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Analysis of projected drought hazards for Hungary

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Abstract. Global climate change may result in severe regional consequences affecting agricultural production potential. One of the essential climatic impacts is associated with drought conditions. Therefore, projected future changes of several drought indices are analyzed for the future period 2071–2100 (compared to 1961–1990, as a reference period) using three different global emission scenarios (A2, A1B, and B2). The monthly time series of the indices have been calculated from the simulation outputs of the regional climate model PRECIS (Providing REgional Climates for Impacts Studies) for Central/Eastern Europe with 25 km horizontal resolution accomplished by the Department of Meteorology, Eötvös Loránd University. According to the results significant drying is projected in the region, especially in summer.

1 Introduction

Global warming may be recognised both in shifts of regional mean climate, and also, in the frequency and intensity changes of different climatological extremes associated with both temperature and precipitation (IPCC, 2007). Temperature increase together with precipitation decrease is likely to result in severe drought consequences, which might especially affect agricultural production and food security. This climatological hazard must be addressed and investigated with special focus on possible future trends. In the past decades, especially, the southern half of Europe suffered longer and more intense drought events (Sheffield and Wood, 2008a; IPCC, 2012). Burke and Brown (2008) compared results of 11 global climate models (GCMs) and showed that a statistically significant increase (by 5–45 %) of drought is projected for land area. GCM simulations project increase in duration and intensity of droughts in many regions of the world, including Southern Europe, the Mediterranean region, and Central Europe (Sheffield and Wood, 2008b; Dai, 2011).

Burke and Brown (2008) highlighted the large uncertainties in projected regional changes in drought when GCM results are considered, therefore regional climate models (RCMs) nested in GCMs should be applied to assess future trends of climatic conditions on national and regional scales. In this study, the PRECIS model developed at the UK Met Office Hadley Centre is used for the Carpathian Basin located in Central/Eastern Europe. In order to evaluate the future drought conditions in the region, different types of drought indices are used, namely, simple precipitation index (PI), standardised precipitation anomaly index (SAI), Lang's rainfall index (LRI), de Martonne aridity index (MAI), Thornthwaite aridity index (TAI), Ped's drought index (PDI), and Foley's anomaly index (FAI). In order to calculate the time series of these indices, monthly temperature and precipitation datasets of PRECIS model experiments accomplished by the Department of Meteorology, Eötvös Loránd University (Bartholy et al., 2009) are used. Simulations for the periods 1961–1990 (as the reference period), and 2071–2100 (using the A2, A1B, and B2 emission scenarios) are analyzed. The last three decades of the century has been selected as the target period in our study due to the robust climate change signal (Pieczka et al., 2011) compared to the climate variability.

In this paper, first, the PRECIS model is introduced, which provides the temperature and precipitation data used to calculate the monthly time series of drought indices for the Carpathian Basin. Definitions of drought indices are presented in Sect. 3. Projected seasonal average changes are discussed in Sect. 4. Finally, the main conclusions are summarised in the last section.

2 Regional climate model PRECIS

The installation and the adaptation of the regional climate model PRECIS at the Department of Meteorology, Eötvös Loránd University (Budapest, Hungary) started in 2004.

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PRECIS is a high resolution limited area model with both atmospheric and land surface modules. The model was developed at the Hadley Climate Centre of the UK Met Office (Wilson et al., 2009), and it can be used over any part of the globe (e.g., Hudson and Jones, 2002; Rupa Kumar et al., 2006). The PRECIS regional climate model is based on the atmospheric component of Hadley Centre Coupled Model (HadCM3) (Gordon et al., 2000) with substantial modifications to the model physics (Jones et al., 2004). The atmospheric component of PRECIS is a hydrostatic version of the full primitive equations, and it applies a regular latitude-longitude grid in the horizontal and a hybrid vertical coordinate. For modelling the Central/Eastern European climate, the target region contains 123×96 grid points, with a horizontal resolution set to $0.22° \times 0.22°$, which gives a resolution of ~ 25 km at the equator of the rotated grid. There are 19 vertical levels in the atmospheric module, the lowest at ~ 50 m and the highest at 0.5 hPa with terrain-following σ-coordinates (σ = pressure/surface pressure) used for the bottom four levels, pressure coordinates used for the top three levels, and a combination in between. The model equations are solved in spherical polar coordinates and the latitude-longitude grid is rotated so that the equator lies inside the region of interest in order to obtain quasi-uniform grid box area throughout the region. An Arakawa B grid (Arakawa and Lamb, 1977) is used for horizontal discretisation to improve the accuracy of the split-explicit finite difference scheme. Due to its fine resolution, the model requires a time step of 5 min to maintain numerical stability. In the post processing of the RCM outputs, daily mean values are used.

