DOI: 10.15201/hungeobull.73.1.1 Hungarian Geographical Bulletin **73** 2024 (1) 3–16.

Seasonal trends in the Early Twentieth Century Warming (ETCW) in a centennial instrumental temperature record from Central Europe

Tímea KOCSIS[1], Rita PONGRÁCZ[2], István Gábor HATVANI[3], Norbert MAGYAR[1], Angéla ANDA[4] and Ilona KOVÁCS-SZÉKELY[1]

Abstract

The goal of the present paper is to investigate whether any objectively defined and statistically significant changes can be discovered in one of the longest homogenized instrumental temperature records in East-Central Europe. Thus, it is hoped that the present analysis will add to earlier attempts and elucidate the persistence of the warming period observed in the early 20th century. Similar to the global tendency, the Early Twentieth Century Warming (hereinafter, ETCW) period can be identified between 1931 and 1951 in the annual mean temperature time series of Keszthely, a small town in Hungary. The Mann-Kendall trend test was used to determine whether a monotonic trend was present, as it is not possible to regard the residuals of the linear trend as normally distributed. A significant rising trend can be observed in the warming period in spring of the years between 1925 and 1951. In case of summer and autumn, this period cannot be characterized as having any significant identifiable trend. A rise in the mean can, however, be recognized. Overall, the specific regional manifestation of the global ETCW may clearly be illustrated in this study via detailed statistical analysis of the temperature records for Keszthely, a location with one of the longest temperature records in Hungary. However, other regions surrounding Hungary show similar climatic trends, emphasizing the fact that the behaviour presented here is not unique to Central and Eastern Europe.

Keywords: change-point detection, Early Twentieth Century Warming (ETCW), temperature records, time series analysis

Received April 2023, accepted February 2024.

Introduction

Changes in weather and climate patterns due to anthropogenic forced global climate change have direct and indirect effects on human life and socio-economic systems. The final two decades of the 20th century, along with the first two decades of the 21st, have been successively warmer than any decade preceding 1850. What is more, global surface temperatures between 2001 and 2020 were 1.1 °C higher than 1850–1900 (IPCC, 2021). This increase in temperatures can be traced back to the beginning of the past century, occurring in two distinct periods, from the mid-1920s to mid-1940s (Przybylak, R. *et al.* 2021) and from 1978 to the present day (Delworth, T.L. and Knutson, T.R. 2000). However, between these two periods of accelerated warming, a stagnation was observed from the 1940s to the 1970s, and a less steep trend from 2000 to approximately 2013 (Hegerl, G.C. *et al.* 2018).

[1] Department of Methodology for Business Analysis, Faculty of Commerce, Hospitality and Tourism, Budapest Business University. Alkotmány utca 9-11., H-1054 Budapest, Hungary. Corresponding author's e-mail: magyar.norbert@uni-bge.hu

[2] Department of Meteorology, Faculty of Science, ELTE Eötvös Loránd University. Pázmány Péter sétány 1/A., H-1117 Budapest, Hungary.

[3] Institute for Geological and Geochemical Research, HUN-REN Research Centre for Astronomy and Earth Sciences. Budaörsi út 45., H-1112 Budapest, Hungary.

[4] Department of Meteorology and Water Management, Georgikon Campus, Hungarian University of Agronomy and Life Sciences. Festetics utca 7., H-8360 Keszthely, Hungary.

Out of these warming periods the one in the first decades of the 20th century was the more prominent, called the "Early Twentieth Century Warming" (ETCW) (Hegerl, G.C. *et al.* 2018). It was found that, besides other factors, natural variability made a large contribution to the ETCW, and particularly to regional anomalies in the 1920s and 1930s. Nonetheless, the ETCW represents a phase of a robust surface warming globally (Semenov, V.A. and Latif, M. 2012), which we might add, was concentrated in higher latitudes (Yamanouchi, T. 2011). On the regional scale, the warming observed the early 20th century displays a noticeable maximum at higher latitudes in the Northern Hemisphere (Delworth, T.L. and Knutson, T.R. 2000).

