Hungarian Geographical Bulletin 63 (4) (2014) 365–378.
DOI: 10.15201/hungeobull.63.4.1

Estimated changes of drought tendency in the Carpathian Basin

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Abstract

Drought conditions are often characterized by various drought indices. In this paper different types of indices (i.e. standardized precipitation anomaly index, Thornthwaite's aridity index, and Ped's drought index) are used to estimate the future changes in drought conditions in the Carpathian Basin. For this purpose 25 km horizontal resolution gridded outputs of several regional climate models are used from the project ENSEMBLES covering the period 1951–2100 and taking into account the A1B emissions scenario. The results suggest remarkable drying in the region, especially, in summer, which emphasize the importance of developing appropriate adaptation strategies addressing this issue.

Keywords: drought index, ENSEMBLES, regional climate model simulation, climate change

Introduction

Climatic conditions evidently affect the biosphere as well as the human societies. Anthropogenic activity influences the biosphere through land use change and agriculture (e.g. cultivating selected crops and thus decreasing biodiversity) for several centuries. Moreover, the 250 year long industrial activities (especially, fossil fuel combustion) resulted in increasing atmospheric concentration of greenhouse gases. As a consequence, global and regional warming has been detected (IPCC, 2013), which intensified drought conditions in many regions including Central and Southern Europe (IPCC, 2012). Hungary is certainly affected by this potential risk since it is located in the continental Central European zone. In the recent years, the entire continent was hit by a severe drought event in 2003, which included Hungary as well, as the whole Carpathian Basin (Tallaksen, L.M. *et al.* 2011). On the basis of

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the measurement recorded by the Hungarian Meteorological Service the annual precipitation of the country was only 75 percent of the climatic mean (for the period 1971–2000). In 2011 the annual precipitation in Hungary was even smaller, only 72 percent of the normal value. Parts of the country were affected by drought events in 2002, 2007 and 2012.

Due to the recent increasing frequency of unusual years, it is essential to assess the possible future conditions in the country using regional climate model (RCM) simulations. These tools are widely used to estimate the primary climatic conditions, i.e. temperature and precipitation. Projected changes are summarized for Hungary in Pongrácz, R. *et al.* (2011), according to which regional warming is very likely to continue and increase in this century. Projected precipitation changes are varying throughout the year. RCMs clearly estimate summer drying for this century, however, in the other seasons different RCMs estimate different tendencies both in intensity and sign. Drought conditions are not determined only by precipitation conditions but also by temperature changes, this bivariate dependence can be assessed by drought indices.

In this paper first, the different types of drought indices are summarized and the three indices used in this paper are presented in details. Then, data outputs of RCM simulations available from project ENSEMBLES are described, followed by the discussion of the results. Finally, the conclusions are drawn.

Drought indices

Several aspects of the climatic system are directly or indirectly affected by precipitation deficiency, i.e. drought events. Therefore different scientific communities use different approaches to define drought itself and measures to characterize it. For instance, atmospheric science defines meteorological drought as a long period of time with considerably less precipitation amount than climatic mean. Other aspects may highlight the agricultural consequences, and define agricultural drought when the soil moisture is inadequate, and yields are considerably less than average because of the water shortage. Furthermore, hydrological drought refers to a period of below normal stream-flow, thus, focusing on the hydrological impacts of the lack of precipitation, such as reduced groundwater levels. Finally, economic drought considers the monetary value of drought-related damages, which can happen when the water shortage has an effect on human activity and on economy.

One of the most often used measures of drought includes the definition of several drought indices, which are able to quantify the temporal and spatial range of dry periods. The can be classified into different categories. Typically, there are four main groups of indices, which are widely used: the precipitation, the water balance, the recursive and the soil moisture indices

(Faragó, T. *et al.* 1988). *Table 1* summarizes the traditional classification of drought indices, whereas *Table 2* lists most of the well-known drought indices according to Dunkel, Z. (2009).

