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Will dry events occur more often in Hungary in the future?

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Abstract
Dry years and dry summers in Hungary have been analyzed using the regional climate model REMO for the time periods 1961–2000 and 2001–2100. Dry periods were determined and classified by intensity, considering modeled and observed precipitation and temperature data. The intensity of dry events was defined according to the negative precipitation deviation and positive temperature deviation from the climate period 1961–90. The proportion of dry years and dry summers is equivalent in the model and observations in the past. On average, the intensity of dry years simulated by the regional climate model REMO is the same as observed, whereas dry summers have more extreme conditions in the model. Based on the results of three IPCC scenario simulations (B1, A1B, A2), the probability of dry events will be higher in the second half of the 21st century. In the scenarios A1B and A2 a dry summer may happen every second year and the consecutive dry periods will last longer. For 2051–2100 the intensity of dry events increases significantly in all scenarios compared to the control period. From the analyzed scenarios B1 has the lowest future greenhouse gas emission rates, so that the smallest changes are also projected for the second half of the 21st century.

Keywords: extreme events, dry events, precipitation- and temperature deviation, regional climate modeling, climate scenarios

1. Introduction

Extreme weather events are rare and intense, and they often have severe effects on the environment. A drought is a very complex natural disaster, and many parameters are responsible for its occurrence (e.g. atmospheric circulation, precipitation, temperature, humidity, soil moisture). Contrary to other extreme meteorological events, droughts are the most slowly developing ones and often have the longest duration. The beginning, end and intensity of a drought are hard to predict (Pálfai 1994, Jankó Szép *et al* 2005). A drought is a relative event, its definition depends on the climate, soil and vegetation conditions of the region. Commonly used definitions of droughts are meteorological, agricultural, hydrological and socioeconomic (Wilhite and Glantz 1985, Bussay *et al* 1999); the precipitation deficit during a long time period is an important parameter in all of them. The intensity and effects of droughts have been investigated and estimated with diverse indices, which are based on specific meteorological and soil parameters (Palmer 1965, Pálfai 1991, McKee *et al* 1993, Jankó Szép *et al* 2005).

Under an expected increase in greenhouse gas concentrations, global as well as regional climate models (GCMs and RCMs, respectively) consistently show an increase in near surface temperatures over Europe within the 21st century (Houghton *et al* 2001, Giorgi and Bi 2005, Déqué *et al* 2005). Furthermore, an enhancement of the interannual variability of summer climate, both for temperature and precipitation, is projected by RCMs for Europe in addition to increases in mean temperature: an increase in the variability of European summer temperature (Schär *et al* 2004, Seneviratne *et al* 2006) as well as an added occurrence of severe summertime flooding events

Table 1. Analyzed data and time periods.

Time period	Model and data		Horizontal resolution	Lateral boundaries
1961–2000	Data from OMSZ–VITUKI[a]		Station data	—
	CRU data[b]		0.5°	—
	REMO[c] validation simulation		0.44°	ERA-40[d] re-analyses
1951–2000	REMO control simulation		0.44°	ECHAM5/MPI-OM[e]
2001–2100	REMO scenario simulations	B1	0.44°	ECHAM5/MPI-OM
		A1B	0.44°	ECHAM5/MPI-OM
		A2	0.44°	ECHAM5/MPI-OM

[a] Data for 87 precipitation and 31 temperature stations from the Hungarian Weather Service (OMSZ) and from the Hungarian Environmental Protection and Water Management Research Institute (VITUKI).
[b] Gridded station data (Mitchell *et al* 2004).
[c] Regional climate model (Jacob 2001, Jacob *et al* 2001).
[d] ECMWF re-analysis product (Uppala *et al* 2005).
[e] Global circulation model (Roeckner *et al* 2006, Jungclaus *et al* 2006).

and an extension of the length of dry spells (Christensen and Christensen 2003, Semmler and Jacob 2004, Pal *et al* 2004) are expected for the 21st century.

