ORIGINAL PAPER

Seasonal temperature and precipitation record breakings in Hungary in a warming world

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Abstract

Climate change is leading to new daily record-breaking values globally. Since there is a clear shift towards the higher temperature values, the ratio of the numbers of new record high temperatures to record lows indicates the acceleration of global warming differently at regional levels—but is there an amplification for precipitation records as well? The main purpose of this regional analysis is to determine how many record highs/lows are broken on a seasonal level, and how large the area affected is, which enables us to assess the potentially large impacts at a local scale. The analysis is based on the statistical characteristics that the number of record breakings decreases exponentially with time for a stationary climate (when natural variability prevails). The assessment focuses on Hungary and considers the past from 1971 and the future from 2021. Results suggest that (1) currently the ratio of the numbers of new record high to record low temperatures is higher in Hungary than globally, particularly for summer and autumn (around 3.5); (2) substantially more new warm records and almost no cold records are expected by the late century (with a ratio of 140–160) following a high emission scenario, particularly in summer, when the impacts of these record breakings are the largest; (3) new precipitation records in the region are much less affected by the anthropogenic activity.

Keywords Climate change · Extremes · RCP scenarios · HUCLIM · RCM simulations

Mathematics Subject Classification 86A08

1 Introduction

Global warming is undoubtedly detected now (IPCC 2021) and it is one of the biggest threats to civilization as it affects most regions and sectors, at least to a certain degree.

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The World Meteorological Organization (WMO 2021) stated that 2021 was the seventh consecutive year with at least 1 °C warmer global climatic conditions compared to the pre-industrial period before 1900. This unprecedented fast warming also brings more and more new climatic records occurring around the world since climate change alters the probability of occurrences by changing the distribution of various meteorological variables, which can happen (i) due to the change in mean values, (ii) due to the increase in variance, or (iii) through increases in both the mean and the variance. In the case of temperature, the first possibility results in fewer cold extremes together with more new hot extremes, and the second possibility brings more new records on both sides of the distribution, while the combination of them can cause the most severe consequences as it may result in much more record-breaking hot extremes (Folland et al. 2001). Consequently, new temperature records serve as good indicators of the pace of climate change. One of the main aims of the current study is to evaluate this pace of change for Hungary for both the past few decades and the remaining part of the twenty-first century.

Following the law of Clausius–Clapeyron, higher temperature values result in potentially higher absolute humidity in the troposphere, which implies more water vapour to be held in the near-surface layers of the atmosphere. Thus, warmer conditions accelerate the hydrological cycle (e.g., Pratap and Markonis 2022). Observations suggest this theory in some regions that the high and very high precipitation values were observed more and more frequently as global warming progresses (e.g., Fischer and Knutti 2016), but the highest extremes have somewhat lower amplification (Dyrrdal et al. 2021). Our question is whether or not the record-high precipitation values will overcome the expected frequency of stationary climate in Hungary in the future, and if yes then by how much.

Boer (2009) showed several years ago already that on the one hand, internal variability of annual temperature decreases with global warming for most extratropical regions, but the Mediterranean region is an exception (note that Hungary, the target area of this study, is located in the vicinity of this special region). On the other hand, the opposite can be assumed for precipitation: higher annual variability is expected in a warming world. Furthermore, Portmann et al. (2009) showed that regional changes in precipitation and temperature lead to changes in extreme precipitation only in some regions. Szabó and Szépszó (2016) showed that the internal variability of seasonal precipitation would increase in the Carpathian basin. We are aware that RCM model results of precipitation at the high tail have higher uncertainty than temperature (e.g., Fantini et al. 2018), but the current study aims to justify this above-mentioned general hypothesis by (i) the precipitation observations since the 1970s within the area of Hungary, and by (ii) climate model simulations for various future projections on a seasonal scale.

A further motivational factor for us was the fact that local impacts are usually more sensitive to the tails of the distribution, i.e., the changes in minima and maxima are of more interest instead of the changes in the mean (e.g., Easterling et al. 2000). Thus, the present regional analysis of the minimum and maximum temperature record-breakings for Hungary may serve as important information for the local impact community as well, since it has not been addressed over Hungary at all. The distributions of daily temperature and precipitation are different substantially due to the absolute scale of

daily precipitation amounts resulting in a very asymmetric distribution curve. That is why we aim to analyse the right tail of precipitation distribution only in order to assess changes in daily maximum records in addition to both the left and right tails of temperature distribution curves.

2 Data and methods

For the analysis, we used daily maximum and minimum temperature and precipitation data from several sources in order to detect trends in observations and evaluate the effects of possible future anthropogenic activities. The Hungarian Meteorological Service compiled the HUCLIM database (https://odp.met.hu/) for Hungary with $0.1°$ resolution on the basis of quality-controlled station measurements. The gridded, homogenised temperature and precipitation data used in the current study cover the period of 1971–2020. For the future, we evaluated the results of regional climate model (RCM) simulations (with a horizontal resolution of $0.11°$) driven by different global climate models (GCMs). Since the driving GCM fundamentally determines RCM simulation outputs, we selected GCM/RCM pairs with a more diverse GCM option rather than with RCM diversity. More details are shown in Table 1. The simulated daily temperature and precipitation data (available from the EURO-CORDEX database, as described by Kotlarski et al. 2014) cover the period of 1971–2005 from the historical RCM runs, and the period of 2006–2100 from the scenario runs using the RCP4.5 and RCP8.5 scenarios. The RCP8.5 scenario is a non-mitigation, business-as-usual scenario, while the RCP4.5 assumes greenhouse gas emission reduction from around 2040 (more details are described by van Vuuren et al. 2011). This small ensemble of RCM simulations and the two different scenarios allow us to capture both the model and scenario uncertainty inherently part of the climate model simulation results regarding temperature and precipitation (Szabó and Szépszó 2016).

The probability for new record-breakings under theoretically constant, stationary climate conditions becomes very low with the growing length of the data series, asymptotically converges to $1/n$ (Glick 1978), thus, in a stationary climate the occurrence of record-breakings decreases in time with $1/i$, where $i = 2, \ldots, n$, (n is the sample size, here $n = 50$ in observations and $n = 130$ in simulated time-series). The current study uses 1971 as the base year, so the probability to set a new record high or low value in

Table 1 Simulations used in the study

GCM↓/RCM →	RCA4*	RACMO22E**
EC-EARTH	✓	✓
CNRM-CM5	✓	✓
IPSL-CM5A-MR	✓	
NorESM1-M	✓	

*Samuelsson et al. (2015)
**van Meijgaard et al. (2012), v1 with EC-EARTH, v2 with CNRM-CM5

1972 is 0.5, in 1973 it is 0.33, etc. In order to get the theoretically expected number of record-breaking events in a time series of n years is $1 + 1/2 + \ldots + 1/n$. The total is just around 4 occurrences altogether in 50 years. Glick (1978) showed from real samples in stationary climate conditions for the early twentieth century that one can only expect around 5 record-breakings within 100 years, and 7.5 in 1000 years. This is definitely not the case under climate change conditions, regardless of the cause of climate change.

Since record-breakings can occur in various value ranges depending on the elevation and the day of the year, in the current analysis, we checked the daily values in each grid point on each calendar day whether they surpassed the previously set maximum or minimum value derived from all data of previous years. For warm and precipitation record-breakings we determined the maximum values and checked whether these values are higher than in previous years, while for cold record-breakings minimum values were identified and checked whether they are lower than in previous years. Since the starting year in this analysis for observations is 1971, we selected this year as the start for the model simulation results as well. Climate fluctuations or internal variability is the natural part of the climate system, so we allowed the time series to be long enough to reach its climatological normals on the distribution tails as well (using the per se 30-year length for climate), and consequently we only show the results on the graphs from 2001.

