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Projected changes in the drought hazard in Hungary due to climate change

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Abstract–In the Carpathian Basin, drought is a severe natural hazard that causes extensive damage. Over the next century, drought is likely to remain one of the most serious natural hazards in the region. Motivated by this hazard, the analysis presented in this paper outlines the spatial and temporal changes of the drought hazard through the end of this century using the REMO and ALADIN regional climate model simulations.

The aim of this study was to indicate the magnitude of the drought hazard and the potentially vulnerable areas for the periods 2021–2050 and 2071–2100, assuming the A1B emission scenario. The magnitude of drought hazard was calculated by aridity (De Martonne) and drought indices (Pálfai drought index, standardised anomaly index). By highlighting critical drought hazard areas, the analysis can be applied in spatial planning to create more optimal land and water management to eliminate the increasing drought hazard and the related wind erosion hazard.

During the 21st century, the drought hazard is expected to increase in a spatially heterogeneous manner due to climate change. On the basis of temperature and precipitation data, the largest increase in the drought hazard by the end of the 21st century is simulated to occur in the Great Hungarian Plain. Moreover, the changes in the extreme indices (e.g., days with precipitation greater than 30 mm, heat waves, dry periods, wet periods) suggest that the frequency and duration of drought periods will increase. The drought hazard is projected to be lowest in the westernmost part of Hungary. This result is based on qualitative and quantitative analyses that showed the changes in precipitation, temperature, and extreme indices.

Key-words: regional climate change, ALADIN and REMO models, drought hazard, drought indices

1. *Introduction*

Drought is a severe natural phenomenon that occurs on most of the continents, and it causes extensive damage (*Kogan*, 1997). Drought is one of the most prevalent environmental hazards in parts of Europe and Russia (*Briffa et al.*, 1994, *Meshcherskaya* and *Blazhevich*, 1997). In the Carpathian Basin, drought is one of the most severe natural hazards, causing serious damage to the national economy, agriculture, and water resources. The lack of water during drought periods is harmful for all living organisms, including humans, and can result in social and economic consequences, such as drinking water shortages and reductions in agricultural yields.

Despite the seriousness of this phenomenon, drought is not a well-defined term, and the technical and colloquial uses of this term vary greatly. The absence of a precise and universally accepted definition of drought can lead to confusion concerning whether a drought exists and what the severity is. This imprecision causes considerable debate among meteorologists, farmers, and public officials. Researchers use the term "drought" to describe periods when precipitation is below average, leading to water shortages, and unmet demand for water (*Vermes et al.*, 2000). Drought is a creeping phenomenon. It is often difficult to ascertain when a drought begins, as the deficiency of moisture in a region takes time to emerge (*Changnon*, 1987), and when it ends (*Warrick et al.*, 1975). In addition to precipitation, a number of factors play a significant role in the evolution of a drought. These factors include evaporation, which is affected by temperature and wind, soil type and its ability to store water, the depth and presence of groundwater supplies, and vegetation. Accounting for these factors, three types of droughts are commonly noted: meteorological (*Palmer,* 1965, *Farago et al.,* 1989), agricultural (*Maracchi*, 2000), and hydrological (*Pálfai*, 2002a; *Hisdal* and *Tallaks*en, 2003). In addition, the terms "drought" and "aridification" are often confused. It is important that drought be distinguished from aridification. Generally, drought is described as a temporary phenomenon (*Dracup et al*., 1980), while aridification is described as the process of a region becoming increasingly dry.

Due to the discrepancies in describing these phenomena (differing definitions of event duration and numerous measurement methods – *Heim,* 2002), researchers often apply numerical methods or indices (e.g., the Palmer index, Standardised precipitation index (SPI), De Martonne index, and the Pálfai aridity index (PAI)) to define drought-affected areas (*Svoboda et al*., 2002; *Dunkel*, 2009). The application of these indices can eliminate the uncertainty of estimating the spatial and temporal extent and severity of a drought.

In the Carpathian Basin, drought is a severe natural hazard that causes extensive damage, and it is regarded as the most prominent natural hazard of the next century (*Bakonyi*, 2010). Therefore, the aim of this study was to outline the spatial and temporal changes in the drought hazard until 2100 by using experiments of the REMO and ALADIN regional climate models. These model simulations are suitable for this analysis because they use the A1B scenario (*Nakicenovic* and *Swart*, 2000), which represents intermediate estimations for the changes in greenhouse gas emissions over the next century, to model anthropogenic forcing. These model experiments have been used successfully in previous climate studies (*Szépszó* and *Horányi*, 2008; *Csima* and *Horányi*, 2008; *Pieczka et al.*, 2010; *Rannow et al*. 2010; *Mezősi et al*. 2012).

These models predicted a continuous, but not constant temperature increase in the Carpathian Basin, with the most intense increase occurring in the summer months (the rate of change is similar to that experienced between 1980 and 2010). The change in annual precipitation simulated by model experiments is not significant; however, the distribution of precipitation within a year is likely to change more significantly, the decreasing summer and increasing winter precipitation would result more homogenous distribution of the precipitation throughout the year (*Tables 1* and *2*) (*Bartholy et al.*, 2008; *Szabó et al.*, 2010; *Csorba et al.* 2012).

