IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 119, No. 2, April– June, 2015, pp. 129–142

Projected changes of extreme precipitation using multi-model approach

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(Manuscript received in final form October 6, 2014)

Abstract—Excessive precipitation may result in different environmental and socio-economical damages. In order to mitigate or avoid the potential losses associated to these, it is essential to provide estimations of precipitation tendencies for the future, which facilitate to build appropriate adaptation strategies in time. In this paper we used bias-corrected daily precipitation outputs of 11 regional climate model (RCM) simulations to determine the projected precipitation trends for the Carpathian Basin. According to the results of the analysis of precipitation indices, frequency of extreme precipitation will generally increase in the entire Central/Eastern European domain, except in summer, when decreasing trend is very likely in Hungary as well as in the southern regions.

Key-words: regional climate change, heavy precipitation, precipitation intensity, percentile values, climate index

1. Introduction

In the recent years, extreme precipitation events have become more frequent as well as more intense in many regions of Europe, e.g., in the western part of Central Europe since 1961 (*Kyselý*, 2009; *Seneviratne et al.*, 2012). This is especially valid for winter. In other seasons and other regions, including the

Carpathian Basin, the observed trends are not significant and inconsistent for the past (e.g., *Klein Tank* and *Können*, 2003; *Bartholy* and *Pongrácz*, 2005; 2007). In order to be prepared for the coming changes and make appropriate plans in various socio-economic sectors, it is essential to provide future estimates of mean precipitation trends and extreme events. Different sectors, different activities consider extreme precipitation very differently. Therefore, several types of extreme indices can be defined for describing these events (*Zhang et al.*, 2011). One of the most widely used types is based on exceeding various threshold values, which can be an absolute value (e.g., 10 mm, 20 mm, etc.) or a given (e.g., 90th, 95th, etc.) percentile of long climatological time series. Other more complex indices consider duration, intensity, and/or persistence of the events. Extreme indices usually focus on daily scale using daily precipitation totals. Despite the huge demand of sub-daily scale extreme analysis, there is a lack of such studies due to reliable data availability.

Climate model simulations for the future suggest that number of heavy precipitation days is likely to increase in the northern mid-latitudes in the 21st century, especially in winter (*IPCC*, 2012). Furthermore, in some regions more heavy precipitation days are likely to occur despite of the projected decrease in total precipitation amount. For instance, in Europe, more frequent extreme precipitation events are likely to occur in the coming decades (e.g., *Kyselý et al.*, 2011; 2012; *Rajczak et al.*, 2013). For Hungary, PRUDENCE (*Christensen et al.*, 2007) simulation results suggest that extreme precipitation events are projected to increase in winter, whereas a general decrease is estimated in summer (*Bartholy et al.*, 2008).

Intense precipitation may lead to a severe flood event, which is considered one of the major possible natural hazards on society. Specifically, in Central Europe, river flood risk and vulnerability are likely to have grown in many areas in the recent years (*Kundzewicz et al.*, 2005). As Working Group II of the Intergovernmental Panel on Climate Change (IPCC) pointed out in the Fifth Assessment Report (*IPCC*, 2014), river management is the main factor determining the flood trends of the past. Although the detected regional flood trends in Europe are inconsistent and statistically not significant for the past (*Renard et al.*, 2008, *Stahl et al.*, 2010), it is important to estimate the future change of precipitation, especially extremes, in order to develop appropriate river management strategies. According to the results of *Dankers* and *Feyen* (2008), extreme discharge levels are projected to occur in many European rivers.

In this paper, extreme precipitation is analyzed for Hungary using climate model simulations output. For this purpose, precipitation-related climate indices calculated from bias-corrected time series serve as main indicators for future climate change. First, the data and the applied indices are described. Results are discussed for indices based on (i) absolute value thresholds, (ii) percentile-based thresholds, and for intensity-based indices.

2. Data and methods

In order to estimate the future extreme precipitation trends, outputs from 11 regional climate models (RCMs) embedded in global climate models (GCMs) are analyzed taken into account the intermediate SRES A1B emission scenario (*Nakicenovic* and *Swart*, 2000). According to this scenario, the population is estimated to increase up to 8.7 billions and decline after the middle of the 21st century. The energy demand is assumed to be covered from both fossil fuels and renewable/nuclear energy sources. Thus, global mean CO_2 concentration level is estimated to reach 717 ppm by 2100. Simulation datasets are available with 25 km horizontal resolution on daily scale for 1951–2100 from the ENSEMBLES project (*van der Linden* and *Mitchell*, 2009). Due to the general underestimation of summer precipitation and overestimation of winter precipitation (*Pongrácz et al.,* 2011), raw data have to be bias-corrected prior to the detailed analysis. The applied correction (*Pongrácz et al*., 2014) is based on a quantile matching technique (*Formayer* and *Haas*, 2010) for which E-OBS datasets (*Haylock et al.*, 2008) serve as reference for the 1951–2000 time period. The 25 km horizontal resolution gridded daily E-OBS data were created in the framework of the ENSEMBLES project by interpolating measured datasets of meteorological stations from all over Europe. For the area focused in this analysis, data from about 400 stations were used (note that the spatial coverage is not homogeneous).