Table 1. Classification of drought indices

Index types	Examples
Precipitation indices	Relative anomaly index Standardized precipitation anomaly index Relative precipitation anomaly index Precipitation anomaly index
Water balance indices	Lang's rainfall index De Martonne aridity index Thornthwaite index
Recursive indices	Foley's anomaly index Palmer's drought index
Soil moisture indices	Ped's drought index Relative soil moisture index
Remotely sensed indices	Vegetation index Normalized difference vegetation index

Precipitation indices are suitable for the separation of wet and dry periods, as well as for the determination of variability. They are simple and do not require large datasets. Water balance indices are more complex. In addition to precipitation they also take into account temperature, which is used as the main factor of evaporation from the output side of the water balance. Recursive indices consider cumulative effects of precipitation shortage since they use data from the preceding period and hence characterize longer time periods. Soil moisture indices are able to estimate crop loss and agricultural water shortage. The main advantage of the indices based on remotely sensed information is the good spatial coverage for large areas.

In order to keep a reasonable length of this paper, standardized precipitation anomaly index (*SAI*), Ped' s drought index (*PDI*) and Thornthwaite's aridity index (*TAI*) are used to estimate the projected trends of dry climatic conditions by the end of the 21st century in the Carpathian Basin (Thornthwaite, C.W. 1948; Ped, D.A. 1975).

One of the most simple indices is *SAI* (Katz, R.W. and Glantz, M.H. 1986). The main advantage of this dimensionless index that it can be calculated only from precipitation time series. In addition, *SAI* is a standardized measure for seasonal differences and for precipitation in different climatic areas. Based on the definition the negative/positive trend of *SAI* implies drier/wetter climatic conditions. The drought classification using *SAI* values is shown in *Table 3.*

TAI is widely used in agrometeorological studies (Thornthwaite, C.W. 1948). For calculating *TAI* temperature time series are also used in ad-

Table 2. Definition of drought indices

Nr.	Index	Temporal resolution	Definition	Used data
1.	Precipitation index [mm]	week, month, season	$P - m(P)$	– precipitation sum (P) – mean precipitation ($m(P)$)
2.	Standardized precipitation anomaly index (SAI) [%]	week, month	$\frac{P - m(P)}{d(P)}$	– precipitation sum (P) – mean precipitation ($m(P)$) – standard deviation of precipitation ($d(P)$)
3.	Relative precipitation amount	week, month	$\frac{P}{m(P)}$	– precipitation sum (P) – mean precipitation ($m(P)$)
4.	Relative precipitation anomaly index	week, month	$\frac{P - m(P)}{m(P)}$	– precipitation sum (P) – mean precipitation ($m(P)$)
5.	De Martonne index [mm/°C]	month	$\frac{12 \cdot P}{T + 10}$	– precipitation sum (P) – temperature (T)
6.	Thornthwaite index	month	$1.65 \cdot \left(\frac{P}{T + 12.2} \right)^{\frac{10}{9}}$	– precipitation sum (P) – temperature (T)
7.	Lang rainfall index [mm/°C]	any given time period	$\frac{P}{T}$	– precipitation sum (P) – temperature (T)

Table 2. Continued

Nr.	Index	Temporal resolution	Definition	Used data
8.	Selyaninov's hydro-thermal coefficient [mm/°C]	day	$\frac{P}{\sum_{T\geq 10} T}$	– precipitation sum (P) – temperature (T)
9.	Aridity index	–	$\frac{P}{PE}, \frac{P}{\frac{R_n}{L}}$	– precipitation sum (P) – evapotranspiration (PE) – radiation balance (R_n) – latent heat (L)
10.	Bowen ratio	day	$\frac{H}{LE}$	– sensible (H) and latent (LE) heat flux
11.	Ped's drought index, 1st approximation	–	$\frac{\Delta T}{d(T)} - \frac{\Delta P}{d(P)}$	– precipitation sum (P) – temperature (T) – standard deviation of temperature ($d(T)$) and precipitation ($d(P)$)
12.	Ped's drought index, 2nd approximation	–	$\frac{\Delta T}{d(T)} - \frac{\Delta P}{d(P)} - \frac{\Delta W}{d(W)}$	– precipitation sum (P) – temperature (T) – soil moisture (W)
13.	Relative soil moisture content	–	$\frac{W}{AWC}$	– actual (W) and available (AWC) soil moisture
14.	Foley's anomaly index (FAI) [mm]	month	$FAI_1 = \Delta P_1$ $FAI_k = FAI_{k-1} + \Delta P_k$	– precipitation sum (P)