Exploring regional temperature features over the course of the ETCW is much more enlightening than looking at the global mean (Brönnimann, S. 2009). The ETCW was most evident in the Arctic, and in winter (Bokuchava, D.D. and Semenov, V.A. 2021), with the Arctic surface temperature warming more than twice as fast as global temperatures (Svendsen, L. *et al.* 2018). Atmospheric circulation fluctuations are important for the early 20th century Arctic warming (Tokinaga, H. *et al.* 2017). A considerable part of regional manifestations of the ETCW appeared outside of the Arctic, including across the USA, Western Europe, and the North and South Atlantic (Hegerl, G.C. *et al.* 2018; Bokuchava, D.D. and Semenov, V.A. 2021). The end of the ETCW in Central Europe was marked by summer heatwaves, droughts, and cold winters (Hegerl, G.C. *et al.* 2018). The ETCW was probably caused by the combined effects of long-term natural climate variations in the North Atlantic and North Pacific and the influence of natural radiative forcing, as well as the growing concentration of greenhouse gases in the atmosphere (Bokuchava, D.D. and Semenov, V.A. 2021). Utilizing a Bayesian change-point detection method, a change-point can be observed in the data of Greenland ice cores at the beginning of the 20th century (centred on 1933) (Hatvani, I.G. *et al.* 2022).

Research of climate features during the ETCW is mainly based on conventional weather observations from the continental surface, measurements taken at sea by ships, and some climate proxy data; even if data-saving initiatives aim at supplementing the global climate record in this period (Allan, R. *et al.* 2011 – in: Hegerl, G.C. *et al.* 2018), the main sources of information about climate change remain ordinary measurements. The existing historical observations recorded by national meteorological and hydrological services, although considered to be incomplete, may nonetheless augment our knowledge of key climate processes and climate change (Dee, D. *et al.* 2021).

Meteorological instruments have been widely used since 1850 in Europe, the Eastern USA and some other regions, including, sporadically, the oceans (Stott, P. *et al.* 2018). Instrumental meteorological measurements were conducted from the 18th century in Italy, Belgium, Sweden, Spain, and Russia (Moberg, A. *et al.* 2000; Camuffo, D. and Jones, P.D. 2002). National weather yearbooks began to be published around 1860 in many countries (Jones, P.D. 2001). Instrumental temperature time series are available from 1760 for the Alpine zone (Böhm, R. *et al.* 2001). The longest instrumental temperature time series in the Czech Republic is for Prague-Klementinum, starting in 1775 (Brázdil, R. *et al.* 2012). In Poland, the mean annual temperature records for the periods 1779–1998 (Warsaw) and 1792–1995 (Cracow) are analysed by Przybylak, R. (2010). In Budapest, regular meteorological observations started in 1780 (Camuffo, D. 2018). Official instrumental meteorological observations began in 1851 in Austria, and in 1870 in Hungary (this was the epoch of the Austro-Hungarian Monarchy). Keszthely station was one of the earliest working stations in the Hungarian network, a network that was organized according to the Western European standards of the time. It is also interesting because there is a special microclimate at that location in consequence of the presence of the nearby large lake, Balaton.

Despite the long time series, in the literature there is a marked lack of research dealing with the ETWC in Central Europe.

The aim of the present study is to explore the presence of objectively defined and statistically significant changes occurring in one of the longest East-Central European homogenized instrumental temperature records. Hence, the present study complements previous efforts and elucidates the persistence of the observed warming period in the early 20th century.

