simulations suggest considerable decrease of the return period, thus implying wetter conditions in all subregions (only two RCM simulations project increase of winter return periods, namely, ALADIN and HIRHAM driven by ARPEGE).

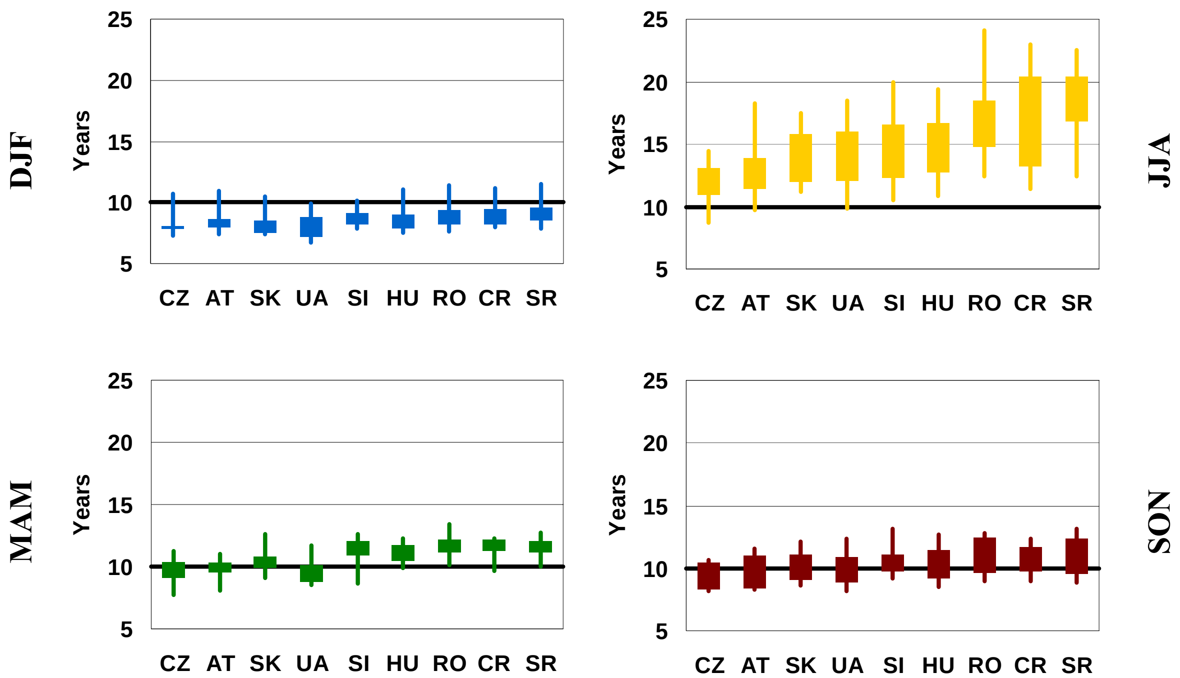

Fig. 4. The maximum, minimum, upper, and lower quartile values of the 10-year seasonal return period of the daily precipitation amount for nine subregions (CZ: southeastern Czech Republic, AT: eastern Austria, SK: Slovakia, UA: southwestern Ukraine, SI: Slovenia, HU: Hungary, RO: Romania, CR: Croatia and SR: northern Serbia).

The projected seasonal changes of 10- and 20-year return periods are compared for Hungary in *Fig. 5*. In general, the signs of the projected changes by one particular RCM simulation are identical for both return periods. It can be clearly seen that all the RCM simulations suggest clear increasing return period in summer. Most of the RCM simulations project similar rate of changes, except three RCM simulations (HIRHAM driven by ARPEGE, CLM driven by HadCM, and HadRM3Q driven by HadCM), when, when extremely large changes (larger than twofold increasing) is projected for Hungary in case of the 20-year return period of daily precipitation sum. The projected changes are considerably smaller for the other three seasons than for summer. Nevertheless, the estimated changes of the 10-year return period are slightly larger than the changes of the 20-year return period in winter and autumn.

