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Analysis of expected climate change in the Carpathian Basin using the PRUDENCE results

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Abstract—Expected temperature and precipitation changes are analyzed for the Carpathian Basin and, especially, in Hungary, for the 2071-2100 period using outputs of the PRUDENCE project for the A2 and B2 emission scenarios. Different regional climate models (RCMs) of PRUDENCE use 50 km as horizontal spatial resolution, which enables us to estimate the climate change on regional scale. Composite maps of the expected seasonal temperature change and trend analysis of extreme temperature indices suggest that a regional warming trend is evident in the Carpathian Basin. According to the results the largest warming is expected in summer. Negative temperature extremes are projected to decrease while positive extremes tend to increase significantly. The climate simulation results suggest that the expected change of annual total precipitation is not significant in the Carpathian Basin. However, significantly large and opposite trends are expected in different seasons. Seasonal precipitation amount is very likely to increase in winter, and it is expected to decrease in summer, which implies that the annual distribution of precipitation is expected to be restructured. The wettest summer season may become the driest (especially in case of A2 scenario), and the driest winter is expected to be the wettest by the end of the 21st century. The extreme precipitation events are expected to become more intense and more frequent in winter, while a general decrease of extreme precipitation indices is expected in summer.

Key-words: regional climate model, temperature, precipitation, Carpathian Basin, extreme climate index, expected trend

1. Introduction

Spatial resolution of global climate models (GCMs) is inappropriate to describe regional climate processes; therefore, GCM outputs may be misleading to compose regional climate change scenarios for the 21st century (*Mearns et al.*, 2001). In order to determine better estimations for regional climate parameters, fine resolution regional climate models (RCMs) can be used. RCMs are limited area models nested in GCMs, i.e., the initial and boundary conditions of RCMs are provided by the GCM outputs (*Giorgi*, 1990). Due to computational constrains, the domain of an RCM evidently does not cover the entire globe, and sometimes not even a continent. On the other hand, their horizontal resolution may as fine as 5–10 km. The first project completed in the frame of the European Union V Program is the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects), which involved 21 European research institutes and universities. The primary objectives of PRUDENCE were to provide high resolution (50 km × 50 km) climate change scenarios for Europe for 2071–2100 using dynamical downscaling methods with RCMs (using the reference period 1961–1990), and to explore the uncertainty in these projections (*Christensen et al.*, 2007). Results of the project PRUDENCE are disseminated widely via Internet (http://prudence.dmi.dk) and several other media, and thus, they support socio-economic and policy related decisions.

In the frame of the project PRUDENCE, the following sources of climate uncertainty were studied (*Christensen*, 2005):

- Sampling uncertainty. Simulated climate is considered as an average over 30 years (2071–2100, reference period 1961–1990).
- Regional model uncertainty. RCMs use different techniques to discretize the differential equations and to represent physical processes on sub-grid scales.
- Emission uncertainty. RCM runs used two IPCC-SRES emission scenarios, namely, A2 and B2. 16 experiments from the PRUDENCE simulations considered the A2 scenario, while only 9 of them used the B2 scenario.
- Boundary uncertainty. RCMs were run with boundary conditions from different GCMs. Most of the PRUDENCE simulations used HadAM3H as the driving GCM. Only a few of them used ECHAM4 or ARPEGE (*Déqué et al.*, 2005).

In this paper, the regional climate change projections are summarized for the Carpathian Basin using the outputs of all available PRUDENCE simulations. Results of the expected mean temperature and precipitation change by the end of the 21st century are discussed using composite maps. Furthermore, the expected changes of the extreme climate indices following the guidelines suggested by one of the task groups of a joint WMO-CCl (World Meteorological Organization Commission for Climatology)/CLIVAR (a project of the World Climate Research Programme addressing Climate Variability and Predictability) Working Group formed in 1998 on climate change detection (*Karl et al.*, 1999; *Peterson et al.*, 2002) are also analyzed.

2. Data

Adaptation of RCMs with 10–25 km horizontal resolution is currently proceeding in Hungary, namely, at the Department of Meteorology, Eötvös Loránd University (*Bartholy et al.*, 2006), and at the Hungarian Meteorological Service (*Horányi*, 2006). Results of these RCM experiments are expected within 1–2 years, however, impact studies and end-users need and would like to have access to climate change scenario data much earlier. Also, for the Hungarian National Climate Change Strategy (accepted by the Parliament in March 2008), climate change input data are needed for Hungary. Therefore, in order to fulfill this instant demand with preliminary information, outputs of PRUDENCE simulations (for the 2071–2100 and 1961–1990 periods) are evaluated and offered for the Carpathian Basin. Composite maps of expected temperature and precipitation change cover the Carpathian Basin (45.25°–49.25°N, 13.75°–26.50°E). Since the project PRUDENCE used only two emission scenarios (i.e., A2 and B2), no other scenario is discussed in this paper. In case of the A2 scenario, 16 RCM experiments are used, while in case of B2, only outputs of 8 RCM simulations are available (*Table 1*).