Materials and methods

Keszthely centennial homogenized temperature time series

The Keszthely (E 17°14′, N 46°44′ – *Figure 1*) monthly temperature time series spans 1871 to 2018 and was measured at the long-established Georgikon Academy of Agriculture in Keszthely, and later, at a meteorological station of the Hungarian Meteorological Service. Keszthely is located on the northern shore of Lake Balaton, a 17,000–19,000-year-old water body and the largest shallow lake in Central Europe (surface area: about 600 km², average depth: 3.25 m). As the last overall publication dealing with the climate of Balaton was published 50 years ago (Béll, B. and Takács, B. 1974), and due to the absence of a permanent measuring network around the lake, the meteorological dataset of weather conditions over and around the lake originates from two permanent lakeshore meteorological stations (Keszthely and Siófok) that have made observations over the long term (Anda, A. *et al.* 2023). Using the categories of the Koppen-Geiger classification, the climate of Keszthely is temperate continental (Cfb), with an annual long-term mean air temperature of 10.5 °C, with a monthly minimum of -1.03 °C during January, and a maximum of 21.14 °C in July. The average annual precipitation sum is 673.3 ± 137.9 mm, though with a large monthly variation of between 32.7 and 76.1 mm in the driest January, and wettest July, respectively. In winter, the lake may be covered with ice, sometimes thicker than 0.5 m, factor impacting the air temperature during early spring.

The time series explored here were quality controlled and homogenized by the Hungarian Meteorological Service. Homogenization was conducted using the MASH tool (Szentimrey, T. 1999, 2008), which eliminates errors and inhomogeneities while filling the gaps in the data (Izsák, B. and Szentimrey, T. 2020). The MASH procedure was originally developed for the homogenization of monthly series. It is a relative method and depending on the distribution of the meteorological elements under examination, additive (e.g., for temperature) or multiplicative (e.g., for precipitation) models can be employed (Szentimrey, T. 2006).

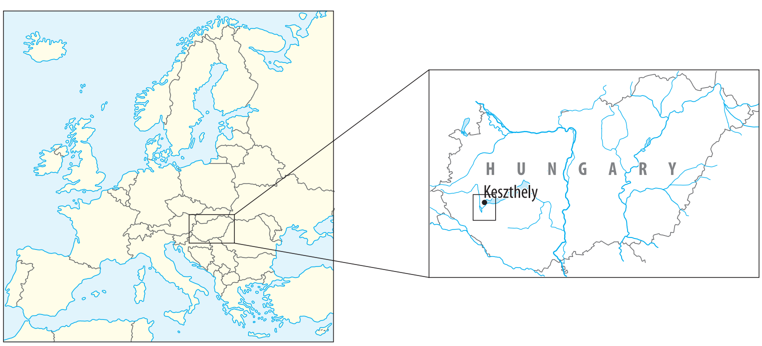

Fig. 1. Location of Keszthely, Hungary (46°44′N, 17°14′E, elevation 114.2 m above Baltic Sea level). *Source*: Redrawn from Kocsis, T. *et al.* 2020.

Methodology

After giving an overall description of the Keszthely mean temperature time series (K_T) regarding long-term trends (see the first part of section 'Results and discussion'), the data was aggregated into annual and seasonal (winter: DJF, spring: MAM, summer: JJA, autumn: SON), and abrupt changes in the time series were sought using change-point analysis. There are numerous change-point detection techniques applied in the exploration of climatic (proxy) variables (e.g., Ducré-Robitaille, J.-F. *et al.* 2003; Reeves, J. *et al.* 2007; Ruggieri, E. 2013; Topál, D. *et al.* 2016; Hatvani, I.G. *et al.* 2020), and of these, Bayesian change-point analysis (BCPa) (see the second part of section 'Results and discussion') was selected for the present study, due to its ability to provide uncertainty estimates of the number (even multiples) and timing of change-points, a key advantage over a frequentist approach (Ruggieri, E. 2013). In the segments, thus, determined, numerous aspects of the mean temperature time series are described and assessed for the presence of prevailing significant trends.