Droughts are a recurrent feature in Hungary's climate, relatively dry and warm weather events having a very high probability in this country (Szinell *et al* 1998). Similar to global and continental trends, annual mean temperatures became warmer during the second half of the 20th century, and a significant increase in drought frequency has been observed (Szinell *et al* 1998). A continuous, extraordinarily dry period with severe droughts occurred in the Carpathian Basin between 1983 and 1994 (Pálfai 1994). In particular, summers were warmer in the last 15 years (1990–2004) compared with the climate period 1961–90. The precipitation decreased in the last century, the strongest negative trend appeared in spring (Szalay *et al* 2005). The number of days with precipitation of more than 1 mm decreased, whereas the intensity of precipitation events increased in the last century (Bartholy and Pongrácz 2006).

Analyzing the results of 16 GCMs for four different IPCC (Intergovernmental Panel on Climate Change) emission scenarios (A1, A2, B1, B2), winter and spring in Hungary will be wetter, while summer and autumn will be drier in the future. In addition to the projected increase in the variability of precipitation, this may lead to an increased probability of drought hazards (Bartholy 2003).

Therefore in this study we will use the RCM REMO to discuss the following questions.

- How accurately can the RCM REMO simulate past dry events?
- What are the frequencies and intensities of dry years and dry summers in the model and in the past observations?
- Will climate change have an effect on proportion and intensity of dry events in Hungary in the future?

In section 2 the data and methods used and the main steps of the analyses are described. Results are presented in section 3: in 3.1 the projected temperature conditions at the end of the 21st century, which were the motivation for studying dry periods, are investigated; in 3.2 the proportion and in 3.3 the intensity of dry events are analyzed under past and future climate conditions. In section 4 conclusions of this analysis are drawn.

2. Data and methods

2.1. Model and data

Country-wide means of annual and monthly precipitation and 2-m temperatures were analyzed for Hungary, using modeled and observed data (table 1).

To analyze extreme events on a country scale regional modeling is essential due to the relatively coarse resolution of recent GCMs. REMO (Jacob 2001, Jacob *et al* 2001) is a hydrostatic regional climate model for the atmosphere, which has also been used within the EU-Project PRUDENCE (Jacob *et al* 2007). It is based on the 'Europamodell', the former numerical weather prediction model of the German Weather Service (Majewsky 1991). The physical parameterizations were implemented from the global climate model ECHAM4 at the Max Planck Institute for Meteorology in Hamburg (Roeckner *et al* 1996).

REMO runs continuously for long time periods with updates of the lateral boundaries every 6 h. It is possible to simulate statistical characteristics of meteorological quantities, but it cannot be expected that every single weather event is calculated realistically in time and space: individual years which are dry in observations can be different from those in the simulation.

The following three types of REMO simulations in the climate mode have been studied (table 1).

(a) Validation simulation for the past (REMO-ERA40, 1961–2000): lateral boundaries provided by ERA-40 re-analyses (Uppala *et al* 2005) have been used to drive REMO. The analyzed station data are available for the period 1961–2000, therefore these 40 years were selected from the REMO-ERA40 simulation for validating the model with observed data.

(b) Control simulation for the past (1951–2000): REMO was used with lateral boundary conditions taken from the coupled atmosphere–ocean GCM ECHAM5/MPI-OM

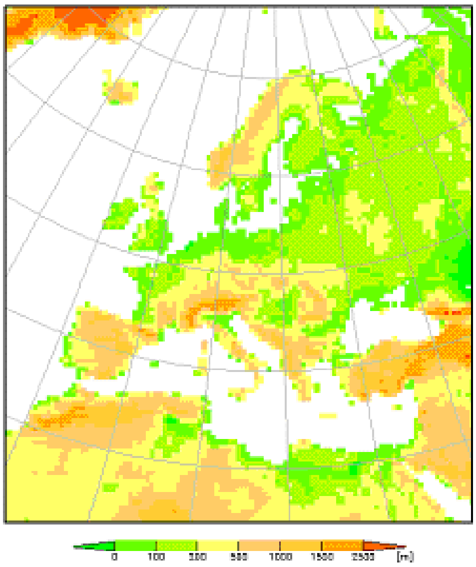

Figure 1. Simulation domain.

(Roeckner *et al* 2006, Jungclaus *et al* 2006). This is the reference simulation for the scenario simulations.