Table 2. Continued

Nr.	Index	Temporal resolution	Definition	Used data
15.	Palmer drought severity index	month	$PDSI_0 = 0$ $PDSI_k = PDSI_{k-1} + \frac{Z_k}{3} - 0.103 \cdot PDSI_{k-1}$	– moisture anomaly index (*Z*)
16.	Bhalme-Mooley drought index	month	$i_k = c_1 \cdot i_{k-1} + \frac{SAI_k}{c_2}$ $BMDI = \frac{1}{n} \cdot \sum_{i=1}^{n} i_k$	– SAI index – region specific value for the coefficients (c_1 and c_2)
17.	Vegetation index	day	$\frac{NIR}{VIS}$	– reflected radiation in the near infrared electromagnetic wavelength (*NIR*) and in the visible electromagnetic wavelength (*VIS*)
18.	Normalized difference vegetation index (NDVI)	day	$\frac{NIR - VIS}{NIR + VIS}$	– reflected radiation in the near infrared electromagnetic wavelength (*NIR*) and in the visible electromagnetic wavelength (*VIS*)
19.	Crop water stress index (CWSI)	day	$\frac{PE - ET}{PE}$	– potential (*PE*) and actual (*ET*) evapotranspiration
20.	Stress degree day (SDD)	month	$SDD = \sum_k (T_C - T_A)$	– remotely sensed surface and standard air temperature (T_C and T_A, respectively)

dition to precipitation (Kemp, D. 1990). Decreasing/increasing trend of *TAI* means drier/wetter climatic conditions. *Table 4* shows the different drought categories according to *TAI*.

For complex studies it can be useful to compare standardized values of temperature and precipitation in order to obtain a more accurate result. *PDI* (Bagrov, N.A. 1983; Ped, D.A. 1975) is a soil moisture index, which trends are opposite to *SAI* or *TAI*, namely, decreasing/increasing trend indicates wetter/drier conditions. *PDI* values close to zero (between –1 and +1) implies neutral states. Drought classification using *PDI* values is shown in *Table 5.*

Table 3. Drought categories defined on the basis of SAI values

SAI values	Category
> 2.0	extremely wet
1.5 to 2.0	severely wet
1.0 to 1.5	moderately wet
–1.0 to +1.0	near normal
–1.0 to –1.5	moderately dry
–1.5 to –2.0	severely dry
< –2.0	extremely dry

Table 4. Drought categories defined on the basis of TAI values

TAI values	Category
> 6.4	wet
3.2 to 6.4	semi-arid
1.6 to 3.2	arid
< 1.6	extremely dry

Table 5. Drought categories defined on the basis of PDI values

PDI values	Category
< –3	extremely wet
–3 to –2	severely wet
–2 to –1	moderately wet
1 to 2	moderately dry
2 to 3	severely dry
> 3	extremely dry

Data

To assess uncertainty due to natural and anthropogenic forcing factors, future climatic conditions are estimated with an ensemble of climate models. For Europe the five-year-long project ENSEMBLES studied the projected climate changes (van der Linden, P. and Mitchell, J.F.B. 2009). The regional climate models (RCMs) run at 25 km spatial resolution for 1951–2100 used the SRES A1B emissions scenario, which estimates the atmospheric carbon-dioxide level to 532 ppm and 717 ppm by 2050 and 2100, respectively (Nakicenovic, N. and Swart, R. 2000).