Preprocessing and change-point analysis

To achieve common variability and increase the signal-to-noise ratio relative to the magnitude of the supposed changes a 10-year low-pass filter was applied to all the time series. This aided the detectability of valid change-points (Ruggieri, E. and Antonellis, M. 2016; Ruggieri, E. 2018). The time series were then centred and subjected to the linear model of the Bayesian change-point algorithm of Ruggieri, E. (2013) (BCPa for short).

The BCPa involves three key steps:

1. The calculation of the probability of the data given by the model between any two time points. This encompasses all potential climate regimes (in terms of timing) within the dataset.

2. The utilization of the probabilistic calculations from step 1 as building blocks to assemble these segments recursively, incrementally adding one possible change-point at a time.

3. The application of Bayes' rule to calculate the posterior distribution of the parameters of interest – here the number and location of change-points – as well as the parameters of the regression model in each interval (Hatvani, I.G. *et al.* 2020).

In a nutshell, BCPa can generate the posterior distribution on both the number and location of change-points in a data set. For an additional overview on change-point analysis (see Ruggieri, E. 2013, 2018).

In terms of parameterization, the model has several parameters which need to be specified, including those of the prior distribution of regression coefficients and the residual variance, which are known as hyper-parameters (Quiang, R. and Ruggieri, E. 2023). Here, the parameterization followed that the method of Hatvani, I.G. *et al.* (2022) on climate proxy time series, specifically:

- prior on the regression coefficients $k_0 = (0.001, 0.01)$;
- prior on the variance of the residuals, $v_0 = 1$, σ_0 = variance of each time series;
- the minimum distance between successive change-points, $d_{min} = 10$ steps (years in the present case);
- the maximum number of change-points $k_{max} = 50$;
- the number of sampled solutions, *num. samp* = 10,000.

The prior parameters were deliberately selected to represent a minimum of prior information, allowing the inference to be primarily driven by the actual data. In general, in any case where the model is sensitive to the k_0, v_0, and σ_0 parameters, the number of change-points is influenced while their location or distribution is left unaffected. In simpler terms, adjusting these parameters can modify the detection threshold of the model, but will not result in the shift of a change-point from one section of the data to another. For a detailed explanation of the parameters, the reader is referred to Ruggieri, E. (2013) and the supplemental online material of Hatvani, I.G. *et al.* (2022).

Because BCPa determines the probability of a change-point at a given location – thus, providing uncertainty estimates – and the change-point time series obtained were passed through a 5-year centralized rolling summary function in order to cumulate the probability dispersed between consecutive years. This cumulative probability is the probability of the change-point(s) shown in the study. Only "practically certain" change-points with a 5-year sum probability > 80 percent were considered in the evaluation. In addition, a 5-year window was considered when evaluating the coincidence of the differently aggregated *T* time series, as was done in Hatvani, I.G. *et al.* (2022), but even more rigorously.

Trend analysis and descriptive stats

The aim was to determine the general tendencies of the time series. As the temperature data underwent homogenization using MASH, there was no need to check the data for homogeneity.

The common linear regression (trend) based on ordinary least squares method was used, along with a control to conform to the demand of normal distribution of the residuals using the Shapiro-Wilk normality test (Shapiro, S.S. and Wilk, M.B. 1965). The decision over significance was made at the 5 percent significance level. Beside the tendencies, absolute deviation from the mean was calculated for every year on annual, seasonal, monthly levels to obtain information about the tendencies of the variability. After searching for change-points in the time series, they were segmented according to the change-points. Any tendencies in the segmented time series were determined using linear trend. In cases where the distribution of the residuals is significantly different from normal distribution, the Mann-Kendall (MK) non-parametric trend test was applied to determine the tendency of the segments at α = 5 percent. The simple MK trend test is based upon the work of Mann, H.B. (1945) and Kendall, M. (1975), and it is closely related to Kendall's rank correlation coefficient.