(c) Emission scenario simulations for the future (2001–2100): lateral boundaries to drive REMO are again taken from ECHAM5/MPI-OM GCM. Three scenario simulations were available for the analyses, which are based on three different IPCC-SRES emission scenarios: B1, A1B and A2 (Houghton *et al* 2001, Nakicenovic *et al* 2000).

- B1: rapid changes in economic structures, reductions in material intensity, introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability.
- A1: very rapid economic growth, global population peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system; A1B means a balance across all sources.
- A2: continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.

At the end of the 21st century projected globally averaged greenhouse gas emission rates and surface warming are highest in A2 and lowest in B1 out of these three scenarios (IPCC 2007).

For analyzing dry events in this study, the 21st century was divided into two parts: each 50 years long. A 50-year reference period (1951–2000) was determined in the 20th century, too.

The simulation domain covers Europe (figure 1). The horizontal grid resolution is 0.44°, with 109 × 121 grid boxes, the grid specification has been adopted from the RCM set-up used in the EU-project ENSEMBLES.

2.2. The main steps of the data analyses

Dry events have been defined and classified according to their intensity using both precipitation and temperatures from model results and observations.

Definitions for droughts from meteorological, hydrological and agricultural aspects already exist and are constructed via diverse parameters and indices. Commonly used drought indices are the standard precipitation index (SPI) (McKee *et al* 1993), which is based on the precipitation sum over a given time scale, and the Palmer drought severity index (PDSI) (Palmer 1965), which can be considered as an indicator of soil moisture. In assessing impacts of climate change Dubrovsky *et al* (2005a, 2005b) and Hayes *et al* (2005) applied SPI, PDSI and the Z-value as relative drought indices for studying changes in the drought event characteristics under future climate conditions.

One aim of the present study was to analyze the drying tendency for Hungary in the 21st century. The future climate conditions were described according to monthly precipitation and temperature results of the RCM REMO. Only precipitation and temperature conditions have been studied, therefore a new classification was developed to analyze dry years and dry summers and the term 'dry event' has been used instead of 'drought'.

Here, dry events have been defined relatively: if a period can be characterized with low precipitation conditions with respect to a reference period it is called dry. Precipitation deviations (ΔP) and temperature deviations (ΔT) have been calculated for the reference period 1961–90, which is the most commonly used reference period for this kind of analysis.

For individual years:

- the observed data have been compared with observations from the reference period
- the REMO results have been compared with the REMO data from the reference period.

The following categorization was developed and used: depending on the length of the period with low precipitation, dry years and dry summers have been analyzed separately. For dry summers, precipitation sums and temperature means have been calculated from May to August. Considering precipitation deviations, two main groups have been determined for dry years and dry summers:

- extreme dry year (EDY): if the negative ΔP was larger than 15%,
- moderate dry year (MDY): if the negative ΔP was 5–15%,
- extreme dry summers (EDS): if the negative ΔP was larger than 25%,
- moderate dry summers (MDS): if the negative ΔP was 15–25%.

According to ΔT further categories have been created within these groups (see tables 2 and 3). These thresholds are based on the ΔPs and ΔTs of extreme/moderate dry years and summers in Hungary for the past and characterize the Hungarian circumstances quite well.

The number of events in these categories has been determined in REMO and in the observations too. The total