Let the actual maximum temperature record be called *RTmax(d,g)* on day *d* within a season and in gridpoint *g*. At the beginning of the analysis i.e. in 1971, this is equal to the actual maximum temperature *Tmax* on day *d* within a season and in gridpoint *g*:

$$RTmax(d, g) = Tmax(1971, d, g) \qquad (1)$$

New maximum temperature records (*NRmax(y,d,g)*) are indicated in year *y*, on day *d* within a season and in gridpoint *g*, as follows:

$$NRmax(y, d, g) = \begin{cases} 1, \ if \ Tmax(y, d, g) > RTmax(d, g) \\ 0, \ otherwise \end{cases} \qquad (2)$$

where *y* goes from 1972 to *Yend*, which is 2020 for observations and 2100 for simulated data; *d* goes from 1 to *Sday*, which is 90 for DJF (winter), 91 for SON (autumn), 92 for MAM (spring) and JJA (summer); and *g* goes from 1 to *Ngrid*, which is 1104 for observations and 700 for simulations.

When in year *y1 NRmax(y1,d,g) = 1* in Eq. (2), then the new record (*RTmax(d,g)*) will be set to the actual value (*Tmax(y1,d,g)*):

$$RTmax(d, g) = Tmax(y1, d, g) \qquad (3)$$

and in the following years this new record will be used in Eq. (2) until again a new record is identified in gridpoint *g*, on day *d*.

Similarly, new minimum temperature records are indicated in year y, on day d within a season and in gridpoint g, using daily minimum temperature $Tmin$ as follows:

$$NRmin(y, d, g) = \begin{cases} 1, \ if \ Tmin(y, d, g) < RTmin(d, g) \\ 0, \ otherwise \end{cases} \qquad (4)$$

Also, new high precipitation records are indicated in year y, on day d within a season and in gridpoint g, using daily precipitation Pre as follows:

$$NRpre(y, d, g) = \begin{cases} 1, \ if \ Pre(y, d, g) > RPre(d, g) \\ 0, \qquad\qquad otherwise \end{cases} \qquad (5)$$

The number of record-breakings is summed for each year and each season to get the seasonal total number of records for gridpoint g in the case of $Tmax$, $Tmin$ and Pre, and for the entire country:

$$Sum(y, g) = \begin{cases} \sum_{d=1}^{Sday} NRmax(y, d, g) \ if \ Tmax \\ \sum_{d=1}^{Sday} NRmin(y, d, g) \ if \ Tmin \\ \sum_{d=1}^{Sday} NRpre(y, d, g) \ \ if \ Pre \end{cases} \qquad (6)$$

$$SumHU(y) = \frac{\sum_{g=1}^{Ngrid} Sum(y, g)}{Ngrid} \qquad (7)$$

From the spatial aspect, we also analysed how large area is affected by a new record occurring on one day at least in a specific year.

$$SpatialHU(y) = \frac{\sum_{g=1}^{Ngrid} \min(Sum(y, g); 1)}{Ngrid} \qquad (8)$$

Similar methodology is used by Meehl et al. (2009), who analysed Tmax and Tmin records for the United States using only GCM outputs and previous emission scenario families. Later on, Meehl et al. (2016) complemented their analysis with spatial variability aspects and addressed precipitation records as well. The use of GCM simulations may be appropriate for such an extended target area that these studies focused on. However, in the current study, the use of RCM simulations is necessary to provide more details on a regional scale, and thus, to allow more precise analysis focusing on a much smaller Central European country. The use of newer scenarios and several RCMs instead of coarser GCMs gives the novelty of this study.

Although both GCM and RCM simulations inherently have systematic biases to a certain degree emerging from different sources, there is no need for specific bias adjustment for the future in the current analysis. In general, if a model simulation is too warm against the observations, one needs to eliminate this bias on the basis

of the past with a bias correction method, and this same method is applied to the future period as well (since there is no information on how systematic errors will change in the future, an example is found in Pongrácz et al. 2014). In the present case, we are only interested in the signal of the model simulations, by comparing a given simulated year to its own preceding year, regardless of whether it is biased or not. Note that the dynamical biases of GCMs may possibly affect our study on regional high temperature records since some GCMs fail to represent properly the jets and the changes in the atmospheric circulation (e.g., Rousi et al. 2022) stemming from the Arctic amplification (Coumou et al. 2018). On the other hand, the results for both observations and future projections, are tested for statistical significance at 0.1 level using the Welch's t-test (Welch 1947), which is indicated in the corresponding figures. In this process, we compare whether or not the 20-year seasonal record-breakings are significantly different from the stationary climate values.

3 Results and discussion

3.1 Observed temperature record-breakings

Temperature record-breakings can happen in any season, on any day of the year, however, seasonal warming are different from one another (Izsák and Szentimrey 2020), that is why we show the results for each season separately and only from 2001 in the graphs. Just a few years appeared to be extreme regarding maximum records in all seasons, and there is no correlation between consecutive seasons regarding new extremes. The highest number of new high records occurred (Fig. 1) in JJA in the last 20 years—with the most breakings in 2012, meanwhile, this season shows the highest inter-annual variability as well. In general, a larger number of records occurred in SON with lower variability, while DJF shows the least number of new records (except 2006/07 winter, which was the warmest winter throughout Europe as discussed by Luterbacher et al. 2007). As for the warm records-affected area within the country (Fig. 2), we have observed a decrease in DJF and an increase in SON, fortunately when impacts are less harmful on the human health.

Coincidently with global warming, new minimum records clearly occurred less frequently than the new maximums in the past 20 years in Hungary (Fig. 3), especially in JJA, followed by SON as the second. DJF generally has the highest uncertainty in temperatures, as it is affected either by the Siberian anticyclone bringing very low temperature values or the Icelandic cyclone bringing oceanic air to the Central European area, where Hungary is located. On the other hand, in DJF significantly lower number of new cold records were observed and less area was affected in the last decade (Fig. 4). MAM shows higher variability as well for record low occurrences, resulting in lower predictability of spring grain yields. This is also supported by Fig. 4, where the affected area has increased only in this season.

As for the spatial distribution of the new high records in the period of the last two decades (Fig. 5), some spatial variability can be recognised. In MAM, more warm records occurred mostly over the western part of the country, these are statistically significant and around 1–1.5 days per year more compared to the stationary climate. In
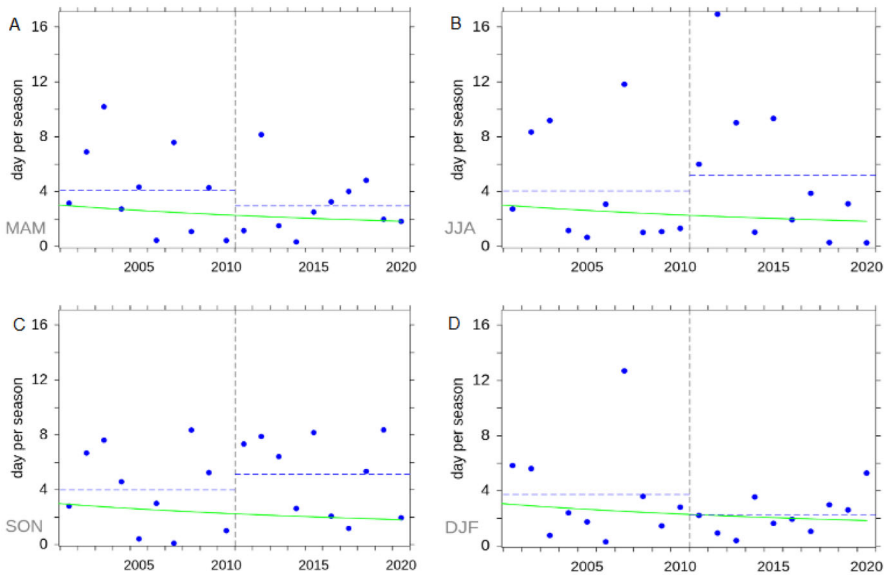
Fig. 1 The number of days when new maximum temperature record was observed in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) between 2001 and 2020 [day/season]. Values are averaged over Hungary, blue dashed lines indicate the decadal means, green line represents the stationary climate. Decadal means and the dominant parts of the individual years are over the stationary climate, however, more than half of the individual years are below the stationary climate in winter (colour figure online)

