What climate can we expect in Central/Eastern Europe by 2071-2100?

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Abstract Based on the regional climate model (RCM) results of the project PRUDENCE, expected climate change estimations for the Carpathian basin are summarized and discussed for the 2071-2100 period. The different RCMs used 50 km as the horizontal resolution, and evaluated the A2 and B2 global emission scenario. Results suggest that in case of temperature, a warming trend is evident in the Carpathian basin. The largest warming is expected in summer. The expected change of annual total precipitation is not significant. However, significantly large and opposite trends are expected in different seasons. Seasonal precipitation amount is very likely to increase in winter, while 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 in expected to be the wettest by the end of the 21st century. It is evident that all these climate processes affect agricultural activity and disaster management strategy. In order to prepare for the changing climate conditions, results of this regional climate change analysis may serve as basic information.

Key words: *regional climate change, temperature, precipitation, Carpathian basin, regional climate model*

1. Introduction

The Fourth Assessment Report of the Intergovermental Panel on Climate Change (IPCC) Working Group I was published in February 2, 2007. According to this report (IPCC, 2007), the main key processes influencing the European climate include (i) increased water vapour transport from low to high latitudes, (ii) changes of variation of the atmospheric circulation on interannual as well, as longer time scales, (iii) reduction of snow cover during winter in the northeastern part of the continent, (iv) drying of the soil in summer in the Mediterranean and central European regions. For instance, the heat wave occurred in summer 2003 in Europe can be considered as a consequence of a long period of anticyclonic weather (Fink et al., 2004), which coincided with a severe drought in the region (Black et al., 2004). In case of Europe, it is likely that the increase of annual mean temperature will exceed the global warming rate in the 21st century. The largest increase is expected in winter in northern Europe (Benestad, 2005), and in summer in the Mediterranean area. Minimum temperatures in winter are very likely to increase more than the mean winter temperature in northern Europe (Hanssen-Bauer et al., 2005), while maximum temperature values in summer are likely to increase more than the mean summer temperature in southern and central Europe (Tebaldi et al., 2006). As far as precipitation, the annual sum is very likely to increase in northern Europe (Hanssen-Bauer et al., 2005) and decrease in the Mediterranean area. On the other hand, in central Europe, which is located at the boundary of these large regions, precipitation is likely to increase in winter, while decrease in summer. In case of the summer drought events, the risk is likely to increase in central Europe and in the Mediterranean area due to decreasing summer precipitation and increasing spring evaporation (Pal et al., 2004; Christensen and Christensen, 2004). As a consequence of the European warming, the length of the snow season and the accumulated snow depth are very likely to decrease over the entire continent (IPCC, 2007).

Spatial resolution of global climate models (GCMs) are 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 the boundary conditions of RCMs are provided by the GCM outputs (Giorgi, 1990). Due to computational constrains the domain of an RCM does not cover the entire globe, 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 5th 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, 2005). 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 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 scenario, 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. First, results of the expected temperature change by the end of the 21st century are discussed, and then, expected change of the other important climate parameter, precipitation is presented.

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

	Institute	RCM	Driving GCM	Scenario
1	Danish Meteorological Institute	HIRHAM	HadAM3H	A2, B2
2		HIRHAM	ECHAM5	A2
3		HIRHAM high resolution	HadAM3H	A2
4		HIRHAM extra high res.	HadAM3H	A2
5	Hadley Centre of the UK Met Office	HadRM3P (ensemble/1)	HadAM3P	A2, B2
6		HadRM3P (ensemble/2)	HadAM3P	A2
7	ETH (Eidgenössische Technische Hochschule)	CHRM	HadAM3H	A2
8	GKSS (Gesellschaft für Kernenergie-	CLM	HadAM3H	A2
9	verwertung in Schiffbau und Schiffahrt)	CLM improved	HadAM3H	A2
10	Max Planck Institute	REMO	HadAM3H	A2
11	Swedish Meteorological and	RCAO	HadAM3H	A2, B2
12	Hydrological Institute	RCAO	ECHAM4/OPYC	B2
13	UCM (Universidad Complutense Madrid)	PROMES	HadAM3H	A2, B2
14	International Centre for Theoretical Physics	RegCM	HadAM3H	A2, B2
15	Norwegian Meteorological Institute	HIRHAM	HadAM3H	A2
16	KNMI (Koninklijk Nederlands Meteorologisch Inst.)	RACMO	HadAM3H	A2
17	Météo-France	ARPEGE	HadCM3	A2, B2
18		ARPEGE	ARPEGE/OPA	B2