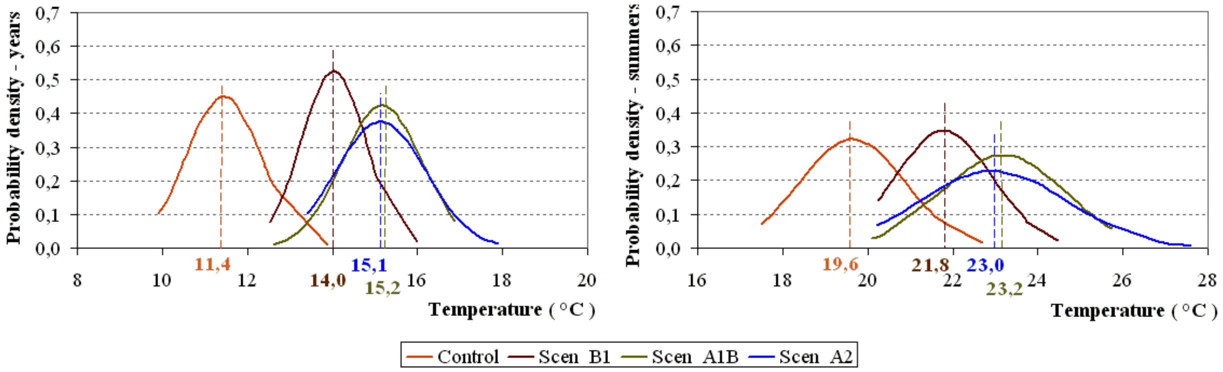

Figure 2. Gauss normal distribution of mean 2-m temperature in Hungary for the period 1961–90 (Control) and for 2071–2100 (Scen); on the left-hand side for annual mean values, on the right-hand side for summer mean values.

Table 2. Number of dry years in the period 1961–2000.

Neg. ΔP ΔT	>15% >0.5 °C	>15% 0–0.5 °C	>15% <0 °C	EDY total	5–15% >0.5 °C	5–15% 0–0.5 °C	5–15% <0 °C	MDY total	EDY + MDY total
CRU	4	2	1	7	2	5	1	8	15
OMSZ–VITUKI	5	1	2	8	3	4	3	10	18
REMO-ERA40	3	2	2	7	3	4	1	8	15

Table 3. Number of dry summers in the period 1961–2000.

Neg. ΔP ΔT	>25% >1 °C	>25% <1 °C	EDS total	15–25% >0.5 °C	15–25% <0.5 °C	MDS total	EDS + MDS total
CRU	4	3	7	4	3	7	14
OMSZ–VITUKI	4	3	7	5	3	8	15
REMO-ERA40	9	3	12	3	3	6	18

number of dry years is the sum of EDYs and MDYs, and for dry summers the sum of EDSs and MDSs. For analyzing the intensity of dry events, ΔPs and ΔTs of all dry years and dry summers have been averaged, and the results for simulated and observed dry periods have been compared. Finally, the results of the three emission scenario simulations have been studied for the 21st century, and the trends of proportion and intensity of dry events have been analyzed.

An investigation of the uncertainties of this analysis due to internal model variability would require an ensemble of simulations. Nevertheless, only one realization for the control run and each of the three emission scenario simulations was available.

3. Results

3.1. Temperature conditions at the end of the 21st century

REMO simulations for the IPCC SRES emission scenarios (B1, A1B, A2) have been analyzed according to temperature changes in a 30-year period at the end of the 21st century (2071–2100) with respect to the 30-year climate period in the 20th century (1961–90). The time period 2071–2100 was selected to be consistent with studies in other projects (like PRUDENCE), so that results can be compared.

For scenario A1B, figure 2 shows an increase in annual mean temperature of 3.8 °C and an increase in the summer mean temperature of 3.6 °C in Hungary: the Gauss curves are shifted towards higher temperatures. In the period 1961–90, a year with an annual mean of 13 °C was an extreme warm year, but in 2071–2100 the same temperature could be representative for an extreme cold year. Summers show the same tendency. For A1B and A2, the Gauss curves in summer are flatter and wider than in the control period. This means that not only the temperatures but also the variability could be significantly higher at the end of the 21st century, and the possibility of extreme warm events increases. High temperatures intensify the impact of dry conditions. Therefore these results motivated us to study whether these events occur together with a drying tendency in precipitation conditions.

3.2. Proportion of dry events

3.2.1. Validation period (1961–2000). Dry events defined in section 2.2 have been classified, and for each category the number of dry years and dry summers has been determined (tables 2 and 3).

