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Comparison of Simulated Trends of Regional Climate Change in the Carpathian Basin for the 21st Century Using Three Different Emission Scenarios

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Abstract – The present paper discusses the regional climate modeling experiments for the 21st century for the Carpathian Basin using the model PRECIS. The model PRECIS is a hydrostatic regional climate model with 25 km horizontal resolution developed at the UK Met Office, Hadley Centre. Simulated future changes – in mean climatic values, distributions and empirical probabilities – are analyzed for the period 2071–2100 (compared to 1961–1990, as a reference period). Significant warming is projected at 0.05 level for all of the A2, A1B, and B2 scenarios, the largest warming is estimated in summer. Not only the mean value is likely to change, but also the distribution of daily mean temperature. By the end of the century the annual precipitation in the Carpathian Basin is likely to decrease, and the annual distribution of monthly mean precipitation is expected to change. Significant drying is projected in the region in summer, while in winter the precipitation is estimated to increase.

Regional climate modeling / PRECIS / Temperature / Precipitation / Carpathian Basin

Kivonat – Az éghajlat várható alakulása a Kárpát-medencében a XXI. század során három különböző emisszió-szcenárió esetén. E cikk bemutatja a PRECIS regionális klímamodellel a XXI. századra végzett szimulációs futtatásaink eredményét a Kárpát-medence térségére. A PRECIS modell 25 km-es térbeli felbontást alkalmazó, hidrosztatikus regionális éghajlati modell, melyet a Brit Meteorológiai Szolgálat Hadley Központjában fejlesztettek ki. A szimulációk felhasználásával megvizsgáltuk a 2071–2100 időszakra várható éghajlatváltozást (az 1961–1990 referencia-időszakhoz viszonyítva), melyhez a meteorológiai paraméterek átlagértékeit, eloszlását és empirikus valószínűségeket is figyelembe vettünk. A modell 95%-os szinten szignifikáns melegedést prognosztizál Magyarország és a Kárpát-medence egész területére az A2, az A1B és a B2 forgatókönyvek esetén egyaránt. A legnagyobb változás mindhárom esetben nyáron várható. Eredményeink alapján egyértelmű, hogy nemcsak az átlaghőmérséklet növekedésére kell számítanunk, de a hőmérséklet eloszlása is jelentősen módosul a jövőben. Az évszázad végére a Kárpát-medencében éves átlagban a csapadék csökkenése, valamint az év során lehulló csapadékösszeg eloszlásának időbeli átrendeződése valószínűsíthető. A PRECIS szimulációk az ország egész területén szignifikáns szárazodást prognosztizálnak a nyári évszakban mind a három vizsgált szcenárió esetén. Télen viszont a csapadék növekedésére számíthatunk.

Regionális éghajlatmodellezés / PRECIS / hőmérséklet / csapadék / Kárpát-medence

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INTRODUCTION

On the basis of about 20 years' international research in the frame of the Intergovernmental Panel on Climate Change (IPCC), there is no doubt that due to anthropogenic activity the Earth is facing a global warming (IPCC 2007). Global climate models (GCMs) are widely used to estimate the future climate change, however, for regional scale analysis their coarse resolution (typically 150–200 km) limits their applicability in assessment of the regional consequences of global warming. Regional climate models nested in GCMs (Giorgi 1990) may lead to better estimations of future climate conditions in the European subregions as well as in other parts of the world since the horizontal resolution of these RCMs is much finer (around 10–25 km) than the GCMs' (IPCC 2007).

The Carpathian Basin is located in the target regions of several recent EU-projects (e.g., PRUDENCE (http://prudence.dmi.dk, Christensen – Christensen 2007), ENSEMBLES (www.ensembles-eu.org, van der Linden – Mitchell 2009), CECILIA (www.cecilia-eu.org, Halenka 2007), CLAVIER (www.clavier-eu.org, Jacob et al. 2008)) that focused on regional climate change in the 21st century using high-resolution climate model simulations, as well, as on the environmental impacts of projected climate change. In the frame of international cooperative projects, four regional climate models have been successfully adapted and tested for the region, two of them at the Eötvös Loránd University, Budapest: PRECIS (**P**roviding **Re**gional **C**limates for **I**mpact **S**tudies), and RegCM (**Reg**ional **C**limate **M**odel) (Bartholy et al. 2009a). By now after completing several RCM experiments for the Carpathian Basin and its vicinity, it is possible to estimate the future changes in the climatic means and extremes in this region for the 21st century (Torma et al. 2008, Bartholy et al. 2009a,b,c, Pieczka et al. 2010, Krüzselyi et al. 2011). These projections are especially important for planning at the low-elevation retreating limits of the closed forest zone, such as in Hungary (Mátyás 2010).

In the next section of this paper the model PRECIS is introduced, then outputs of the different experiments are used to analyze the simulated temperature and precipitation change by 2071–2100 for Hungary (compared to 1961–1990, as a reference period). Besides the evaluation of mean climate changes, extreme conditions are also discussed. Finally, the main conclusions are summarized in the last section.

1 REGIONAL CLIMATE MODEL PRECIS

PRECIS is a high resolution limited area model with both atmospheric and land surface modules. The model was developed at the Hadley Centre of the UK Met Office (Wilson et al. 2009), and it can be used over any part of the globe (e.g., Hudson – Jones 2002, Rupa Kumar et al. 2006, Taylor et al. 2007, Akhtar et al. 2008). The PRECIS regional climate model is based on the atmospheric component of HadCM3 (Gordon et al. 2000) with substantial modifications to the model physics (Jones et al. 2004). The horizontal resolution of the model can be set up to 25 or 50 km. In our studies, we used the finest possible horizontal resolution. The target region contains 123×96 grid points, with special emphasis on the Carpathian Basin and its Mediterranean vicinity containing 105×49 grid points *(Figure 1)*. In the vertical direction the model contains 19 levels using hybrid coordinates (Simmons – Burridge 1981).