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., 2006a; 2006b), and at the Hungarian Meteorological Service (Horányi, 2006). Results of these RCM experiments are expected within 2-4 years, however, impact studies and end-users need and would like to have access to climate change scenario data much earlier. Therefore, in order to fulfill this instant demand with preliminary information, outputs of PRUDENCE simulations are evaluated and offered for the Carpathian basin. In case of the A2 scenario 16 RCM experiments are used, while in case of B2, only outputs of 8 RCM simulations are available. Since the project PRUDENCE used only these two emission scenarios, no other scenario is discussed in this paper.

Table 1 lists the name of the contributing institutes, the RCMs, the driving GCMs, and the available scenarios we used in the composite maps. Composite maps of expected temperature and precipitation change cover the Carpathian basin (45.25°-49.25°N, 13.75°-26.50°E). The climate projections of PRUDENCE are available for the end of the 21st century (2071-2100) using the reference period of 1961-1990.

3. Temperature projections for the Carpathian basin

Composite maps of the mean expected seasonal temperature change are shown for both A2 and B2 scenario in Fig. 1 (left and right panel, respectively). In order to represent the uncertainty of these composites, standard deviation values of the RCM model results are also determined and mapped for all seasons. 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 expected summer warming ranges are 4.5-5.1°C and 3.7-4.2°C for the A2 and B2 scenario, respectively. In case of spring, the expected temperature increase inside Hungary is 2.9-3.2°C (for A2 scenario) and 2.4-2.7°C (for B2 scenario). On the basis of seasonal standard deviation fields, the largest uncertainty of the expected temperature change occurs in summer for both emission scenario (Bartholy et al., 2007).

Table 2. Expected mean temperature increase by 2071-2100 for Hungary in case of A2 and B2 scenario using 16 and 8 RCM simulations, respectively

Scenario	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
A2	2.9-3.2 °C	4.5-5.1 °C	4.1-4.3 °C	3.7-4.3 °C
B2	2.4-2.7 °C	3.7-4.2 °C	3.2-3.4 °C	2.9-3.2 °C

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 2.5°C and less than 4.8°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°C), while the largest in winter (1°C). The largest temperature increase is expected in summer, 4.8°C (A2) and 4.0°C (B2). The smallest temperature increase is expected in spring (3.1°C and 2.5°C in case of A2 and B2 scenario, respectively).

