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1. INTRODUCTION

In order to build regional adaptation and mitigation strategies, global climate simulation results must be downscaled for local analysis, which can better serve end-users' needs. This is especially important in case of precipitation due to the large temporal and spatial variability. Furthermore, the high potential risks of drought events on agricultural production and the possible flood events in the area also highlight the importance of this issue.

In this paper, simulations of 25 km horizontal resolution regional climate models (RCM) nested in coarse resolution global climate models (GCMs) are used to estimate the future climate conditions in Central/Eastern Europe. The driving lateral and boundary conditions are provided by three different GCMs: (i) ECHAM developed by the Max Planck Institute in Hamburg (Roeckner et al., 2006), (ii) HadCM developed by the UK Met Office Hadley Centre (Gordon et al., 2000), and (iii) ARPEGE developed by Météo-France (Déqué et al., 1998). The RCM experiments were carried out as one of the major tasks of the ENSEMBLES project (van der Linden and Mitchell, 2009) funded by the European Union 6th framework programme between 2004 and 2009. They cover the 1951-2100 period and applied the intermediate SRES A1B emission scenario, for which the estimated CO_2 concentration levels by 2050 and by 2100 are 532 ppm, and 717 ppm, respectively (Nakicenovic and Swart, 2000).

2. BIAS CORRECTION

In the present analysis, precipitation outputs of 11 RCM experiments are used (Table I).

The raw precipitation outputs of ENSEMBLES' RCM experiments were compared to the E-OBS gridded daily data (Haylock et al., 2008) for 1951-2000. Simulated values usually significantly overestimate the observations in Central/Eastern Europe, except in summer when mostly underestimations were found (Pongracz et al., 2011). These biases of the raw RCM outputs are corrected using quantile matching technique when the monthly empirical distribution functions of each grid cell are fitted (Formayer and Haas, 2010) to the observed distribution represented by the gridded E-OBS data.

Table I: List of the selected RCMs, their driving GCMs, and the responsible institutes used in this analysis

RCM	Driving GCM	Institute
HadRM3Q0	HadCM3Q	HC, UK
RCA3	HadCM3Q	C4I, Ireland
CLM	HadCM3Q	ETHZ, Switzerland
RCA	HadCM3Q	SMHI, Sweden
RCA	ECHAM5	SMHI, Sweden
RACMO	ECHAM5	KNMI, Netherlands
REMO	ECHAM5	MPI, Germany
RegCM	ECHAM5	ICTP, Italy
HIRHAM5	ECHAM5	DMI, Denmark
HIRHAM	ARPEGE	DMI, Denmark
ALADIN	ARPEGE	CNRM, France

An example of the distribution fitting is shown for a selected grid cell in Fig. 1. Then, the calculated bias correcting factors are applied to the outputs of RCM experiments for the future 2000-2100 period.

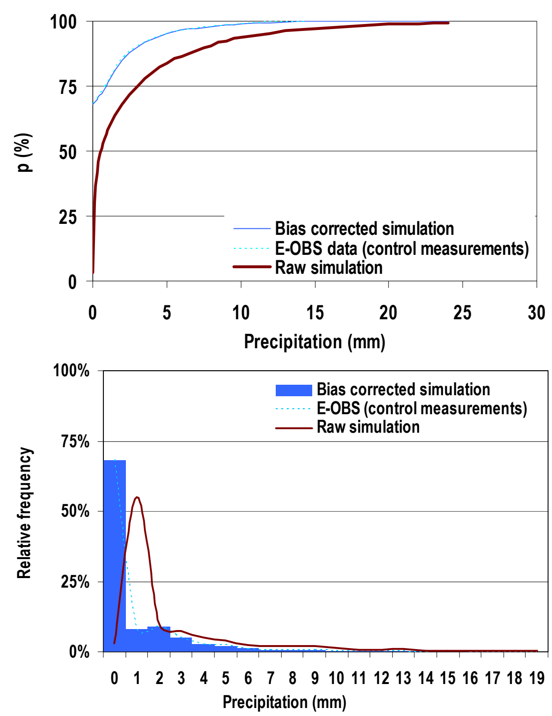

Fig. 1: Bias correction of raw simulation data, 1951-2000. Empirical distributions of January daily data from the grid cell located at 47.625°N, 19.625°E are shown.

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3. CLIMATE INDICES

In order to assess future climate tendencies in the analyzed region, several precipitation-related indices are analyzed on seasonal scales. Definitions applied to the 20th century trend analysis in Bartholy and Pongracz (2007) are used for the 21st century here. The present analysis includes the number of wet days using several threshold values, e.g., 1 mm, 5 mm, 10 mm, 20 mm (RR1, RR5, RR10, RR20, respectively), the number of dry days when the daily precipitation is less than 1 mm (DD), the maximum number of consecutive dry days (CDD), the highest 1-day precipitation amount (RX1), the greatest 5-day rainfall total (RX5), the simple daily intensity index (SDII), which is the average precipitation on rainy or snowy days.