In case of the control period (1961–1990), the initial conditions and the lateral boundary conditions (IC&LBC) for the regional model can be provided by ERA-40 reanalysis (Uppala et al. 2005) or by the HadCM3 ocean-atmosphere coupled GCM. For the validation of the PRECIS simulations CRU TS 1.2 data sets (Mitchell – Jones 2005) and E-OBS data (Haylock et al. 2008) were used. Significance of the bias fields were checked using Welch's t-test (Welch 1938). According to the results, PRECIS is able to sufficiently reconstruct the climate of the reference period (Bartholy et al. 2009b,c). The annual cycle of temperature is well represented, the bias (i.e., difference between simulated and observed annual and seasonal mean temperature) is found to be mostly within the interval (–1 °C; +1 °C). The largest bias values are found in summer, when the average overestimation of PRECIS over Hungary is 2 °C in case of the ERA40-driven, and 2.3–3 °C in case of the GCM-driven simulations. For precipitation a slight overestimation is dominant (only one of the completed experiments showed a small underestimation in summer), the spatial average of the bias is less then 10 mm/month (except spring). The largest precipitation bias can be found in spring which is significant in each gridpoint within the borders of Hungary. The overestimation is around 20 mm/month, which corresponds to a 40–50% relative difference between observation and simulation.

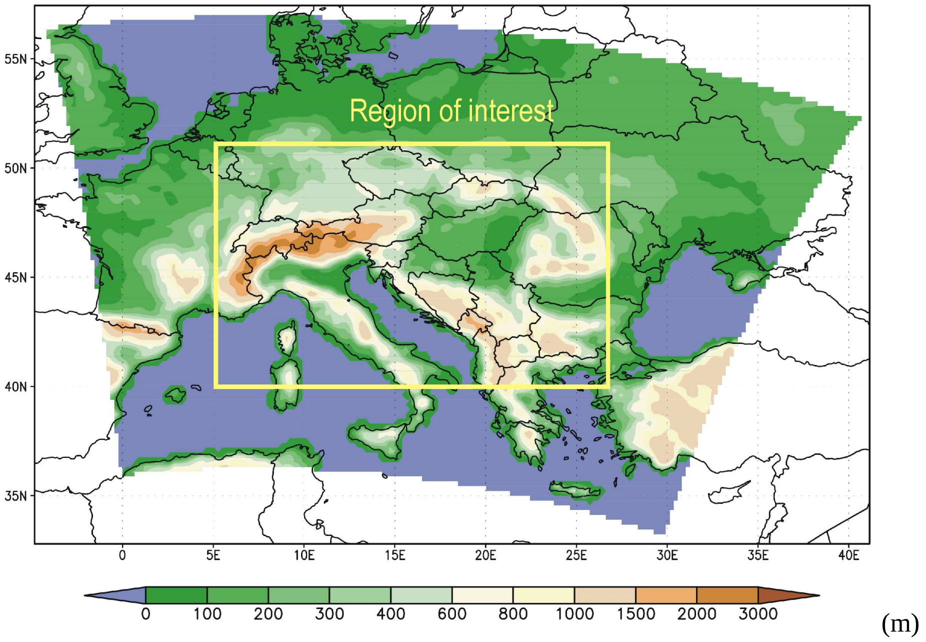

Figure 1. Geographical location and topography of the selected integration domain of model PRECIS

For the future (2071–2100) three experiments were completed, namely, for the A2, A1B, and B2 global emission scenarios (Nakicenovic – Swart 2000). The estimated global mean CO_2 concentration level for the end of the century is 856 ppm, 717 ppm, and 621 ppm, respectively. Thus, A2 can be considered the most pessimistic, and B2 the most optimistic among these scenarios. Our findings for the projected change of temperature and precipitation (compared to 1961–1990) are discussed in the next two sections.

2 SIMULATED TEMPERATURE CHANGE BY 2071–2100

For 2071–2100 A2, A1B, and B2 scenario runs have been completed using the model PRECIS. A2 scenario implies the highest temperature values in the Carpathian Basin (due to the highest estimated CO_2 concentration level). The projected annual mean temperature change for Hungary is between 4.0 °C and 5.4 °C. The projected seasonal mean changes are summarized in *Table 1*. It can be clearly seen that the largest warming is likely to occur in summer (the spatial average of the simulated change is 6.0–8.0 °C). The least warming is projected for spring and winter. The simulated change is significant at 0.05 level for each season and grid point (Pieczka et al. 2010).

Table 1. Projected seasonal mean temperature change (°C) for Hungary by 2071–2100 (reference period: 1961–1990)

	Winter	Spring	Summer	Autumn
B2 scenario	3.2	3.1	6.0	3.9
A1B scenario	4.1	3.7	6.7	5.0
A2 scenario	4.2	4.2	8.0	5.2

The year-to-year variation of seasonal mean temperature for Hungary is presented in *Figure 2*. All the time series highlight the significant warming for each season and for all scenarios. The largest seasonal warming is projected for summer. The mean temperature in autumn is likely to increase more than in spring, thus autumn may become warmer than spring due to the robust warming in late summer/early autumn (Bartholy et al. 2009c). The year-to-year variation in the transition seasons is also likely to increase to up to 1.5–2 times of their current value in case of the A2 and B2 scenarios, however, such a change is not projected for A1B. Standard deviation of winter mean temperature is projected to slightly decrease in case of all scenarios. According to the simulations, the presently quite large standard deviation in summer is likely to slightly decrease for B2, and slightly increase for A1B and A2 scenarios, but no robust change is projected. On the continuous 140-years simulation of A1B the warming trend is obvious for each season, with the highest rate in summer – to visualize this tendency, the fitted linear trends using the least squares method are shown for the entire 1961–2100 period.