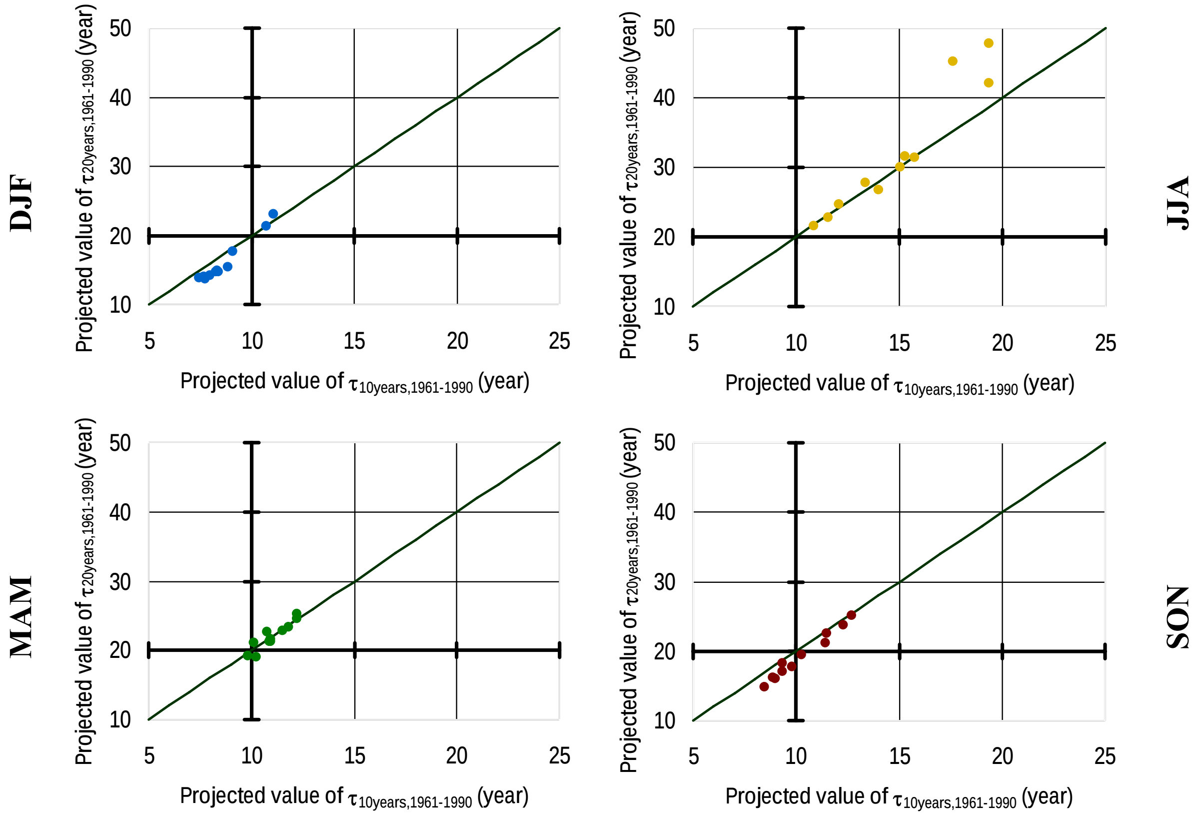

Fig. 5. Scatter-plot diagrams based on the 11 RCM simulations of the 10- and 20-year seasonal return periods for Hungary by 2071–2100 relative to the reference period, 1961–1990. Each dot represents the results of one RCM simulation.

In the second part of this section, we analyze the projected changes of the selected precipitation indices focusing on Hungary. According to the 11 bias-corrected RCM simulations in the 2021–2050 period, smaller changes are projected than in the 2071–2100 period (*Fig. 6*). By the mid-century, only a few

RCM simulations project statistically significant seasonal changes and the average estimated changes do not exceed 11%. In most of the indices, the signs of the projected changes are identical, which implies that the tendencies are likely to continue throughout the 21st century. In general, RR1 and RR5 (precipitation days exceeding 1 mm and 5 mm, respectively) are projected to decrease in summer and increase in winter. However, by the late century, almost all RCM simulations estimate significant decrease in summer (the average projected decrease is 27% relative to the reference period both for RR1 and RR5), and increase in winter for RR5 (the average projected increase is 25%). CDD and MDS in summer are projected to increase significantly in Hungary by the end of the 21st century (by 42% and 41% on average, respectively), clearly implying considerably drier future summers. Similar conclusions were found in *Bartholy et al.* (2013).