The necessary initial and lateral boundary conditions were provided by outputs of global climate models (GCMs). Here we use 9 RCM experiments driven by ECHAM5 (Roeckner, E. *et al*. 2006) and HadCM3Q (Gordon, C. *et al.* 2000; Rowell, D.P. 2005) GCMs. These global models were run at the Max Planck Institute in Hamburg Germany, and the Hadley Centre of the UK MetOffice, respectively.

For the analysis of drought conditions in the Carpathian Basin gridded monthly mean temperature values and monthly precipitation amounts of the RCM outputs (*Table 6*) were used for the end of the 21st century (2071–2100). As a reference period 1961–1990 was selected.

Table 6. Used regional climate model simulations, their running institutes, and the driving global climate models

RCM	Institute, country	Driving GCM
HadRM3Q	METO-HC, United Kingdom	HadCM3Q
CLM	ETHZ, Switzerland	
RCA3	C4IR, Ireland	
RCA	SMHI, Sweden	
RegCM	ICTP, Italy	ECHAM5
RACMO2	KNMI, Netherlands	
REMO	MPI, Germany	
HIRHAM	DMI, Denmark	

Results

In order to investigate the future change of the Hungarian drought conditions seasonal mean drought index values have been calculated for the last three decades of the 21st century using the gridded outputs of each RCM, and compared to the reference period. For the spatial analysis the differences are mapped in *Figures 1, 2* and *3* using *SAI*, *TAI* and *PDI*, respectively. The four columns represent the different seasons.

The maps in the upper four rows show the results from the RCM simulations driven by HadCM3Q GCM, whereas the lower five rows contain the results from the ECHAM5-driven RCM simulations. Yellow and red colors of the scale indicate drier conditions, while green and blue colors suggest wetter climate. In case of *SAI* (standardized precipitation index) and *TAI* (Thornthwaite's aridity index) decreasing trends imply drying. Opposite to these indices, increasing *PDI* (Ped's drought index) values indicate drier conditions.

From the maps the drying tendency in summer is clearly seen in using any of the three indices. The other three seasons are also dominated by drying tendencies, however, winter is likely to become wetter according to *SAI* (*Figure 1*), which can be explained by the definition of this index, namely, it is based only on precipitation amount, whereas *TAI* and *PDI* also consider temperature.

The average seasonal projected changes are summarized in *Tables 7, 8* and *9* for Hungary using the grid-cells located within the country. Besides all the individual RCM results, the averages and the standard deviations of the 9-member-ensemble are calculated. The larger projected changes are indicated by italic characters. Since the scales of the three indices are different therefore different thresholds are used: in case of *SAI*, *TAI* and *PDI* large changes are defined as exceeding 0.3, 2.0 and 0.4 in absolute value, respectively. Again note that the signs of the *PDI* changes are opposite to those of *SAI* or *TAI* changes.