JJA, the greatest number of new warm records can be detected in the southwestern part of Hungary, with values slightly above + 3 days per year (and this is also significant). In SON, statistically, significantly more new warm records occurred in the whole country compared to the stationary climate, peaking over some regions at + 3 days per year. In DJF, high temperature records did not happen more often than the stationary climate, particularly in the northwestern part of Hungary. Only some regions around the southern and eastern borders experienced slightly more records. In this study we did not aim to provide possible explanations on the spatial differences within the country since it would require a further thorough analysis of additional data sets. They are probably related to synoptical scale factors.

As far as the observed new cold records relative to the stationary climate, maps (Fig. 6) show more white areas (i.e. smaller difference against stationary climate), and mainly JJA and SON indicate fewer records-breakings than the frequency with no climatic trend. This is somewhat different from the work of Rowe and Derry (2012), who found that minimum records are decreasing more than maximum records are increasing for the United States (even if their results were analysed for 1961–2010 and on an annual basis). The spatial patterns in DJF show that new cold records occurred with around similar or slightly above the constant climate values in the middle of the country (where flatlands are suitable for agriculture and low extremes as well), while in MAM, this can be identified only over a small area of northeastern Hungary (historically well-known cold spots).
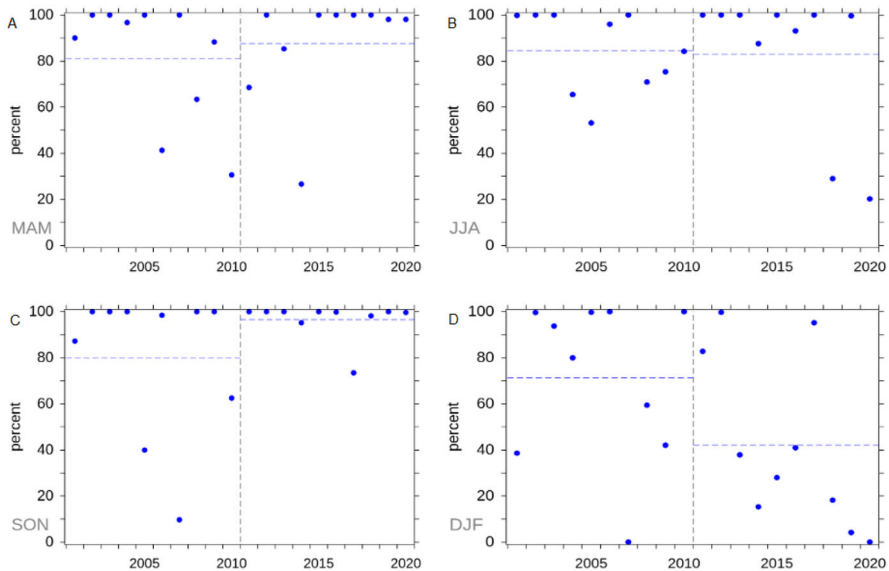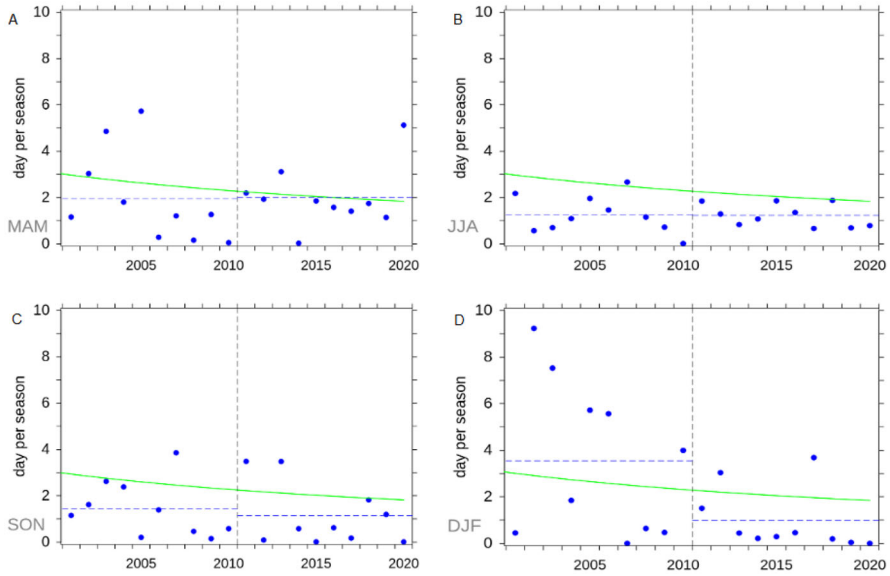
Fig. 2 The percent of area affected in Hungary by new maximum temperature records on any day in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) observed between 2001 and 2020 relative to the total number of grid cells [percent]. Blue dashed lines indicate the decadal means. Quite large percent of the total area is affected in most years, except in winter when even the decadal average decreased substantially (colour figure online)

It is a good indicator to show how the seasonal distribution changes for temperature in a warming world by capturing the ratio of the numbers of new record highs to record lows. The values averaged between 2001 and 2020 were 3.7 and 3.5 for JJA and SON, respectively (higher than the global means), and smaller by half for MAM and DJF, with values of 1.7 and 1.3, respectively. Similarly, ratios for the United States in the 2000s were around 2 on an annual basis (Meehl et al. 2016), while for selected Central-European cities outside Hungary they were between 2 and 5 in the 2000s, and a quadratic relationship between the mean and the changes in this ratio was identified by Beniston (2015).