Table 1. List of RCMs with their driving coupled GCMs used in the composite analysis

	Institute	**RCM**	**Driving GCM**	**Scenario**
1	Danish Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2, B2
2		HIRHAM	ECHAM4/OPYC	A2
3		HIRHAM high res.	HadAM3H/HadCM3	A2
4		HIRHAM extra high res.	HadAM3H/HadCM3	A2
5	Hadley Centre of the UK Met Office	HadRM3P (ensemble/1)	HadAM3P/HadCM3	A2, B2
6		HadRM3P (ensemble/2)	HadAM3P/HadCM3	A2
7	ETH (Eidgenössische Technische Hochschule)	CHRM	HadAM3H/HadCM3	A2
8	GKSS (Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt)	CLM	HadAM3H/HadCM3	A2
9		CLM improved	HadAM3H/HadCM3	A2
10	Max Planck Institute	REMO	HadAM3H/HadCM3	A2
11	Swedish Meteorological and Hydrological Inst.	RCAO	HadAM3H/HadCM3	A2, B2
12		RCAO	ECHAM4/OPYC	B2
13	UCM (Universidad Complutense Madrid)	PROMES	HadAM3H/HadCM3	A2, B2
14	International Centre for Theoretical Physics	RegCM	HadAM3H/HadCM3	A2, B2
15	Norwegian Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2
16	KNMI (Koninklijk Nederlands Meteorologisch Inst.)	RACMO	HadAM3H/HadCM3	A2
17	Météo-France	ARPEGE	HadAM3H/HadCM3	A2, B2
18		ARPEGE	ARPEGE/OPA	B2

According to the A2 global emission scenario, fertility patterns across regions converge very slowly resulting in continuously increasing world population. Economic development is primarily regionally oriented, per capita economic growth and technological changes are fragmented and slow. The projected CO_2 concentration may reach 850 ppm by the end of the 21st century (*IPCC*, 2007), which is about triple of the pre-industrial concentration level (280 ppm). The global emission scenario B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. According to the B2 scenario, the projected CO_2 concentration is likely to exceed 600 ppm (*IPCC*, 2007), which is somewhat larger than a double concentration level relative to the pre-industrial CO_2 conditions.

Regional analysis of the detected trend of different extreme climate indices for the Carpathian Basin is discussed by *Bartholy* and *Pongrácz* (2005, 2006, 2007), where the list and definition of the indices can be found also. In this paper, the expected future trends of extreme climate indices are analyzed in the Carpathian Basin using daily temperature and precipitation outputs of four different RCMs run by the (i) Danish Meteorological Institute (DMI), (ii) Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, (iii) Royal Meteorological Institute of the Netherlands (Koninklijk Nederlands Meteorologisch Institute, KNMI), and (iv) Swiss Federal Institute of Technology Zurich (Eidgenössische Technische Hochschule Zürich, ETHZ). For all of these simulations the boundary conditions were provided by the HadAM3H/HadCM3 (*Rowell*, 2005) global climate model of the UK Met Office (Table 1). DMI used the HIRHAM4 RCM (*Christensen et al.,* 1996), which has been developed jointly by DMI and the Max-Planck Institute in Hamburg. ICTP used the regional climate model RegCM, which was originally developed by *Giorgi et al.* (1993a, 1993b) and then improved as described by *Giorgi et al.* (1999) and *Pal et al.* (2000). KNMI used the RACMO2 (*Lenderink et al.*, 2003), which combines dynamical core of the HIRLAM Numerical Weather Prediction System with the physical parameterization of the European Centre for Medium-range Weather Forecasting used for the ERA-40 re-analysis project. ETHZ used the Climate High Resolution Model (CHRM) RCM described by *Vidale et al.* (2003). Model performances of the four selected RCMs are analyzed by *Jacob et al.* (2007) using the simulations of the reference period 1961-1990. Besides the A2 scenario experiments, DMI and ICTP accomplished further experiments using the B2 emission scenario.

3. Analysis of the expected regional climate change

Composites of the mean seasonal temperature (daily mean, maximum, and minimum) and precipitation changes are mapped for both A2 and B2 scenarios. The spatial variation of the composite maps are summarized in tables for the gridpoints located inside Hungary. In order to represent the uncertainty of the composite maps, standard deviations of the RCM model results are also determined and mapped for all seasons.

First, the expected temperature change is discussed, followed by the analysis of the expected precipitation change for the Carpathian Basin.

3.1. Temperature

Fig. 1 presents the expected seasonal temperature change for A2 and B2 scenarios (left and right panel, respectively). Similarly to the global and the European climate change results, larger warming can be expected for A2 scenario in the Carpathian Basin than for B2 scenario. The largest temperature increase is expected in summer, while the smallest increase in spring. The same conclusion can be drawn from *Table 2*, where the intervals of the seasonal temperature increase are summarized for the area of Hungary. The largest warming is expected in summer for both scenarios: in case of the daily mean temperature the interval of the expected increase is 4.5–5.1°C (A2) and 3.7–4.2°C (B2), in case of the daily maximum temperature these intervals are 4.9–5.3°C (A2) and 4.0–4.4 (B2), and in case of the daily minimum temperature these intervals are 4.2–4.8°C (A2) and 3.5–4.0°C (B2). According to the climate projections, the expected increase of mean temperature in summer is between the expected warming of the maximum temperature and that of the minimum temperature. In case of spring, the expected temperature increase inside Hungary is 2.8–3.3°C (for A2 scenario) and 2.3–2.7°C (for B2 scenario).

Fig. 2 summarizes the expected mean seasonal warming for Hungary in case of A2 and B2 scenarios. In general, the expected warming by 2071–2100 is more than 2.4 °C and less than 5.1 °C for all seasons and for both scenarios. Expected temperature changes for the A2 scenario are larger than for the B2 scenarios. The smallest difference is expected in spring (0.6–0.7 °C), and the largest in winter (1.0–1.1 °C). The largest daily mean temperature increase is expected in summer, 4.8 °C (A2) and 4.0 °C (B2). The smallest daily mean temperature increase is expected in spring (3.1 °C and 2.5 °C in case of A2 and B2 scenarios, respectively). Expected increase of the daily maximum temperature exceeds that of the daily minimum temperature by about 0.1–0.6 °C (the largest is in summer), except in winter when the seasonal average daily minimum temperature is projected to increase by 4.1 °C (using the A2 scenario) and 3.0 °C (using the B2 scenario), both of them are 0.1 °C larger than what is projected for the daily maximum temperature increase.