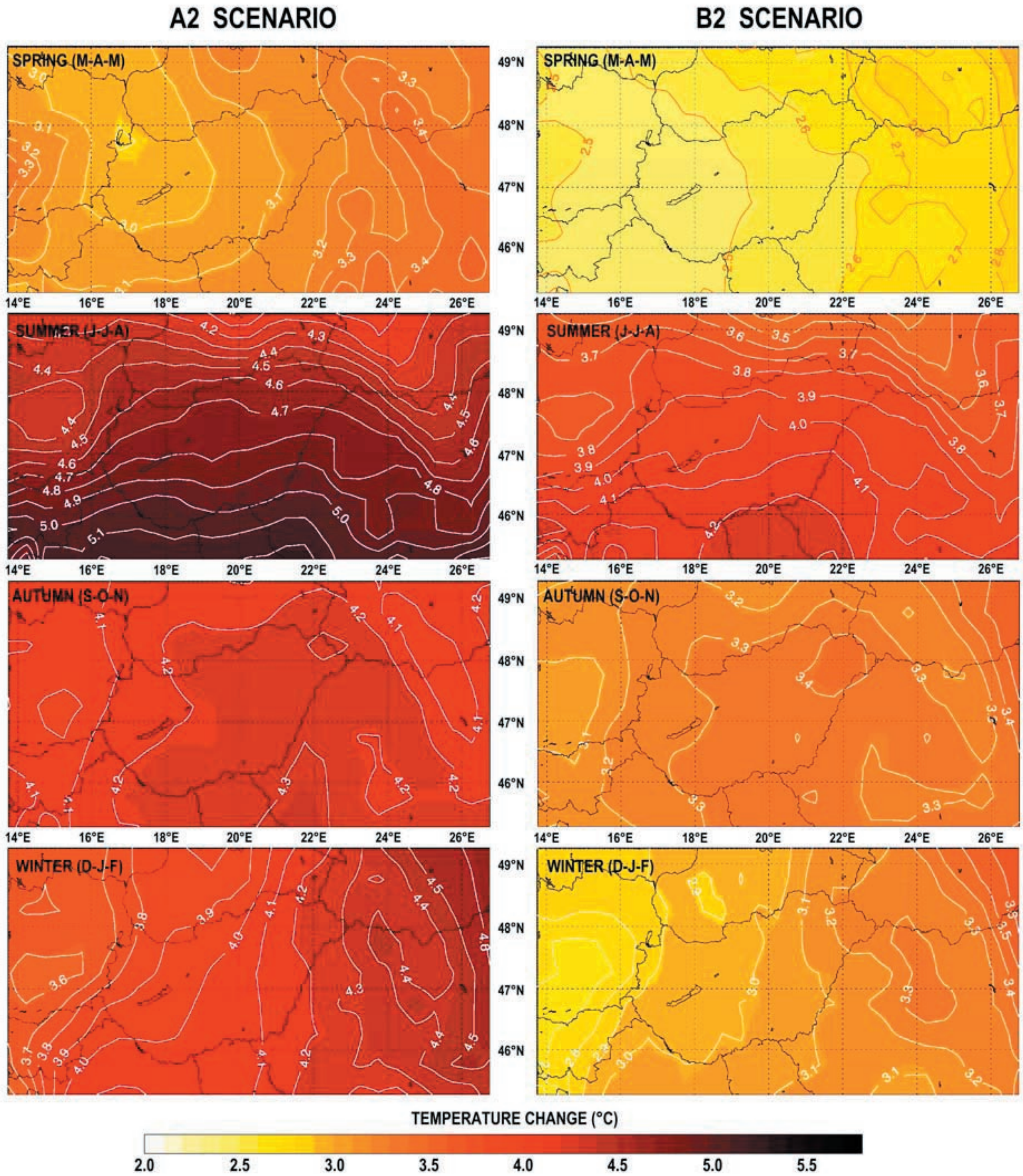

Fig. 1. Seasonal temperature change (°C) expected by 2071-2100 for the Carpathian basin using the outputs of 16 and 8 RCM simulations, A2 (left panel) and B2 (right panel) scenario.

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 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.