A detailed description of the methodology of the simple MK trend test is given by Gilbert, R.O. (1987), and Hipel, K.W. and McLeod, A.I. (1994). The test statistic is based on *S*, which represents the number of signs between the elements of the times series. A positive value for *S* means that there is a rising trend, a negative value for *S*, the contrary. With the help of descriptive statistics (mean, standard deviation) and trend analysis, the reasons for the presence of a change-point were explored. The simple MK trend test does not consider the possible autocorrelation of the data. The presence of positive autocorrelation in the data increases the chance of detecting trends when actually none exist, and vice versa (Hamed, K.H. and Rao, A.R. 1998). This effect of the existence of autocorrelation in data is often ignored: Hamed, K.H. and Rao, A.R. (1998) supposed a modified non-parametric trend test suited to auto-correlated and gave a detailed description of it. Modified MK trend test for auto-correlated. In the case of the detection of a non-parametric trend, Sen's slope estimator (Sen, P.K. 1968) was applied. This is a non-parametric method that can calculate the change per unit time (direction and volume). Sen's method uses a linear model to estimate the slope of the trend (Da Silva, R.M. *et al.* 2015). In the case of a proven autocorrelation in the dataset, the modified version of the MK trend test was applied *(Figure 2).* AR1 values were higher than the critical value for the annual mean temperature data, for summer seasonal mean time series, and July *(Figure 3).* The autocorrelation of the data and the normal distribution of the residuals were taken into account in the analysis of the variability as well.

The trend estimations and the change-point analysis were performed in the *R* statistical environment (R Core Team, 2019). The modified *MK stats* and *trend* packages were used for trend analysis, *band-pass* filtering was performed with the *band-pass* function of the *astrochron* package (Meyers, S.R. 2014) and change-point detection was performed using the Bayesian change-point algorithm (Ruggieri, E. 2013).

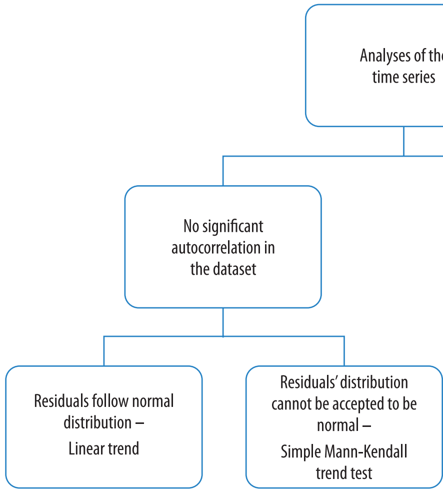

Fig. 2. Decision making flow-chart for choosing method. *Source*: Authors' own elaboration.

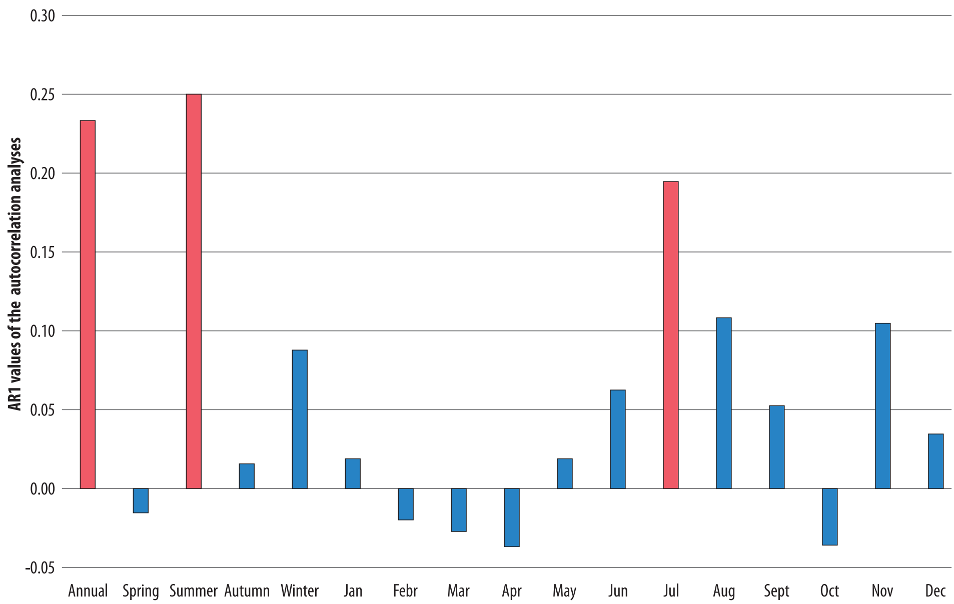

Fig. 3. Autocorrelation (AR1) of the time series (significant autocorrelations are in red). *Source*: Authors' own elaboration.