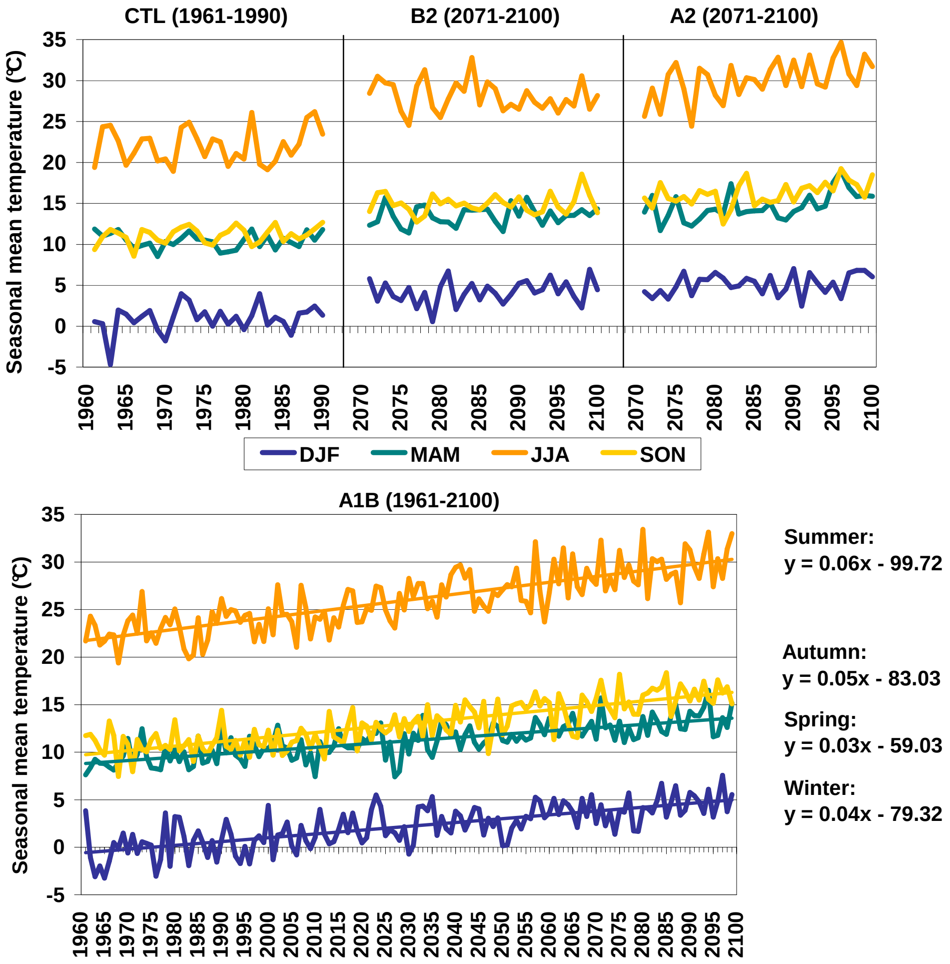

Figure 2. Year-to-year variation of seasonal mean temperature (°C) for Hungary. In case of A1B simulation the fitted linear trends are also shown for 1961–2100

In *Figure 3* Box-Whisker plot diagrams calculated from the simulated values of monthly temperature anomalies for 2071–2100 (relative to the 1961–1990 monthly mean values) in all the gridpoints located within Hungary, are shown for all scenarios. The small rectangles represent the lower and the upper quartiles, and the vertical lines indicate the minimum and the maximum of the sample (the size of the entire sample is 6,870). The lower quartile values are always positive (and in most of the summer and autumn months the minimum values are also above 0 °C), which highlights the projected warming trend. The middle 50% of the sample is represented by the boxes: the larger the size, the larger the variance of the sample. In case of the different scenarios, the total ranges of the middle-half of the monthly anomalies are similar (around 2–5 °C), the largest ranges are projected in the summer months. Negative anomalies compared to the mean of 1961–1990 are likely to occur by 2071–2100 only in a few cases and locations, mainly in the winter months (especially, in December and February).

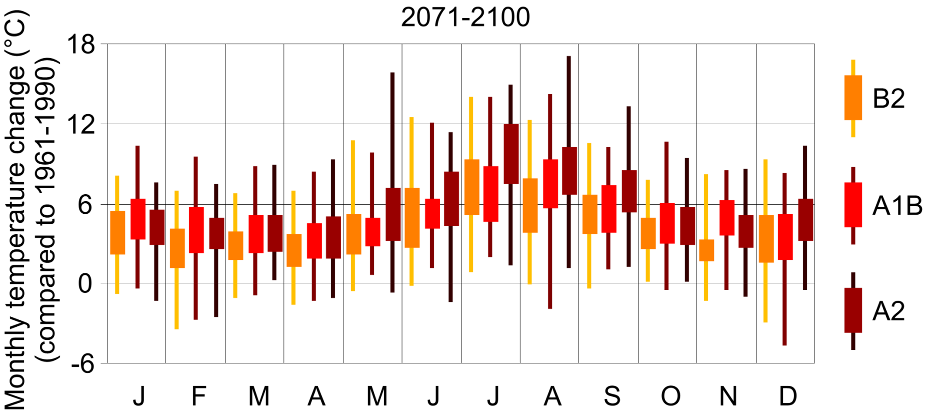

Figure 3. Distribution of projected monthly temperature change (°C) in the gridpoints located within Hungary for 2071–2100 (reference period: 1961–1990)

The distribution change of simulated daily mean temperature is also analyzed. The results for January and July (being the coldest and the warmest months, respectively) can be seen in *Figure 4*.

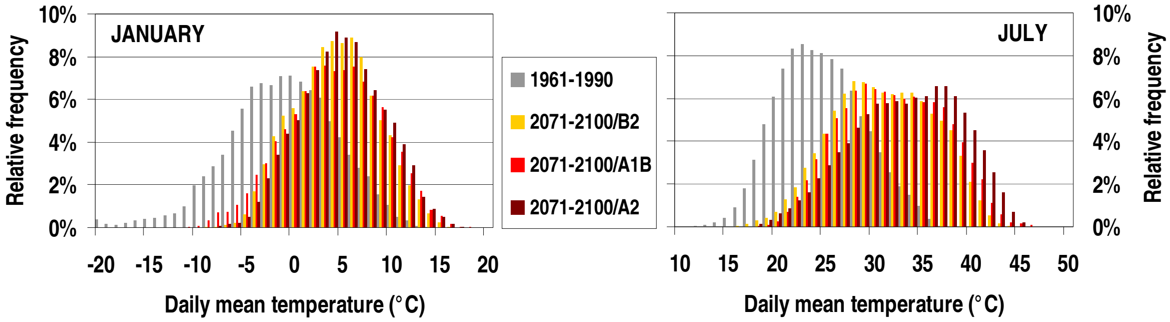

Figure 4. Distribution change of simulated daily mean temperature in January (left panel) and July (right panel)

In January the distribution is projected to shift towards the larger temperature values (the projected monthly mean change is about +5.2 °C, +5.0 °C, and +5.7 °C in case of B2, A1B, and A2 scenario, respectively), which implies less cold and more warm and record warm periods in winter. In July (shown in the right panel) not only a shift, but also a shape-change of the empirical distribution is visible. The relative frequency values of different temperature intervals are likely to change remarkably (the projected monthly mean temperature increase is about +6.3 °C, +7.1 °C, and +8.4 °C in case of B2, A1B, and A2 scenario, respectively). The projected distribution changes for these three scenarios are very similar in the winter months (January is shown in this paper as an example), but differ more in case of the summer months (especially in July and August, from which July is shown in *Figure 4*). Thus, for the summer the simulations imply less cold and more hot periods, and larger record hot conditions than in the reference period. This frequency shift is larger in case of A2 scenario than A1B or B2 scenario.