After the correction, several precipitation-related climate indices are calculated. This paper focuses on excessive precipitation, whereas analysis of the lack of precipitation, i.e., drought-related indices can be found in *Pongrácz et al*. (2014). Among the indices connected to extreme precipitation (*Table 1*), two indices are defined by using different absolute threshold values (RR10, RR20), two indices indicate precipitation intensity (RX1, RX5) for different durations, and six indices are based on percentiles of daily precipitation amount (R90p, R95p, R99p, R90pGT, R95pGT, R99pGT). The grid cell values of all the 10 indices are calculated from the 11 bias-corrected RCM simulations for Central/Eastern Europe (covering the area of 43.625°–50.625°N, 13.875°–26.375°E) for the whole 1951–2100 simulation period. In this analysis, mean seasonal changes for the 2021–2050 and 2071–2100 periods are determined relative to the 1961–1990 reference period. Moreover, nine subregions are defined in the selected domain (Southeastern Czech Republic, Eastern Austria, Slovakia, Southwestern Ukraine, Slovenia, Hungary, Romania, Croatia, and Northern Serbia), for which the spatial average of annual and seasonal mean changes are calculated.

Table 1. Name, definition, and unit of the analyzed precipitation-related climate indices

Index	Definition	Unit
RR10	Number of heavy precipitation days ($R_{day} \geq 10$ mm)	day
RR20	Number of very heavy precipitation days ($R_{day} \geq 20$ mm)	day
RX1	Highest 1-day precipitation amount ($R_{max,1day}$)	mm
RX5	Highest 5-day precipitation amount ($R_{max,5day}$)	mm
R90p	The 90th percentile of daily precipitation time series	mm
R95p	The 95th percentile of daily precipitation time series	mm
R99p	The 99th percentile of daily precipitation time series	mm
R90pGT	Fraction of total precipitation above the base period's 90th percentile ($\sum(R_{2071–2100} > R90p_{1961–1990})/\sum R_{2071–2100}$)	%
R95pGT	Fraction of total precipitation above the base period's 95th percentile ($\sum(R_{2071–2100} > R95p_{1961–1990})/\sum R_{2071–2100}$)	%
R99pGT	Fraction of total precipitation above the base period's 99th percentile ($\sum(R_{2071–2100} > R99p_{1961–1990})/\sum R_{2071–2100}$)	%

3. Results and discussion

First, analysis of exceeding absolute daily precipitation threshold values is presented for the mid- and late-century compared to the reference period 1961–1990. Then, the projected changes of percentile-based indices are evaluated. Finally, intensity-type precipitation indices are analyzed.

3.1. Estimated future changes of precipitation indices using absolute threshold values

On a daily scale, 10 mm and 20 mm precipitation amounts are usually considered as heavy and very heavy precipitation days, respectively. Due to the different processes resulting in rainfall or snowfall, these days occur generally more often in summer than in winter, i.e., more precipitation occur from convective systems in the summer months. Two indices (RR10 and RR20) are analyzed in this paper and compared seasonally for the three selected time slices (1961–1990, 2021–2050, and 2071–2100). The average numbers of days are very different for the two indices, therefore, different scales and units are used in *Fig. 1*, i.e., RR10 and RR20 are shown as the mean frequency in 10 and 30 years, respectively. In July and August both indices are projected to decrease relative to the reference period 1961–1990, moreover, in May and June, RR10 is likely to decrease by the end of the 21st century. In all the other months, indices are projected to increase on average.

If we consider the estimated changes between the middle and late 21st century, the two indices differ in the three autumn months, namely, RR10 is projected to increase in September and October, whereas RR20 is likely to decrease in these two months. In November, the opposite is projected: RR10 tends to decrease and RR20 tends to increase.