Tables 2 and 3 show that the number of dry events simulated by the model and the observations agree rather well in most categories and in total too, but the number of extreme

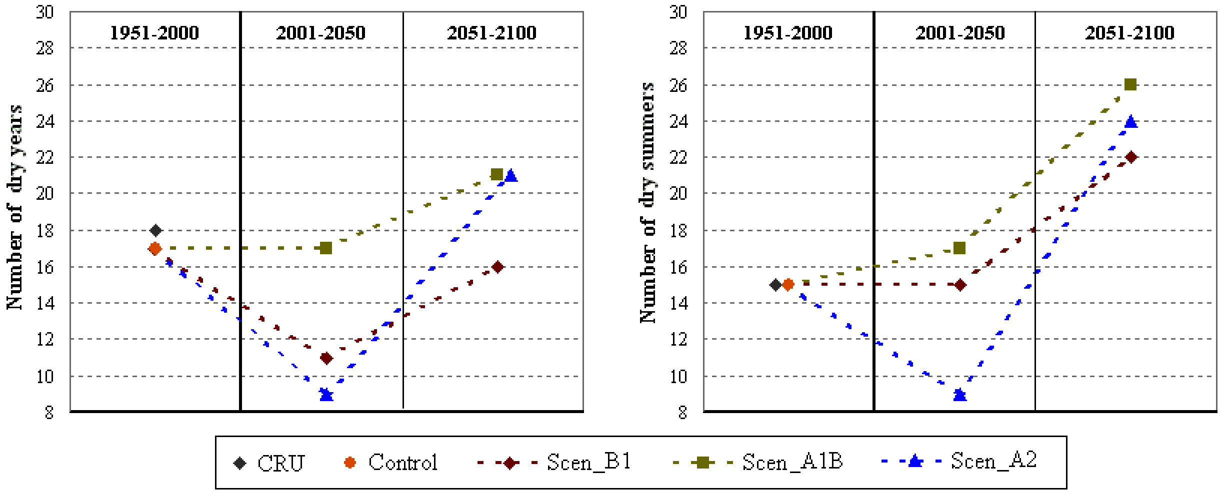

Figure 3. Total number of dry years (left) and dry summers (right).

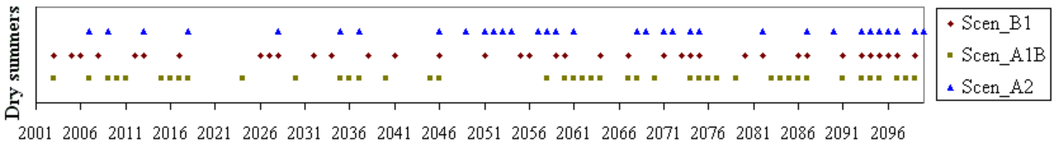

Figure 4. Dry summers for 2001–2100.

dry summers is overestimated by REMO: for 1961–2000 the modeled data and the station data are similar in the frequencies of dry years and dry summers with specified intensity. Within the analyzed 40-year period, 15 years were dry, and a dry summer occurred more than every third year. From dry years and dry summers every second was extremely dry. More than half of the extreme dry events can be characterized with high positive temperature deviations. The higher number of EDSs in REMO may relate to the summer drying problem of RCMs (Hagemann *et al* 2004).

3.2.2. Control and emission scenario simulations (1951–2100). The probability of dry events has been analyzed using the results of the three scenario simulations (B1, A1B and A2).

The total number of dry years and dry summers in the control simulation is very close to the number of events calculated with the CRU observational database (figure 3), which shows the excellent quality of the control simulation with respect to the analyzed topic. Figure 3 shows that until 2050 the probability of the occurrence of dry years does not change in A1B, and decreases in scenarios B1 and A2. The probability of dry summers will be lower only in the A2 scenario. For 2051–2100, the number of dry events increases significantly in all scenarios. For dry summers this increase is more significant than for dry years. In the A1B scenario, 26 dry summers happen, 11 more than 1951–2000. This means that in the second half of the 21st century every second summer may be a dry one.

In scenario A2 the relatively low frequency of dry summers for 2001–2050 is probably caused by the high SO_2 emission rate that induces lower radiation and therefore lower temperature. The huge increase in the number of dry events in the 21st century may be related to the strong continuous increase in the CO_2 emission and decrease in SO_2 emission during the second half of the 21st century, which causes a higher radiation rate and increased temperature.

Not only the probability of dry summers, but also the number of consecutive years with dry events increase in all scenarios after the middle of the 21st century (figure 4). Here, five or six dry summers in succession may occur compared to two or three for 2001–50. In the last 10 years of the 21st century almost all summers can be classified as dry. Dry years show the same tendency (not shown).