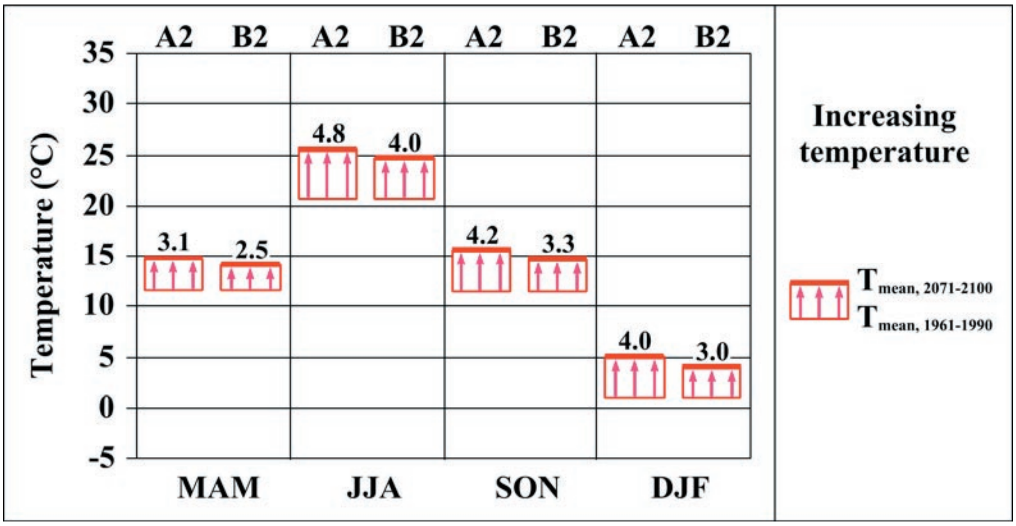

Fig. 2. Expected seasonal increase of mean temperature (°C) for Hungary (temperature values of the reference period, 1961-1990, represent the seasonal mean temperature in Budapest).

Similarly to the mean temperature, expected seasonal warming of daily maximum and minimum temperature in the Carpathian basin was mapped. The maximum and minimum temperature increase expected in Hungary is summarized in Table 3 and Fig. 3 (similarly to Table 2 and Fig. 2 for the mean temperature).

Table 3. Expected increase in maximum and minimum temperature by 2071-2100 for Hungary in case of A2 and B2 scenario using 16 and 8 RCM simulations, respectively

	Scenario	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
Maximum	A2	2.8-3.3 °C	4.9-5.3 °C	4.3-4.6 °C	3.7-4.2 °C
	B2	2.4-2.6 °C	4.0-4.4 °C	3.3-3.5 °C	2.6-3.0 °C
Minimum	A2	3.0-3.2 °C	4.2-4.8 °C	4.0-4.2 °C	3.8-4.6 °C
	B2	2.3-2.7 °C	3.5-4.0 °C	3.0-3.2 °C	2.8-3.5 °C

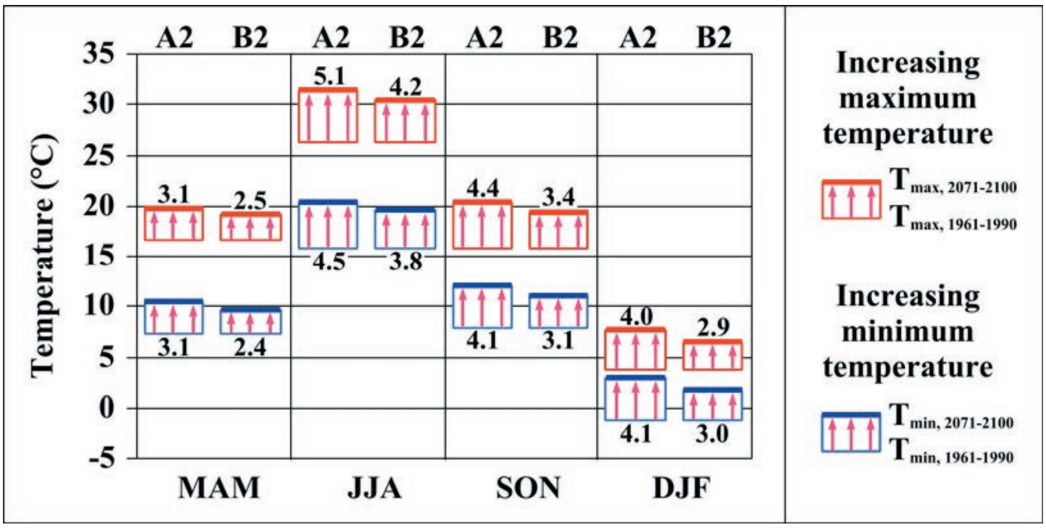

Fig. 3. Expected seasonal increase of daily minimum and maximum temperature (°C) for Hungary (temperature values of the reference period, 1961-1990, represent the seasonal mean temperature in Budapest).