On the basis of seasonal standard deviation fields (*Bartholy et al.*, 2007), the largest uncertainty of the expected temperature change occurs in summer for both emission scenarios.

Similarly to mean temperature, expected seasonal increase of daily maximum and minimum temperatures in the Carpathian Basin was also mapped

(*Bartholy et al.*, 2007). *Fig. 3* compares the projected increases of the winter and summer average daily maximum temperatures for the A2 and B2 scenarios. It can be seen that the spatial structure of the expected warming is similar to that of the expected daily mean temperature increase (*Fig. 1*), but in case of the maximum temperature the projected warming is larger by about 0.1–0.2 °C in winter and 0.3–0.4 °C in summer than in case of the mean temperature.

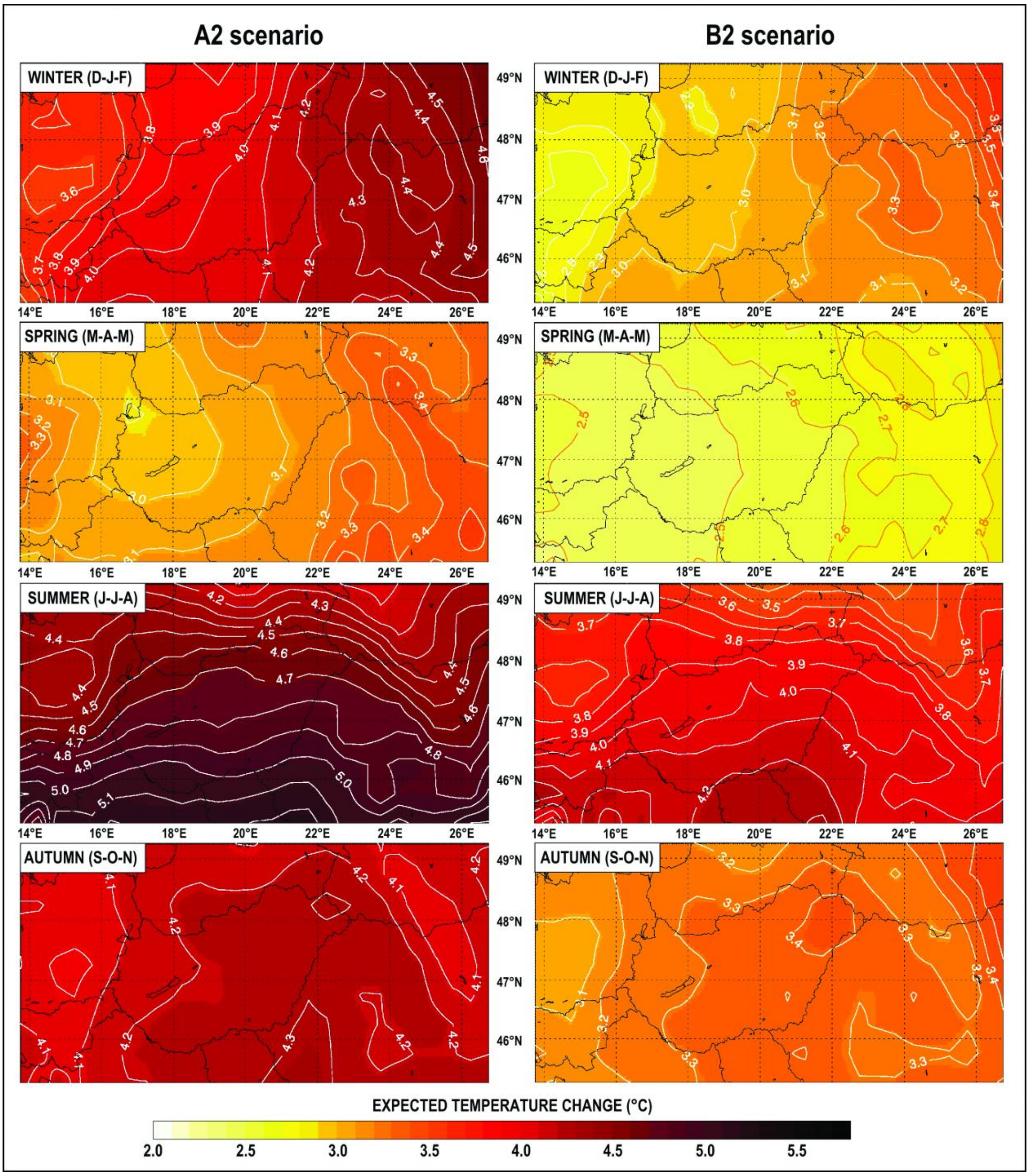

Fig. 1. Seasonal temperature change (°C) expected by 2071–2100 for the Carpathian Basin using the outputs of 16 and 8 RCM simulations in case of A2 and B2 scenarios, respectively (reference period: 1961–1990).