The grid cell values of all the 9 indices are calculated from the bias-corrected precipitation data sets for the entire selected domain covering the latitude 43.5°-50.5°N, and longitude 14°-26.5°E for the whole simulation period (1951-2100) using all the 11 RCM experiments. Projected seasonal changes by 2021-2050 and 2071-2100 periods relative to the 1961-1990 reference period are mapped. Furthermore, spatial average changes for 9 subregions within the domain are estimated for each season both for the middle and the end of the 21st century.

In this paper, CDD, RR1 and RR10 are discussed in details in the following three sections.

4. ESTIMATED FUTURE TREND OF CDD

CDD is the maximum number of consecutive dry days (when precipitation does not exceed 1 mm). Projected seasonal changes by 2071-2100 period relative to the 1961-1990 reference period are shown in Fig. 2. The composite maps are determined as the weighted average of the results from all the 11 RCM experiments taking into account the driver GCMs.

The results clearly suggest that consecutive dry periods in the region are likely to lengthen in the future. The spatial average changes for the whole domain are 0%, 11%, 46%, and 14% in winter, spring, summer, and autumn, respectively. In all the four seasons larger increases are projected at the southern than the northern part of the domain. For instance, in summer the estimated composite increase of CDD exceeds 50% in Serbia and Romania by 2071-2100, whereas it is less than 40% in the southeastern Czech Republic (Table II). Moreover, the projected increase is larger by 2071-2100 than by 2021-2050 both in the entire domain and all the subregions. The estimated trends are not linear; smaller changes are likely to occur in the first half of the 21st century than in the second half, which implies accelerating changes.

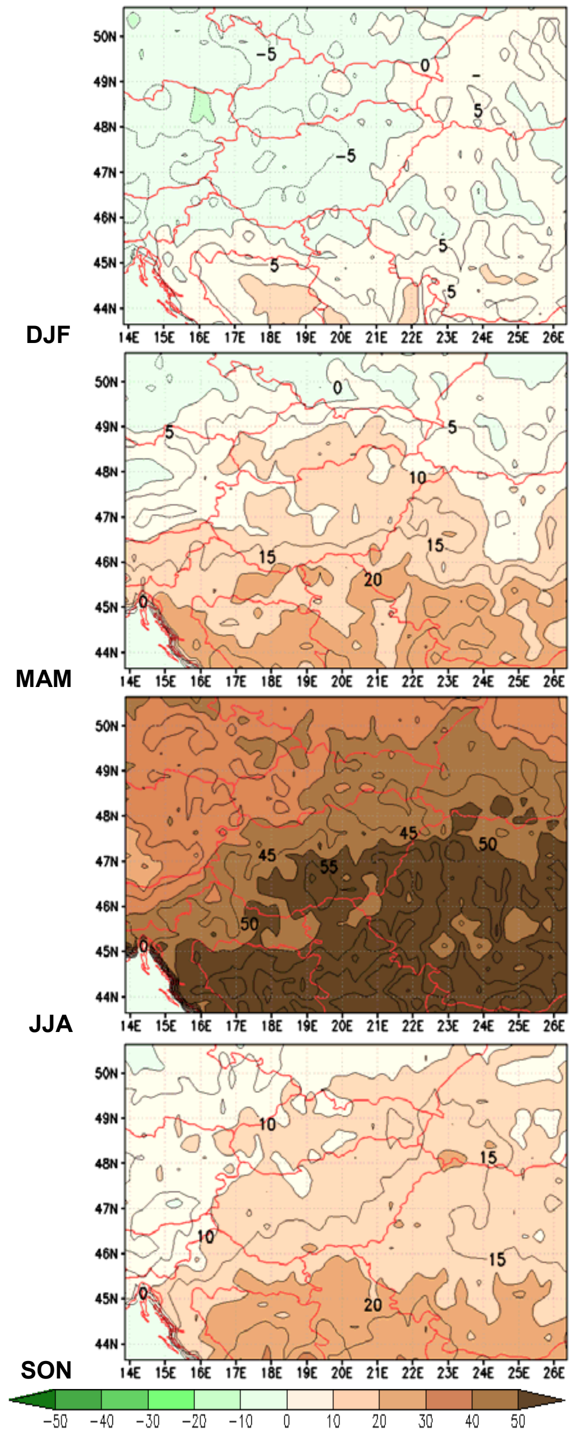

Fig. 2: Composite map of the projected seasonal mean changes (%) of CDD by 2071-2100 relative to the reference period, 1961-1990

Table II: Spatial average values in summer in the 1961-1990 reference period for the 9 subregions and the projected changes by the 2021-2050 and 2071-2100 periods. The numbers in parentheses indicate the numbers of RCM experiments, which resulted in statistically significant increase of CDD at 0.05 level.