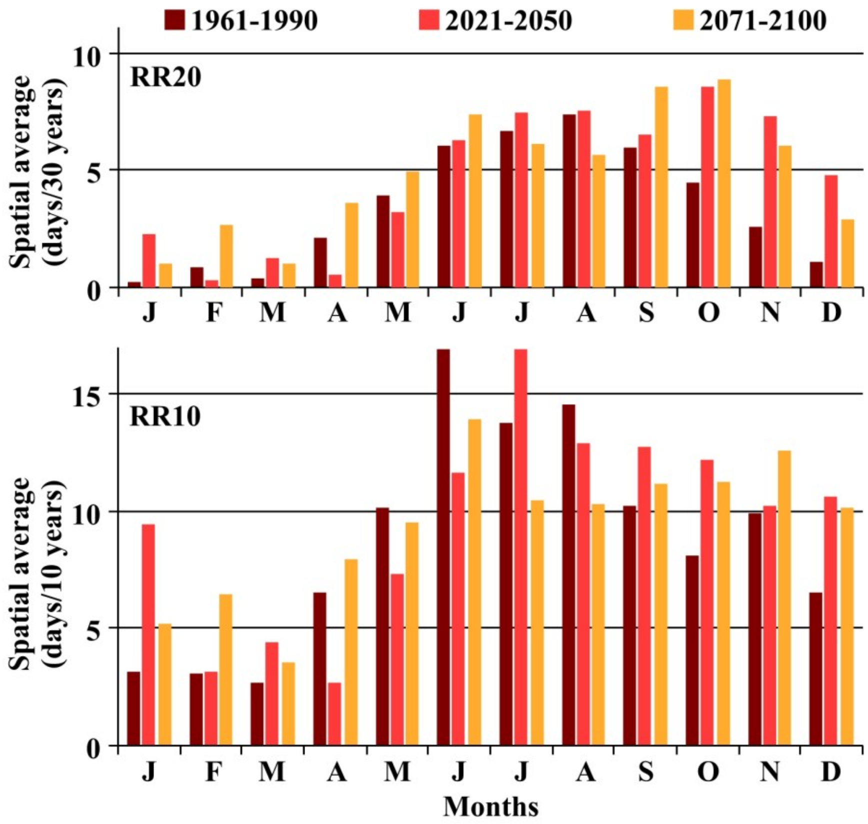

Fig. 1. Multi-model monthly average values of RR20 (upper panel) and RR10 (lower panel) for Hungary in 1961–1990, 2021–2050, and 2071–2100. Original units from Table 1 are modified to show simulated occurrence frequencies in longer time periods, 30 and 10 years, respectively.

Higher values are projected for 2021–2050 relative to 1961–1990 for both RR10 and RR20 in January, March, July, and December (which implies dominantly the winter half-year). This is followed by the decrease of average index values in the second half of the century. On the contrary, in April and May, both RR10 and RR20 are projected to decrease first, and then, increase by the last few decades of the century (in case of RR10, the estimated mean changes are similar also for June).

3.2. *Estimated future changes of percentile-based precipitation indices*

From the aspect of excessive precipitation, this paper focuses on large percentiles, i.e., the 90th, 95th, and 99th percentile values themselves, and the precipitation totals above these percentile thresholds relative to the entire precipitation totals. The seasonal mean changes of these percentile-based precipitation indices by the end of the 21st century compared to the reference period are summarized in *Fig. 2* for Hungary.

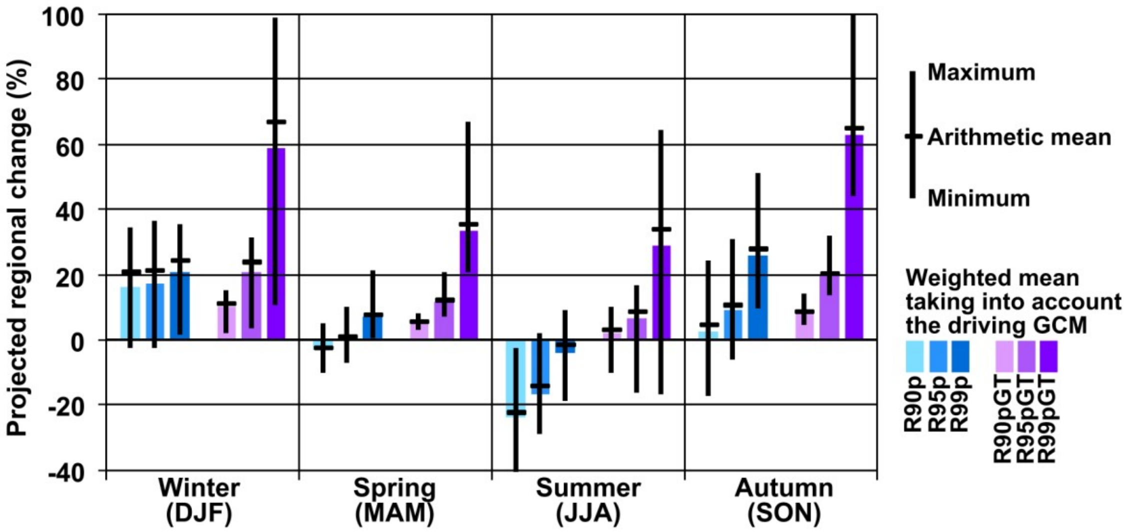

Fig. 2. Projected seasonal mean changes (%) of the percentile-based precipitation indices for Hungary by 2071–2100 relative to the reference period 1961–1990. The thicker bars indicate the average changes on the basis of RCM projections using equal weights to the driving GCMs. The thinner bars indicate the total ranges of RCM projections.