3.2 Observed precipitation record-breakings

Precipitation generally has higher spatial and temporal variability than either the minimum or the maximum temperature, which is also reflected in the record-high values of the precipitation distribution. Looking at the time series of the number of new precipitation records per year (Fig. 7), it can be recognised that values are generally lower than for warm records (in the case of precipitation, the values never exceed 6 days per year in any season of any year), with relatively high year-to-year variability. One can note that, in general, the frequency of new records converges closer over time to the stationary climate (i.e. the green line in the figures), which means climate change affects the distribution of precipitation certainly less compared to temperature in this
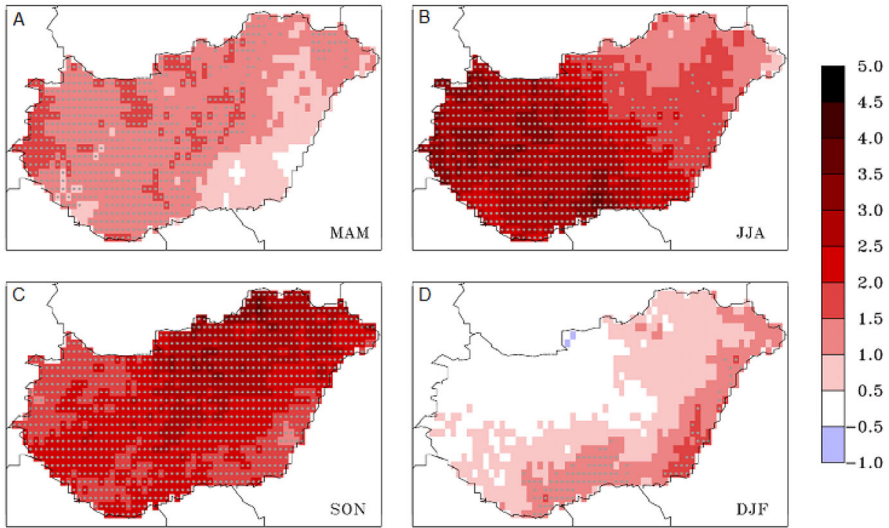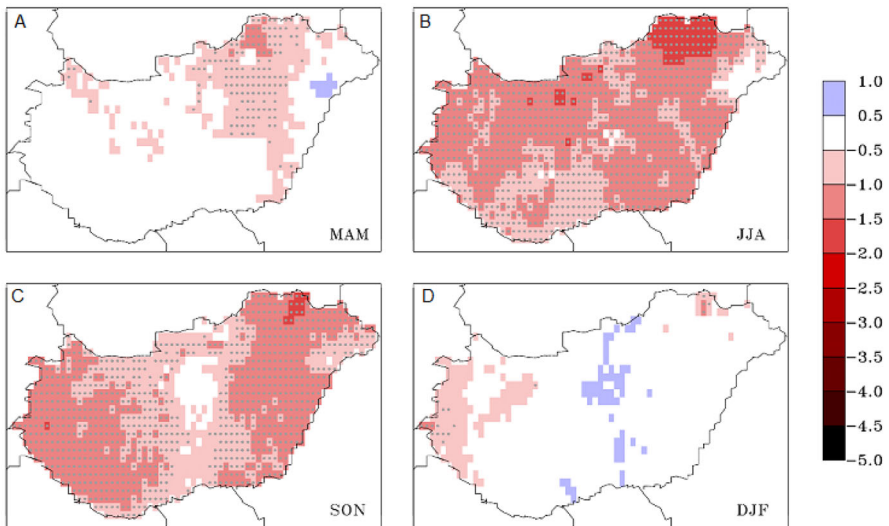
Fig. 3 The number of days when new minimum temperature record was observed in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) between 2001 and 2020 [day/season]. Values are averaged over Hungary, blue dashed lines indicate the decadal means, green line represents the stationary climate. Decadal means and the dominant parts of the individual years are mostly below the stationary climate (colour figure online)
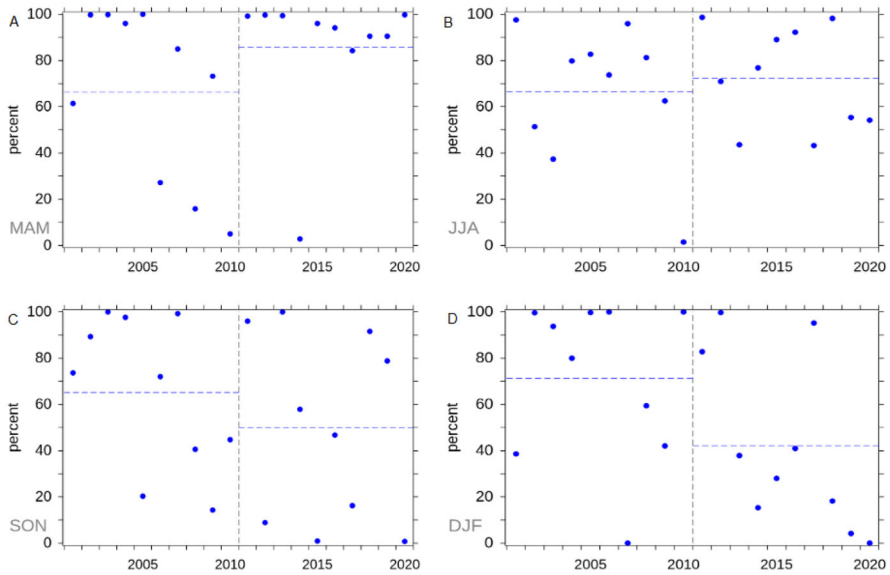

Fig. 4 The percent of area affected in Hungary by new minimum temperature records on any day in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) observed between 2001 and 2020 relative to the total number of grid cells [percent]. Blue dashed lines indicate the decadal means. The variability of the extension of the affected area is high with almost the entire country affected to a few percent only (colour figure online)
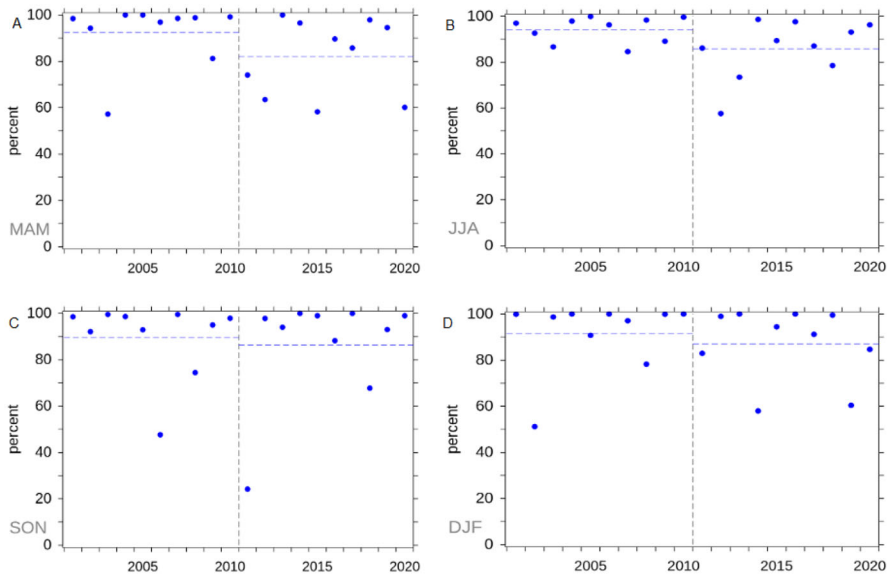
Fig. 5 The seasonally summed number of days when a new maximum temperature record was observed **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF), compared to the stationary climate [day/year in each season]. Values are averaged over 2001–2020, and positive values (red colours) indicate areas with more records observed compared to the stationary climate. Dots indicate significant differences on the basis of Welch-test at 0.1 level. The most new records occurred in SON and JJA, while the least in DJF (colour figure online)