Table 1. Changes in the projected mean annual and seasonal temperature (°C) compared with the mean from the period of 1961–1990 based on the REMO and ALADIN model experiments (*Szabó et al.*, 2010)

Period	**Year**	**Spring**	**Summer**	**Autumn**	**Winter**
2021–2050	(+1.4)–(+1.9)	(+1.1)–(+1.6)	(+1.4)–(+2.6)	(+1.6)–(+2.0)	+1.3
2071–2100	+3.5	(+2.3)–(+3.1)	(+4.1)–(+4.9)	(+3.6)–(+3.8)	(+2.5)–(+3.9)

Table 2. Changes in the projected mean annual and seasonal precipitation (%) compared with the mean from the period of 1961-1990 based on the REMO and ALADIN model experiments (*Szabó et al.*, 2010)

Period	**Year**	**Spring**	**Summer**	**Autumn**	**Winter**
2021-2050	(–1)– 0	(–7)–(+3)	–5	(+ 3)–(+14)	(–10)–(+7)
2071–2100	(–5)–(+3)	(–2)–(+2)	(–26)–(–20)	(+10)–(+19)	(–3)–(+31)

Climate simulations show that extreme climate events may occur more frequently in the Carpathian Basin over the next century, and that more prolonged and severe hot and dry periods are projected. The number of frost days could decrease by 30 % by 2050 and by 50 % by the end of the 21st century, and the number of summer days (T_{max}>25 °C) could become double or even triple the present number (*Szépszó,* 2008). The projection for precipitation involves more uncertainty, in certain seasons even the tendency is contradictory in the REMO and ALADIN model simulations (*Szabó et al.,* 2010). Uncertainties in these long-term climate simulations arise from the nearly unpredictable social and economic changes that may occur over the next century and from the internal variability of the climate system (*Bartholy* and *Pongrácz,* 2010). However, despite the prediction limitations, this analysis can provide valuable information for future environmental and spatial planning (*Mezősi et al.*, 2012).

The aim of this study is to predict the magnitude of the drought hazard and the potentially vulnerable areas in Hungary for the periods 2021–2050 and 2071–2100, assuming the A1B emission scenario. This analysis can be used to highlight the critical drought areas. This information can be considered in spatial planning to create more optimal land and water management and to eliminate the increasing drought hazard and the related wind erosion hazard. These hazard projections can become an integral part of drought planning, preparedness, and mitigation efforts at the national, regional and local levels.

2. Methods

2.1. Determination of the landscape units

Due to the resolution of the climate data, an analysis of the 230 traditional, environmentally homogeneous micro-regions of Hungary were not possible; therefore, 18 larger landscape units were defined (*Fig. 1*). The areas of the defined units are better suited to the resolution of the climate data and the demands of spatial planning. The determination of the landscape units was based on the spatial diversity of landscape shaping factors (relief, soil, geology, vegetation, land use, and climate). The borders of the units were matched to the shapes of larger natural landscape units (e.g., micro-regions along the middle and lower sections of the Tisza River) and economic regions (e.g., central Hungary), where the border was justified by the climate dependence of the land use.

Due to their small areas, these landscape units are not substantive climatically. However, the physical parameters are relatively homogeneous in the units; therefore, any climate change affects the entire unit in the same way. An analysis on this scale can be important for the recognition of probable future climate effects and in the development of strategic spatial plans.

1 Little Hungarian Plain
2 Western part of the Carpathian Basin
3 Zala Hills
4 Marcal basin and Komárom Plain
5 Transdanubian Mountains
6 Hilly region of Inner Somogy
7 Transdanubian Hills
8 Dráva Plain and Mecsek Mountains
9 Mezőföld Plain
10 Danubian Plain
11 Danube-Tisza Interfluve
12 Gödöllő Hills
13 Western part of the North Hungarian Mountains
14 Eastern part of the North Hungarian Mountains
15 Plain of Upper Tisza
16 Plains of Nyírség and Hajdúság
17 Central part of the Great Hungarian Plain
18 Körös-Maros Interfluve

Fig. 1. The examined landscape units (after *Csorba et al*., 2012)

2.2. Calculation of the climate data

The simulated future changes of the climate parameters were analyzed using two regional climate models, REMO and ALADIN. The models utilize the A1B scenario, which represents the average changes of greenhouse gas emissions, to model anthropogenic climate forcing. The A1B scenario describes an integrated world with rapid economic growth, slowing population increases, a quick spread of new and efficient technologies, and a balanced emphasis on all energy sources (*Nakicenovic* and *Swart,* 2000). The resolution of the climate data was 0.22 ° (approximately 25 km). The climate projections were generated by the Numerical Modelling and Climate Dynamics Division of the Hungarian Meteorological Service.

Daily temperature and precipitation data for the periods 2021–2050 and 2071–2100 were used in the calculations. The temperature and precipitation data changes are in °C and mm, respectively, with respect to the reference period of 1961–1990. The following changes in the extreme climate indices were also generated from the two models: frost days in days/year; summer days (T_{max}>25 °C) in days/year; extremely heavy precipitation days ($R_{day}\geq 30$ mm), in days/year; and the simple daily intensity index (SDII), which is a measure of the precipitation amount per rainy day ($R_{day}\geq 1$ mm), in mm/day. From all of these data, average yearly and monthly data were calculated and evaluated for the two study periods. Regional average values were calculated for the landscape units based on the climate parameters at each grid point.