Table 2. Expected increase in mean, maximum, and minimum temperatures (°C) by 2071–2100 for Hungary in case of A2 and B2 scenarios using 16 and 8 RCM simulations, respectively (reference period: 1961–1990)

Temperature	Scenario	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
Mean	A2	3.7–4.3	2.9–3.2	4.5–5.1	4.1–4.3
	B2	2.9–3.2	2.4–2.7	3.7–4.2	3.2–3.4
Maximum	A2	3.7–4.2	2.8–3.3	4.9–5.3	4.3–4.6
	B2	2.6–3.0	2.4–2.6	4.0–4.4	3.3–3.5
Minimum	A2	3.8–4.6	3.0–3.2	4.2–4.8	4.0–4.2
	B2	2.8–3.5	2.3–2.7	3.5–4.0	3.0–3.2

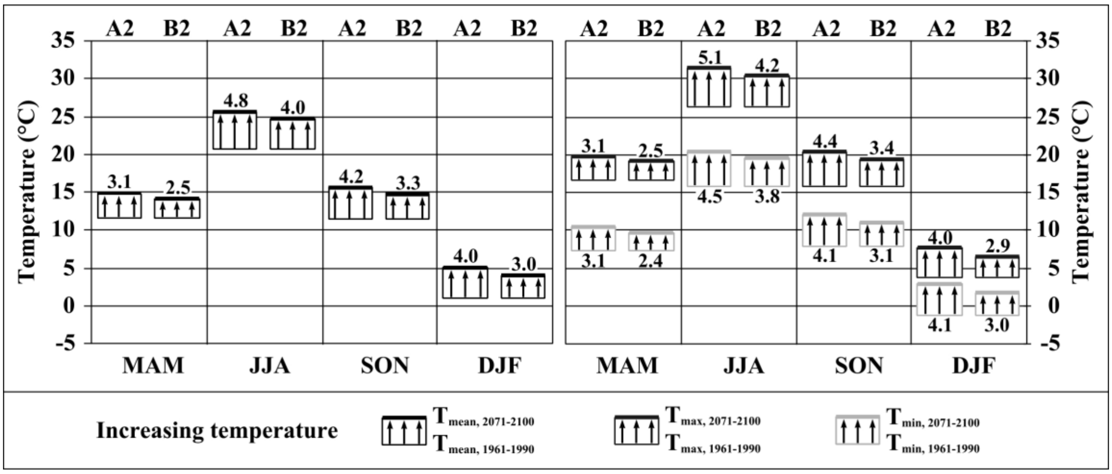

Fig. 2. Expected seasonal increase of daily mean, minimum, and maximum temperatures (°C) for Hungary (temperature values of the reference period 1961–1990 represent the seasonal mean temperature in Budapest).

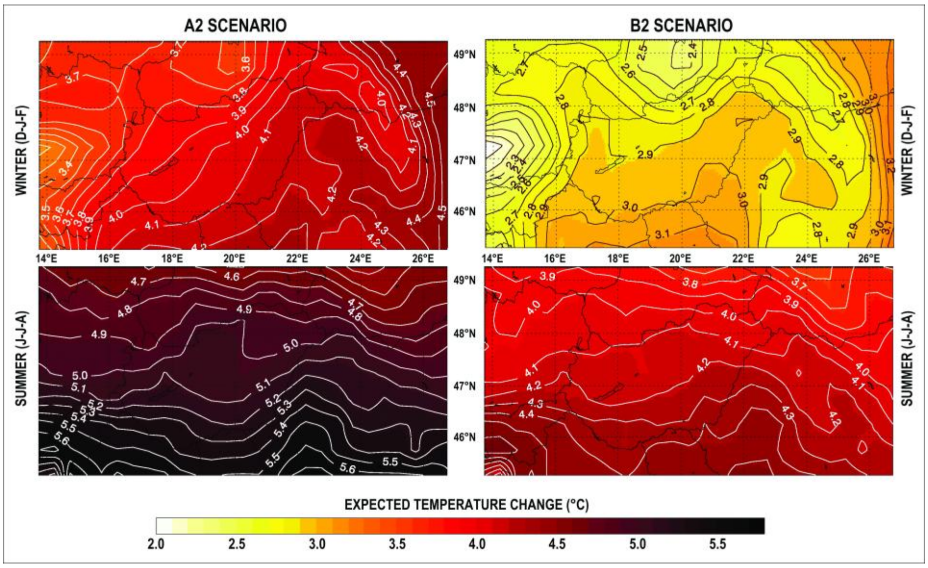

Fig. 3. Expected change of daily maximum temperature (°C) in winter and summer by 2071–2100 for the Carpathian Basin using the outputs of 16 and 8 RCM simulations in case of A2 and B2 scenarios, respectively (reference period: 1961–1990).

The expected trends of the extreme temperature indices are compared in *Fig. 4* for A2 and B2 scenarios using the daily temperature outputs of the regional climate modeling experiments (both for the 1961–1990 and 2071–2100 periods) of four different institutes (i.e., DMI, ICTP, KNMI, and ETHZ). The annual values of the indices are calculated as a spatial average of all the grid points located in Hungary, and then, the expected change is determined. According to the results, negative extremes are expected to decrease, while positive extremes tend to increase significantly. Both imply regional warming in the Carpathian Basin. The largest increase due to this warming trend can be expected in case of extremely hot days (Tx35GE), hot nights (Tn20GT), hot days (Tx30GE), warm nights (Tn90), and warm days (Tx90) by more than 100%. The expected changes are larger in case of the more pessimistic A2 emission scenario than in case of B2, the ratio is about 1–3. The expected warming trends of all the temperature indices are completely consistent with the detected trend in the 1961–2001 period (*Bartholy* and *Pongrácz,* 2006, 2007).