The initial and the lateral boundary conditions for the regional model are taken from the HadCM3 ocean-atmosphere coupled GCM using $2.5° \times 3.75°$ latitude-longitude resolution. According to the validation, PRECIS is able to sufficiently reconstruct the climate of the reference period in the Carpathian Basin (Bartholy et al., 2009; Pieczka et al., 2011). Temperature and precipitation bias fields of the PRECIS simulations can be considered acceptable if compared to other European RCM simulations (Jacob et al., 2007; Pongrácz et al., 2011). Therefore, the PRECIS model can be used to estimate future climatic change of the Carpathian Basin. For the future (2071–2100), three experiments have been completed so far, according to A2, B2 and A1B global emission scenarios (Nakicenovic and Swart, 2000), respectively. The A2 scenario is the least optimistic and B2 is the most optimistic, as indicated by the CO_2 concentration level projected by 2100 (856 ppm and 621 ppm, respectively). In case of the A1B scenario CO_2 concentration level by 2100 is estimated to increase to 717 ppm (Nakicenovic and Swart, 2000).

3 Drought indices

Drought indices (Dunkel, 2009) are commonly used to characterise drought conditions. They can be grouped into four different types. (i) Precipitation indices are simple and require solely precipitation data, however, they are suitable for separating dry and wet periods, as well as determining temporal variability. PI and SAI are used in the present study. (ii) Water balance indices consider other elements of the water balance besides precipitation, mainly evaporation as a function of temperature. LRI, MAI, and TAI are calculated in the present study. (iii) Recursive indices consider data from preceding period, and thus characterise long time periods. A classical example of recursive indices is the Palmer Drought Severity Index, PDSI (Palmer, 1965), which we did not use in this study due to the complex calculation algorithm. FAI is used instead. (iv) Soil moisture indices are able to estimate loss in crop yields and water shortage; here, PDI is used.

Different drought indices emphasize different aspects of drought, therefore, for a complex regional analysis covering the most drought characteristics one should evaluate several drought indices (IPCC, 2012).

PI is the simplest drought index (Kane and Trivedi, 1986), which considers the precipitation anomaly as follows:

$$\mathrm{PI} = P_i - m(P), \tag{1}$$

where P_i is the actual monthly precipitation amount in mm, and $m(P)$ is the average monthly precipitation amount for 1961–1990 in mm. Negative and positive values are associated with dry and wet climatic conditions, respectively. The main advantage of PI is the simple calculation using only one climatic variable. However, precipitation by itself may not be sufficient to characterise drought events.

Precipitation can be normalised by using the standard deviation, and thus, SAI is defined (Katz and Glantz, 1986) as follows:

$$\mathrm{SAI} = \frac{P_i - m(P)}{d(P)}, \tag{2}$$

where P_i is the actual monthly precipitation amount in mm, while $m(P)$ and $d(P)$ are the average monthly precipitation amount and standard deviation for 1961–1990, respectively (both are expressed in mm). Similarly to PI, negative and positive values are associated with dry and wet climatic conditions, respectively. Normalisation helps to compare intensity of dry and wet months in case of non-homogeneous annual distribution. However, this index still uses only one climatic variable.