In order to evaluate the projected distribution change from a spatial aspect, a special method has been developed. The main aim of this method is to quantify the empirical probability of temperature or precipitation anomalies exceeding given thresholds based on the model simulations, and then to compare to the occurrence determined from observational datasets (such as the E-OBS gridded data (Haylock et al. 2008)). The comparison enables the provision of a clear message to the impact modelers on the distribution shift for instance.

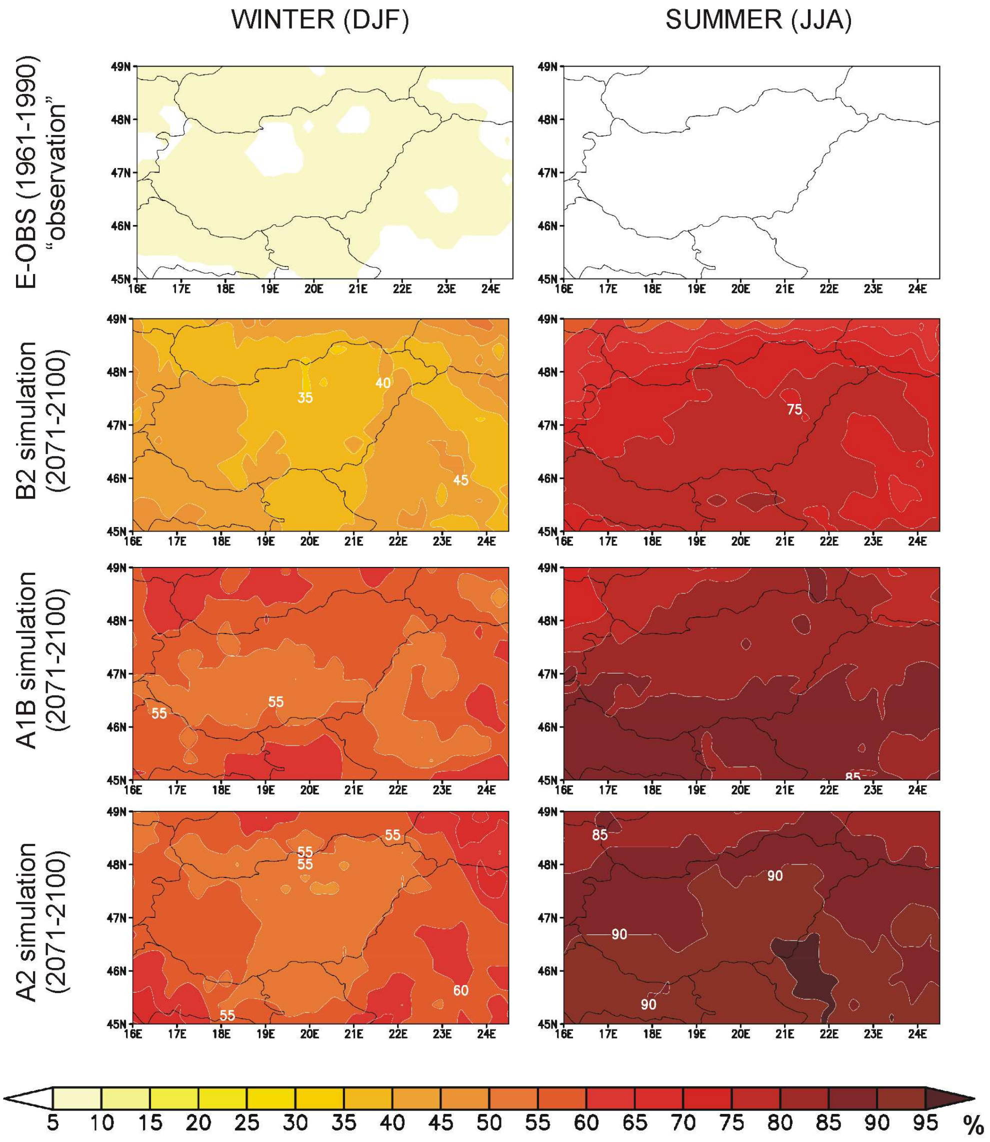

Figure 5. Seasonal empirical probability of monthly temperature anomaly exceeding 4 °C (relative to the 1961–1990 monthly mean values)

Among the various threshold values used during the analysis *Figure 5* shows the empirical probability of temperature anomaly exceeding 4 °C in winter and summer for the reference period (1961–1990) and the target period (2071–2100) for the three scenarios. (PRECIS experiments project at least 4 °C annual warming for Hungary.) For the end-users these maps may provide useful spatial information about the probability of threshold exceedance. In past climatic conditions, monthly temperature anomaly exceeding 4 °C occurred in about 5–10% of all the winter months, and it hardly ever happened in the other seasons (only summer and winter are shown). According to the PRECIS simulations, this is very likely to change in the future: by the end of the 21st century the monthly temperature anomaly (e.g., the difference from the mean of 1961–1990) exceeding 4 °C will become quite frequent (B2: 35–45% in winter, 70–80% in summer; A1B: 50–60% in winter, 80–85% in summer, A2: 50–60% in winter, 85–95% in summer). The largest probability values can be seen in summer. The spatial structure of the empirical probability fields is similar, but the values differ, namely, probability values for A2 are larger than for A1B and B2. In summer a zonal structure can be recognized, with the largest probability values in the eastern/southern part of Hungary.