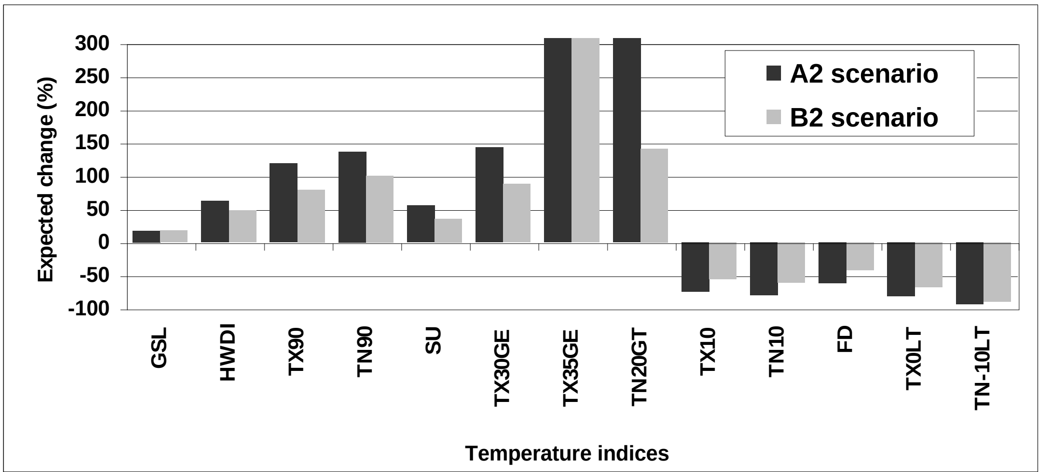

Fig. 4. Expected change of the extreme temperature indices in case of A2 and B2 scenarios (2071–2100) based on the daily outputs of the regional climate models of DMI, ICTP, KNMI, and ETHZ (reference period: 1961–1990).

In order to evaluate the model performance, temperature bias is determined for each RCM output fields using the simulations for the reference period (1961–1990), and the CRU (Climate Research Unit of the University of East Anglia) database (*New et al.*, 1999). In general, the RCM simulations overestimate the temperature in most parts of the Carpathian Basin, however, small underestimation can be seen in the western and northeastern boundary of the selected domain (*Bartholy et al.,* 2007). The largest overestimation can be detected in the southern part of Hungary (1.0–1.5 °C). In the northern part of Transdanubia and the northern part of the Great Plains the temperature is overestimated by 0.5–1.0 °C, while in the northeastern part of the country the overestimation is only 0–0.5 °C.

3.2. *Precipitation*

Similarly to temperature projections, composites of mean seasonal precipitation change and standard deviations are mapped for both A2 and B2 scenarios for the 2071–2100 period. *Fig. 5* presents the expected seasonal precipitation change for A2 and B2 scenarios (left and right panel, respectively) for the Carpathian Basin. The annual precipitation sum is not expected to change significantly in this region (Bartholy et al., 2003), but it is not valid for seasonal precipitation. According to the results shown in Fig. 5, summer precipitation is very likely to decrease (also, slight decrease of autumn precipitation is expected), while winter precipitation is likely to increase considerably (slight increase in spring is also expected).