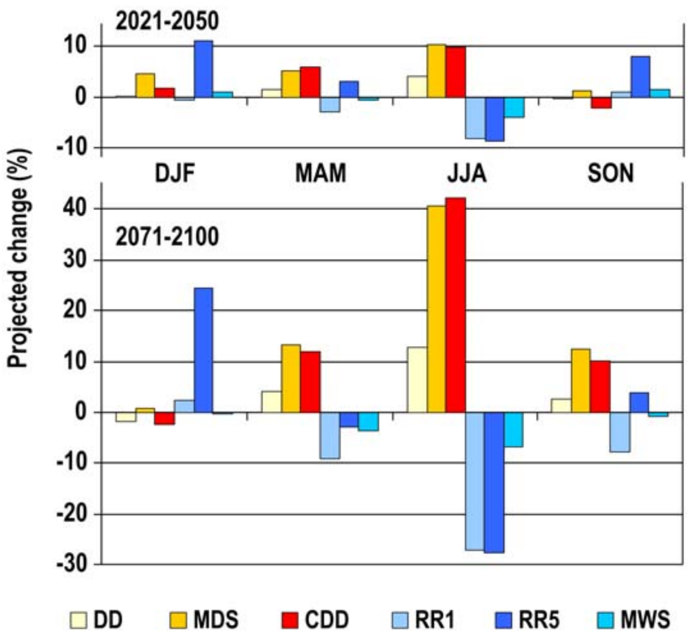

Fig. 6. Projected seasonal mean changes of climate indices for Hungary by 2021–2050 (upper panel) and 2071–2100 (lower panel) relative to the reference period, 1961–1990. Definitions of these indices are listed in *Table 2*.

The spatial pattern of the projected mean seasonal changes by the mid to late century are shown for CDD in *Fig. 7* (this index focuses on long dry periods when precipitation does not exceed 1 mm). The spatial averages of the estimated changes for the whole domain are –0.1%, +11%, +42%, and +10% in winter, spring, summer, and autumn, respectively (for Hungary the average projected changes are as follows: –2%, +12%, +42%, and +11%). In all the four seasons, larger increases are projected for the southern parts of the selected domain than for the northern regions. For instance, the estimated mean increase of CDD in summer is about 50% in Serbia and Romania by 2071–2100, whereas it is less than 40% in southeastern Czech Republic. In Hungary, the average summer value of CDD is 14 days in 1961–1990, which is projected to increase by 42%, and thus, exceeding 20 days by the end of the 21st century.