Subregion	1961-90 (E-OBS)	Projected change by 2021-2050	Projected change by 2071-2100
E-Austria	9 days	4% (2)	35% (8)
SE-Czech	14 days	5% (2)	38% (9)
Croatia	11 days	14% (3)	49% (10)
Hungary	21 days	12% (3)	48% (9)
Romania	12 days	19% (6)	54% (11)
Serbia	15 days	20% (6)	59% (11)
Slovakia	11 days	7% (2)	40% (10)
Slovenia	10 days	10% (2)	40% (8)
W-Ukraine	11 days	10% (2)	41% (10)

The projected spatial average changes by the individual RCM experiments are shown in Figs. 3, 4, and 5 for the SE-Czech, the Hungarian, and the Romanian subregions, respectively. These three subregions are located in the northwestern-southeastern axis of the domain, thus provide an overall summary for the entire domain. In summer, the individual RCM estimations clearly result in considerable increase of CDD by the last three decades of the 21st century. Most of the RCM experiments suggest statistically significant change at 0.05 level (these are indicated by filled symbols on the graphs). The ECHAM-driven RCM experiments (indicated by triangles) estimate smaller rates of future increase than HadCM- or ARPEGE-driven RCM simulations (indicated by squares and circles, respectively).

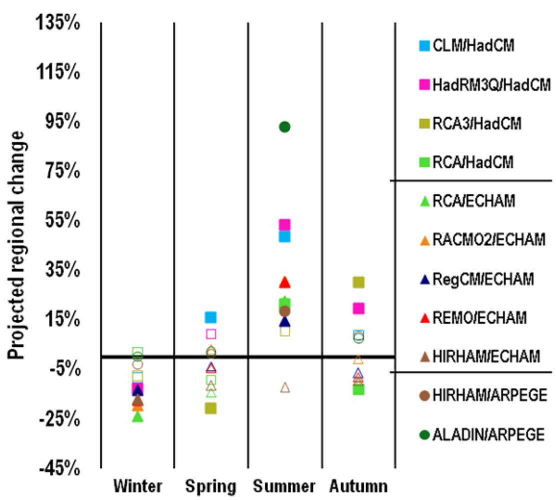

Fig. 3: Projected seasonal mean changes (%) of CDD in the SE-Czech subregion by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of CDD at 0.05 level.

The projected CDD changes involve uncertainties not only in the rate but also in the sign for the other three seasons. Moreover, less individual RCM experiments estimate statistically significant seasonal changes than in summer.

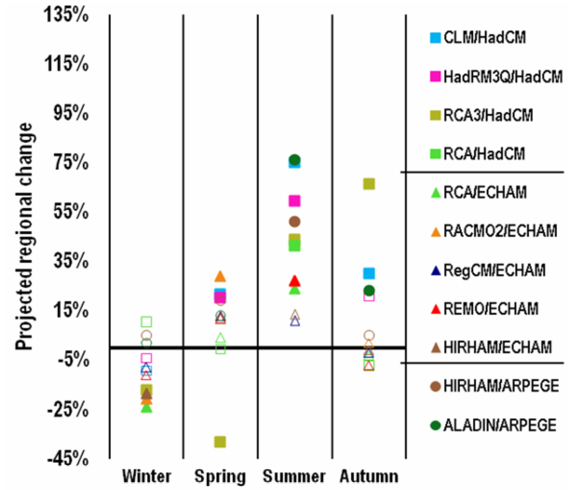

Fig. 4: Projected seasonal mean changes (%) of CDD in Hungary by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of CDD at 0.05 level.

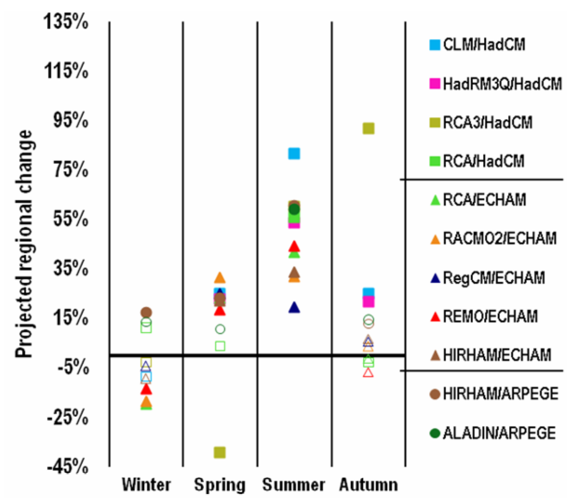

Fig. 5: Projected seasonal mean changes (%) of CDD in the Romanian subregion by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of CDD at 0.05 level.