3.3. Intensity of dry events

3.3.1. Validation period (1961–2000). The intensity of dry events has been characterized using the relation of ΔP and ΔT.

Figure 5 shows that the simulated intensity of dry years agrees well with observations. The differences in the averaged values between the model and observed data are caused by the greater number of years with >25% ΔP in the model. For dry summers figure 5 also shows a larger standard deviation of ΔP and ΔT values and a significantly higher proportion of extreme dry and warm events in the model, which has already been discussed in section 3.2.1.

REMO simulates not only more extreme dry and warm summers, but also more extreme wet and cold ones (figure 6).

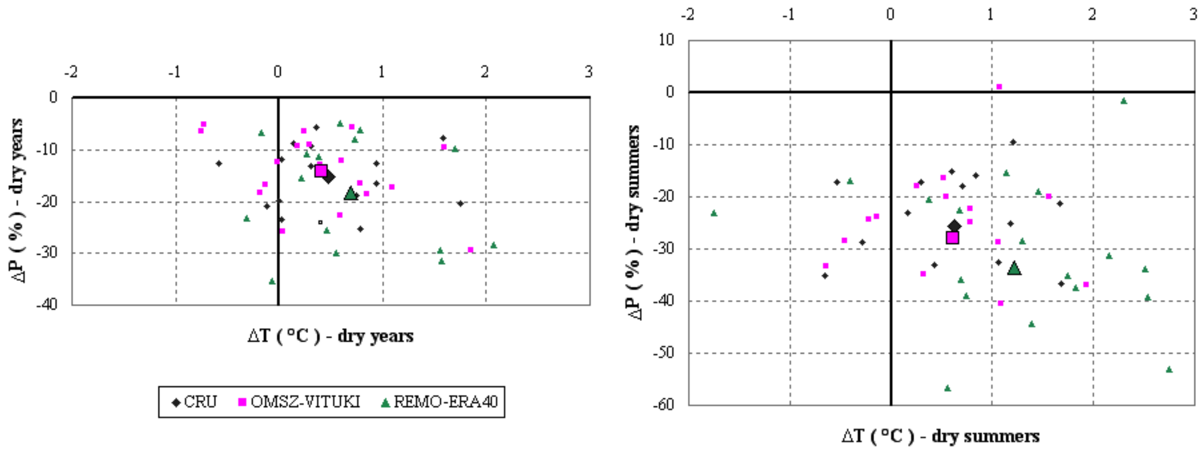

Figure 5. Intensity of all dry years (left) and dry summers (right) for 1961–2000. The small symbols represent the individual dry events, the big ones the averages of the clusters.