2.3. Assessing the change in drought hazard

One method of evaluating drought hazard is calculating drought or aridity indices. Several indices use only precipitation and temperature data, while others evaluate the soil moisture condition or water budget and may be recursive (e.g., the widely known and frequently used Palmer index). All of these indices have advantages and disadvantages; therefore, comprehensive studies generally apply a number of indices to obtain a better result by eliminating the deficiencies of a single index (e.g., the US Drought Monitor uses seven different indices).

During this research, two different methods were applied to assess the future changes in the drought hazard and associated results. A qualitative analysis was applied to define the tendencies of the changes, and a quantitative analysis was used to provide numerical values for the changes.

In the qualitative analysis, the future climate change trends were assessed, and the current probability of drought occurrence in the landscape units was analyzed using the PAI (*Pálfai*, 1984, 1990, 2002b). The present-day conditions were compared with the tendencies due to climate change. The tendencies caused by climate change and the regions with similar characteristics were identified by cluster analysis. The temperature and precipitation data and 4 extreme climate indices (average number of summer days, average number of frost days, average number of heavy precipitation days - with precipitation above 20 mm, and the SDII precipitation index, describing number of precipitation days – above 1 mm rainfall) were used in the cluster analysis. After extracting the factor coefficients for the regions, hierarchical clustering applied, where natural groupings can be detected. Cluster analysis of the factors coefficients gave an alternative linkage approaches and metrics. The assessment identified the sensitivity of the landscape units and the vulnerable areas. This method did not provide information about the magnitude of the changes, but it took more parameters into account than did the aridity and drought indices. This result means that a more complex description of the changes can be provided that considers which extreme climate indices enhance or eliminate the effect of mean temperature and precipitation changes.

To evaluate the magnitude of the changes, aridity and drought indices were calculated. For the investigation, three indices with different temporal resolutions and that were determined through different calculation methods were selected. The indices were calculated by using observed meteorological data of the reference period (1961–1990) and the projected changes of the model simulations. This method of choosing indices reduced the errors from the models and allowed differences within a year to be estimated.

2.4. Aridity index: De Martonne (IDM)

To begin, an aridity index was calculated. Aridity indices primarily characterize the climate of a region rather than the drought hazard. However, as aridity increases, the occurrence of drought can become more frequent and the severity can grow, thereby increasing the drought hazard. From among several aridity indices, the De Martonne index was selected, which is based on annual temperature and precipitation data.

De Martonne index (*IDM*):

$$IDM = P/(T+10)\ ,$$

where P is the annual precipitation and T is the annual mean temperature. The temporal resolution of the input data is low, but this index is widely used (*Doerr,* 1963; *Botzan et al.,* 1998; *Grieser,* 2006; *Paltineanu et al.,* 2007; *Baltas*, 2007; *Livada* and *Assimakopoulos,* 2007; *Lungu et al*., 2011). It was observed that the index properly demonstrates the spatial differences of drought.

The future drought hazard can be estimated by calculating drought indices. These indices were developed to describe the drought level on annual and sub-annual timescales. In this study, average values for the 30-year periods (2021–2050 and 2071–2100) was calculated, therefore, the drought levels in individual years could be notably different in the landscape units. Due to the uncertainties in the climate projections, it is not advisable to calculate the indices for shorter periods. In addition, a long-term average value showing the tendency of the change can be more applicable for spatial planning purposes.

2.5. Drought indices: $PaDI_0$ and the standardized anomaly index (SAI)

Two drought indices were calculated, the $PaDI_0$ index and the standardized anomaly index (*SAI*). The $PaDI_0$ index uses monthly temperature and precipitation data, and average monthly data were evaluated for the two study periods (*Pálfai* and *Herceg*, 2011). The $PaDI_0$ is based on the *PAI* and is used in Hungary, but its simplicity allows for wider use. Both $PaDI_0$ and *PAI* is a relative indicators that characterize the drought with one numerical value that is associated with one agricultural year.

PaDI₀ index:

$$PaDIo = \frac{\left[\sum_{i=apr}^{aug} Ti\right] \;/\; 5*100}{\sum_{i=oct}^{sept}\left(Pi * wi\right)}\ ,$$

where T_i is the mean monthly temperature from April to August, P_i is the monthly sum of precipitation from October to September, and w_i is a weighting factor (*Table 3*). The weighting factor expresses the importance of the months in the evolution of drought. The $PaDI_0$ index characterizes a drought with one numerical value for one agricultural year. The index focuses on the drought occurring in the vegetation period, as is indicated by the monthly weighting factors. The index was developed in Hungary, and it reveals the drought periods particularly well under the climatic conditions of the Carpathian Basin.

Table 3. Weighting factors w_i of monthly precipitation in $PaDI_0$ (*Pálfai* and *Herceg*, 2011)

Month	**Weight factor (w_i)**	**Month**	**Weight factor (w_i)**
October	0.1	April	0.5
November	0.4	May	0.8
December	0.4	June	1.2
January	0.5	July	1.6
February	0.5	August	0.9
March	0.5	September	0.1

To describe the role of precipitation changes in the changing drought hazard, an index was calculated using only precipitation data. The SAI was used to characterise the precipitation variability in a particular region. The main advantage of this index is the low data demand; however, in some situations, it does not indicate the drought level correctly (*Katz* and *Glantz*, 1986, *McKee et al*., 1993). Generally, the index is calculated for shorter periods (from 1 to 12 months), but it was computed for the two 30-year periods in this case. Even when calculated over longer periods, the SAI produces acceptable temporal and spatial differences in the drought hazard. For this evaluation, three-month SAI values were calculated for the most drought-prone and agriculturally important period, from June to August.