In winter, the multi-model composites suggest a slight decrease of CDD in the southeastern Czech and the Hungarian subregions (by 6% and 4%, respectively), whereas a slight increase in Romania (by 3%). The largest decreases are projected by the ECHAM-driven RCM experiments.

In spring, the multi-model composites suggest a moderate increase of CDD in Hungary and Romania (by 12% and 17%, respectively), whereas no change is estimated in the southeastern Czech subregion. The only RCM experiment projecting significant decreases (by 20% in the SE-Czech Republic and by 40% in

Hungary and Romania) is carried out by the Irish RCA3 model driven by HadCM.

Finally, in autumn, the multi-model composites suggest a slight increase of CDD in the southeastern Czech subregion (by 5%), and a moderate increase in Hungary and Romania (by 14% and 18%, respectively).

5. ESTIMATED FUTURE TREND OF RR1

RR1 is the number of wet days when daily precipitation exceeds 1 mm. Projected seasonal changes by 2071-2100 period relative to the 1961-1990 reference period are shown in Fig. 7. Similarly to CDD, the composite maps are determined as the weighted average of the results from all the 11 RCM experiments taking into account the driver GCMs.

The results clearly suggest that wet days with more than 1 mm daily precipitation in the region are likely to occur less often in summer and autumn in the future. The zonal structure can be clearly recognized in all the four seasons. Larger decreasing rates are projected at the southern than the northern part of the domain in summer and autumn, whereas the signs of the estimated changes differ zonally in winter and spring with projected increase in the northern and decrease in the southern part of the domain. The spatial average changes for the whole domain are +2%, -3%, -28%, and -9% in winter, spring, summer, and autumn, respectively. The most pronounced RR1 changes are projected for summer, for which the seasonal values are summarized for the 9 subregions in Table III. In general, the projected decreasing trends of wet days are larger by 2071-2100 than by 2021-2050 in all the subregions. Similarly to CDD, the estimated trends are not linear; smaller changes are likely to occur in the first half of the 21st century than in the second half, which implies accelerating changes of RR1, too. By the middle of the 21st century 4-5 RCM experiments suggest statistically significant decrease of RR1 at 0.05 level in most of the subregions except Eastern Austria and the Southeastern Czech Republic (where only 2 and 1 RCM experiments result in statistically significant decreasing trend). By the last three decades of the 21st century most of the RCM experiments (9-11 out of 11) suggest statistically significant decrease of RR1 in the individual subregions. The zonal difference can be illustrated by the subregional average decreasing rates. In the northern/northwestern part of the domain (i.e., in Eastern Austria and the Southeastern Czech Republic) RR1 is likely to decrease by less than 20%, whereas it is estimated to decrease by more than 30% in the southern subregions, e.g., in Serbia, Romania, and Croatia.

The projected spatial average changes by the individual RCM experiments are shown in Figs. 8, 9, and 10 for the SE-Czech, the Hungarian, and the Romanian subregions, respectively.

In summer, the individual RCM estimations clearly result in considerable decrease of RR1 by the last three decades of the 21st century. In general, all the RCM experiments suggest statistically significant change (by 12-45%) at 0.05 level. There are only 2 RCM experiments in case of the Southeastern Czech subregion projecting less than 10% future change, which are not significant at 0.05 level.