Fig. 6 The seasonally summed number of days when a new minimum temperature record was observed **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF), compared to the stationary climate [day/year in each season]. Values are averaged over 2001–2020, and negative values (red colours) indicate areas with less records observed compared to the stationary climate. Dots indicate significant differences on the basis of Welch-test at 0.1 level. The least new records compared to the stationary climate occurred in JJA and SON (colour figure online)
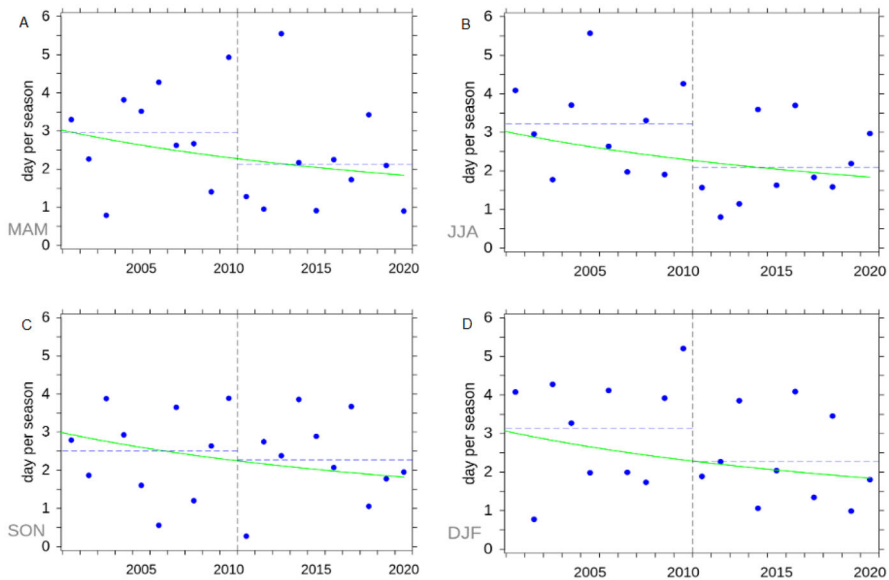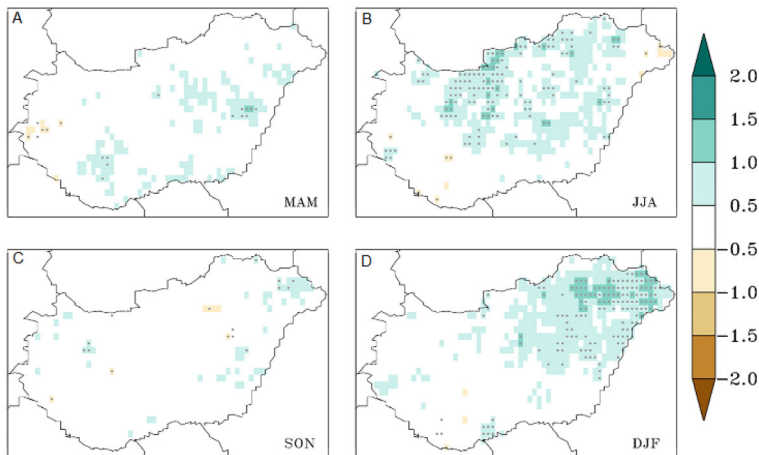
Fig. 7 The number of days when new high precipitation record was observed in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) between 2001 and 2020 [day/season]. Values are averaged over Hungary, blue dashed lines indicate the decadal means, green line represents the stationary climate. Even though the decadal means decreased, the individual years are highly variable around the stationary climate in all seasons (colour figure online)

region. As for the observations, it is of lower probability on a decadal mean that a new precipitation record is set anytime nowadays in any season, and this is also reflected in the affected areas (Fig. 8) which are also getting slightly lower.

The spatial variability (Fig. 9) reflects also the previous conclusions: more precipitation record-breakings can only be detected in JJA and in DJF in the past 20 years compared to the stationary climate, which is statistically significant over the northern-central region of Hungary in JJA, and the northeastern parts in DJF (reaching only around a surplus of 1 day per year compared to the stationary climate). It should be noted that the JJA (boreal summer) daily values and particularly the extremes are generally much higher than those in DJF (winter) since convective precipitation is the main source of the former resulting in larger impacts in JJA than in DJF. In the transient seasons (MAM and SON), the number of new records oscillated around the green lines in Fig. 7, thus, resulting in a similar decreasing probability compared to the stationary climate. This is in a bit disagreement with Robinson et al. (2021), who analysed largely aggregated regions and no seasons, but showed that the region where Hungary is located shows a 20–30%, statistically significant deviation from stationary climate.

Fig. 8 The percent of area affected in Hungary by new high precipitation records on any day in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) observed between 2001 and 2020 relative to the total number of grid cells [percent]. Blue dashed lines indicate the decadal means. More than half of the total area is affected in most years (colour figure online)


Fig. 9 The seasonally summed number of days when a new high precipitation record was observed **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF), compared to the stationary climate [day/year in each season]. Values are averaged over 2001–2020, and positive values (greenish colours) indicate areas with more records observed compared to the stationary climate. Dots indicate significant differences on the basis of Welch-test at 0.1 level. The most new records occurred in JJA and DJF mostly in the north-central and north-eastern parts, respectively (colour figure online)

3.3 Future temperature record-breakings

The observed trend in the past 20 years regarding temperature record-breakings will continue to increase in the following decades, however, there are some concerns from the latest publication of Vautard et al. (2023) that most GCMs underestimate the recent signal in summer extremely high values of maximum temperature in Western Europe and slightly overestimate it over our area of interest. Following the high emission scenario of RCP8.5, we increasingly deviate from the stationary climate as approaching the end of the twenty-first century (Fig. 10, dark red bars). This means that more and more new warm records are expected in the following decades, especially in JJA and SON: reaching an average of 4–5 new records per year in the last four decades of the twenty-first century in JJA. Projected frequencies are substantially lower for MAM and DJF, but still clearly above the stationary climate. While the change in record-breakings in DJF, or even in MAM and SON, imply positive effects due to possible energy savings regarding heating, the projected changes in JJA affects adversely, and even harmful to human health with each new record over the course of a summer heatwave. Consequently, adaptation to such events is absolutely necessary.

Even though uncertainty stemming from the different RCM simulations is relatively large in any given scenario, one can easily recognise that following the RCP4.5 scenario with mitigation policies ends in deviation from the previously mentioned business-as-usual RCP8.5 scenario after a few decades, and the projected frequency of record-breakings is closer to the stationary climate values (Fig. 10, pink bars). The projected
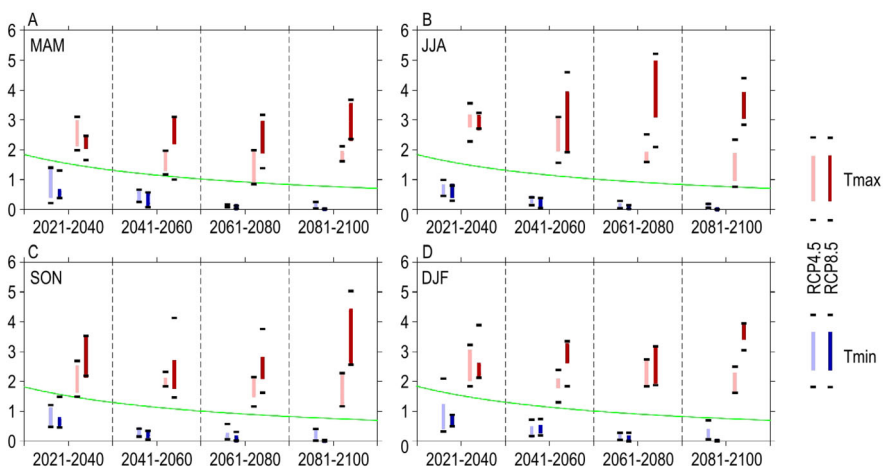
Fig. 10 The projected average number of days when new maximum (redish) and minimum (bluish) temperature record is broken in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) following RCM simulations in the future [day/year in each season]. Values are averaged over Hungary and for 20 years. The ranges cover the means of four RCM simulations, short black lines indicate the minimum and maximum means of the RCM simulations. Darker colour bars: RCP8.5, lighter colour bars: RCP4.5. Continuous green line represents the stationary climate. The new Tmax (Tmin) records are projected to exceed (stay below) the stationary climate (colour figure online)

RCM simulation results are below 2 new records per year per season, furthermore, some simulations even reach the lower values for stationary climate (around 1 day per year), implying conditions with anthropogenic emissions turn to decrease, and global warming slows down converging to a quasi-stationary climate. The largest difference between the two scenarios is projected with no overlapping RCM simulations over a 20-year period: in 2061–2080 for JJA only, and in 2081–2100 for all seasons.