SAI:

$$SAI = \frac{P - m(P)}{d(P)} \ ,$$

where P is the precipitation amount, $m(P)$ is the average precipitation of the reference period, and $d(P)$ is the standard deviation of the precipitation in the reference period (1960–1990).

These indices provide numerical values of the changes in the drought hazard even though they analyse only a few parameters. These indices do not provide the most accurate value for the drought hazard because they use only the temperature and precipitation data (they do not even use evaporation or groundwater level data). However, all of the input data are extractable from the applied climate models. The aim of this study was not to give an accurate value of future changes in the drought hazard but to show the tendencies on the meso-scale.

3. Results

3.1. Qualitative analysis of the future drought hazard

The *PAI* (*Pálfai*, 2004) shows that the highest drought level was located in the landscape unit of the Great Hungarian Plain, and it decreased toward the north and west. The highest *PAI* values were in the central and southern part of the Great Hungarian Plain. The lowest values were in the higher elevations of the Alpokalja region and on the higher hills of the North Hungarian Mountains (*Fig. 2*).

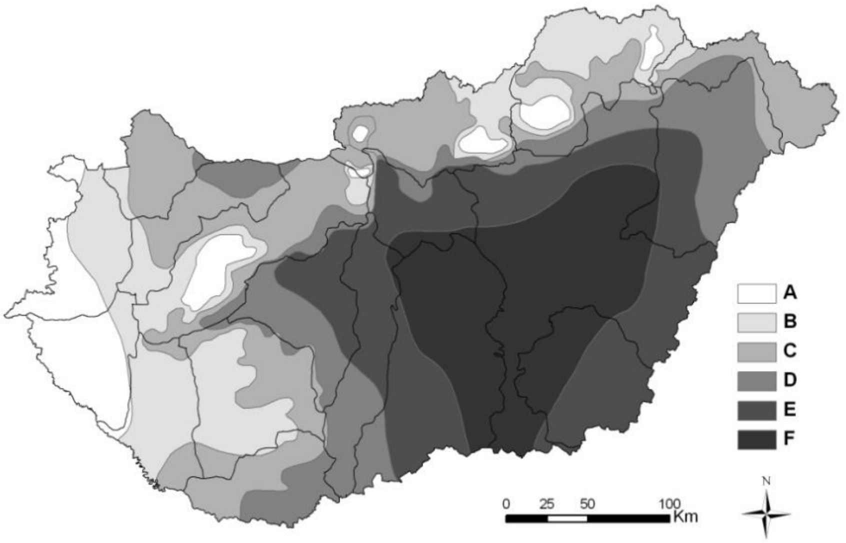

Fig. 2. Drought map of Hungary (*Pálfai*, 2004) (A: drought free; B: mild; C: moderate; D: medium; E: high; F: extremely high rate of exposure).

Despite the small area and the relatively low topographic diversity of the region, the two climate simulations showed spatial differences in the parameters. Four regions in Hungary with different climate change tendencies were defined by a cluster analysis based on the temperature, precipitation and extreme indices. In these regions, the climate change tendencies indicated diverse alterations of the social and ecological systems. The climate change in the 21st century affects the drought hazard differently in each of the four regions (*Mezősi et al.,* 2012).

The climate change tendencies in these regions have similar characteristics. The region type 1 is located along a west central corridor ranging from north to south. Moderate temperature increases and distinct changes in extreme temperature events are projected. Future precipitation is projected to increase with higher rates but moderate changes in extreme rainfall events. The region type 2 covers the northeastern regions along the Slovakian border. This region had the lowest annual mean temperatures and the highest intraregional temperature variation. Moderate future increases are simulated with moderate increases in the number of extreme event days. The region type 3 is essentially the Hungarian Great Plain, excluding the Plains of Nyírség and Hajdúság regions. This region has the highest temperatures and the lowest annual precipitation totals. The region is projected to experience the highest temperature increases, greatest changes in extreme temperature events (increases in summer days and decreases in frost days), highest precipitation decline ratios (or at least the lowest precipitation increase ratios), and an increase in the number of heavy rainfall days. The region type 4 covers only two landscape units in the western hilly area. This type is characterized by smaller temperature increases and smaller changes in temperature extremes. This region type is simulated to be more humid and have higher precipitation totals, smaller precipitation change ratios, and smaller change rates with regard to heavy rain events (*Fig. 3*).