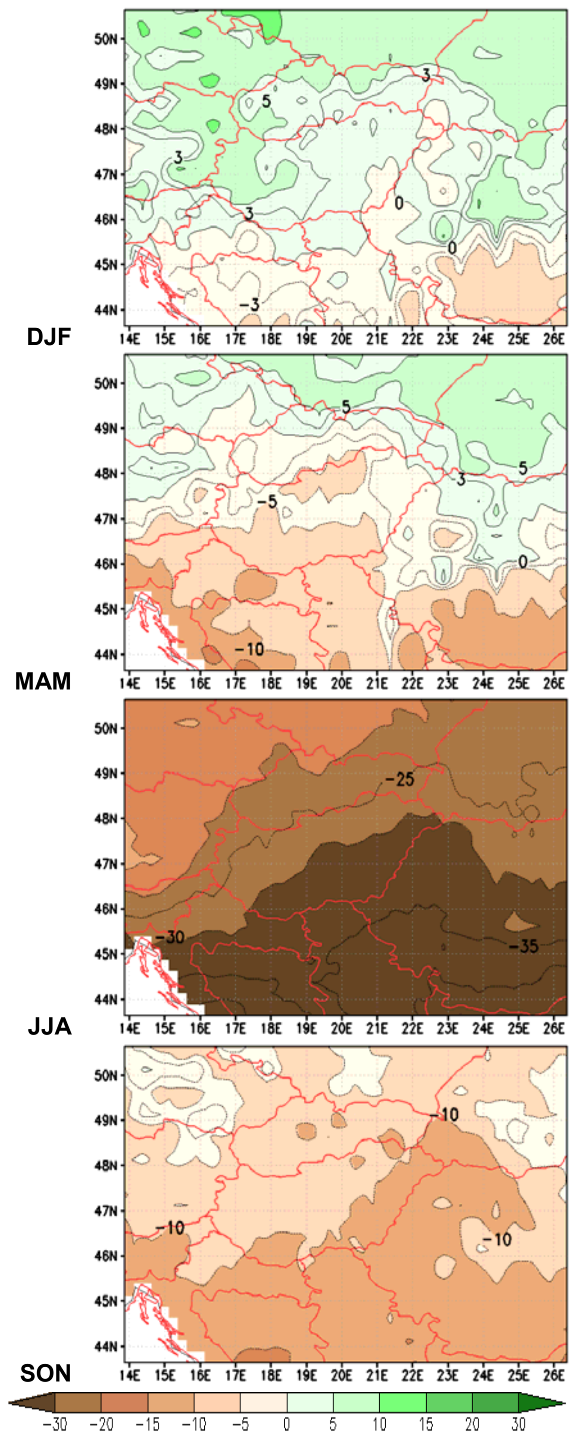

Fig. 7: Composite map of the projected seasonal mean changes (%) of RR1 by 2071-2100 relative to the reference period, 1961-1990

Table III: Spatial average values in summer in the 1961-1990 reference period for the 9 subregions and the projected changes by the 2021-2050 and 2071-2100 periods. The numbers in parentheses indicate the numbers of RCM experiments, which resulted in statistically significant decrease of RR1 at 0.05 level.

Subregion	1961-90 (E-OBS)	Projected change by 2021-2050	Projected change by 2071-2100
E-Austria	41 days	-3% (2)	-18% (9)
SE-Czech	39 days	-3% (1)	-18% (9)
Croatia	29 days	-11% (5)	-32% (11)
Hungary	46 days	-10% (4)	-29% (11)
Romania	33 days	-15% (5)	-34% (11)
Serbia	28 days	-16% (5)	-37% (11)
Slovakia	39 days	-6% (4)	-23% (11)
Slovenia	36 days	-7% (4)	-24% (10)
W-Ukraine	40 days	+3% (4)	-24% (10)

The projected RR1 changes involve uncertainties not only in the rate but also in the sign for the other three seasons. Moreover, less individual RCM experiments estimate statistically significant seasonal changes than in summer.

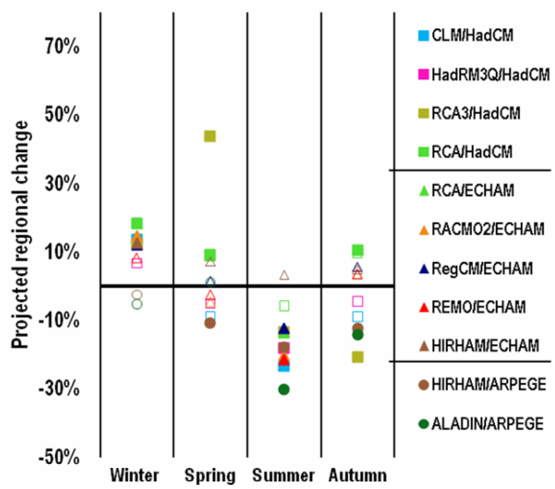

Fig. 8: Projected seasonal mean changes (%) of RR1 in the SE-Czech subregion by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of RR1 at 0.05 level.

In winter, the multi-model composites suggest slight increases of RR1 in the southeastern Czech and the Hungarian subregions (by 7% and 3%, respectively), whereas no change is estimated in Romania on average.

In spring, the multi-model composites suggest moderate decreases of RR1 in Hungary and Romania (by 5%), whereas a slight increase is estimated in the southeastern Czech subregion (by 3%). The largest uncertainties of the results from the individual RCM experiments can be indentified in spring in all the three subregions when both large significant decreases and a very large significant increase are projected (by the Irish RCA3 model simulation driven by HadCM).

Finally, in autumn, the multi-model composites suggest a slight decrease of RR1 in all the three subregions, the largest in Romania (by 11%), and the smallest in the southeastern Czech subregion (by 5%). In Hungary the projected average decrease is 9%. Most of the RCM experiments projecting statistically significant changes estimate RR1 decreases.