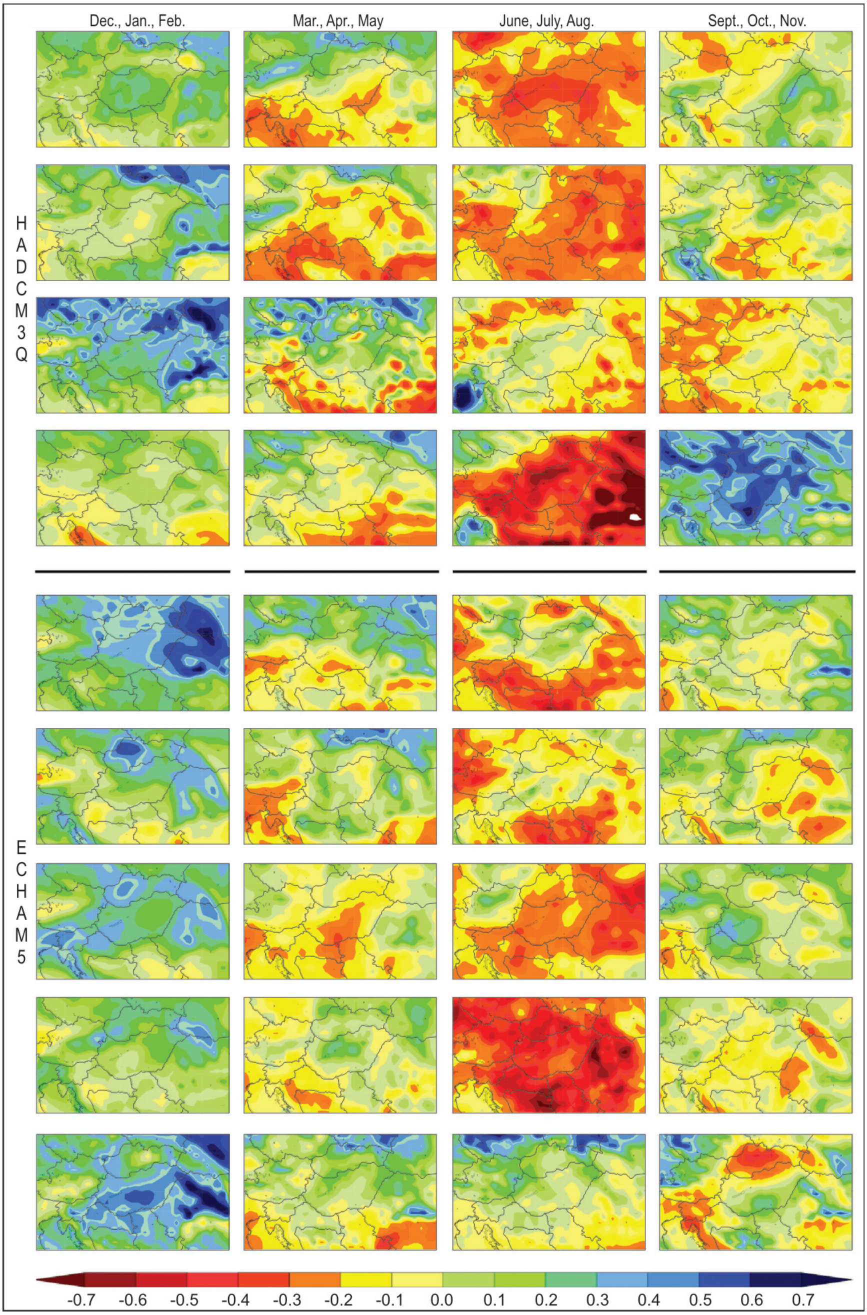

Fig. 1. Projected seasonal changes of *SAI* by 2071–2100 relative to the 1961–1990 reference period using 9 different RCM simulations