Besides precipitation data, temperature is also used when LRI (Lang et al., 1999) is calculated as the simple ratio of the monthly precipitation amount (P_i) in mm and the monthly mean temperature (T_i) in °C. The applied formula is the following:

$$\mathrm{LRI} = \frac{P_i}{T_i}. \tag{3}$$

Table 1. Spatial average of projected seasonal change of drought indices by 2071–2100 considering A1B scenario taking into account the 229 grid points located within Hungary (reference period: 1961–1990). Statistically significant projected changes at 0.05 level are indicated by bold characters. LRI, MAI, and TAI are not relevant for winter because of possible negative temperature values.

Drought index	Winter	Spring	Summer	Autumn
PI (mm)	**+14.7**	+2.7	**−18.7**	−1.8
SAI	**+0.6**	+0.1	**−0.6**	−0.1
LRI (mm/°C)	–	**−4.0**	**−1.3**	**−3.6**
MAI (mm/°C)	–	**−5.8**	**−9.6**	**−7.6**
TAI (mm/°C)	–	**−0.6**	**−1.2**	**−0.9**
PDI	−0.5	−0.3	+0.4	+0.1
FAI (mm)	−0.3	−0.2	−4.3	+6.1

The simple ratio is somewhat modified in case of MAI (de Martonne, 1926), which can be used to determine the potential regions with lack of water. The applied formula is the following:

$$\mathrm{MAI} = \frac{12 \cdot P_i}{T_i + 10}. \tag{4}$$

Agrometeorological studies often use the more sophisticated TAI (Thornthwaite, 1948), which considers an important agricultural effect, the evaporation determined from temperature. Index values can be calculated as follows:

$$\mathrm{TAI} = 1.65 \left(\frac{P_i}{T_i + 12.2} \right)^{\frac{10}{9}}. \tag{5}$$

Standardised values of temperature and precipitation define PDI (Ped, 1979):

$$\mathrm{PDI} = \frac{\Delta T}{d(T)} - \frac{\Delta P}{d(P)}, \tag{6}$$

where ΔP (ΔT) is the difference between the actual monthly precipitation amount (mean temperature) and the average monthly precipitation (temperature) for 1961–1990 in mm (°C); whereas $d(P)$ and $d(T)$ are the 1961–1990 standard deviation values of precipitation in mm and temperature in °C, respectively. The main advantage of this index is that it can be used for identifying short dry and wet periods. This index is different from the other indices because negative values imply wet conditions and positive values indicate dry climatic conditions.

FAI is a recursive index (Foley, 1957), which is able to consider the cumulative effects of moisture surplus or deficiency; thus, the meteorological "memory" is included. The applied formula is the following:

$$\mathrm{FAI}_1 = \Delta P_1 \tag{7}$$

$$\mathrm{FAI}_k = \mathrm{FAI}_{k-1} + \Delta P. \tag{8}$$

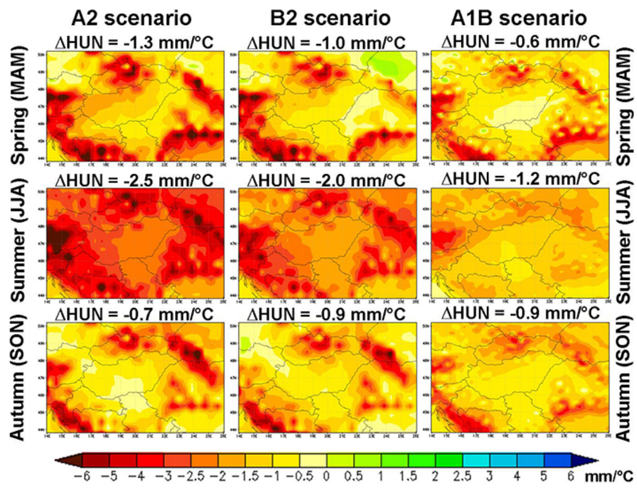

Fig. 1. Projected seasonal change of TAI for three future scenarios, 2071–2100, reference period: 1961–1990. The spatial average changes are shown above the maps taking into account all 229 grid points located within Hungary.