According to Table 3, the largest warming is expected in summer for both scenario: in case of maximum temperature the interval of the expected increase is 4.9-5.3°C (A2) and 4.0-4.4 (B2), while in case of minimum temperature these intervals are 4.2-4.8°C (A2) and 3.5-4.0°C (B2). The expected increase of mean temperature in summer (from Table 2) is between the expected warming of the maximum temperature and that of the minimum temperature. Summarizing the expected mean seasonal increase of daily extreme temperature for Hungary (in Fig. 3), the entire interval of the expected warming include values from 2.4°C to 5.1°C, which is 0.4°C larger than in case of the mean temperature. The largest temperature increases are expected in summer for both scenario, which is not surprising if the above results are considered. The expected increase of the maximum temperature generally is not smaller than the expected increase of the minimum temperature, the only exception is winter.

Table 4. Spatial gradients of expected summer and winter temperature change for the Carpathian basin for 2071-2100 (zonal gradient is positive in case of increasing change from north to south, while meridional gradient is positive in case of increasing change from west to east)

	Scenario	**Summer (JJA)**	**Winter (DJF)**
Mean temperature	A2	Zonal: +0.7 °C	Meridional: +0.6 °C
	B2	Zonal: +0.5 °C	Meridional: +0.5 °C
Maximum temperature	A2	Zonal: +0.6 °C	Meridional: +0.5 °C
	B2	Zonal: +0.4 °C	Zonal: +0.4 °C
Mininimum temperature	A2	Zonal: +0.7 °C	Meridional: +0.8 °C
	B2	Zonal: +0.6 °C	Meridional: +0.7 °C

In order to provide a better overview on the spatial differences of expected temperature changes (both mean and extremes) for Hungary by the end of the 21st century, Table 4 summarizes the spatial gradients of warming for summer and winter. In summer, zonal structure of warming (i.e., increasing values from north to south) can be detected in case of all parameters. On the other hand, in winter, generally a meridional structure of warming is expected (i.e., increasing values from west to east). The only exception is the spatial structure of expected maximum temperature increase in case of B2 scenario, which shows a zonal structure instead. If a larger domain is considered, the meridional gradient dominate the European region in case of this map as well, as the other expected winter temperature change fields (Christensen, 2005). In spring and autumn, the gradient values are much smaller, they do not exceed 0.4 and 0.3, respectively.

4. Precipitation projections for the Carpathian basin

Similarly to the temperature projections, composite maps of mean expected seasonal precipitation change and standard deviations are mapped for both A2 and B2 scenarios for the 2071-2100 period (Fig. 4. left and right panel, respectively). 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. 4, 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).