The fractions of the extreme daily precipitation totals from the entire precipitation totals are dominantly projected to increase, only two RCM (HIRHAM/ARPEGE and HadRM/HadCM3) simulations estimate decrease of summer index values. RCM simulations suggest quite similar changes of R90pGT, the entire multi-model uncertainty is less than 15%. Estimated spatial average changes of R95pGT are less similar compared to those of R90pGT, however, the uncertainty due to the different RCM use does not exceed 33%. The largest multi-model uncertainty in relative changes is projected in case of R99pGT exceeding 45% in all the seasons, moreover, it is 88.5% in winter. Similarly to the uncertainty ranges of multi-model estimations, the projected increases of the fractions of the higher extreme daily precipitation totals are also larger than those of the smaller extremes, i.e., estimated seasonal changes of R90pGT (2–10% on average) are smaller than changes of R95pGT (6–21% on average), which are considerably smaller than changes of R99pGT (33–63% on average). For all the three indices, the largest increase is projected generally in winter and autumn, and the smallest increases are likely to occur in summer and spring.

The spatial structures of the projected seasonal mean changes for the entire domain are shown in *Fig. 3*. The composite maps clearly suggest that the estimated increases are larger in the northern part of the domain than in Hungary, and generally smaller in the southern regions. In summer, overall slight decreases are projected for all the three indices in the southwestern regions. Within Hungary, the projected average changes of all the three indices are generally larger in the eastern lowlands than in the western Transdanubian part of the country. However, in spring, the smallest increases are estimated in the middle subregions of the country.