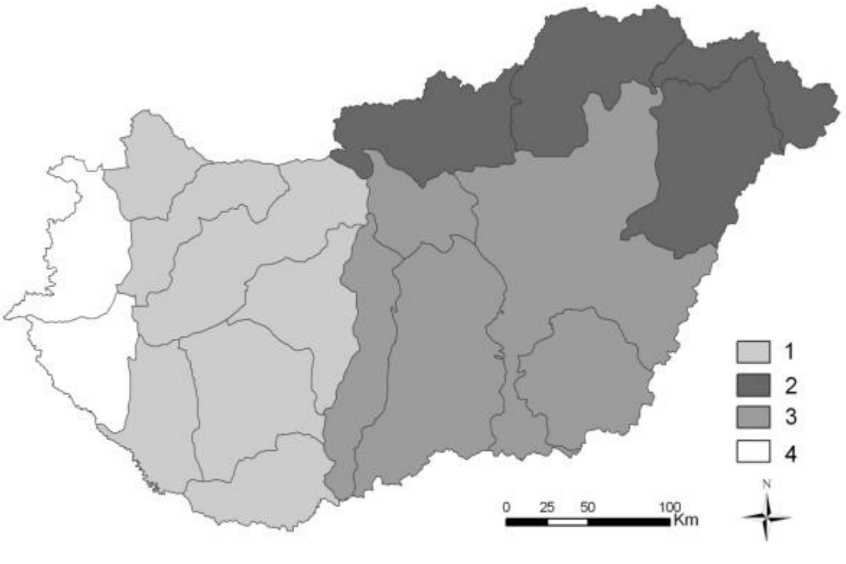

Fig. 3. Regional types of climate change exposure as a result of cluster analysis (*Mezősi et al.,* 2012).

The increase in the annual mean temperature affects the increase in the drought hazard in all regions. The largest increase in the drought hazard by the end of the 21st century is simulated in the third region type, because the increase in the annual mean temperature, increase in the number of summer days, and decrease in precipitation will all be the largest in this region type. Moreover, the increase in the number of extremely heavy precipitation days and the SDII indicated that the precipitation will fall in a more concentrated time period, which suggests that the frequency and duration of drought periods will increase. Additionally, this region already has the highest drought hazard.

In the first and second region types, the temperature increases are also projected to be significant, but the precipitation change will be slight, with a possible small increase. A moderate increase in the drought hazard is projected. The highest precipitation total and the lowest annual mean temperature currently occur in the fourth region, and future changes are projected to be moderate. The drought hazard will be the lowest in this region (*Fig. 4*).

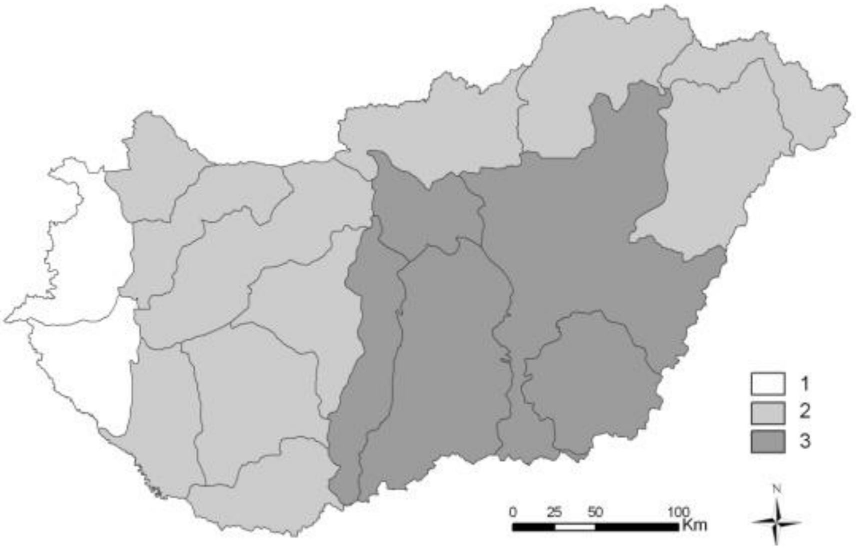

Fig. 4. Future changes in drought hazard due to climate change in the regions with similar characteristics (1. slight increase; 2. moderate increase; 3. major increase).

By using the regions defined by a cluster analysis as a basis for the analysis, the spatial differences and relations between the climate change tendencies and the changes in the drought hazard were revealed. Verification of the results is problematic, but the uncertainties can be reduced by using different calculation methods. Accordingly, the magnitude of the changes and the spatial differences were also analyzed by calculating the De Martonne index, PaDI$_0$ index, and SAI.

4. Quantitative analysis of the future drought hazard

4.1. Changes in the De Martonne index

In the reference period (1961–1990), the value of the De Martonne index varied between 23.7 mm/°C and 33.5 mm/°C in the landscape units on the basis of observed meteorological data. The lowest values, representing the highest aridity, were observed in the southeastern part of Hungary. The landscape units in that region of the country (the Danube-Tisza Interfluve and Körös-Maros Interfluve) were categorized as mediterranean (20 mm/°C ≤ IDM ≤ 24 mm/°C). The largest part of the country was categorized as semi-humid (24 mm/°C ≤ IDM ≤ 28 mm/°C), while some units along the northeastern and western borders were categorised as humid (28 mm/°C ≤ IDM ≤ 35 mm/°C).