Regarding minimum record-breakings (Fig. 10, blue bars) following either scenario according to all RCM simulations, clearly fewer new cold records are projected in all future periods of any season compared to the occurrences in the stationary climate. This does not mean that rarely more new cold records will occur than warm records. The decrease is more emphasised in the case of RCP8.5 scenario, when basically no new minimum records are projected by the end of the twenty-first century in any season, regardless of model simulations. On the other hand, RCP4.5 is different in 2080–2100, and one can expect somewhat more new cold extremes after the previous two decades (2061–2080) since global warming slows down.

The ratios of the numbers of new record highs to record lows by the end of the twenty-first century will still increase by at least an order of magnitude following the RCP4.5 scenario with mitigation to around 60–70 to 1, and it may become more than double as this to around 140–180 regardless of each season following the non-mitigation scenario of RCP8.5. Similar magnitudes were obtained by Meehl et al. (2016) for the North American continent.

In the following, we briefly analyse the spatial distribution of the warmest two decades (2081–2100) of new record high temperature values to emphasise the difference between the RCM simulations and the scenarios over Hungary. Contrary to the above assessment, each of the six individual RCM simulations is evaluated separately. Firstly, Fig. 11 summarises the results for the RCP4.5 mitigation scenario. In general, RACMO simulations project the lowest number of record-breakings throughout the year (the run driven by CNRM-CM5 has the highest intra-annual variability though), while RCA run driven by EC-EARTH projects the highest number of values per season (with statistically significant deviation from stationary climate). Note that even the highest values are below + 1.5–2 days compared to the stationary climate. This is in high correspondence with the climate sensitivity of the RCMs. In JJA, RCM simulations mostly project similar occurrences around the constant climate (shown as white in the maps), and only 2 out of 6 RCM simulations project statistically significant differences. Similarly, dominantly more warm records-breakings are projected by 3, 3, and 5 RCM simulations in SON, MAM, and DJF, respectively.

Regarding the business-as-usual RCP8.5 scenario (Fig. 12), projected results are clearly more robust and the difference from constant climate is statistically significant in all grid points for the end of the century. Projected frequencies vary between + 1 and + 5 deviating from the stationary climate. On average, RCA simulation (driven by NorESM) projects the highest number of new warm records throughout the year, while the lowest numbers are expected according to RCA simulation (driven by CNRM-CM5). For JJA and SON, one of the RACMO simulations projects the highest signal reaching + 5. For MAM, RCA simulation (driven by NorESM) projects clearly the highest occurrences of new warm records, while for DJF, 3 RCM simulations have +
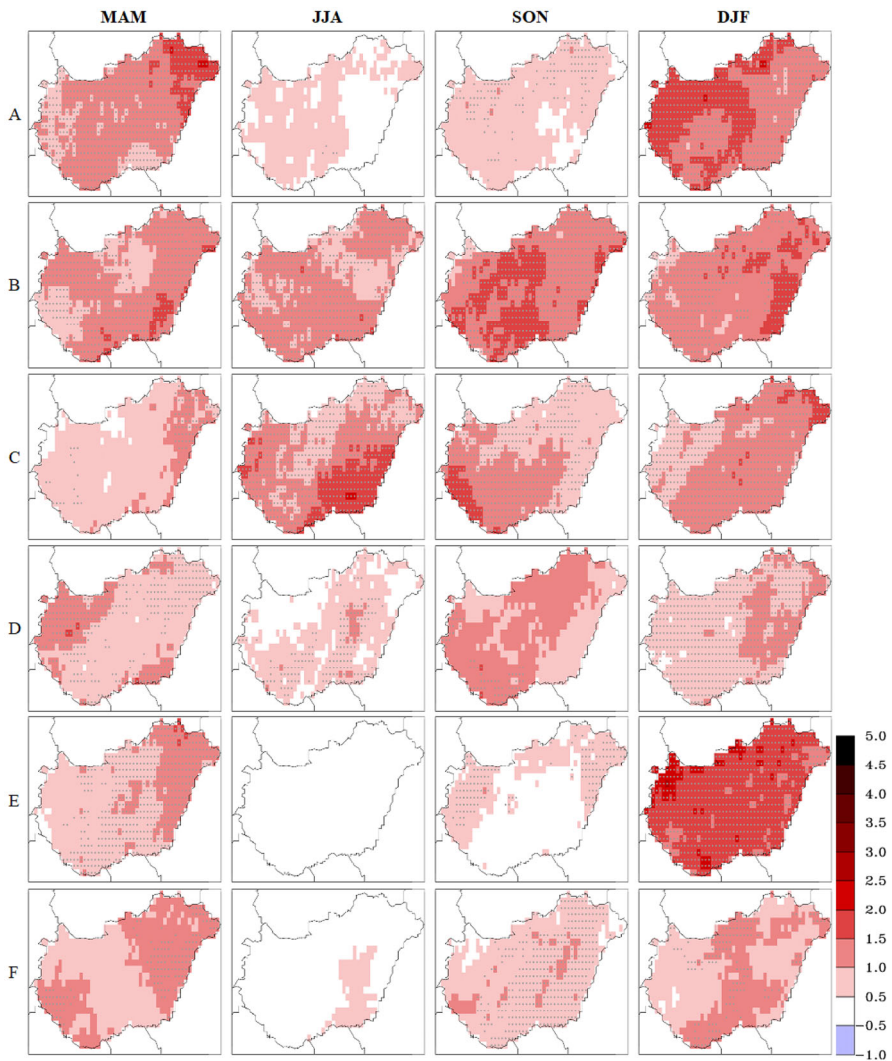
Fig. 11 The seasonally summed projected number of days when a new maximum temperature record is broken by six different RCM simulations in 2081–2100 following the RCP4.5 scenario compared to the stationary climate [day/year in each season]. Values are averaged for 20 years. Positive values (red colours) indicate that more records are broken than in the stationary climate. Dots indicate significant differences using the Welch-test at 0.1 level. **A** CNRM-CM5-RCA, **B** EC-EARTH-RCA, **C** IPSL-CM5-RCA, **D** NorESM-RCA, **E** CNRM-CM5-RACMO, **F** EC-EARTH-RACMO (colour figure online)