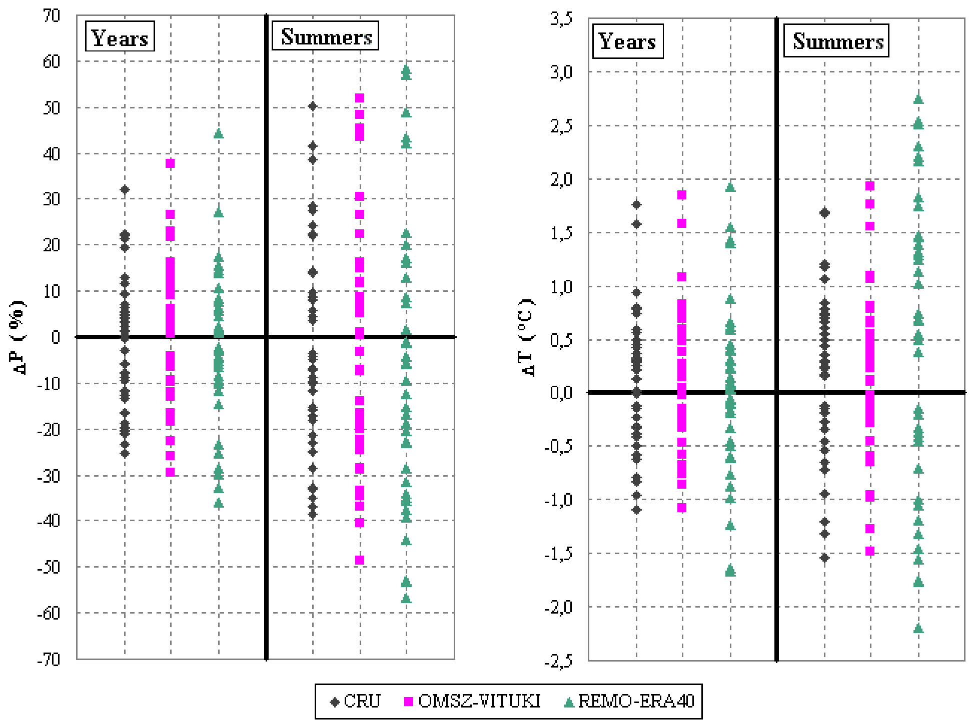

Figure 6. Precipitation and temperature deviations in all years and summers for 1961–2000.

This means that the range of the simulation results is larger than observed, especially in summer.

For summer ΔTs the difference between the highest and lowest model result is 5 °C; in the observations it is less than 3.5 °C. REMO simulates six summers with ΔT above 2 °C, whereas there are none in the observations. Also for yearly and summer ΔPs there is a larger range in the model than in the observations.

3.3.2. Control and emission scenario simulations (1951–2100). The changes in the intensity of dry events in the future have been analyzed by the relation of ΔP and ΔT (figure 7).

For dry years in the period 2001–50, all scenario ΔPs are similar to ΔPs of the control simulation. The clusters visualized by the ellipses shift mainly in the direction of higher temperatures: ΔT is increased by about 1 °C compared to the control simulation. For dry summers, the average ΔP is almost the same in the three scenarios and in the control simulation, whereas their number in A2 is significantly lower (figure 3). Similarly to the dry years, the average ΔT in dry summers increases by 1 °C in scenario A2.

For 2051–2100 the clusters, as displayed by the ellipses, are moving to dryer and warmer conditions, and the intensity of dry years and dry summers increases significantly in all