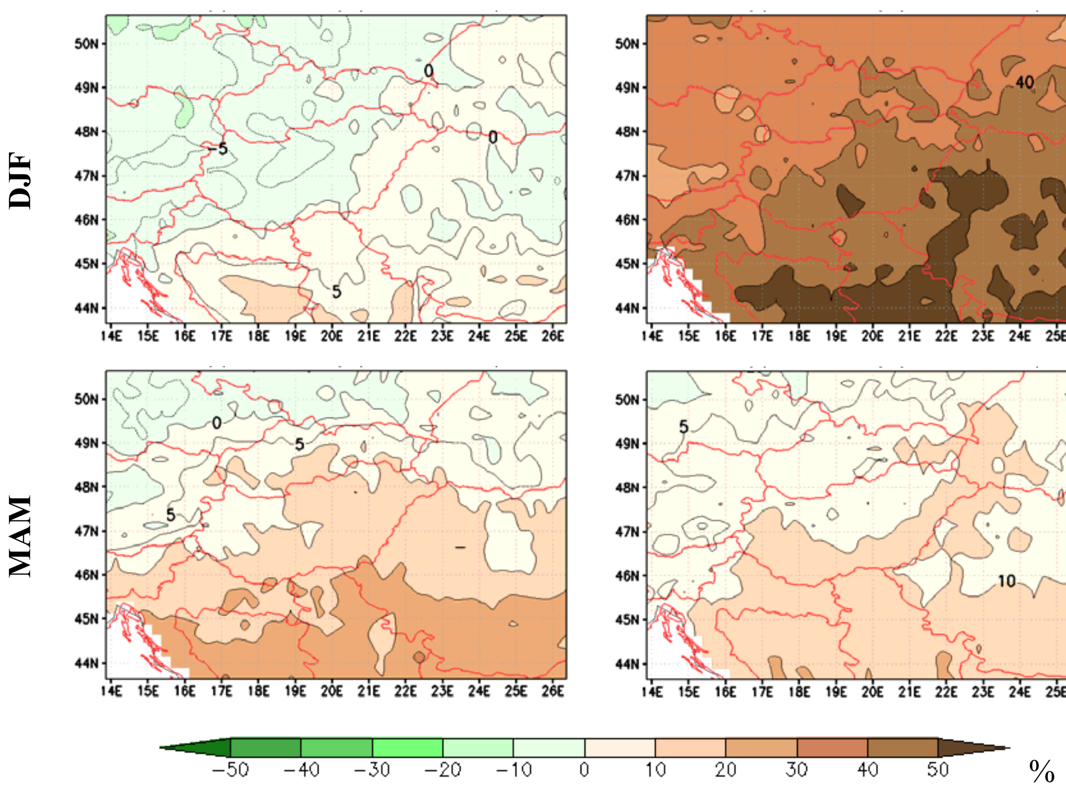

Fig. 7. Composite maps of 11 RCM simulations indicating the projected seasonal mean changes of CDD by 2071–2100 relative to the reference period 1961–1990.

Besides the multimodel seasonal averages, the standard deviations of estimated changes (characterizing the differences between the individual RCM projections) are also important, especially in terms of assessing the uncertainty of projections. The largest standard deviation values of the seasonal changes are found in summer, namely 15–30% depending on the location, with larger standard deviation in the northern regions and smaller in the southern regions of the domain. The smallest standard deviations of the late century changes are in spring (5–15%), however, winter and autumn standard deviation values are roughly in the same range. To present the inter-model uncertainty on decadal scale covering the whole 1951–2100 period, spatial average CDD values taking into account all the gridcells within Hungary are shown in *Fig. 8* for winter and summer. According to the statistical analysis (t-test), the summer increasing trend is significant at 0.05 level, which implies future lengthening of consecutive dry days highly affecting agriculture in the region. The longest seasonal dry periods lasted 15 days on average in summer in the 1950s (only one individual RCM simulation resulted in CDD values for Hungary over 20 days). The RCM simulation ensemble projects dry periods lasting 22 days on average by the last decade of the 21st century, and one of the RCM simulations even resulted in 40-day-long summer dry periods in the 2090s.

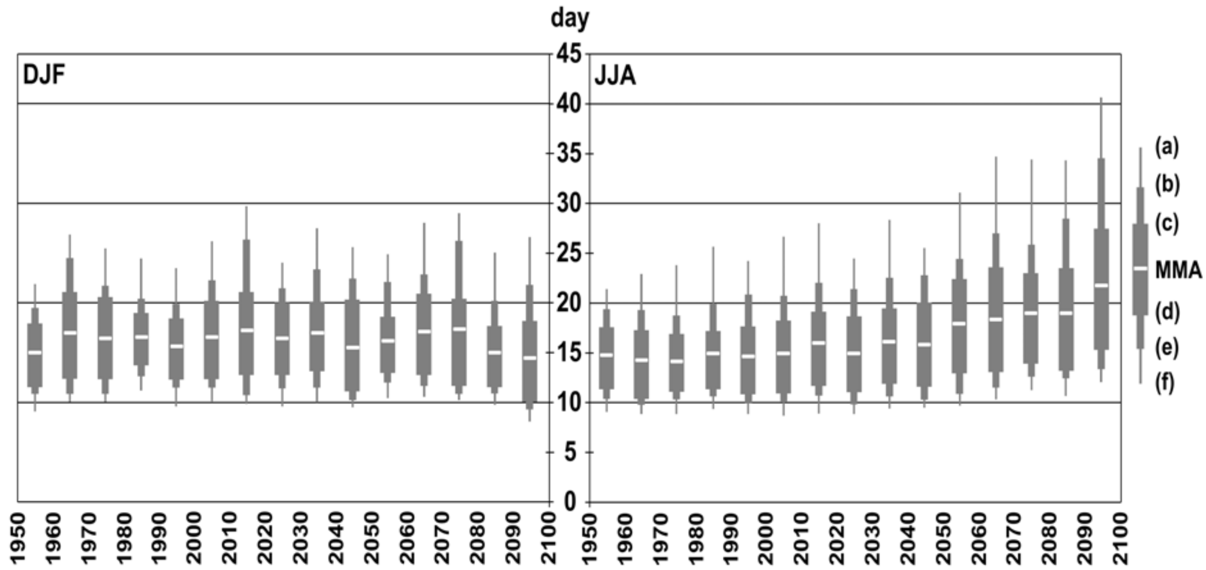

Fig. 8. Average decadal values of CDD in Hungary in winter (left panel) and summer (right panel), 1951–2100. MMA indicates the multi-model average. (a) and (f) indicate the maximum and minimum CDD values, respectively. (b) and (e) indicate the second largest and smallest CDD values, respectively. (c) and (d) indicate the third largest and smallest CDD values, respectively.