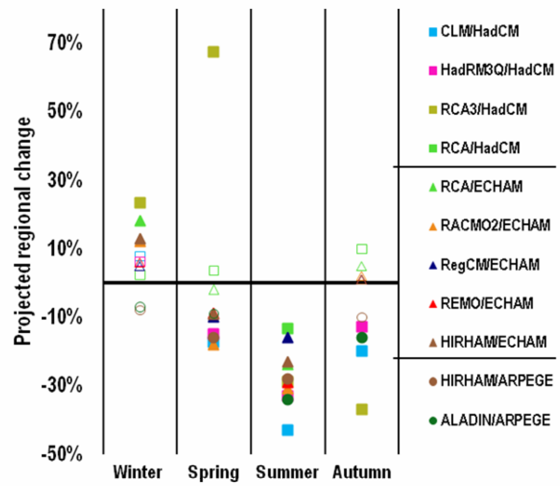

Fig. 9: Projected seasonal mean changes (%) of RR1 in Hungary by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of RR1 at 0.05 level.

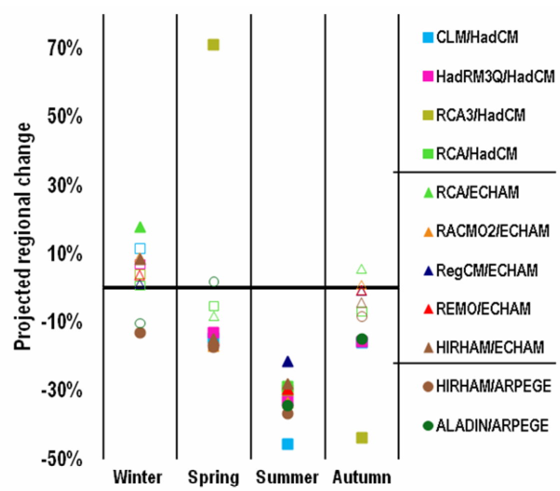

Fig. 10: Projected seasonal mean changes (%) of RR1 in the Romanian subregion by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of RR1 at 0.05 level.

6. ESTIMATED FUTURE TREND OF RR10

RR10 is the number of very wet days when daily precipitation exceeds 10 mm. Projected seasonal changes by 2071-2100 period relative to the 1961-

1990 reference period are shown in Fig. 11. Similarly to RR1 and CDD, the composite maps are determined as the weighted average of the results from all the 11 RCM experiments taking into account the driver GCMs.

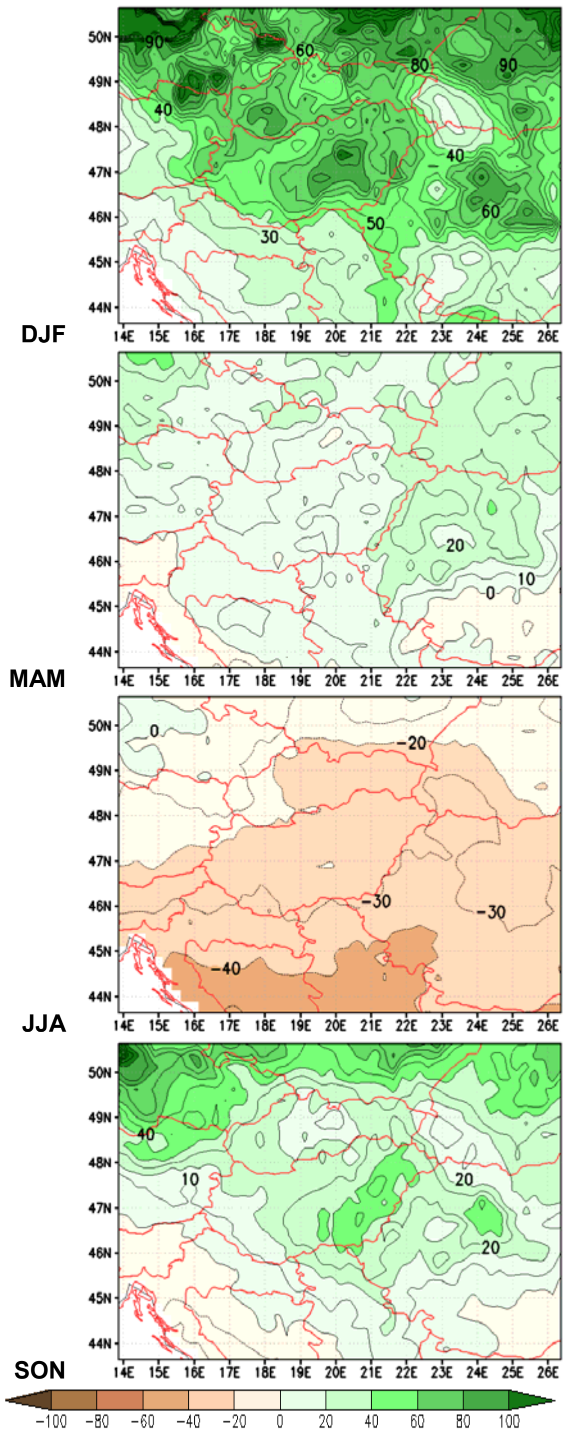

Fig. 11: Composite map of the projected seasonal mean changes (%) of RR10 by 2071-2100 relative to the reference period, 1961-1990