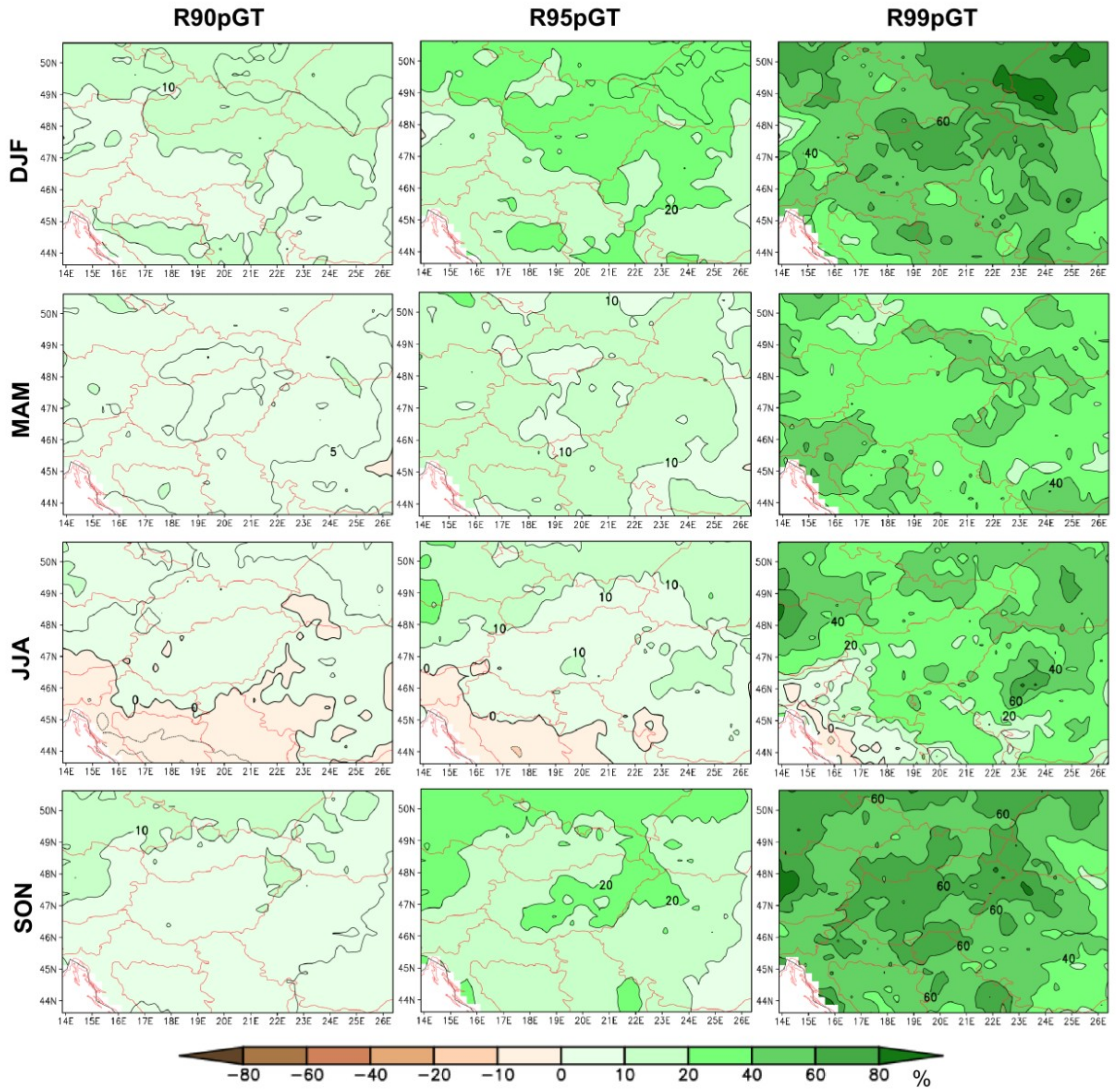

Fig. 3. Projected multi-model mean changes (%) of the fraction of total precipitation greater than the 90th, 95th, and 99th percentiles of daily precipitation in the four seasons (from top to bottom: winter, spring, summer, autumn) for 2071–2100 relative to the reference period 1961–1990.

The entire ranges of the estimated changes of high percentile values of daily precipitation are relatively large, mostly exceeding 25%, except in spring when they are 15–20% (*Fig. 2*). These large ranges suggest quite large uncertainty within the multi-model ensemble, when even the signs of the projected trends can be different (i.e., both increasing and decreasing). However, in winter, all the three percentile values in Hungary are very likely to increase, the estimated multi-model mean changes are 21%, 21%, and 24% for R90p, R95p, and R99p, respectively. In autumn, the higher the extreme percentile, the larger the projected increase. For instance, R99p is projected to increase by about 26% by the end of the 21st century relative to the reference period. In summer, the multi-model ensemble projects clear decrease of R90p (by 23% on average) in Hungary, mainly decrease of R95p (by 15% on average), whereas higher uncertainty is associated to the estimation of changes in R99p: the majority of the RCMs project slight increase (not exceeding 9%), nevertheless, some of the RCMs project relatively high decrease (10–19%), resulting in an overall slight decrease of R99p. Finally, in spring, slight changes are projected in general, which do not exceed 10%. However, note that R99p is estimated to clearly increase (by 7% on average), since all the RCMs project positive changes by 2071–2100 compared to 1961–1990.

The spatial structures of the projected seasonal mean changes are shown in *Fig. 4*. The estimated summer decreases show clear zonal differences, the largest decrease in percentile values of daily precipitation exceeds 40% and 20% in the southern part of the entire domain in case of R90p and R95p, respectively. The summer values of R99p tend to increase in the northern (and especially the northwestern) part of the domain, and decreases of R99p values are projected only in the southern part (the largest average decreases exceed 10%). Within Hungary, the quasi-zonal structure can be recognized as well, as in the entire domain. All the three indices are projected to decrease in summer in the whole country, the largest decreases are likely to occur along the southern border of Hungary. In winter, increases of the indices are estimated in the entire domain, the largest changes are likely to occur in the northern part, especially in the mountainous subregions. Percentile values in the northern part of Hungary are also projected to increase more than in the southern subregions. R99p – representing the very high extreme daily precipitation – is projected to increase in the entire domain also in spring and autumn, however, the projected seasonal average changes are generally smaller than in winter. In the equinox seasons, R90p values are projected to increase in the northern part and decrease in the southern part of the domain, whereas R95p is estimated to increase dominantly (except in small regions in the southern part).