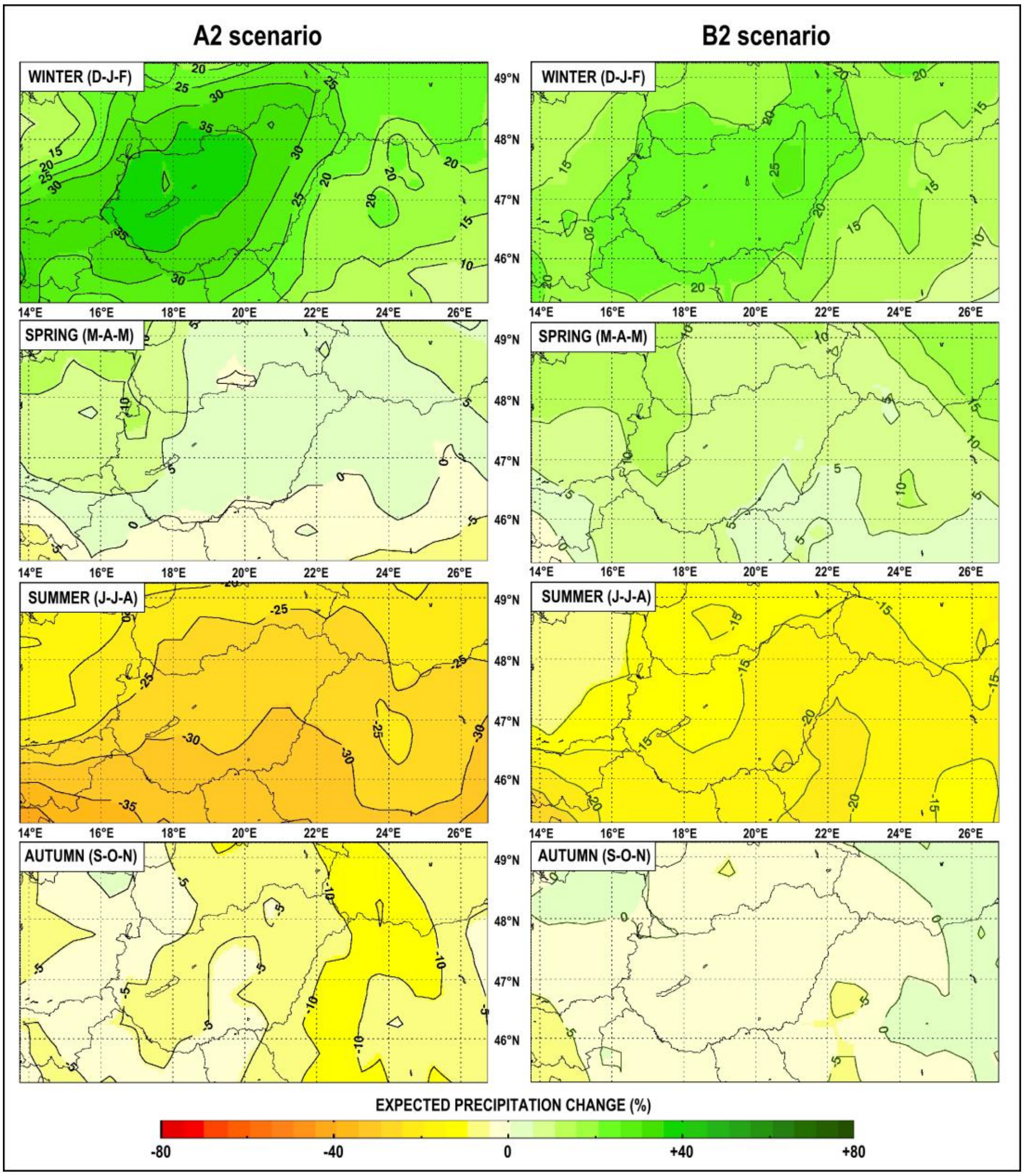

Fig. 5. Seasonal precipitation change (%) expected by 2071–2100 for the Carpathian Basin using the outputs of 16 and 8 RCM simulations in case of A2 and B2 scenarios, respectively (reference period: 1961–1990).

Table 3 summarizes the intervals of seasonal precipitation change for Hungary. In summer, the projected precipitation decrease is 24–33% (A2) and 10–20% (B2). In winter, the expected precipitation increase is 23–37% (A2) and 20–27% (B2). Based on the seasonal standard deviation values (*Bartholy et al.*, 2007), the largest uncertainty of precipitation change is expected in summer, especially, in case of A2 scenario (the standard deviation of the RCM results exceeds 20%).

Table 3. Expected mean precipitation change (%) by 2071–2100 for Hungary in case of A2 and B2 scenarios using 16 and 8 RCM simulations (reference period: 1961–1990)

Scenario	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
A2	(+23) – (+37)	0 – (+10)	(–24) – (–33)	(–3) – (–10)
B2	(+20) – (+27)	(+3) – (+12)	(–10) – (–20)	(–5) – 0

The expected seasonal change of precipitation for Hungary in case of A2 and B2 scenarios are summarized in *Fig. 6*. Black and grey arrows indicate increase and decrease of precipitation, respectively. According to the reference period 1961–1990, the wettest season was summer, then less precipitation was observed in spring, even less in autumn, and the driest season was winter. If the projections are realized, then the annual distribution of precipitation will be totally restructured, namely, the wettest seasons will be winter and spring (in this order) in cases of both A2 and B2 scenarios. The driest season will be summer in case of A2 scenario, while autumn in case of B2 scenario. On the base of the projections, the annual difference between the seasonal precipitation amounts is expected to decrease significantly (by half) in case of B2 scenario (which implies more similar seasonal amounts), while it is not expected to change in case of A2 scenario (nevertheless, the wettest and driest seasons are completely changed).

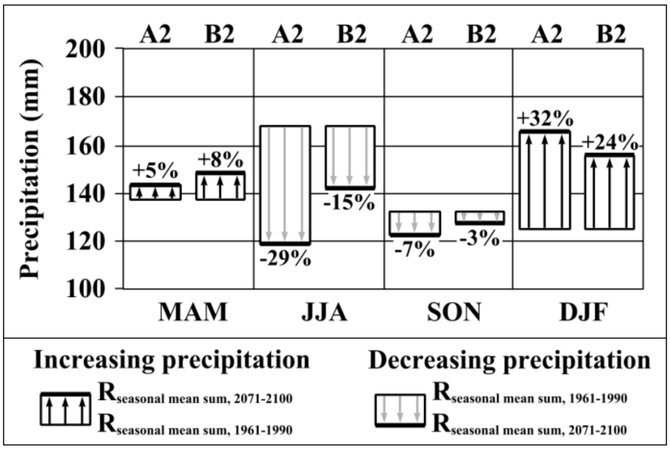

Fig. 6. Expected seasonal change of mean precipitation (mm) for Hungary (increasing or decreasing precipitation is also indicated in %). Precipitation values of the reference period 1961–1990 represent the seasonal mean precipitation amount in Budapest.

Table 4. Expected change of extreme precipitation indices in case of A2 and B2 scenarios (%) (2071–2100) based on the daily outputs of the RCMs of DMI, ICTP, KNMI, and ETHZ (reference period: 1961–1990). In case of the detected trends, signs in parentheses indicate regional mean coefficients being not significant at 95% level.