The results clearly suggest that very wet days with more than 10 mm daily precipitation in the region are likely to occur less often in summer and more frequently in the other three seasons in the future than in the reference period. A quasi zonal structure can be recognized in all the four seasons. Larger decreasing rates are projected in the southern than the northern part of the domain in summer, whereas larger increasing rates are projected in the northern than the southern part of the domain in winter, autumn, and spring. In the equinox seasons slight decreases are estimated on average in the southern part of the domain. The spatial average changes for the whole domain are +24%, +14%, -25%, and +23% in winter, spring, summer, and autumn, respectively.

Table IV: Spatial average values in summer in the 1961-1990 reference period for the 9 subregions and the projected changes by the 2021-2050 and 2071-2100 periods. The numbers in parentheses indicate the numbers of RCM experiments, which resulted in statistically significant decrease/increase of RR10 at 0.05 level.

Subregion	**1961-90 (E-OBS)**	**Projected change by 2021-2050**	**Projected change by 2071-2100**
E-Austria	10 days	0% (-/-)	-15% (6/1)
SE-Czech	6 days	+5% (-/-)	-2% (2/2)
Croatia	8 days	-9% (2/-)	-36% (10/-)
Hungary	7 days	-8% (1/1)	-25% (7/-)
Romania	6 days	-12% (3/-)	-33% (8/-)
Serbia	6 days	-15% (4/-)	-40% (10/-)
Slovakia	7 days	-5% (3/-)	-21% (7/-)
Slovenia	13 days	-9% (2/-)	-28% (9/-)
W-Ukraine	8 days	-4% (3/1)	-19% (6/-)

Table V: Spatial average values in winter in the 1961-1990 reference period for the 9 subregions and the projected changes by the 2021-2050 and 2071-2100 periods. The numbers in parentheses indicate the numbers of RCM experiments, which resulted in statistically significant decrease/increase of RR10 at 0.05 level.

Subregion	**1961-90 (E-OBS)**	**Projected change by 2021-2050**	**Projected change by 2071-2100**
E-Austria	3 days	+8% (-/2)	+42% (-/8)
SE-Czech	1 days	+35% (-/3)	+91% (1/8)
Croatia	7 days	+8% (-/4)	+19% (-/7)
Hungary	2 days	+24% (-/6)	+65% (-/10)
Romania	2 days	+20% (-/6)	+47% (-/8)
Serbia	2 days	+13% (-/3)	+33% (-/9)
Slovakia	1 days	+26% (-/5)	+66% (-/9)
Slovenia	8 days	+4% (-/1)	+18% (-/7)
W-Ukraine	2 days	+33% (-/8)	+73% (-/9)

The most pronounced RR10 changes are projected for summer and winter, for which the seasonal values are summarized for the 9 subregions in Tables IV and V, respectively. In general, the projected decreasing/increasing trends in summer/ winter of very wet days are larger by 2071-2100 than by 2021-2050 in all the subregions. Similarly to RR1 and CDD, the estimated trends are not linear; smaller changes are likely to occur in the first half of the 21st century than in the second half, which implies accelerating changes of RR10, too. By the last three decades of the 21st century most of the RCM experiments (7-10 out of 11) suggest statistically significant increase of winter RR10 in the individual subregions, whereas most of the RCM experiments (6-10 out of 11) suggest statistically significant decrease of summer RR10 in the individual subregions, except in the southeastern Czech subregion (here 2 RCM experiments project summer increase, as well as decrease in RR10).

The projected spatial average changes by the individual RCM experiments are shown in Figs. 12, 13, and 14 for the SE-Czech, the Hungarian, and the Romanian subregions, respectively.

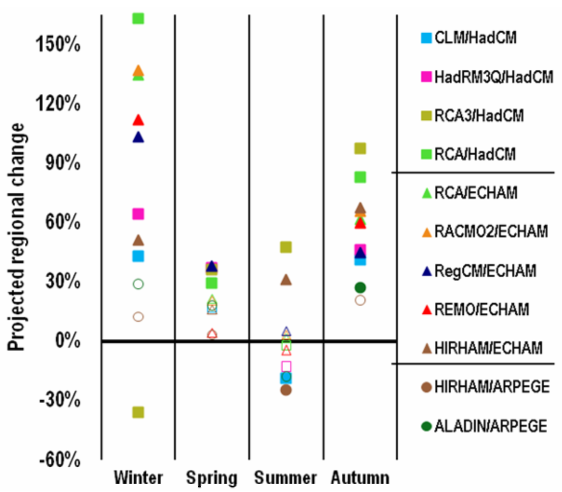

Fig. 12: Projected seasonal mean changes (%) of RR10 in the SE-Czech subregion by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of RR10 at 0.05 level.