3 SIMULATED PRECIPITATION CHANGE BY 2071–2100

The model predicts about 20% annual precipitation decrease on average for Hungary by the end of the 21st century in case of A2 and B2 scenarios, but gives practically no change in annual precipitation in case of A1B. However, if seasonal or monthly simulated changes are evaluated, the largest change is projected for summer, namely, significant drying is likely according to the simulations for the whole country (the simulated precipitation decrease is 34%, 43%, and 58% using spatial averages in case of A1B, B2, and A2, respectively). Also, for spring and autumn the projected trend is negative (except for A1B in spring, when it is slightly positive), but it is much smaller than in summer and not significant at 0.05 level. The direction of simulated precipitation change in the transition seasons involves large uncertainties. In winter a slight increase is projected (in spatial average about 14%), which is significant in case of A2 in the Transdanubium, where the simulated winter precipitation change may exceed 30–40% (Pieczka et al. 2010). The A1B experiment projects a larger, significant precipitation increase (34% in spatial average) for the entire country.

Precipitation is highly variable both in space and time. According to the PRECIS simulations the year-to-year variation in Hungary will remarkably change in the future (*Figure 6 and Figure 7*). The results suggest a major annual redistribution of precipitation, a significant decrease in summer precipitation, as well, as in interannual variation of summer precipitation, and increase of the interannual variation in spring and winter. In summer both the seasonal sum and the temporal standard deviation is likely to decrease dramatically, by about 50% in case of A2 and B2 scenarios. The largest decrease of the standard deviation is expected in June, July, and September, in the rest of the year the simulated changes are less pronounced. However, the simulated year-to-year variation increase of monthly precipitation in spring is quite large, especially, in May in case of A2 scenario. The results from the A1B experiment suggest that by the middle of the century the sum and variation of precipitation in summer and winter will be almost equal, and by the end of the century most of the precipitation will fall during winter – but in some years the opposite may happen (*see Figure 6*). Trends in spring and autumn precipitation change are small and not significant.

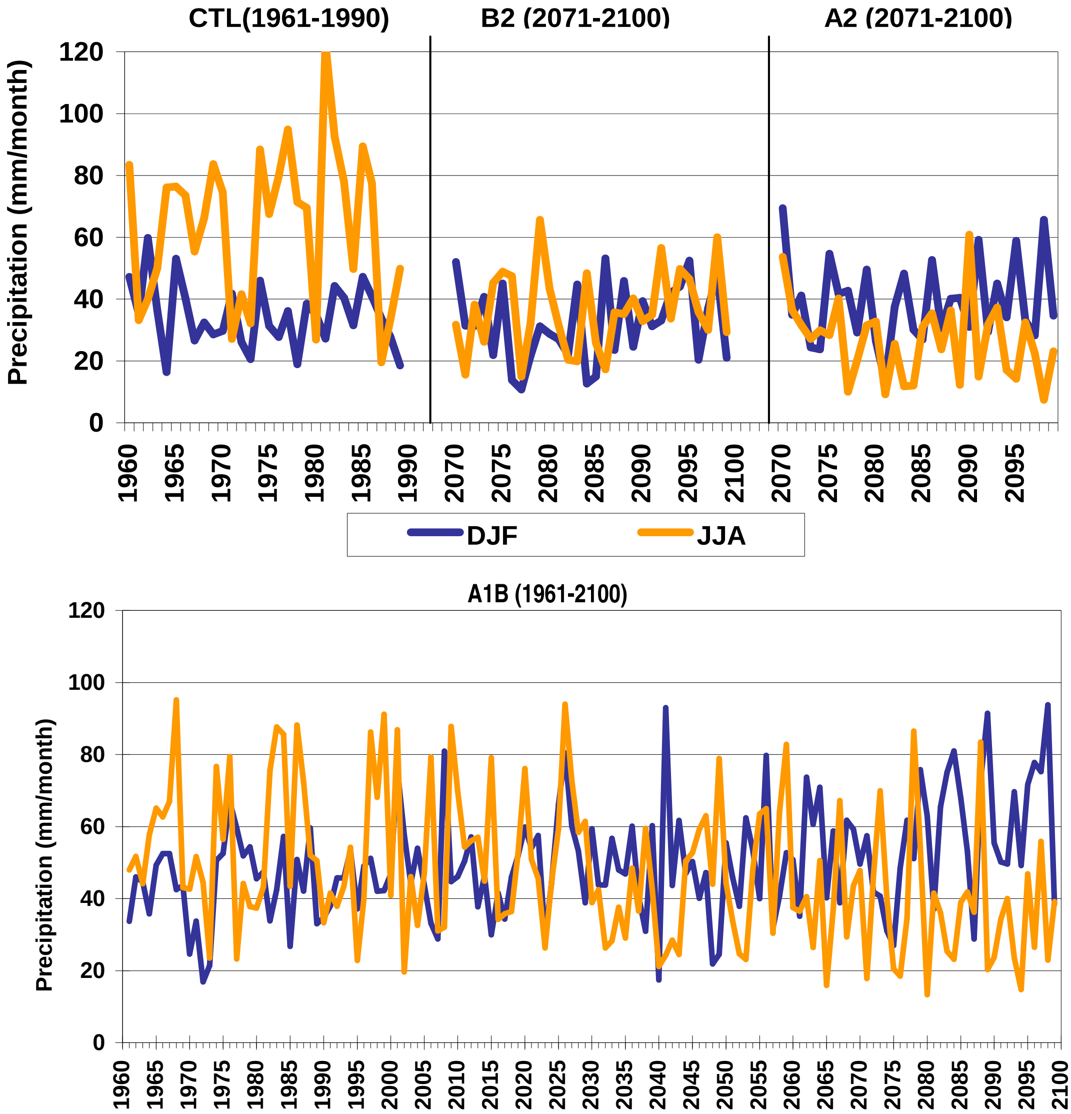

Figure 6. Year-to-year variation of seasonal mean precipitation (mm/month) for Hungary in winter and summer

The projected change in the annual distribution of simulated monthly mean precipitation is shown in *Figure 8*. In the present climate (1961–1990), the wettest months in Hungary are in late spring, early summer (May, June), when the monthly mean precipitation sum exceeds 60 mm. The driest months are January and February with about 30–35 mm total precipitation on average. The PRECIS simulations suggest that in case of all three scenarios, the annual distribution of monthly precipitation is very likely to be restructured in the future. The driest months are projected no longer to occur during winter, but in July and August instead (in case of A2 with less than 20 mm, in case of A1B around 20–25 mm, and in case of B2 with about 25–30 mm on average by 2071–2100). The wettest month of the A2 scenario run is projected to be April with about 65–70 mm precipitation on average, while in case of the B2 and A1B simulations the wettest months are April, May and June with about 60 mm (B2) / over 60 mm (A1B) total precipitation on average.