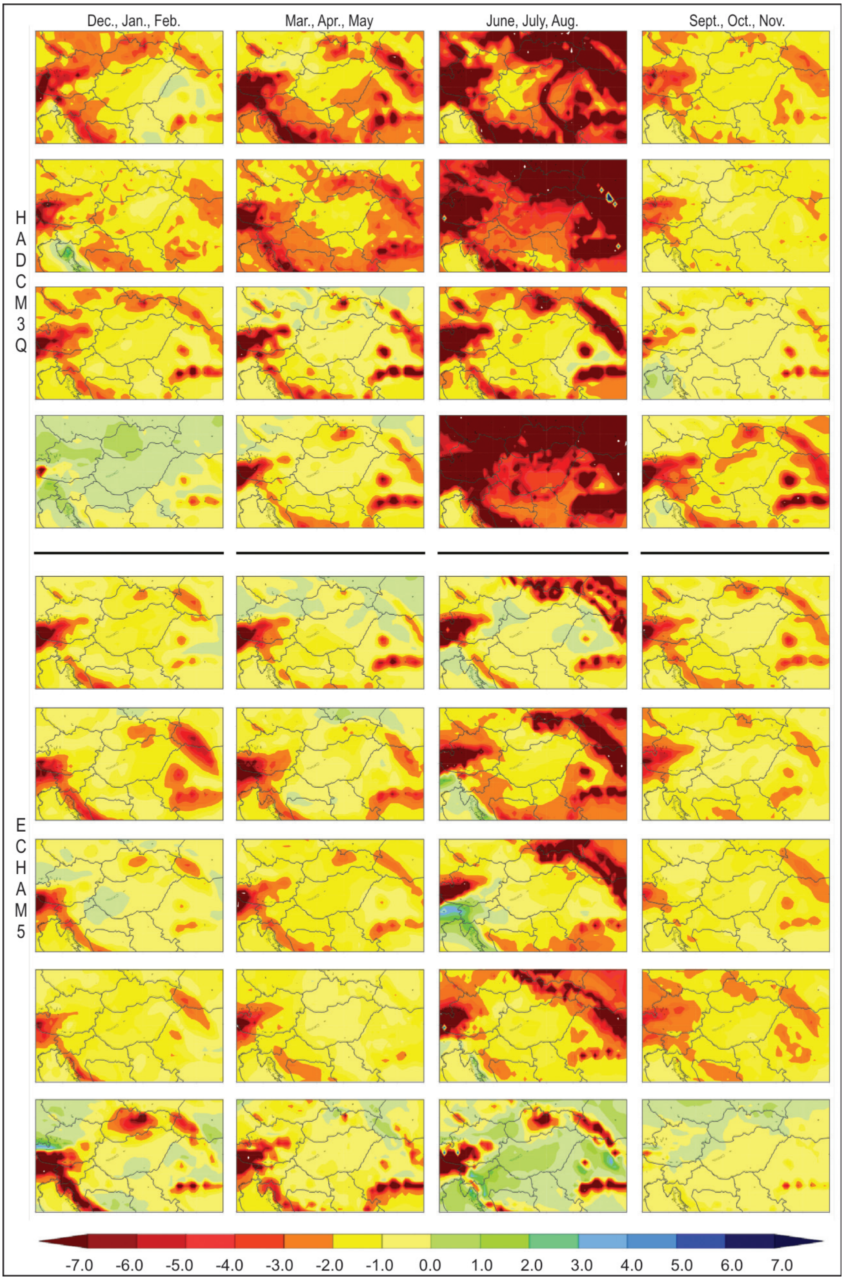

Fig. 2. Projected seasonal changes of *TAI* by 2071–2100 relative to the 1961–1990 reference period using 9 different RCM simulations