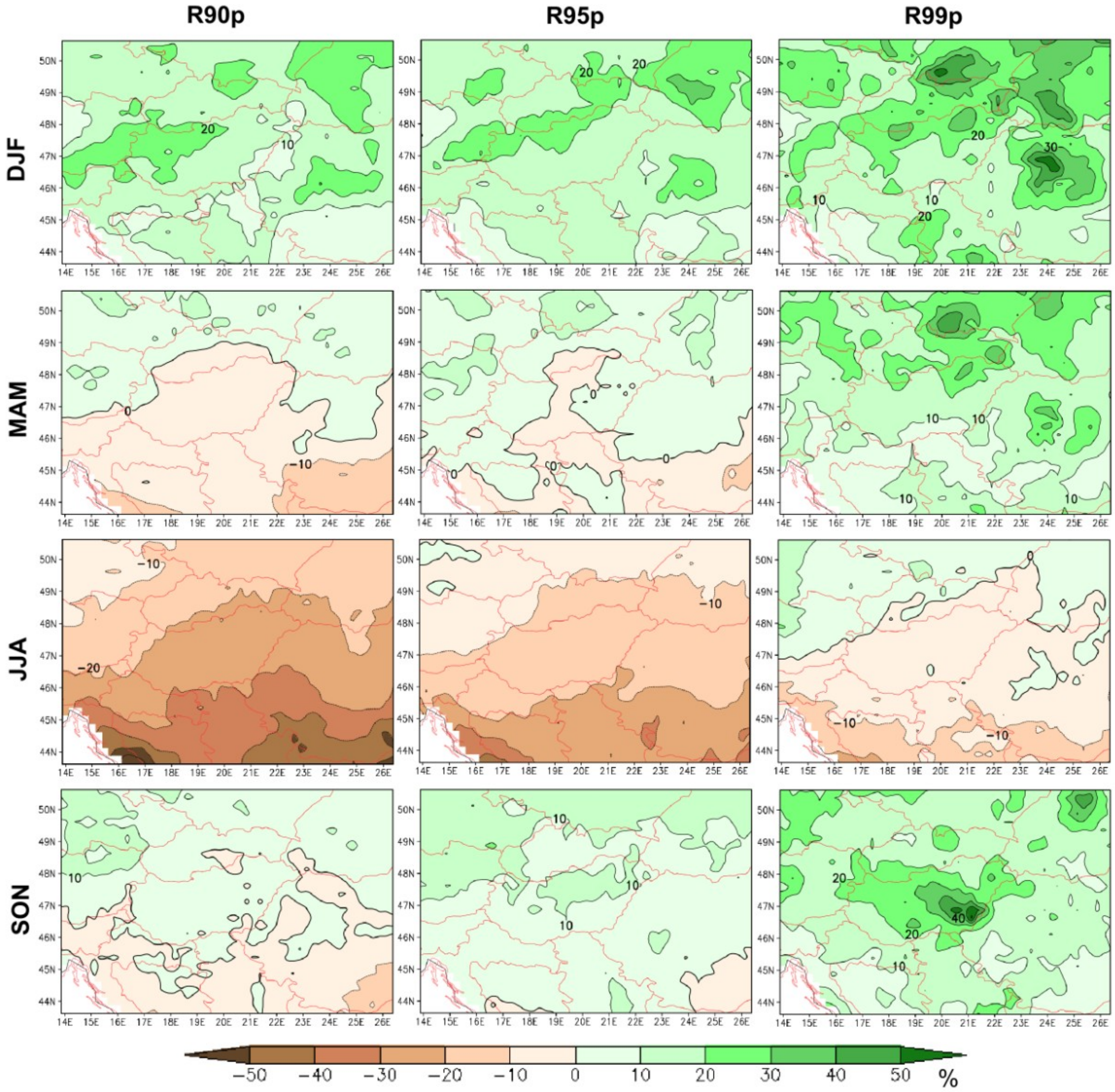

Fig. 4. Projected multi-model mean changes (%) of the 90th, 95th, and 99th percentiles of daily precipitation in the four seasons (from top to bottom: winter, spring, summer, autumn) for 2071–2100 relative to the reference period 1961–1990.

3.3. *Estimated future trends of precipitation intensity indices*

The precipitation intensity is represented in this paper by the highest precipitation totals during 1 day and 5 days (i.e., RX1 and RX5, respectively). The summary of multi-model monthly estimations of spatial average for Hungary is shown in *Fig. 5* for RX5 (similar changes are projected for RX1). These results clearly suggest that the maximum 5-day precipitation totals are projected to increase in the 21st century in all months, except August. The inter-model variability of the estimated RX5 values is much higher in July, August, and September than in the rest of the year (the entire RX5 ranges of RCM-estimations for the winter months do not exceed 20 mm). In general, the inter-model variability of RX5 is projected to increase in the 21st century compared to the reference period.