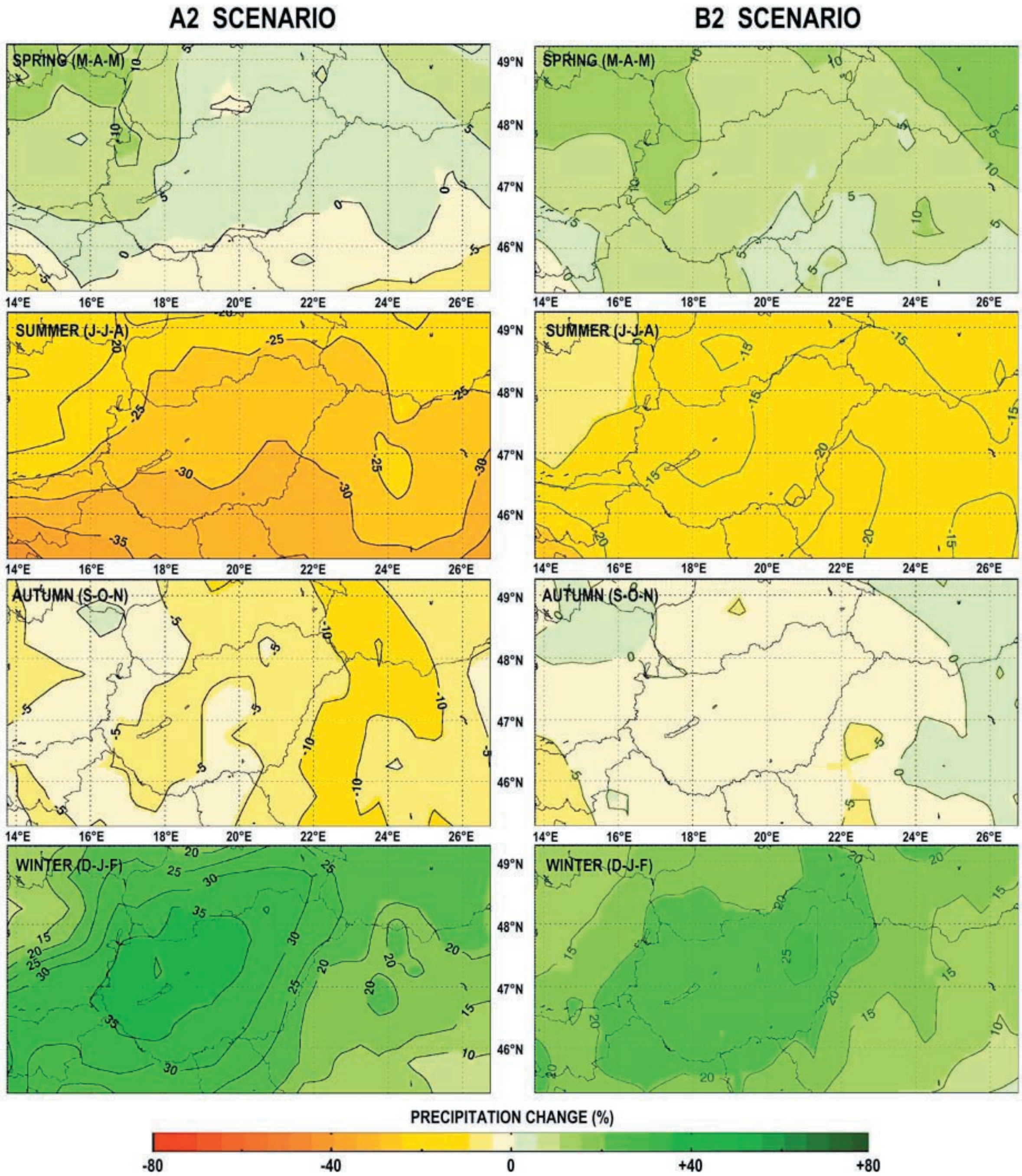

Fig. 4. Seasonal precipitation change (%) expected by 2071-2100 for the Carpathian basin using the outputs of 16 and 8 RCM simulations, A2 and B2 scenario.

Table 5 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, the largest uncertainty of precipitation change is expected in summer, especially, in case of A2 scenario when the standard deviation of the RCM results exceeds 20% (Bartholy et al., 2007).

Table 5. Expected mean precipitation change by 2071-2100 for Hungary in case of A2 and B2 scenario using 16 and 8 RCM simulations, respectively

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

Fig. 5 summarizes the expected seasonal change of precipitation for Hungary in case of A2 and B2 scenarios. Green and yellow 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 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. 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 the driest seasons are completely changed).