4 Projected seasonal trends

Monthly time series of drought indices are calculated from the simulated temperature and precipitation time series for each grid point of the Central/Eastern European domain. Then, the seasonal changes are determined for 2071–2100 relative to the reference period, 1961–1990 considering all the three emission scenarios. Spatial averages of the projected seasonal change are summarised in Table 1 for the intermediate A1B scenario for Hungary.

The largest changes are projected for summer and winter. These estimated changes are significant at 0.05 level (except PDI and FAI). Summer is projected to become drier (the trend is statistically significant at 0.05 level for the entire region, and also in most of the individual grid points), and thus, drought events are very likely to occur more frequently in the future than in the reference period. Contrary to the estimated summer trend, winter is projected to become wetter than today. In case of the other two seasons, the projected changes are slight and the signs are different if considering all the indices. When using the water balance indices (i.e., LRI, MAI, TAI) the estimated decreases are also significant at 0.05 level.

One index is selected to illustrate the spatial structures of the projected seasonal changes. The estimated changes of TAI are mapped for three seasons (drought conditions in winter are irrelevant due to possible freezing) and considering three different scenarios for 2071–2100 compared to the 1961–1990 reference period in Fig. 1. In general, the index values are projected to decrease in all seasons both for Hungary and the entire domain, which implies dryer climatic conditions in the area for the future compared to the reference period. The largest TAI changes suggest that drought

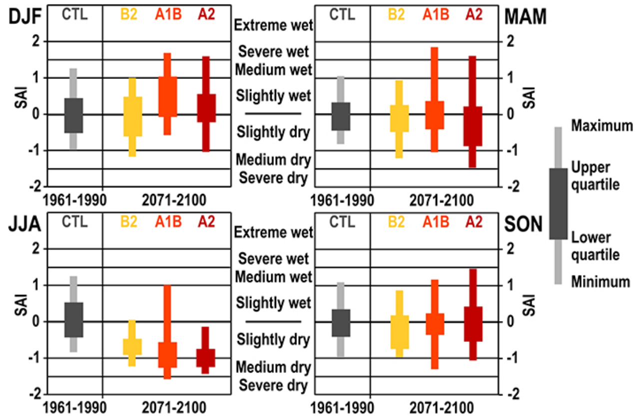

Fig. 2. Inter-annual variability of seasonal SAI time series in Hungary in the reference period (1961–1990) and the target period (2071–2100).

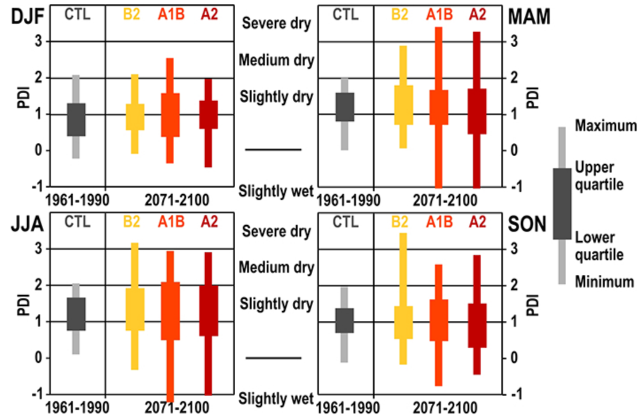

Fig. 4. Inter-annual variability of seasonal PDI time series in Hungary in the reference period (1961–1990) and the target period (2071–2100).

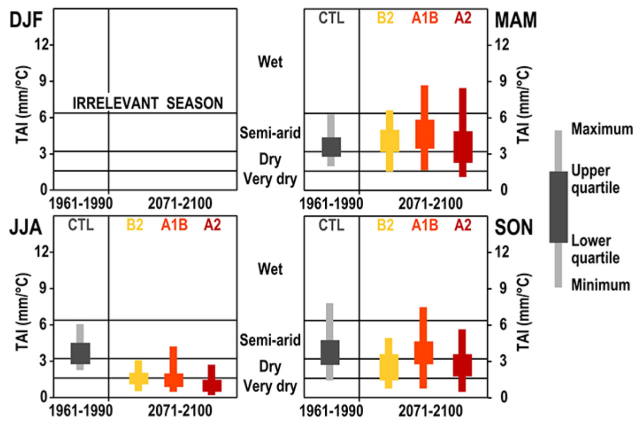

Fig. 3. Inter-annual variability of seasonal TAI time series in Hungary in the reference period (1961–1990) and the target period (2071–2100).

hazard would be the most severe in summer in case of the most pessimistic A2 scenario.