Results and discussion

Overall tendencies in the centennial Keszthely mean temperature time series (K_T)

The autocorrelation was taken into account using the Hamed and Rao method (Hamed, K.H. and Rao, A.R. 1998) for the analysis of the annual mean temperature data as the presence of autocorrelation was proved and an overall significant monotonic increasing tendency (*Figure 4*, A – Sen's slope: 0.004, $S = 1905$, $p = 2.506\ 10^{-02}$) was found for the annual mean, corresponding to a rise on average of 0.4 °C per 100 years. Significant trends were seen for the winter and spring (*Figure 4*, E – winter, Sen's slope: 0.0084, S = 1305, p = 2.896 10^{-02}), with the simple MK test and *Figure 4*, B – spring, slope: 0.0048, $t(146)$ = 2.234, p = 2.703 10^{-02}, with a linear trend), with an increase of 0.84 °C and 0.48 °C per 100 years, respectively. Regarding the summer and autumn, no overall significant ($p > 0.05$) trend was observed. Among the months, linear increasing trends were detected in January (slope: 0.0119, $t(146)$ = 2.259, p = 2.534 10^{-02}) and in November (slope: 0.0086, $t(146)$ = 2.197, p = 2.956 10^{-02}), respectively.

Variability was assessed by examining the absolute deviation from the mean (annual, seasonal, monthly, respectively). The distributions of the residuals cannot be accepted to be normal, therefore the MK test was used. Significant autocorrelation can be detected in the analysed data in September, so an autocorrelated MK test was applied. It is interesting to see the tendencies of the variability, but the only significant monotonic trend can be detected in December. The absolute deviation from the mean temperature in December displays a significant linear decreasing trend (Sen's slope: -0.0042, S = -1235, p = 4.070 10^{-02}). This means that in December, fewer extremities occur.

Abrupt changes and decadal trends in the Keszthely mean temperature time series (K_T)

A change-point can be found in the annual mean temperature data in 1895, with a probability of 99 percent, and another in 1931 with 90 percent probability. The change-point (CP) in 1931 is in good coincidence with the beginning of the ETCW. In 1952, a negative shift can be seen with 80% probability. This may be considered as indicating the end of the ETCW period (see *Figure 4*, A). In the seasonal data, change-points can be detected in 1925 with 99 percent probability in spring, in 1927 in the summer mean temperature and in 1924 in the average temperature of winter. In the time series of autumn, a CP can be seen in 1924 with 80 percent probability. In autumn, a change-point can be seen in 1969 with 99 percent probability. A secondary CP can be identified in 1952 and 1953 in the spring and summer time series, respectively. These change-points are also in good agreement with dates for the beginning (Delworth, T.L. and Knutson, T.R. 2000) and end (Przybylak, R. *et al.* 2021) of the ETCW (see *Figure 4*, B-D). The period of the ETCW can be detected in the annual data and in spring and summer, but in autumn and winter only the beginning can be identified, while the end is missing.

The time series were divided at the CPs that have a probability of 80 percent at least. The year in which the CP was detected becomes the first year of each separate period. Linear trend, or MK trend, was fitted, and the slope coefficient was examined at the 10 and 5 percent significance levels *(Table 1)*. Among the separated parts of the annual mean temperature, significant periods of increase can be observed between 1931 and 1951, and 1985 and 2018. The timing of the first is contemporary with the ETCW. The second is the significant temperature rise being experienced nowadays.