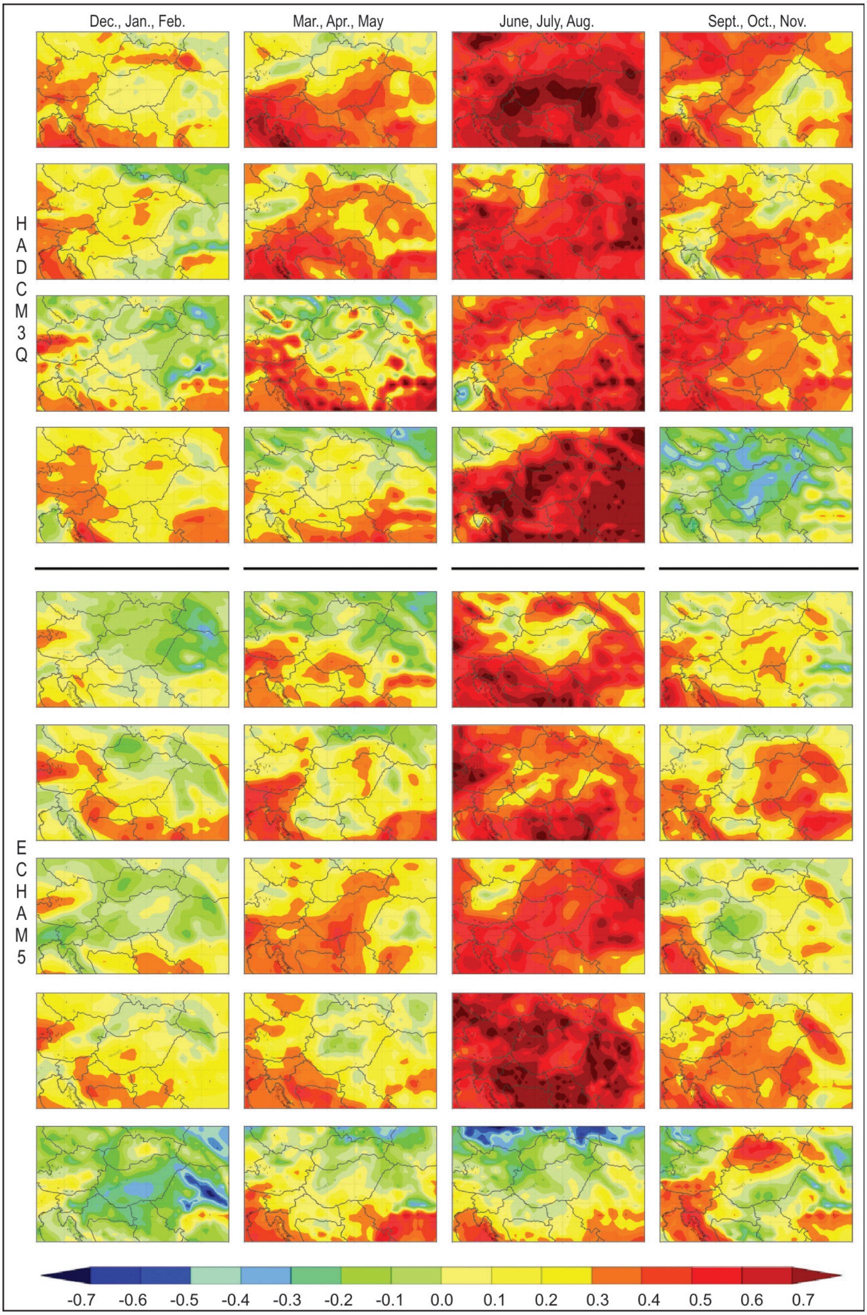

Fig. 3. Projected seasonal changes of *PDI* by 2071–2100 relative to the 1961–1990 reference period using 9 different RCM simulations

*Table 7. The average projected seasonal changes by 2071–2100 relative to the 1961–1990 reference period for Hungary in case of SAI using 9 different RCM simulations**

RCM	DJF	MAM	JJA	SON	Driving GCM
HadRM3Q	0.21	-0.10	*-0.37*	0.05	HadCM3Q
CLM	0.18	-0.18	*-0.34*	-0.16	
RCA3	*0.37*	0.05	-0.08	-0.19	
RCA	0.19	-0.09	*-0.50*	*0.39*	
RCA	0.19	-0.05	-0.15	-0.04	ECHAM5
RegCM	0.22	0.09	-0.07	-0.18	
RACMO2	0.29	-0.12	-0.19	0.00	
REMO	0.18	0.02	*-0.48*	-0.15	
HIRHAM	0.29	0.10	0.09	-0.03	
Ensemble-average	0.24	-0.03	-0.23	-0.03	
Standard deviation	0.07	0.10	0.20	0.18	

* Changes exceeding 0.3 in absolute value are indicated by italics.