In winter, the multi-model composites suggest relatively very large increases of RR10 by the last three decades of the 21st century in all the three subregions; the largest in the southeastern Czech subregion (by 91%), and the smallest in Romania (by 47%). In Hungary the projected average decrease is 65%.

In spring, the multi-model composites suggest moderate increases of RR10 in all the three subregions; by 22%, 14%, and 12% in southeastern Czech, the Romanian, and the Hungarian subregions, respectively. The moderate rates are due to the small number of RCM experiments resulting in statistically significant changes.

In summer, the individual RCM estimations clearly result in considerable decrease of RR10 in Hungary and Romania by the end of the 21st century. In general, most of the RCM experiments suggest statistically significant change (by 15-50%) at 0.05 level. In case of the Southeastern Czech subregion the projections involve uncertainties in the sign of the estimated change. The the multi-model composites suggest moderate decreases of RR10 in Hungary and Romania (by 25% and 33%, respectively), and a slight decrease in the southeastern Czech subregion (by 2%).

Finally, in autumn, the multi-model composites suggest moderate increases of RR10 in Hungary and Romania (by 30% and 16%, respectively), and a large increase in the southeastern Czech subregion (by 58%).

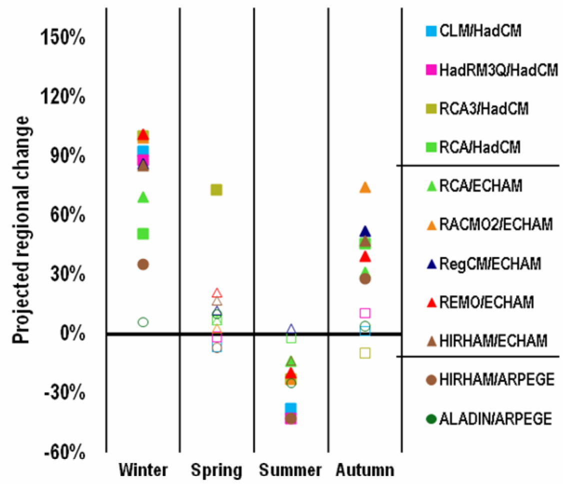

Fig. 13: Projected seasonal mean changes (%) of RR10 in Hungary by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of RR10 at 0.05 level.

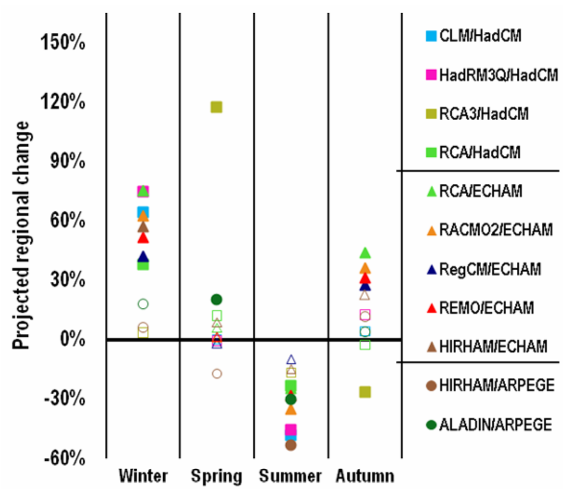

Fig. 14: Projected seasonal mean changes (%) of RR10 in the Romanian subregion by 2071-2100 relative to the reference period, 1961-1990. Filled symbols indicate statistically significant change of RR10 at 0.05 level.

Similarly to RR1 and CDD, results of the Irish RCA3 experiments driven by HadCM are very different from the other RCM experiments, even from those driven by the same GCM. It can be often recognized that the projected trend of RCA3/HadCM is the opposite of all the rest of the RCM simulations (especially in winter in the SE-Czech subregion, in spring in Hungary and Romania, and in autumn in Romania). Moreover, these opposite signs are statistically significant at 0.05 level.

6. CONCLUSION

Projected changes of precipitation-related climate indices for Central/Eastern Europe have been analyzed for the 21st century using bias corrected outputs of several RCM simulations available from the ENSEMBLES database and taking into account the intermediate SRES A1B scenario. The main results can be summarized as follows.

(1) Future summers in the region are projected to become drier compared to the past few decades, which result in longer consecutive dry periods, less wet days, as well as very wet days. These changes are larger in the southern than the northern part of the domain.

(2) In future winters very wet days are very likely to occur more frequently than in the 1961-1990 reference period, especially in the northern part of the domain.

(3) The projected changes are larger within the second half of the 21st century than within the first half, which implies nonlinear, accelerating changes of the climate indices in the region.

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