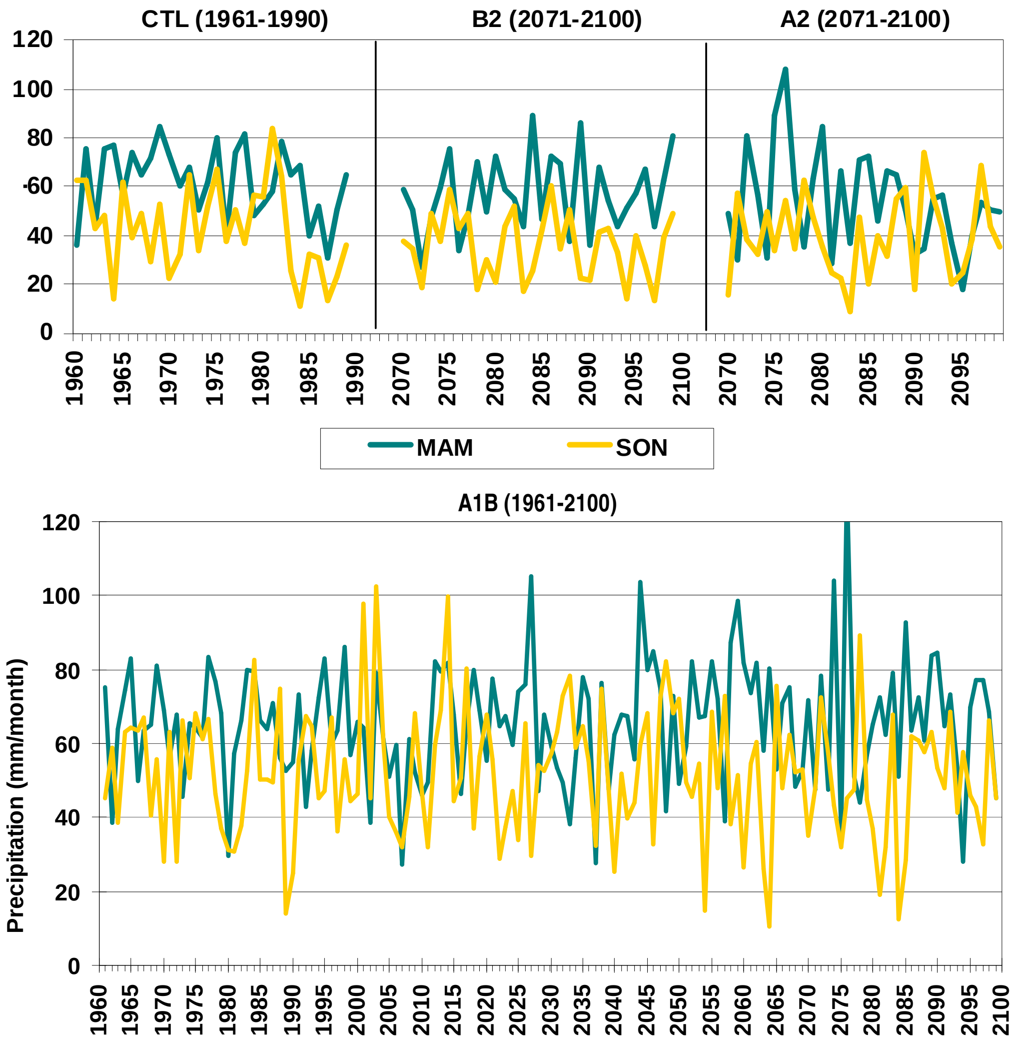

Figure 7. Year-to-year variation of seasonal mean precipitation (mm/month) for Hungary in spring and autumn

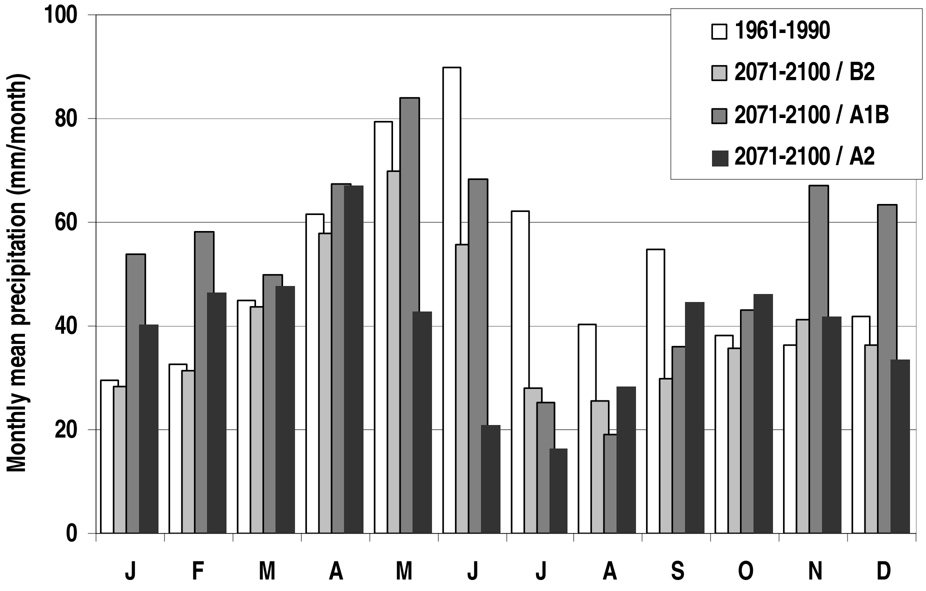

Figure 8. Annual distribution of simulated monthly mean precipitation (mm/month) in the reference period (1961–1990) and in the target period (2071–2100)