*Table 8. The average projected seasonal changes by 2071–2100 relative to the 1961–1990 reference period for Hungary in case of TAI using 9 different RCM simulations**

RCM	DJF	MAM	JJA	SON	Driving GCM
HadRM3Q	-1.92	-1.91	*-6.17*	-1.80	HadCM3Q
CLM	-1.88	*-2.20*	*-11.80*	-1.76	
RCA3	-1.64	-1.66	*-2.18*	-1.11	
RCA	1.71	-1.72	*-6.79*	-1.92	
RCA	-0.57	-1.02	-1.89	-1.73	ECHAM5
RegCM	-0.87	-1.16	*-2.14*	-1.72	
RACMO2	-0.17	-1.79	-1.95	-1.76	
REMO	-0.93	-0.71	*-2.01*	-1.87	
HIRHAM	-0.58	-1.19	0.08	-0.40	
Ensemble-average	-0.76	-1.48	*-3.87*	-1.56	
Standard deviation	1.11	0.48	3.69	0.50	

* Changes exceeding 2.0 in absolute value are indicated by italics.

*Table 9. The average projected seasonal changes by 2071–2100 relative to the 1961–1990 reference period for Hungary in case of PDI using 9 different RCM simulations**

RCM	DJF	MAM	JJA	SON	Driving GCM
HadRM3Q	0.16	0.31	*0.74*	0.30	HadCM3Q
CLM	0.10	0.32	*0.63*	0.28	
RCA3	-0.04	0.28	*0.44*	0.36	
RCA	0.14	0.16	*0.72*	-0.11	
RCA	-0.13	0.14	0.38	0.19	ECHAM5
RegCM	-0.01	0.18	0.39	0.25	
RACMO2	-0.14	0.23	*0.48*	0.19	
REMO	0.11	0.17	*0.71*	0.28	
HIRHAM	-0.19	0.12	0.01	0.23	
Ensemble-average	0.00	0.21	*0.50*	0.22	
Standard deviation	0.13	0.08	0.23	0.13	

* Changes exceeding 4.0 in absolute value are indicated by italics.

The values suggest that the largest drying in Hungary is projected for summer. Compared to the summer changes less intense drying tendencies are likely to occur in spring and autumn. Winters may result more precipitation in the future (*Table 7*. – *SAI*), however, due to the warming trend *TAI* and *PDI* suggest overall drier winters in the late 21st century compared to the reference period (*Tables 8* and *9*, respectively). This can be explained by the increasing evaporation in the warmer environment.

Conclusions

Precipitation and temperature gridded monthly outputs of 9 RCM simulations (available from the ENSEMBLES project) were used to calculate different type of drought indices (*SAI, TAI, PDI*) for the Carpathian Basin considering the A1B emissions scenario. Based on the analysis presented in this paper the following conclusions can be drawn:

(i) Summers of the late 21st century are clearly projected to be substantially drier than the 1961–1990 reference period.

(ii) Winter precipitation tends to increase in the future. However, because of the regional warming and the consequent increase of evaporation climatic conditions are projected to become drier in winter, too.

(iii) Springs and autumns tend to become also slightly drier by 2071–2100 relative to the 1961–1990 reference period.

The overall drying tendency in the region highlights the necessity to develop the appropriate strategies to adapt to the regional climate change. This is especially important for end-users and decision-makers related to agriculture, food and drinking water security.

Acknowledgements: Research leading to this paper has been supported by the following sources: the Hungarian National Science Research Foundation under grant K-78125, K-83909 and K-109109, the European Union and the European Social Fund joint supports (FuturICT.hu TÁMOP-4.2.2.C-11/1/KONV-2012-0013, GOP-1.1.1.-11-2012-0164, and KMR-12-1-2012-0206). The AGRÁRKLÍMA2 project (VKSZ-12-1-2013-0001) and the EEA Grant HU04 Adaptation to Climate Change (EEA-C13-10). The ENSEMBLES data used in this work was funded by the EU FP6 Integrated Project ENSEMBLES (Contract number 505539) whose support is gratefully acknowledged.

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