The previous division was also applicable to the times series of the seasons, as well. In spring all of the separate periods show significant rising tendencies at the 10 percent significance level. A significant increasing trend can be found in the period of the ETCW. Surprisingly, in the summer the ETCW period does not exert a significant influence, but the previous and the next period displayed significant change. Between 1871 and 1926 a significant decreasing trend may be observed in the summer mean temperature (see *Table 1*). The average temperature, however, is higher than the mean of both the previous and subsequent periods. Between 1953 and 2018 a significant temperature rise can be detected *(Figure 5)*. This result is somewhat at odds with the findings of Hegerl, G.C. *et al.* (2018), namely, that in Central Europe droughts and heatwaves marked the end of the ETCW in the late 1940s and early 1950s. Studies analysing the time series of the Palmer Drought Severity Index (PDSI)

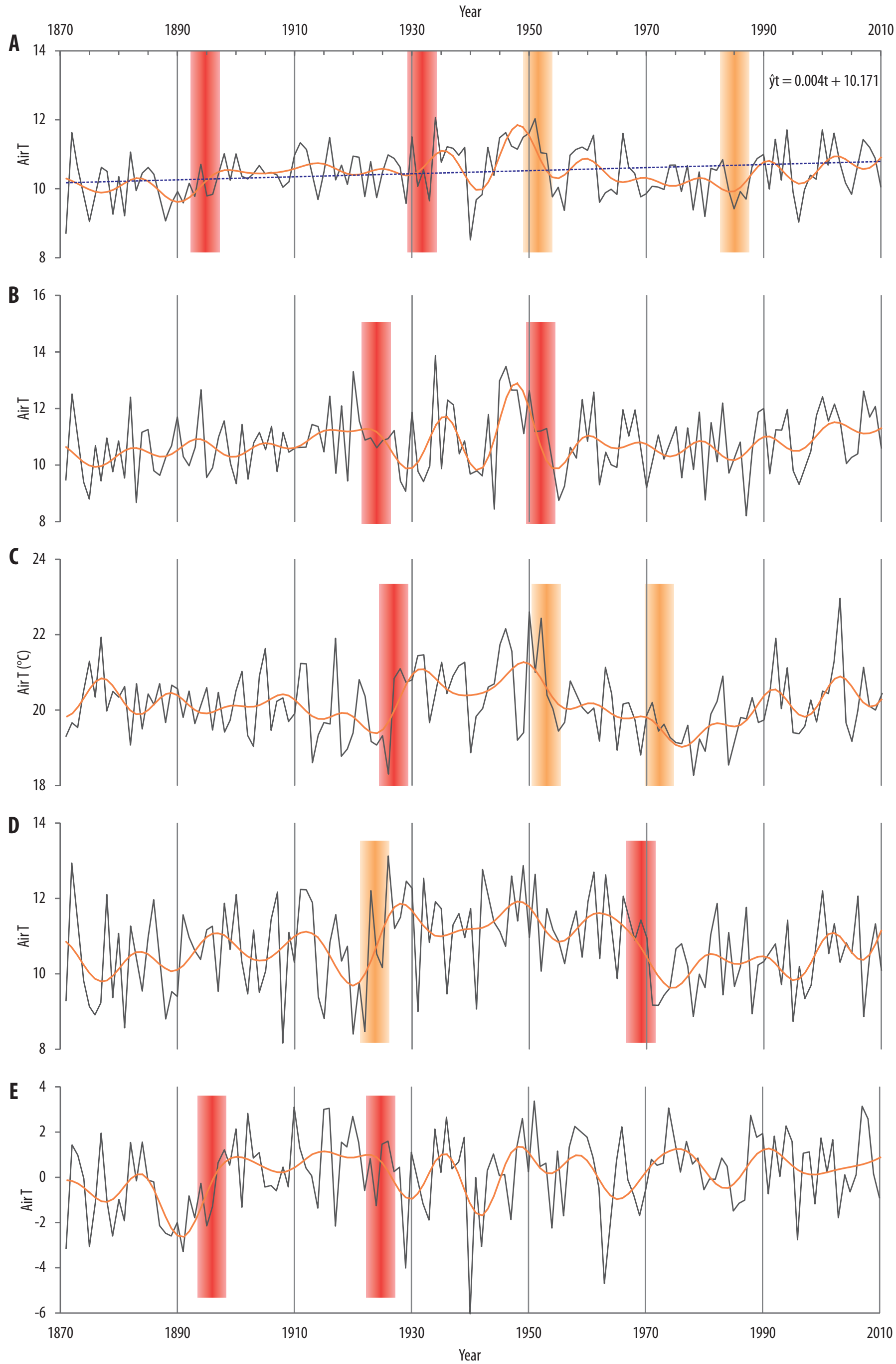

Fig. 4. Keszthely annual (A), spring (B), summer (C), autumn (D), and winter (E) raw (grey), 10-year low-passed (orange) temperature time series spanning 1871–2018. Change-points of posterior probability > 80%, and < 90% are indicated in orange, and those > 90% with a red vertical column. The blue line in part (A) is the linear trend of the annual time series. *Source*: Authors' own elaboration.

Table 1. Segments of the time series in which trends can be identified

<table>
<tr><td>Annual</td><td>1871–1894</td><td>1895–1930</td><td>1931–1951**
(Sen's slope = 0.059)</td><td>1952–1984</td><td>1985–2018**
(slope = 0.042)</td></tr>
<tr><td>Spring</td><td colspan="2">1871–1924**
(slope = 0.018)</td><td>1925–1951*
(slope = 0.062)</td><td colspan="2">1952–2018**
(slope = 0.018)</td></tr>
<tr><td>Summer</td><td colspan="2">1871–1926**
(slope = 0.014)</td><td>1927–1952</td><td colspan="2">1953–2018**
(slope = 0.018)</td></tr>
<tr><td>Autumn</td><td colspan="2">1871–1923</td><td>1924–1968</td><td colspan="2">1969–2018**