Besides the spatial structure, seasonal time series are also analysed. Box-Whisker plot diagrams in Figs. 2–4 illustrate the variability of seasonal SAI, TAI, and PDI time series of 30 yr. The graphs include seasonal spatial averages for the past 1961–1990 and the future 2071–2100 time slices. Thick boxes show the middle 50 % of the distribution by using the lower and upper quartiles. Thin columns indicate the maximum and minimum values, and thus, the entire range of seasonal index values during the 30 yr.

On the basis of SAI values (Fig. 2), individual seasons of the reference period 1961–1990 are considered to have been either slightly wet or slightly dry, and only a few seasons can be categorised as intermediate wet. The most pronounced estimated change of SAI can be identified in summer when very few years are projected to be slightly wet (if any) in the future and the majority of seasons are likely to be characterised by either slightly dry or medium dry conditions.

TAI values (Fig. 3) suggest that the reference period 1961–1990 is considered to have been mainly semi-arid in all the three seasons (winter is not shown in case of this index because of the irrelevance). Summer seasons in the last three decades of this century are projected to be mainly dry or very dry. According to the simulation results, in case of the A2 scenario, most of the summers will be very dry in the future. Furthermore, a slight shift towards drier conditions is projected in autumn, too.

Drought indication of PDI values differs from either SAI or TAI; namely, positive values (changes) imply dry conditions (trends) and negative values (changes) indicate wet conditions (trends). In general, a large increase in PDI variability is projected for 2071–2100 (which is clearly indicated by larger sizes of boxes and columns) compared to the reference period (Fig. 4). Moreover, medium dry conditions are more likely to occur in spring, summer, and autumn than in 1961–1990. In the late 21st century even severe dry conditions might occur in a few seasons.

The projected increase of drought in the region can be partially explained by the complex interactions between the elements of the hydrological cycle (i.e., precipitation, water storage in soil moisture and/or snow, evapotranspiration of the vegetation). This issue was addressed in details by Seneviratne et al. (2010). Peters et al. (2003) discussed the relationship between meteorological droughts and soil moisture deficiency highlighting several uncertainties in modeling. The hydrological cycle is also affected by the change of water use efficiency of plants in case of increased atmospheric CO_2 concentrations (Betts et al., 2007), which needs more attention in the future.

5 Conclusions

In this paper the main focus was on the analysis of precipitation-related climatic conditions using the results from the regional climate modeling experiments of PRECIS. For this purpose we used different types of drought indices. The results suggest that the climate of the Carpathian Basin is projected to become generally drier. The largest drying trend in the 21st century is very likely to occur in summer.

Based on the results, the following conclusions can be drawn.

1. The largest changes in drought indices are projected for summer and winter. Summer is projected to become significantly drier in the region. Winter is generally projected to become wetter.

2. The estimated decreases of the water balance indices (i.e., LRI, MAI, TAI) are significant at 0.05 level in all seasons. However, winter projections are irrelevant in case of these indices because drought conditions cannot be evaluated with them due to possible freezing.

3. Results of projected SAI (standardised precipitation anomaly index) in summer show considerable shift from slightly wet and slightly dry conditions towards dry conditions (slightly dry and medium dry).

4. Results of projected TAI (Thornthwaite aridity index) in summer show considerable shift from semi-arid conditions towards dry and very dry conditions.

5. Results of projected PDI (Ped's drought index) show a large increase in interannual variability. Thus, contrary to the 1961–1990 reference period, medium dry conditions are projected to occur more often in 2071–2100 in summer as well, as in spring and autumn.

6. Future summer drought hazard is projected to be the most severe in case of the A2 scenario, which assumes the highest CO_2 concentration among the emissions scenarios evaluated here.

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