The mean length of dry spells is estimated to increase in Hungary in all seasons during the 21st century (*Fig. 9*). The largest change is projected for summer: MDS will increase by 41%, so the 5-day-long mean dry spells of the reference period are likely to lengthen by 3 days and last for 8 days on average by the end of the 21st century. The mean dry spells were the longest in autumn in the reference period (MDS average value is about 8 days), and the RCM simulations suggest that they will remain the longest in 2071–2100 when MDS is likely to exceed 9–10 days. Smaller and only slight changes are estimated in winter and spring.

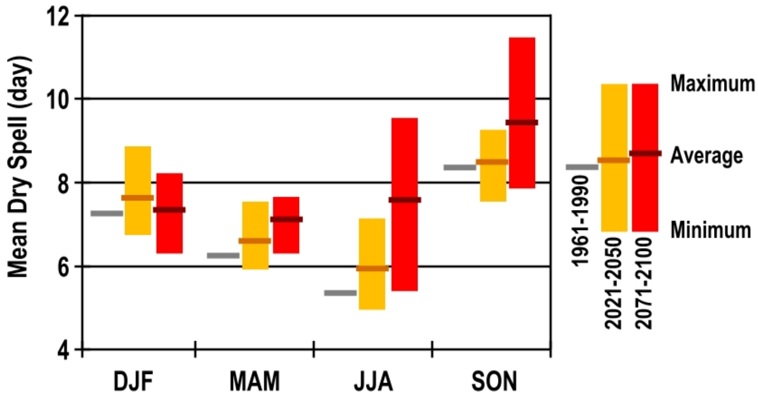

Fig. 9. Spatial average values of MDS in Hungary for three time slices: 1961–1990, 2021–2050, and 2071–2100. Columns represent the projections of the multi-model ensemble.

4. Conclusions

Projected changes of precipitation tendencies for Central/Eastern Europe have been analyzed for the 21st century using bias-corrected outputs of 11 RCM simulations available from the ENSEMBLES database. All the simulations applied 25 km horizontal resolution and took into account the intermediate SRES A1B emission scenario. In order to eliminate the systematic errors, we completed a bias-correction procedure using quantile matching technique. After the correction, we analyzed the return period of daily precipitation amount and different precipitation- and drought-related climate indices for nine subregions. In this paper we focused on the changes of the 10-year return period of daily precipitation amount, the maximum number of consecutive dry days, and the mean length of dry spells in Hungary. The main results can be summarized as follows:

(1) The RCM simulations suggest that the 10- and 20-year return periods will increase in summer by a factor of 1.2–2. Larger increases of the return periods are estimated in the southern parts of the domain than in the northern subregions. The projected changes are considerably smaller for the other three seasons compared to future summer changes. Nevertheless, the estimated changes of the 10-year return period are slightly larger than the changes of the 20-year return period in winter and autumn.

(2) Our results clearly suggest drier summers and wetter winters in the future, especially at the end of the 21st century. In summer, the maximum number of consecutive dry days, the mean length of dry spell, and the total number of dry days are all projected to increase significantly. Furthermore, the mean length of wet spell, the number of wet days, and the number of precipitation days exceeding 5 mm are projected to decrease in Hungary as well as in Central/Eastern Europe. In winter, opposite changes are very likely.

Acknowledgements: Research leading to this paper has been supported by the following sources: the Hungarian Scientific Research Fund under grant grants K-78125 and K109109, the European Union and the European Social Fund through project FuturICT.hu (TÁMOP-4.2.2.C-11/1/KONV-2012-0013). The ENSEMBLES data used in this work was funded by the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged. Furthermore, we acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com), and the data providers in the ECA&D project (http://eca.knmi.nl).

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