2.5–3 values. The largest uncertainty due to the different RCM simulations is projected in JJA or SON.
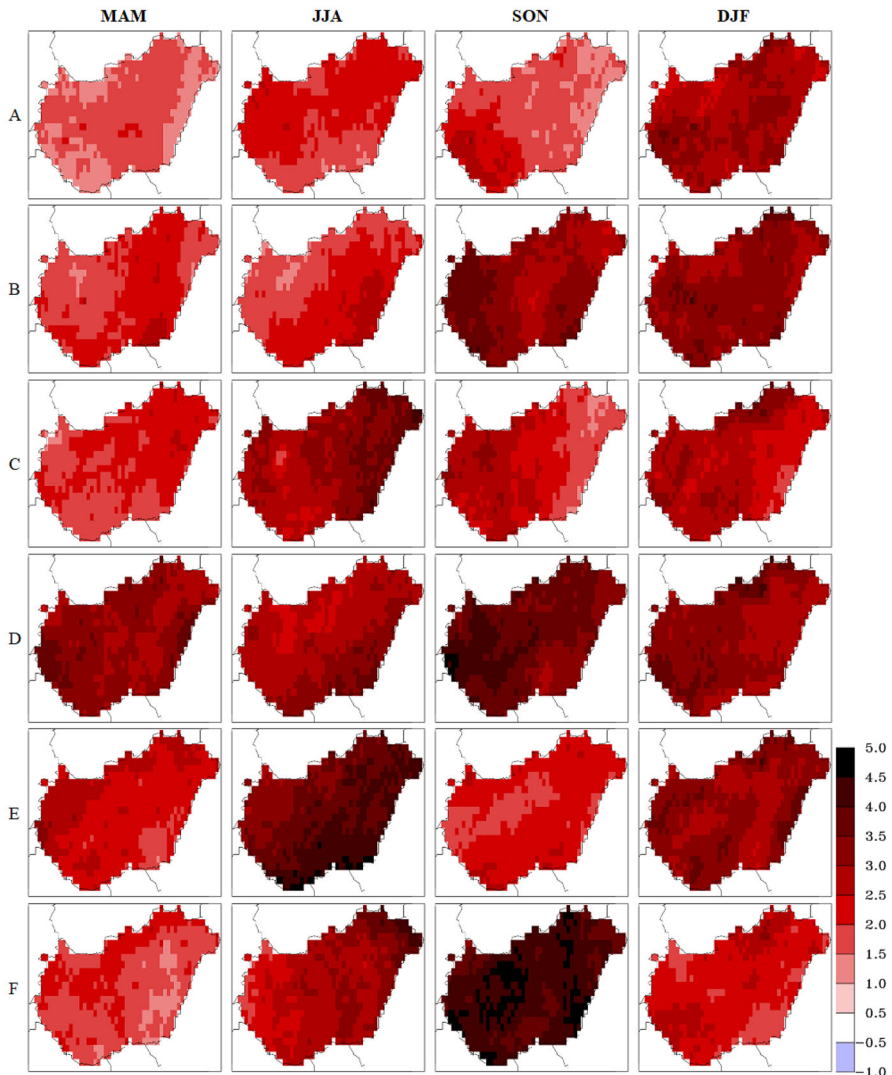
Fig. 12 The seasonally summed projected number of days when a new maximum temperature record is broken by six different RCM simulations in 2081–2100 following the RCP8.5 scenario compared to the stationary climate [day/year in each season]. Values are averaged for 20 years. Positive values (red colours) indicate that more records are broken than in the stationary climate. All grid points are statistically significant using the Welch-test at 0.1 level (dots not shown). **A** CNRM-CM5-RCA, **B** EC-EARTH-RCA, **C** IPSL-CM5-RCA, **D** NorESM-RCA, **E** CNRM-CM5-RACMO, **F** EC-EARTH-RACMO (colour figure online)
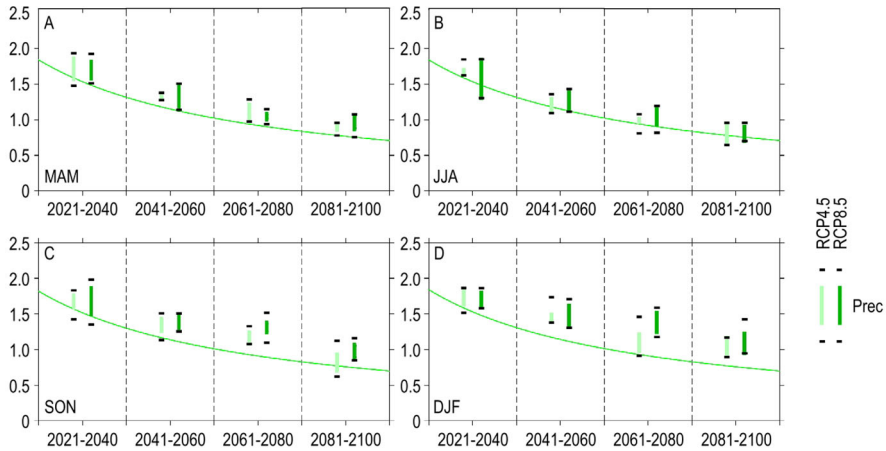
Fig. 13 The projected average number of days when new high precipitation record is broken in **A** spring (MAM), **B** summer (JJA), **C** autumn (SON), and **D** winter (DJF) following RCM simulations in the future [day/year in each season]. Values are averaged over Hungary and for 20 years. The ranges cover the means of four RCM simulations, short black lines indicate the minimum and maximum means of the RCM simulations. Darker green bars: RCP8.5, lighter green bars: RCP4.5. Continuous green line represents the stationary climate. New precipitation records are most likely to exceed the stationary climate in DJF (colour figure online)

3.4 Future precipitation record-breakings

Results on the basis of precipitation for the future are not much different from the past observations: the new record-breakings tend to occur slightly less and less in the future (the expected mean values are below 2 days on average), and they converge to the stationary climate. When normally the highest rainfall amounts occur (i.e. during the convective season, mostly in JJA), the range of the projections of RCM simulations crosses the stationary climate line basically in all future periods (Fig. 13). On the other hand, one can note that following either scenario, in MAM and DJF from 2041 and in SON between 2041 and 2080 nearly all simulation results predict higher occurrences than the constant climate. Regarding the scenario differences, there is always an overlapping range between the two scenarios in each season, but values are usually slightly higher for RCP8.5 than for RCP4.5 after the mid-century—suggesting large internal variability and less sensitivity for anthropogenic activity. No maps are provided for these results.

4 Summary

In this paper, we analysed new seasonal warm, cold, and precipitation record-breakings for Hungary, for which daily data sets of minimum, maximum temperature and precipitation were used from various data sources. We first evaluated observations from 1971, while from 2021 we considered six RCM simulations, each following two different emission scenarios (i.e. the RCP4.5 with mitigation from 2040 and the RCP8.5

a business-as-usual) for the future. This allowed us to take into account the model uncertainty and evaluate the effects of anthropogenic activity. The spatially averaged numbers of new records were compared to the stationary climate for the time series of 2001–2020, the observed affected area, and the means of 20-year periods of new records from 2021 until the end of the twenty-first century. Maps were shown to emphasise the spatial distribution of the recent trends in 2001–2020, and the projected future trends by 2081–2100 compared to the stationary climate. Despite climate models have biases, no bias correction was needed for the simulated results, however, significance tests with a 0.1 level were applied to the results at a grid-point level.

On the basis of the study, the following conclusions can be drawn:

i.   For the past: (1) The highest number of new warm records were observed deviating mostly from stationary climate in the past 20 years in JJA and SON. (2) New cold records tend to occur less and less in JJA and SON as well, reaching the ratio of the numbers of new warm records to cold records 3.5–3.7 in these seasons. (3) The occurrence of cold record-breakings still shows higher variability compared to the stationary climate in MAM and particularly in DJF. (4) New precipitation records did not occur more often in 2001–2020 than expected, except in JJA and DJF over smaller regions in Hungary.

ii. For the future: (1) Substantially more new record high temperatures are projected in the case of RCP8.5 scenario compared to RCP4.5, especially in JJA and SON. (2) As for new cold records, their frequencies converge to zero, and may actually become zero after 2081 according to most RCM simulations following the RCP8.5 scenario. (3) Results for precipitation are more uncertain and they are less different from the stationary climate, furthermore, small differences between the two scenarios can be identified only in some decades, and in SON and DJF mainly.