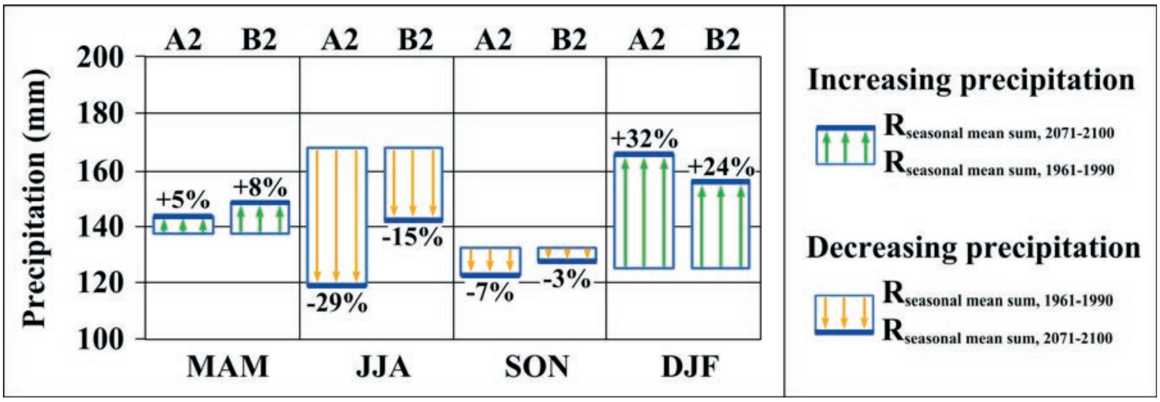

Fig. 5. Expected seasonal change of mean precipitation (mm) for Hungary (increasing or decreasing precipitation is also indicated in %). Precipitation values of the reference period, 1961-1990, represent the seasonal mean precipitation amount in Budapest.

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 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.

Table 6. Spatial gradients of expected seasonal precipitation change for the Carpathian basin for 2071-2100 (zonal gradient is positive in case of increasing change from north to south, meridional gradient is positive in case of increasing change from west to east, and radial gradient is positive in case of increasing change from the boundary to the center)

Scenario	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
A2	Zonal: –10%	Zonal: –8%	Meridional: –7%	Radial: +13%
B2	Zonal: –5%	Radial: –10%	Radial: 0%	Radial: +5%

Table 6 summarizes the spatial gradients of expected seasonal precipitation change. Precipitation is a highly variable meteorological element, therefore, the spatial structure is more complex than in case of temperature. In winter and in spring, the spatial structures of expected precipitation change (for both A2 and B2 scenarios) are dominated by radial and zonal gradients, respectively. In summer, zonal structure can be seen in case of A2 scenario, while radial structure is expected in case of B2 scenario.

5. Discussion and conclusions

The target period of PRUDENCE simulations covers the end of the 21st century (2071-2100), thus, the above results presented for the Carpathian basin provide climate projections for this period. On the other hand, impact studies would require regional climate change scenarios for earlier periods, preferably for the next few decades. The only information source currently available with fine (i.e., 50 km) horizontal resolution for Hungary and other European countries is a special comprehensive assessment based on the PRUDENCE simulations (Christensen, 2005). This country-by-country based analysis is conducted for both the mean temperature values and the precipitation amounts. In order to avoid the specific characteristics of A2 or B2 scenario, a pattern scaling technique has been applied, thus, the changes are expressed relative to a 1 °C global warming. Uncertainties in the estimates of projected changes are due to the use of different GCMs and RCMs, as well, as natural variability. As a result, mean and standard deviation of 25 estimates of temperature and precipitation change are provided for each country. Furthermore, these main statistical parameters are used to fit a normal probability distribution function for the projected change. Table 7 summarizes the mean, the standard deviation, the 5th and the 95th percentiles of the seasonal and annual projected temperature and precipitation changes for Hungary (upper and lower part, respectively). In case of the percentile values, their associated 95% confidence intervals are also provided.