Changes in the drought hazard can be analyzed with categories from the De Martonne index, which defines the drought hazard as low in humid regions, moderate in semi-humid regions, and high in mediterranean regions. Any future changes in the De Martonne index indicate changes in the drought hazard. For the period 2021–2050, the two model simulations showed similar changes; namely, the index values are likely to decrease to 20.7–31.4 mm/°C and 20.7–31.0 mm/°C using REMO and ALADIN outputs, respectively. In the southeastern and central regions of Hungary, four landscape units were transferred to the mediterranean category, and the Nyírség and Hajdúság units were transferred to the semi-humid category. For the period 2071–2100, the value of the index is projected to decrease in all of the units; however, the difference between the model experiments is larger in this period (19.6–28.8 mm/°C in case of REMO and 18.2–27.3 mm/°C in case of ALADIN). In the ALADIN model, the landscape unit of the Great Hungarian Plain, except for the Plains of Nyírség and Hajdúság portions, was transferred to the semi-dry (10 mm/°C ≤ IDM ≤ 20 mm/°C) category. When using outputs of REMO simulation, the spatial distribution of the changes was similar. However, this model indicated less significant changes, and only the Körös-Maros Interfluve unit was transferred to the semi-dry category. The index values also decreased in the humid-category landscape units in the two model simulations, and the units were transferred to the semi-humid category when using outputs of ALADIN simulation. Consequently, the De Martonne index indicates a future increase in the drought hazard over the entire country by 2100. The ALADIN model predicts that the changes will be more pronounced, and that all units will transfer at least one category to a more arid type by 2100. The REMO model showed less pronounced changes, and category changes were typical only in the northern part of the country and in the Hungarian Great Plain. In the Hungarian Great Plain, a new category is likely to appear, namely the semi-dry category, which indicates a very large drought hazard (*Fig. 5*).

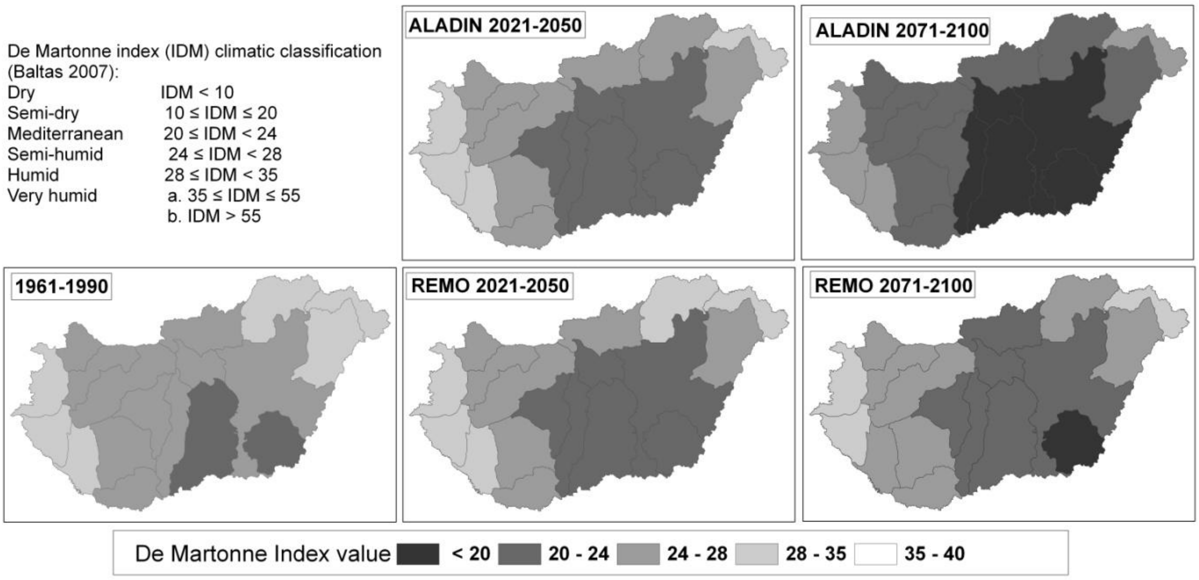

Fig. 5. Values of the De Martonne index in the periods of 1961–1990, 2021–2050, and 2071–2100.

4.2. Changes in the PaDI$_0$ index

The average value of the PaDI$_0$ index for the base period (1961–1990) varied between 3.5 and 5.3 °C/100 mm in the landscape units. These values are lower than those of the PAI (shown in *Fig. 2*). Because the calculation of the PaDI$_0$ was made for distinct years and averaged over 30 years, the extremes are hidden. Nevertheless, this result still correctly predicts the temporal changes. The maximum values of the index, which represent the highest drought hazard, were obtained in the landscape units in the central part of Hungary (the Gödöllő Hills, Danube-Tisza Interfluve, and the Danubian Plain). In contrast, the lowest values occurred in the western part of the country; therefore, the drought hazard was the lowest here.

The changes in the drought hazard can be analyzed using the changes in the drought-level categories of the PaDI$_0$ as a proxy. For the period 2021–2050, both model simulations indicated that the value of the index will increase, varying between 3.9 and 6.0 °C/100 mm (in case of REMO) and between 3.9 and 6.5 °C/100 mm (in case of ALADIN). The highest degree of change was indicated in the southeastern part of Hungary. Using REMO outputs, the maximum values are simulated in the Danube-Tisza Interfluve and Körös-Maros Interfluve units. Using ALADIN outputs, the maximum values are projected in the Körös-Maros Interfluve unit and in the central part of the Great Hungarian Plain unit (*Fig. 6*).