Author contribution Authors applied the FLAE approach for the sequence of authors. P. S. and R. P. contributed to the study's conception and design. Data collection and analysis were performed by P. S. The first draft of the manuscript was written by P. S., and R. P. commented on previous versions of the manuscript. All authors read and approved the final manuscript. Supervisors: J. B. and R. P.

Declaration

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Beniston, M.: Ratios of record high to record low temperatures in Europe exhibit sharp increases since 2000 despite a slowdown in the rise of mean temperatures. Clim. Change **129**, 225–237 (2015). https://doi.org/10.1007/s10584-015-1325-2

Boer, G.J.: Changes in interannual variability and decadal potential predictability under global warming. J. Clim. **22**, 3098–3109 (2009). https://doi.org/10.1175/2008JCLI2835.1

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., Wang, S.: The influence of Arctic amplification on mid-latitude summer circulation. Nat. Commun. **9**, 2959 (2018). https://doi.org/10.1038/s41467-018-05256-8

Dyrrdal, A.V., Olsson, J., Médus, E., Arnbjerg-Nielsen, K., Post, P., Aņiskeviča, S., Thorndahl, S., Førland, E., Wern, L., Mačiulytė, V., Mäkelä, A.: Observed changes in heavy daily precipitation over the Nordic-Baltic region. J. Hydrol. Reg. Stud. **38**, 2214–5818 (2021). https://doi.org/10.1016/j.ejrh.2021.100965

Easterling, D.R., Gerald, A.M., Camille, P., et al.: Climate extremes observations, modeling, and impacts. Science **289**, 2068–2074 (2000). https://doi.org/10.1126/science.289.5487.2068

Fantini, A., Raffaele, F., Torma, Cs., Bacer, S., Coppola, E., Giorgi, F., Ahrens, B., Dubois, C., Sanchez, E., Verdecchia, M.: Assessment of multiple daily precipitation statistics in ERA-Interim driven Med-CORDEX and EURO-CORDEX experiments against high resolution observations. Clim. Dyn. **51**, 877–900 (2018). https://doi.org/10.1007/s00382-016-3453-4

Fischer, E.M., Knutti, R.: Observed heavy precipitation increase confirms theory and early models. Nat. Clim. Chang. **6**(11), 986–991 (2016). https://doi.org/10.1038/nclimate3110

Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Wang, S.W.: Observed Climate Variability and Change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., vanderLinden PJ, Dai X, Maskell K, Johnson CA, (eds.) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (2001)

Glick, N.: Breaking records and breaking boards. Am. Math. Mon. **85**(1), 2–26 (1978). https://doi.org/10.2307/2978044

IPCC: Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews. J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (eds) Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2021). https://doi.org/10.1017/9781009157896.001

Izsák, B., Szentimrey, T.: To what extent does the detection of climate change in Hungary depend on the choice of statistical methods? Int. J. Geomath. **11**, 17 (2020). https://doi.org/10.1007/s13137-020-00154-y

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V.: Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci. Model Dev. **7**, 1297–1333 (2014). https://doi.org/10.5194/gmd-7-1297-2014

Luterbacher, J., Liniger, M.A., Menzel, A., Estrella, N., Della-Marta, P.M., Pfister, C., Rutishauser, T., Xoplaki, E.: Exceptional European warmth of autumn 2006 and winter 2007: Historical context, the underlying dynamics, and its phenological impacts. Geophys. Res. Lett. **34**, L12704 (2007). https://doi.org/10.1029/2007GL029951

Meehl, G.A., Tebaldi, C., Walton, G., Easterling, D., McDaniel, L.: The relative increase of record high maximum temperatures compared to record low minimum temperatures in the US. Geophys. Res. Lett. **36**, L23701 (2009). https://doi.org/10.1029/2009GL040736

Meehl, G.A., Tebaldi, C., Adams-Smith, D.: US daily temperature records past, present, and future. PNAS **113**(49), 13977–13982 (2016). https://doi.org/10.1073/pnas.1606117113

Pongrácz, R., Bartholy, J., Kis, A.: Estimation of future precipitation conditions for Hungary with special focus on dry periods. Időjárás **118**(4), 305–321 (2014)

Portmann, R.W., Solomon, S., Hegerl, G.C.: Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. Proc. Natl. Acad. Sci. U. S. A. **106**, 7324–7329 (2009). https://doi.org/10.1073/pnas.0808533106

Pratap, S., Markonis, Y.: The response of the hydrological cycle to temperature changes in recent and distant climatic history. Prog. Earth Planet Sci. **9**, 30 (2022). https://doi.org/10.1186/s40645-022-00489-0

Robinson, A., Lehmann, J., Barriopedro, D., Rahmstorf, S., Coumou, D.: Increasing heat and rainfall extremes now far outside the historical climate. NPJ Clim. Atmos. Sci. **4**, 45 (2021). https://doi.org/10.1038/s41612-021-00202-w

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., Coumou, D.: Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. Nat. Commun. **13**, 3851 (2022). https://doi.org/10.1038/s41467-022-31432-y

Rowe, C.M., Derry, L.E.: Trends in record-breaking temperatures for the conterminous United States. Geophys. Res. Lett. **39**, L1670 (2012). https://doi.org/10.1029/2012GL052775

Samuelsson, P., Gollvik, S., Jansson, C., Kupiainen, M., Kourzeneva, E., vandeBerg, W.J.: The surface processes of the Rossby Centre regional atmospheric climate model (RCA4). Meteorologie **157**, 42 (2015)

Szabó, P., Szépszó, G.: Quantifying sources of uncertainty in temperature and precipitation projections over different parts of Europe. In: Bátkai, A., Csomós, P., Faragó, I., Horányi, A., Szépszó, G. (eds.) Mathematical Problems in Meteorological Modelling Mathematics in Industry, pp. 207–237. Springer International Publishing, Berlin (2016)

van Meijgaard, E., Van Ulft, L.H., Lenderink, G., de Roode, S. R., Wipfler, L., Boers, R., Timmermans, R.M.A.: Refinement and application of a regional atmospheric model for climate scenario calculations of western Europe, climate changes spatial planning publication: KvR 054/12, the Programme office climate changes spatial planning, Nieuwegein, The Netherlands, ISBN/EAN 978–90–8815–046–3, 44 p (2012)

van Vuuren, D.P., Edmonds, J., Thomson, A., Riahi, K., Kainuma, M., Matsui, T., Hurtt, G.C., Lamarque, J.-F., Meinshausen, M., Smith, S., Granier, C., Rose, S.K., Hibbard, K.A.: Representative concentration pathways: an overview. Clim. Change **109**, 5–31 (2011). https://doi.org/10.1007/s10584-011-0148-z

Vautard, R., Cattiaux, J., Happé, T., Singh, J., Bonnet, R., Cassou, C., Coumou, D., D'Andrea F., Faranda, D., Fischer, E., Ribes, A., Yiou, P., Sippel, S.: Heat extremes in Western Europe are increasing faster than simulated due to missed atmospheric circulation trends (2023). https://hal.science/hal-03937057

Welch, B.L.: The generalization of "Student's" problem when several different population variances are involved. Biometrika **34**(1–2), 28–35 (1947). https://doi.org/10.1093/biomet/34.1-2.28

WMO: State of the Global Climate 2021. WMO-No. 1290, Geneva. 57p (2022)