Precipitation index	**A2 scenario**			**B2 scenario**			**Detected trend**
	Year	**January**	**July**	**Year**	**January**	**July**	**1976–2001**
Rx1 (R_{max})	+17	+29	–2	+13	+23	–5	–
Rx5 ($R_{max,5\ days}$)	+10	+26	–11	+11	+17	–11	+
SDII (R_{year}/RR1)	+10	+16	+13	+7	+12	+1	(+)
R95 ($R_{day} \geq R_{95\%,1961\text{-}90}$)	+7	+60	–30	+14	+35	–22	+
R75 ($R_{day} \geq R_{75\%,1961\text{-}90}$)	–9	+19	–35	+0	+8	–21	+
RR20 ($R_{day} \geq$ 20 mm)	+60	+233	+66	+68	+212	–24	+
RR10 ($R_{day} \geq$ 10 mm)	+14	+95	–11	+20	+58	–14	+
RR5 ($R_{day} \geq$ 5 mm)	–1	+52	–30	+7	+28	–22	(–)
RR1 ($R_{day} \geq$ 1 mm)	–10	+19	–31	–2	+6	–19	–
RR0.1 ($R_{day} \geq$ 0.1 mm)	–11	+9	–3	–3	+1	–10	–
R95T ($\Sigma R_{day:\ when\ R_{day}>R_{95\%,1961–90}}/R_{total}$)	+16	+27	+9	+14	+23	+0	+

Table 4 summarizes the expected future trends of the extreme precipitation indices determined using the climate simulations of four selected RCMs (i.e., HIRHAM4 of the DMI, RegCM of the ICTP, RACMO2 of the KNMI, and CHRM of the ETHZ) for the 1961–1990 and 2071–2100 periods. Expected changes of annual precipitation indices are generally consistent with the detected trends in the last quarter of the 20th century (*Bartholy* and *Pongrácz*, 2005, 2007). However, the expected regional increase or decrease is usually small (not exceeding 20% in absolute value), except of RR20, the number of very heavy precipitation days. Much larger positive and negative changes are projected in January and July, respectively, on the base of the RCM simulations in case of the A2 and B2 scenarios. These results together with the composite maps shown in Fig. 5 suggest that the climate tends to be wetter in January and drier in July in the Carpathian Basin. Since the projected increases of the RR20, RR10, and R95 (these indices describe very extreme precipitation events) exceed 60% in January in case of A2 scenario, and the expected increases of RR0.1 or RR1 (these indices are not related to extreme precipitation) is 9% and 19%, respectively, the extreme precipitation events are expected to become more

intense and more frequent in January. Similar but smaller changes are expected in case of B2 scenario. Furthermore, drought is projected to become more severe in July by the end of the 21st century, which can be derived from the robust decrease of precipitation indices. The largest decrease rates (exceeding 30%) in July are expected in case of the R75, RR1, RR0.1, RR5, and R95 indices for the A2 scenario. The projected monthly changes are smaller for the B2 scenario.

The expected changes of R95 (number of very wet days) are illustrated in *Fig. 7* using annual and monthly (January and July) changes of grid point values of the extreme climate indices for A2 (upper maps) and B2 (lower maps) scenarios. Blue circles in the maps indicate expected increase, while yellow and red circles imply expected decrease. The size of the circles corresponds to the magnitude of the expected changes. In case of the annual change, the expected increasing rate between 2071–2100 and 1961–1990 in Hungary is about 9% and 18% on average using the A2 and B2 emission scenarios, respectively. Much larger changes are projected in January, namely, +59% and +41% for the country. Opposite changes can be expected in July, the average decrease is expected about 28% (A2) and 23% (B2) for the grid points located in Hungary.

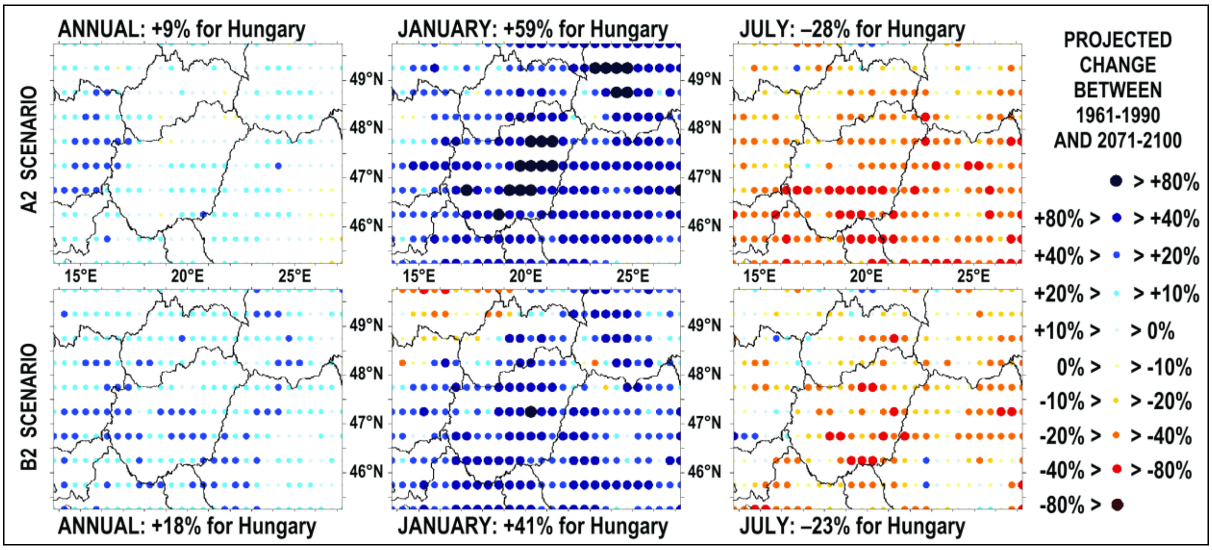

Fig. 7. Expected change of annual and monthly number of very wet days (R95) in case of A2 and B2 scenarios (2071–2100) compared to the reference period (1961–1990). Maps are determined using simulated daily precipitation amounts of the regional climate model of DMI.