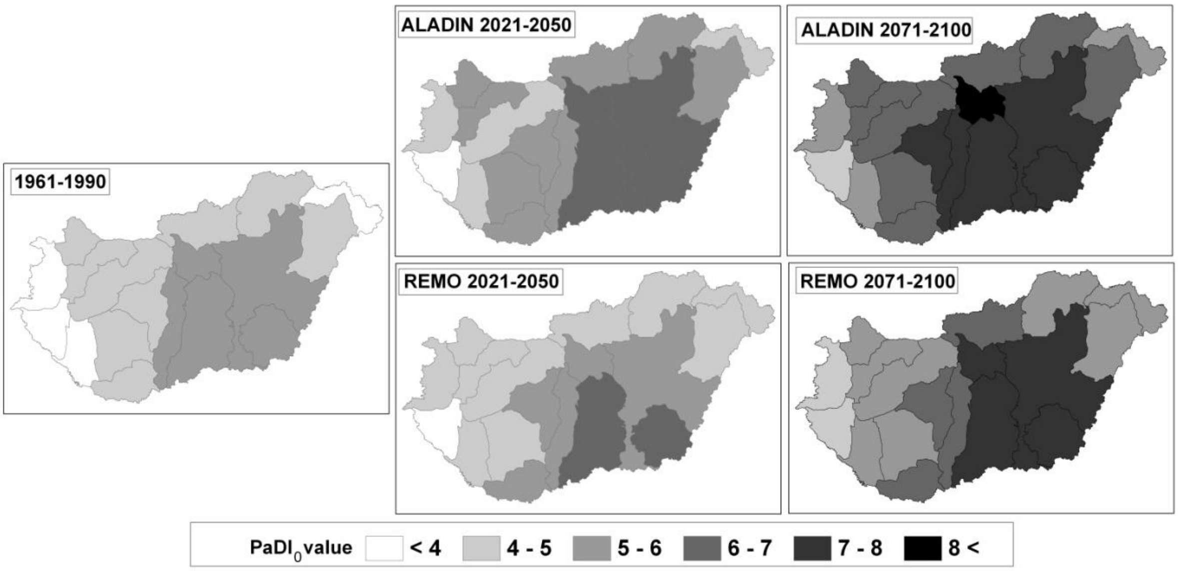

Fig. 6. Values of the PaDI$_0$ index in the periods of 1961-1990, 2021-2050, and 2071-2100.

For the period 2071–2100, the drought hazard is projected to increase, but significant differences were recognized between the model simulations (4.7–7.5 °C/100 mm and 4.8–8.4 °C/100 mm using REMO and ALADIN outputs, respectively). According to the REMO model, the maximum values are simulated in the Körös-Maros Interfluve unit and the central part of the Great Hungarian Plain unit. The predicted value of the index based on the ALADIN model is expected to exceed the highest values of the REMO model in the Gödöllő Hills unit.

4.3. Changes in the SAI

Changes in the precipitation were analyzed using the SAI for the three summer months (June to August), when the drought hazard is the highest.

According to the three-month SAI, the drought hazard is not projected to change significantly (the value varied between –1 and 1) until the 2021–2050 period, although there is notable uncertainty in these results considering the differences between the two model simulations. The model simulations indicate different rates of change, and in the northern and western parts of Hungary, the trend of the changes was different. A considerable increase in the drought hazard is simulated only in the southeastern part of Hungary, where both model simulations indicate the same tendency (*Fig. 7*).