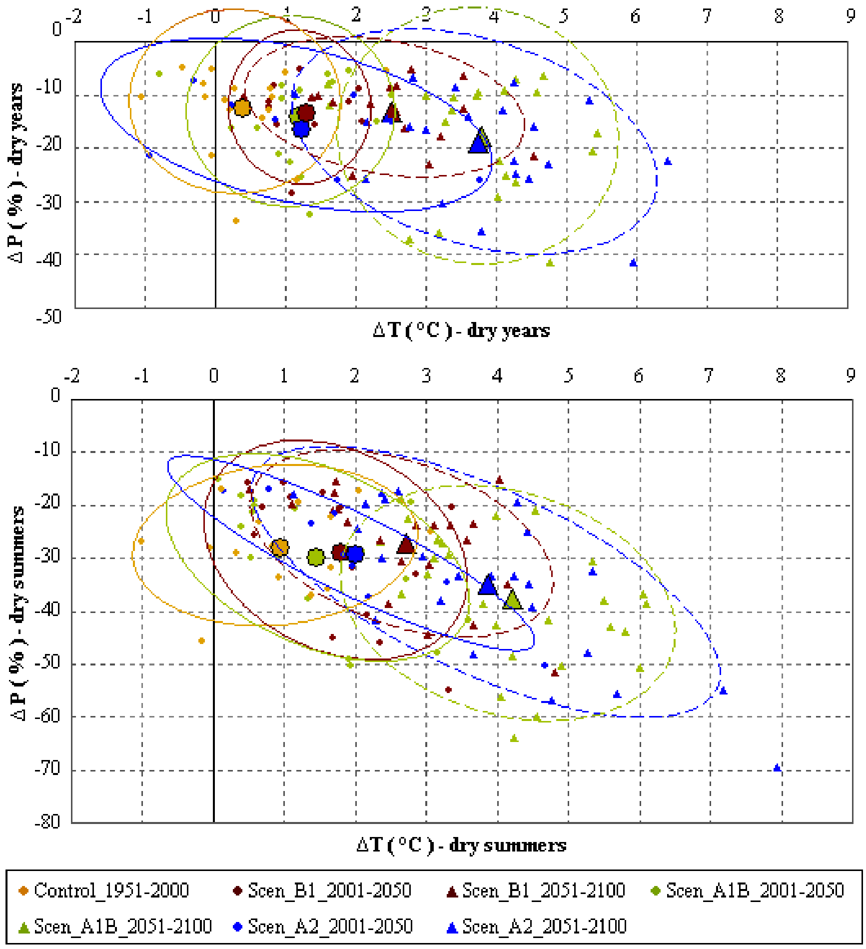

Figure 7. Intensity of all dry years (top) and dry summers (bottom). The small symbols represent the individual dry events, the big ones the averages of the clusters. The ellipses describe the place of the different clusters with a 95% confidence level.

scenarios, for dry summers more strongly than for dry years. For dry years not only the probability but also the intensity is the same in A1B and A2 in this period. The average ΔT is 3.5 °C higher than 1951–2000, the increase of negative ΔP is above 5%, compared to the average of the last 50 years in the 20th century.

In dry summers for A1B, the average ΔP in the second half of the 21st century will be almost 10% higher and the average ΔT 3.2 °C higher than in the control period. At the beginning of the 21st century, the average ΔT in A1B was the lowest from the three scenarios and became the highest at the end of the century. From A1B and A2 results it is clearly visible that summers with extreme low precipitation can be characterized in most cases with extreme high temperatures. The very dry and extreme warm summers become more frequent, as was discussed in section 3.2.2.

From the analyzed scenarios B1 shows the smallest changes compared to the control period. Precipitation deviations do not change significantly in the 21st century, and the average ΔT in dry summers is 1.8 °C compared to 3–3.5 °C in A1B and A2.

4. Conclusions

Dry events in Hungary have been analyzed using the regional climate model REMO for the validation simulation (1961–2000) and climate change experiments (1951–2100). Dry years and dry summers have been defined according to precipitation and temperature deviations from the climate period 1961–90. The frequency and intensity of simulated and observed dry events have been compared for the past. The changes of probability and intensity of dry years and dry summers have also been studied for the future, analyzing the results of three IPCC scenario simulations (B1, A1B, A2).

The major findings of the analysis are as follows.

Validation period (1961–2000):

- The statistical characteristics of dry years and dry summers can be simulated quite well with REMO in comparison with observations.
- Simulated and observed data agree in the frequency of dry years and dry summers. Only the proportion of extreme dry summers is overestimated by REMO.
- On average, the intensity of dry years simulated by REMO is the same as in the observations, whereas dry summers have more extreme conditions in the model.

- The range of precipitation and temperature deviation in REMO is larger than in the observations, especially in summer.

Control and emission scenario simulations (1951–2100):

- For all scenarios, the probability of dry years and dry summers is not higher in the first half of the 21st century; their intensity increases only through the higher temperature compared to the period 1951–2000.
- For 2051–2100, the number of dry events is significantly higher; in A1B and A2 every second summer can be a dry one. The number of consecutive dry events also becomes larger compared to the first half of the 21st century.
- In the second part of the 21st century the intensity of dry events increases significantly in all scenarios compared to the control period, in dry summers more than in dry years. The average ΔP and ΔT are very similar in A1B and A2. In the second half of the 21st century B1 shows significantly lower changes than the other two scenarios.

The significant drying tendency during the last 100 years in Hungary (Szinell *et al* 1998) seems to extend to the end of the 21st century as has also been shown in the analysis of regional climate model simulations carried out in the PRUDENCE project. In Hungary the warming and drying of summers is stronger than the global trends (Christensen 2005). The increased variability of summer temperatures in model simulations was also discussed by Schär *et al* (2004) and Seneviratne *et al* (2006).

An increase in the number and length of dry periods may have a severe impact on agriculture and forestry. In the Carpathian Basin for all zonal tree species limits of distribution (called xeric forest and tree limits) are determined by climatic aridity. Spontaneous climatic selection is driven at the xeric limits by recurrent droughts, therefore the described shifts in probability of dry periods may cause catastrophic changes in lowland regions at the xeric limit (Mátyás 2007).

Analyzing drying tendencies under future climate conditions may support the process of adaptation to the projected changes.

Acknowledgments

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