In order to evaluate the model performance, precipitation bias is determined for all the RCM output fields using the simulations for the reference period (1961–1990), and the CRU database (*New et al.*, 1999). In general, the RCM simulations overestimate the precipitation in most parts of the Carpathian Basin, however, underestimation can be seen in the southwestern part of the region (*Bartholy et al.*, 2007). In Hungary, the bias is not exceeding 15% in absolute values. The precipitation is slightly underestimated in the western/-

southwestern part of the country, while precipitation in the other large parts (including the entire Great Plains and the eastern part of Transdanubia) is slightly overestimated.

4. Conclusions and discussion

On the basis of the results shown in this paper, the following conclusions can be drawn using the RCM experiment outputs of the PRUDENCE project.

(1) Expected seasonal temperature increase for the Carpathian Basin in case of the A2 scenario is larger than in case of the B2 scenario, which is in good agreement with the expected global and European climate change results (*IPCC*, 2007). The smallest difference between the A2 and B2 scenarios is projected for spring (0.6–0.7 °C), while the largest for winter (1.0–1.1 °C).

(2) The largest daily mean temperature increase is projected for summer, 4.8 °C (A2) and 4.0 °C (B2), while the smallest seasonal warming is expected in spring, 3.1 °C (A2) and 2.5 °C (B2).

(3) The largest increase of maximum and minimum temperatures is expected also in summer for both scenarios. In case of maximum temperature, the intervals of the expected warming are 4.9–5.3 °C (A2) and 4.0–4.4 °C (B2), while in case of minimum temperature, these intervals are 4.2–4.8 °C (A2) and 3.5–4.0 °C (B2). Expected increase of the daily maximum temperature exceeds that of the daily minimum temperature, except in winter.

(4) The extreme temperature indices associated with cold climatic conditions are projected to decrease in the Carpathian Basin by 2071–2100 while the positive extremes tend to increase significantly. The expected changes of the extreme temperature indices are larger in case of the A2 scenario than in case of the B2 scenario.

(5) The annual precipitation sum is not expected to change significantly in this region, but it is not valid for seasonal precipitation sums. Summer precipitation is very likely to decrease, furthermore, slight decrease of autumn precipitation is expected. On the other hand, winter precipitation is likely to increase considerably, and slight increase in spring is also expected.

(6) The projected summer precipitation decrease is 24–33% (A2) and 10–20% (B2), while the expected winter precipitation increase is 23–37% (A2) and 20–27% (B2).

(7) In the reference period (1961–1990), the wettest season was summer, while the driest season was winter. If the projections are realized, then the annual distribution of precipitation will be totally restructured. Namely, the wettest season will be winter in case of both A2 and B2 scenarios. The driest season will be summer in case of A2 scenario, while autumn in case of B2 scenario.

(8) Expected changes (for 2071–2100) of annual precipitation indices are small, but generally consistent with the detected trends in 1976–2001. The projected changes in winter and summer are opposite to each other, which means that large positive and negative changes of monthly precipitation indices are projected in January and July, respectively. Projected increase of very extreme precipitation events exceeds 60% in January, while the expected increases of not extreme precipitation indices do not reach 20%. These results imply that the extreme precipitation events are expected to become more intense and more frequent in January. Furthermore, drought is projected to become more severe and a general decrease of extreme precipitation indices is expected in July.

The analysis discussed in this paper is based on the PRUDENCE simulations, which means that only very few GCMs (mainly HadAM3H/HadCM3, some RCM experiments used ECHAM4/OPYC, and ARPEGE/OPA) are used as driving data of RCMs, which can be considered as limitations of the presented analysis. In an earlier paper (*Bartholy et al.*, 2003), 16 GCM outputs (i.e., ECHAM1, ECHAM3, ECHAM4, HadCM2, UKHI-EQ, UKTR, GFDL-TR, NCAR-DOE, UIUC-EQ, CGCM1-TR, CCC-EQ, BMRC-EQ, CSIRO1-EQ, CSIRO2-EQ, CSIRO-TR, and CCSR-NIES) are analyzed for Hungary in case of A1, A2, B1, and B2 scenarios. The results of the multi-GCM analysis are very similar to most of the findings of the present paper. The quartile range of the expected seasonal temperature change by the end of the 21st century is 3.0–5.5°C in winter, 2.1–3.9°C in spring, 3.0–4.6°C in summer, and 3.0–4.5°C in autumn in case of A2 scenario. The expected temperature increase is smaller for B2 than for A2 scenario. The quartile intervals for the B2 scenario are as follows: 2.0–3.8°C in winter, 1.5–2.5°C in spring, 2.0–3.1°C in summer, and 2.0–3.0°C in autumn. Thus, the projected warming is somewhat smaller than the expected temperature increase of the RCM simulations of PRUDENCE in most of the seasons except winter. However, one must not forget that the horizontal resolution is far more coarse in case of the GCMs (where only 1 or 2 gridpoints represent the entire area of Hungary) than RCMs. For the seasonal precipitation projections the GCM quartile ranges are also considerably smaller, especially, in case of winter and summer (the sign of the projected changes are the same as in the RCM simulations). The GCMs suggest that wetter winters and drier summers are expected by the end of the 21st century (the quartile intervals are (+5%)-(+25%) for A2 and (+2%)-(+15%) for B2 in winter, and (–2%)–(–24%) for A2 and (–2%)–(–15%) for B2 in summer). The projected precipitation changes in spring and autumn are very small (around zero), which also supports the RCM-based results discussed in the present paper.

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