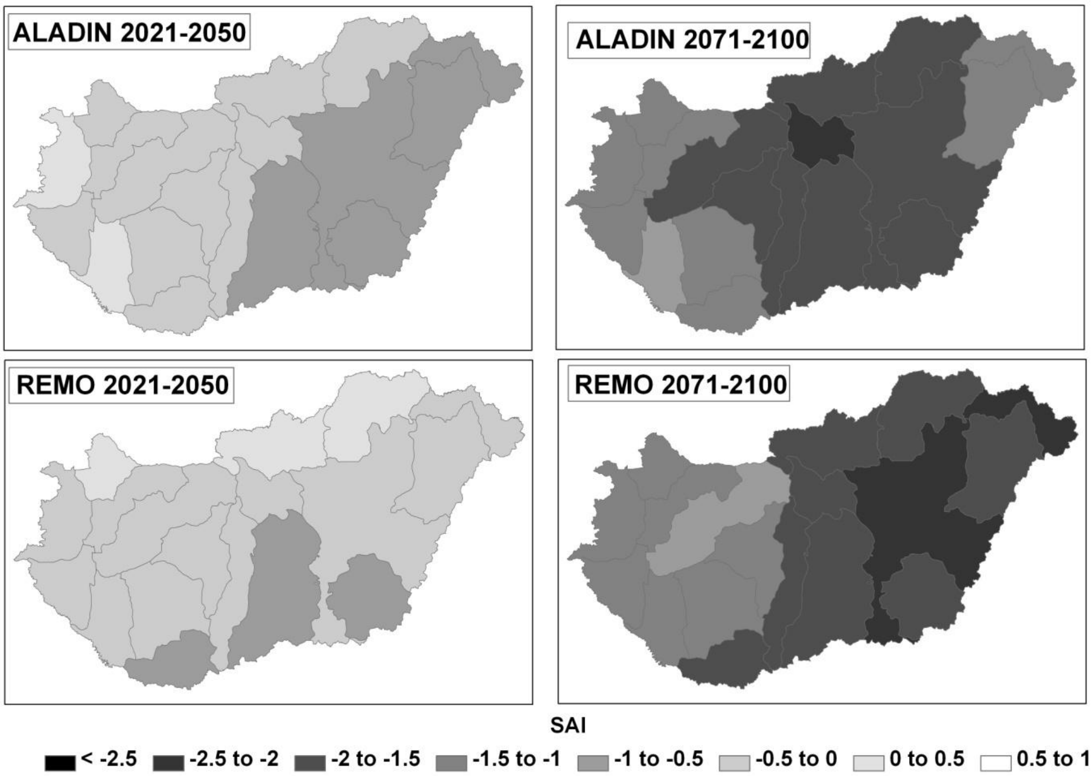

Fig. 7. Values of the SAI in the periods of 2021-2050 and 2071-2100

Both model simulations have clearly indicated an increase in the drought hazard in the summer months for the entire country by the end of the 21st century. Even despite the uncertainty of the precipitation projection, the value of the SAI varied between –0.5 and –2.5 in the period 2071–2100. The highest rate of precipitation decrease, with respect to the base period (1961–1990), is simulated in the northern part of the Great Hungarian Plain and the North Hungarian Mountains. However, due to the more favorable initial conditions in the North Hungarian Mountains, the drought hazard will be less serious even with large changes. The most critical drought hazard projected in all of the landscape units is in the north central part of the Great Hungarian Plain. The value of the SAI is below –2 in this unit, which indicates extreme dryness.

5. Conclusion

During the 21st century, the drought hazard in Hungary is likely to increase in a spatially heterogeneous manner due to climate change. The future changes in the drought hazard were assessed using two approaches, namely a qualitative and quantitative analysis. The two approaches provided similar results for the changes in the drought hazard. These assessments showed that the drought hazard is expected to increase throughout the country but with spatially different magnitudes. The maximum increase in the drought hazard is projected in the five landscape units of the Hungarian Great Plain. According to the qualitative analysis, the future tendency of the changes in the precipitation, temperature, and extreme indices is the most severe in terms of drought level in these units. The quantitative analysis confirmed these results. The most intensive changes in the calculated indices are likely to occur in the same landscape units. For these five units, the initial value and the amount of increase in the $PaDI_0$ were the highest, and the SAI value were the lowest in the country. The maximum change in the De Martonne index is likely to occur in these units, but, due to the initial conditions, the highest drought hazard is simulated in these units by the end of the 21st century.

By 2021–2050 period, the increase in the drought hazard is projected to be not significant. However, the results from the ALADIN simulations showed that the drought hazard is likely to increase in the landscape units of the Hungarian Great Plain, while the results from the REMO simulations indicated a significant increase only in the two southernmost units of the Hungarian Great Plain. These two landscape units currently have the highest drought hazard, causing climate change to generate severe drought problems in these units first. By 2071–2100 period, both model experiments indicated a significant drought hazard increase in all units of the Hungarian Great Plain. The results showed that the Körös-Maros Interfluve unit is projected to have the worst drought hazard. The De Martonne index was found to be highest on the basis of both model simulations for this unit, and the results from the REMO simulations showed that the $PaDI_0$ index was the highest. The *SAI*, based only on precipitation data, indicated that the most severe drought hazard is simulated in the Gödöllő Hills and the central part of the Great Hungarian Plain, but this index does not consider temperature changes. In the Gödöllő Hills, the results from the ALADIN simulations showed that the $PaDI_0$ index indicated the most intense drought hazard. This indicated that, despite the smaller temperature increases, the intense precipitation changes in the summer months are likely to cause severe water supply problems in this area.

According to the qualitative and quantitative analyses, the westernmost part of Hungary is likely to have the lowest drought hazard due to favorable changes in the precipitation, temperature, and extreme indices in this region.

This analysis, based on climate simulation data, suggests that the drought hazard will increase in the entire country, and that the most intense changes are simulated in the Hungarian Great Plain, which is currently the most drought-affected area. The Körös-Maros Interfluve and the Gödöllő Hills are particularly vulnerable. In these areas, more serious drought problems are projected to occur by the end of the 21st century than at present. The modification of drought hazards can be a slow process, but future strategies and landscape planning should include the development of mitigation strategies and preparations for environmental damage.

The drought hazard projections have several uncertainties. The most important uncertainties are the lack of verification and an accurate definition of the error. Further uncertainty is associated with the A1B scenario, as the projected data are only valid for a definite socio-economic development path. Despite these limitations, the present data set and analysis of the smaller units can provide valuable data for several sectors of society, including the economy, as the analysis can highlight the critical drought areas. This information can promote the development of optimal spatial planning strategies to create more optimal land and water management, which can mitigate the consequences of drought at national, regional and local levels. Preparing for prospective droughts by developing optimal land use and water management plans is a key objective of spatial planning to mitigate the damage caused by droughts

Additionally, these calculations consider only climate parameters, while other environmental parameters (e.g., the water-holding capacity of soils, groundwater depth and wind conditions) should be taken into consideration to obtain a more detailed and accurate definition of the drought hazard. The positive or negative characteristics of these parameters can locally modify the drought hazard.

The positive or negative characteristics of these parameters can locally modify the drought hazard. Therefore, further analysis is required to reveal how the drought hazard influences the complex interrelationship between the soil water, salinity of the soil and soil water, groundwater depth, land use, land cover, or local relief situation.

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