Overall, the model PRECIS predicts a drier climate in the Carpathian Basin. The more pronounced changes will probably happen during winter and summer months. In case of the empirical probability analysis threshold values –20% and +20% were selected since two of the presented experiments suggest 20% annual precipitation decrease for Hungary. The empirical probability of negative precipitation anomaly exceeding –20% in past (1961–1990) climatic conditions occurred in about 40–55% of all the autumn months, and 30–40% of all the months in the other three seasons (*Figure 9*). According to the PRECIS simulations, a drying tendency is projected by the end of the 21st century, especially, in the summer months (the occurrence of the monthly precipitation anomaly exceeding –20% increases significantly to 70–80% in case of B2 and A1B, and 80–90% in case of A2 scenarios). In winter a less pronounced frequency increase is expected (B2: to 40–60%, A2: to 30–50%), and in case of A1B even a slight decrease can be seen (to 20–30%).

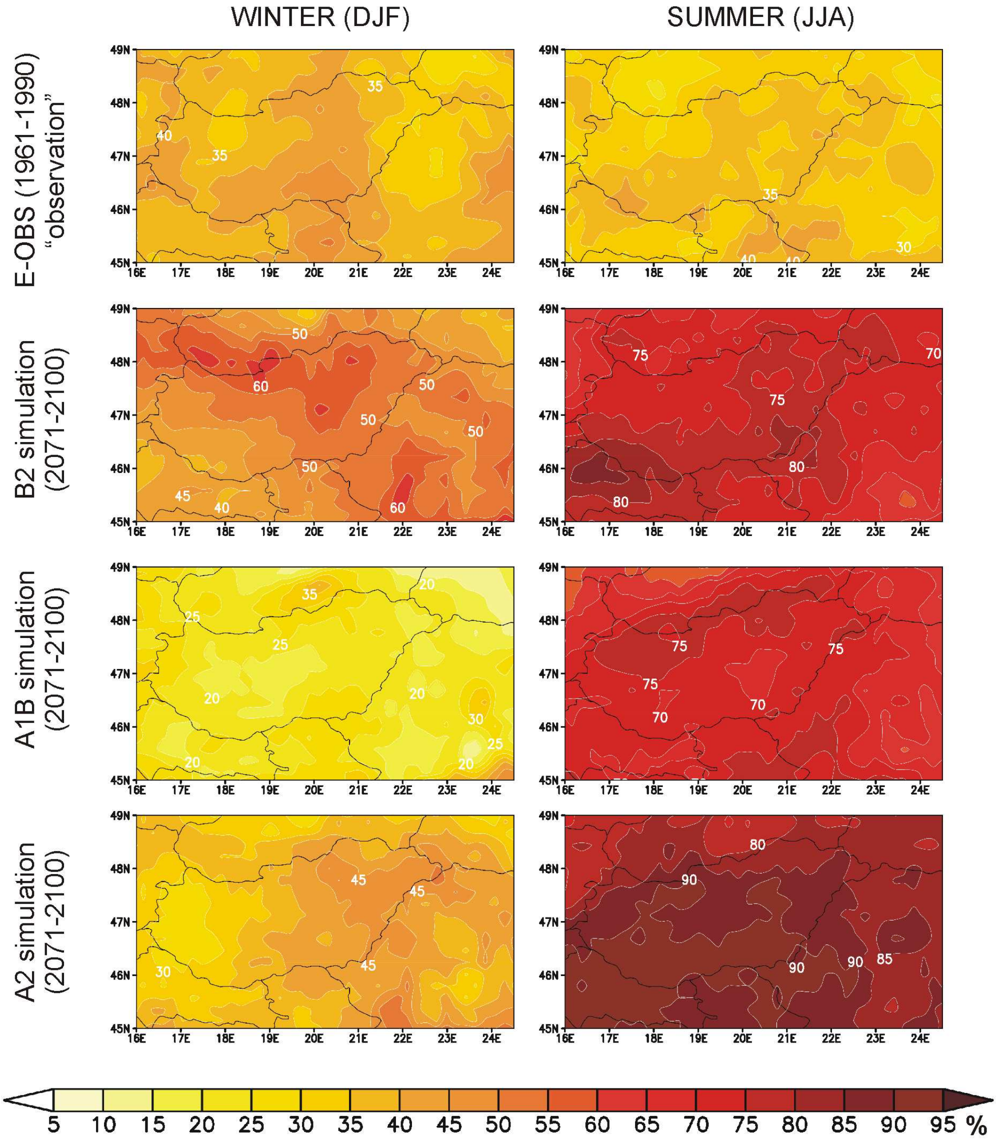

Figure 9. Seasonal empirical probability of monthly precipitation anomaly exceeding –20% (relative to the 1961–1990 monthly mean values)

The empirical probability of positive precipitation anomaly exceeding 20% in the past climatic conditions occurred about 25–35% of all the months throughout the year. A major decrease is projected for the summer months: the probability of wet conditions decreases to 0-20% in case of B2, to 5–15% in case of A1B, and to 0–10% in case of A2 *(Figure 10)*. Based on these maps (*Figures 9* and *10*) it can be clearly seen that in case of the A2 scenario the amplitude of the summer changes are likely to be larger than in case of B2 or A1B. For winter the changes are less pronounced for B2, but for A2 a major increase is projected in the Transdanubium (from 25–35% to 45–55%) and for A1B scenario for the entire country (to 45–60%), as we mentioned earlier. In winter, in case of A2 the wetter periods are likely to become more frequent in the whole country, while the dry periods will become less frequent mainly in the area of Transdanubium. This finding is even more pronounced in case of A1B scenario, however, valid not only for parts of the country but for the entire area.