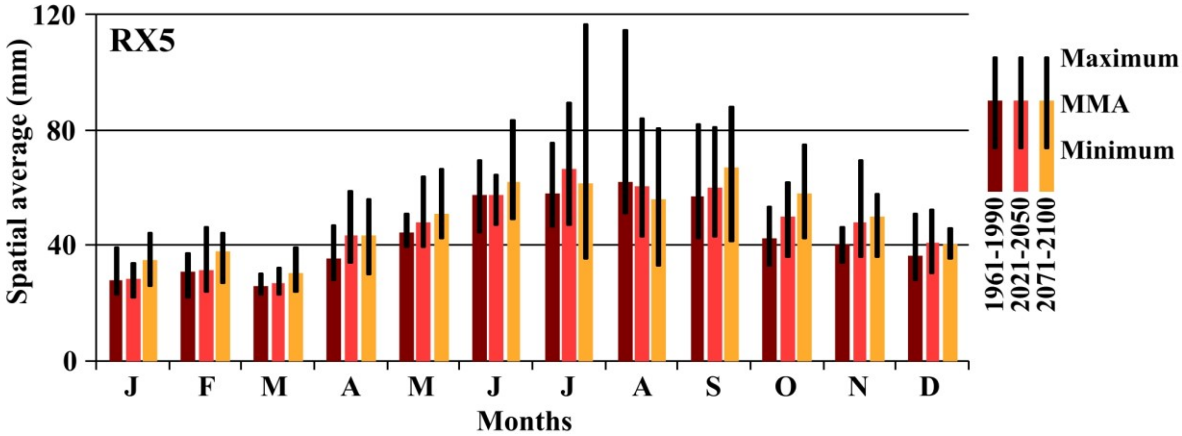

Fig. 5. Comparison of estimated monthly average values of RX5 for Hungary in 1961–1990, 2021–2050, and 2071–2100 using 11 RCM simulation outputs. MMA indicates the multi-model average.

Composite maps of the projected seasonal mean changes of RX1 show the spatial structures of the estimated changes by 2071–2100 relative to 1961–1990 (*Fig. 6*). Increasing trends are projected for all seasons, except in summer in the southern part of the domain, where the estimated negative changes on average imply decreasing trends for the future. The estimated spatial average changes of RX1 for the whole domain are 20%, 11%, 2%, and 23% in winter, spring, summer, and autumn, respectively. In summer, a zonal structure similarly to the changes of the summer percentile values can be recognized: in the northern part of the selected domain RX1 is projected to increase, whereas in the southern subregions it is projected to decrease. Specifically, the estimated multi-model average changes by the late 21st century in summer are +11% and –8% in the southeastern Czech Republic and in Croatia, respectively. In Hungary, the largest increase is estimated in autumn (+23%), when projected changes calculated from 9 individual RCM simulations (out of 11 total experiments studied in this paper) are statistically significant.

Since the largest increases are likely to occur in winter and autumn, more detailed temporal analysis is presented for these two seasons in *Fig. 7* showing the average decadal values of RX1 from the 1950s to the 2090s for Hungary. The ensemble of the individual RCM simulations clearly suggest increasing trends in the multi-model mean as well as in the 1st, 2nd, and 3rd maximum and minimum decadal values of RX1. All these trend coefficients are statistically significant at 0.05 level. The estimated overall change of the multi-model mean between the 1950s and 2090s is 30% in winter, and 33% in autumn, when the decadal average of the highest daily precipitation amount is very likely to exceed 24 mm in the 2090s (and it was about 18 mm in the 1950s according to the RCM simulations).