Table 7. Statistical characteristics of expected increase of temperature (°C) and precipitation (%) for Hungary relative to 1°C global warming using 25 RCM simulations (Christensen, 2005). In case of percentiles, the values in brackets indicate the 95% confidence intervals.

	Annual	**Spring (MAM)**	**Summer (JJA)**	**Autumn (SON)**	**Winter (DJF)**
TEMPERATURE					
Mean	1.4	1.1	1.7	1.5	1.3
Standard deviation	0.3	0.3	0.4	0.3	0.3
95th percentile	1.9 [1.8-2.1]	1.6 [1.5-1.8]	2.4 [2.2-2.6]	2.0 [1.8-2.1]	1.9 [1.7-2.1]
5th percentile	0.9 [0.7-1.0]	0.6 [0.5-0.8]	1.0 [0.8-1.2]	1.0 [0.8-1.1]	0.8 [0.6-0.9]
PRECIPITATION					
Mean	-0.3	0.9	-8.2	-1.9	9.0
Standard deviation	2.2	3.7	5.3	2.1	3.7
95th percentile	3.4 [2.2-4.6]	7.0 [5.0-9.0]	0.5 [(-2.3)-(3.2)]	1.5 [0.4-2.7]	15.0 [13.0-16.9]
5th percentile	-3.9 [(-5.1)-(-2.8)]	-5.2 [(-7.2)-(-3.3)]	-16.9 [(-19.5)-(-14.1)]	-5.3 [(-6.4)-(-4.2)]	3.0 [1.0-5.0]

In case of temperature (Table 7 upper part), all seasonal, as well, as annual temperature increase expected in Hungary is larger than the global 1°C warming, which implies that this region is quite sensitive to the global environmental change. The projected summer and autumn regional warming (1.7°C and 1.5°C, respectively) is larger than the annual increase (1.4°C), while the expected winter (1.3°C) and spring (1.1°C) warming is smaller than the annual temperature increase.

According to the results presented in Table 7 (lower part) for the precipitation, the annual amount in Hungary is not expected to change significantly. On the other hand, considerable precipitation decrease and increase are projected for summer and for winter, respectively. Slight changes are expected for autumn (some decrease) and for spring (some increase). These results confirm the conclusions drawn from the precipitation maps in the previous section, which implies that the expected shift in the annual distribution of precipitation starts quite early.

On the basis of our research results shown in this paper, the following conclusions can be drawn.

- 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 largest and the smallest warming is expected in summer and in spring, respectively.
- For all the four seasons and for both scenarios, the expected warming by 2071-2100 is between 2.5°C and 4.8°C. The largest 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). The smallest difference between the A2 and B2 scenarios is projected for spring (0.6°C), while the largest for winter (1°C).
- In the reference period (1961-1990), RCM simulations overestimate the temperature in most of the Carpathian basin, however, small underestimation can be seen in the western and the northeastern boundaries of the selected domain.
- The largest increase of maximum and minimum temperatures is expected in summer for both scenario. In case of maximum temperature, the interval of the expected warming is 4.9-5.3°C (A2) and 4.0-4.4 (B2), while in case of minimum temperature, these intervals are 4.2-4.8°C (A2) and 3.5-4.0°C (B2). In general, the expected increase of maximum temperature is not smaller than the expected increase of minimum temperature, the only exception is winter.
- In summer, zonal structure of projected warming (i.e., increasing values from north to south) can be expected in case of all temperature parameters. On the other hand, in winter, generally a meridional structure of warming is expected (i.e., increasing values from west to east). In spring and autumn, the gradient values are much smaller, they do not exceed 0.4 and 0.3, respectively.
- 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.
- 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).
- 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.
- In winter and in spring, the spatial structures of expected precipitation change (for both A2 and B2 scenarios) are dominated by radial and zonal gradients, respectively. In summer, zonal structure can be seen in case of A2 scenario, while radial structure is expected in case of B2 scenario.

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