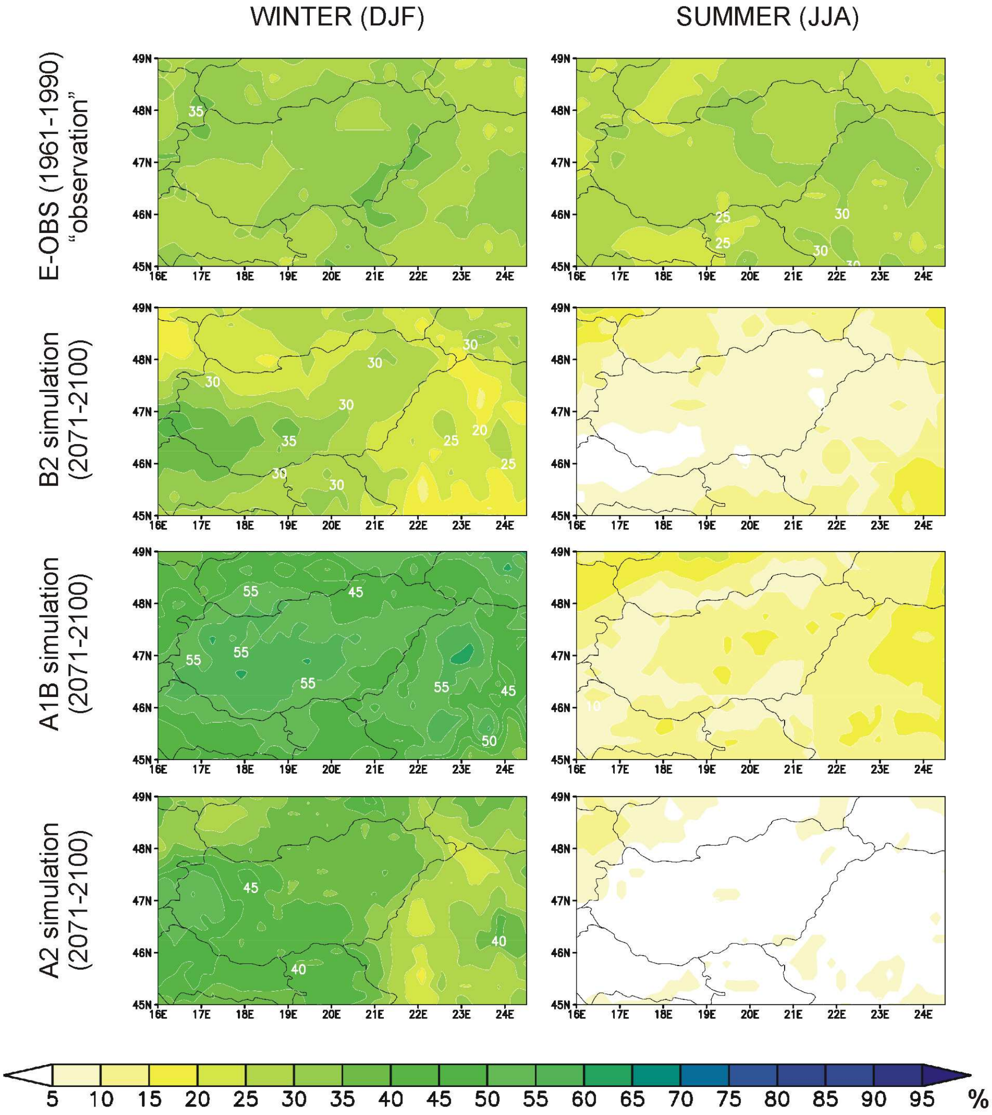

Figure 10. Seasonal empirical probability of monthly precipitation anomaly exceeding +20% (relative to the 1961–1990 monthly mean values)

4 SUMMARY

The climate conditions of the 1961–1990 (reference) and 2071–2100 periods have been simulated using the PRECIS regional climate model. In the present paper the projected temperature and precipitation changes for the Carpathian Basin for the end of the 21st century (compared to the mean of 1961–1990) have been analyzed. The main conclusions can be drawn as follows.

(i) The sign of the simulated temperature change is the same for all the three scenarios, the projected annual temperature increase is in the range of 4.0–5.4 °C. The amplitude of the projected warming is the largest in case of A2, according to which the highest CO_2 concentration level is estimated.

(ii) In all the four seasons significant warming is projected at 0.05 level in all simulations, the largest warming is likely to occur in summer (for Hungary the spatial average warming by the end of the 21st century is likely to reach 6–8 °C).

(iii) Not only the mean climatic conditions will change, but also the distribution of the daily (and monthly) mean temperature, implying more frequent warm and hot periods and greater record hot conditions than in the 1961–1990 reference period.

(iv) By the end of the century the annual precipitation in the Carpathian Basin is likely to decrease by about 20% for both A2 and B2 scenarios. The A1B scenario does not project such annual changes.

(v) Significant drying is projected in the region, especially, in summer (the seasonal precipitation amounts as well, as the probability of occurrence of wetter periods are likely to decrease in Hungary) while in winter the precipitation is projected to increase. The direction of precipitation change in the transition seasons is uncertain, the simulations do not estimate significant changes.

(vi) According to the PRECIS simulations the annual distribution of monthly mean precipitation is also expected to change. In the 1961–1990 reference period the wettest months in Hungary occurred in May and June, and the driest months were January and February. In the 2071–2100 future period, the driest months are projected to be July and August, while the wettest April, May and June.

PRECIS is only one of the four RCMs adapted and used for assessing the regional climate change in Hungary. Obviously, these experiments differ in many aspects, e.g., in model formulation, physical parameterization, spatial resolution, driving boundary conditions and forcings. Due to these differences besides the robust future changes suggested by the different RCM results the uncertainties associated to the estimated changes for the Carpathian Basin can be also assessed (Krüzselyi et al. 2011). Moreover, previous RCM results based on PRUDENCE outputs (Batholy et al. 2008) and ENSEMBLES outputs (Bartholy et al. 2011) also enable us to evaluate the PRECIS simulations. Compared to these other RCM experiments, PRECIS results for Hungary project somewhat warmer conditions than the mean temperature change of all the available simulation results. The largest seasonal warming projected for summer by PRECIS simulations are consistent with other results (Bartholy et al. 2008, 2011). In case of precipitation projections, the uncertainty is much larger than in case of temperature. The RCM results often disagree in the sign of the projected seasonal and annual changes, which are often non-significant. However, the summer drying is estimated by most of the RCM experiments, as well, as PRECIS runs presented in this paper. Slightly wetter winter conditions are also likely to occur in the future compared to the reference period 1961–1990. From this sense PRECIS simulations are consistent with the available RCM results.

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