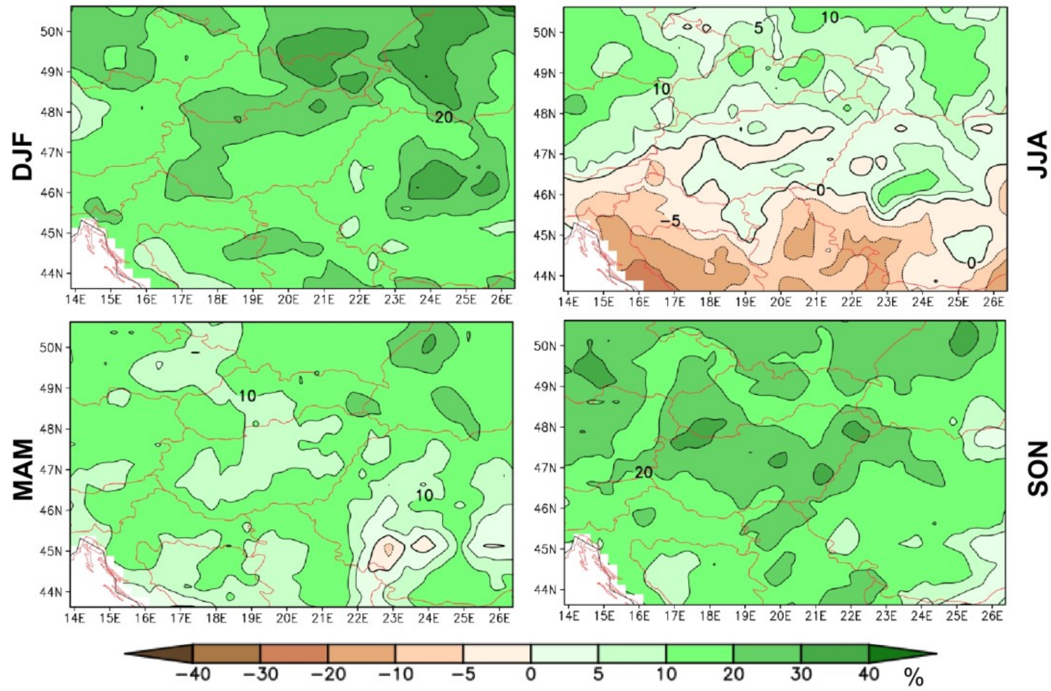

Fig. 6. Composite maps of the projected seasonal mean changes (%) of RX1 by 2071–2100 relative to the reference period 1961–1990. Average changes are calculated on the basis of RCM projections using equal weights to the driving GCMs.

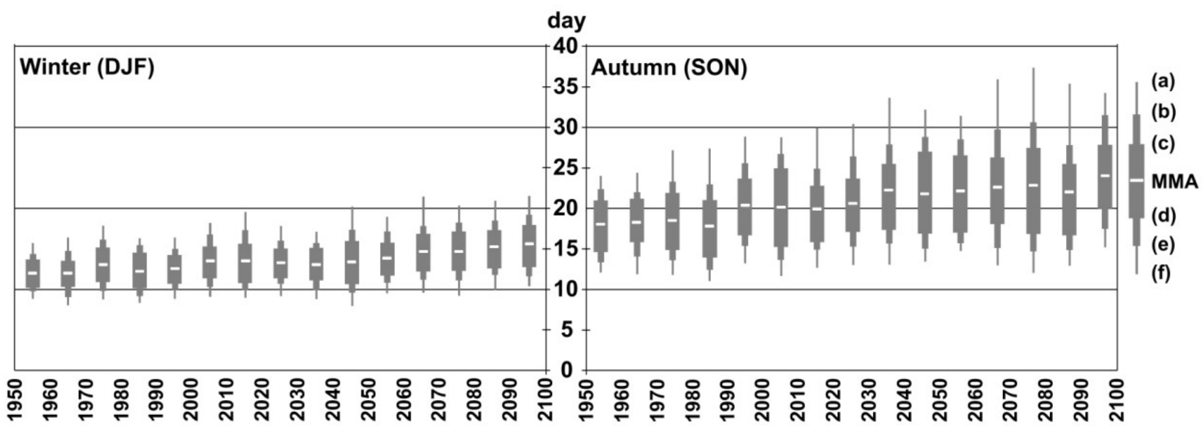

Fig. 7. Average decadal values of RX1 for Hungary in winter (left panel) and autumn (right panel), 1951–2100. MMA indicates the multi-model average. (a) and (f) indicate the maximum and minimum RX1 values, respectively. (b) and (e) indicate the second largest and smallest RX1 values, respectively. (c) and (d) indicate the third largest and smallest RX1 values, respectively.

4. Conclusions

Estimated changes of extreme precipitation conditions in Central/Eastern Europe (with special focus on Hungary) have been analyzed in this paper using bias-corrected daily precipitation outputs of 11 RCM simulations from the ENSEMBLES project considering the intermediate A1B scenario. Based on the results, the following conclusions can be drawn for the late 21st century relative to the reference period.

(i) Excessive precipitation (R90p, R95p, R99p) is mostly estimated to increase, except in summer, when decrease is projected both in Hungary and in the southern regions of the entire domain.

(ii) The fraction of the excessive precipitation relative to the total amount (R90pGT, R95pGT, R99pGT) is projected to increase in general. Only a few RCMs estimate slight decrease in summer for Hungary, and the multi-model average change in summer is slightly negative in the southwestern part of the entire domain.

(iii) Frequency of heavy precipitation (RR10, RR20) is projected to decrease in summer, and increase in the rest of the year.

(iv) Precipitation intensity (RX1, RX5) is likely to increase overall. However, in summer decreasing trend is estimated in the southern parts of the selected domain.

Overall, remarkable increasing trends of precipitation extremes are projected for Central/Eastern Europe by 2071–2100 relative to the 1961–1990 reference period. These changes may result in more frequent and more severe river flooding, therefore, in order to mitigate the vulnerability of the region, it is highly suggested to develop appropriate flood protection and management strategies in time considering these estimated changes.

***Acknowledgements*–**Research leading to this paper has been supported by the following sources: the Hungarian Scientific Research Fund under 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), and the AGRÁRKLIMA2 project (VKSZ_12-1-2013-0001). 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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