(Sen's slope = 0.024)</td></tr>
<tr><td>Winter</td><td>1872–1895</td><td>1896–1923</td><td colspan="3">1924–2018</td></tr>
</table>

*Significant at 10%, **at 5% significance level.

for the 20th century in Hungary state that significant wet sub-periods are detectable in the first half of the 20th century, while dry breaks occurred in the second half of the century (Horváth, Sz. *et al.* 2005). Szinell, C.S. *et al.* (1998) also confirmed that droughts generally occurred more frequently in the second half of the century in Hungary. Szinell, C.S. *et al.* (1998) analysed the PDSI series between 1881 and 1995, and found no change at Keszthely stations in terms of drought. Makra, L. *et al.* (2005) detected significant wet periods in the first part of the 20th century (between 1901 and 1940) for East Hungary. Hegerl, G.C. (2018) also mentions that the ETCW period was also a period of cold winters.

The Hungarian Meteorological Service publishes the time series of extreme cold and hot indices for Keszthely, among other stations in the country, on its homepage (www.met.hu). The graphs published on the website suggest that in the ETCW period days of extreme cold (e.g., number of cold days, number of frosty days) and the number of hot days were more frequent. Examining only the data for autumn, the ETCW cannot actually be detected. The only significant period is between 1969 and 2018, with an increasing trend in the seasonal mean temperature data. In the time series for winter, no significant trend can be detected in any segment. The beginning of the last segment (1924) is contemporary with the beginning of the ETCW, but the end cannot be detected.

With help of the descriptive statistics (mean, standard deviation) of the segments shown in *Table 2*, and trend analysis, the reasons for the presence of a change-point were explored. The change-point in the annual data in 1895 was probably caused by a rise of the mean, and a decline in SD. Between 1931 and 1951, a significant increasing trend is accompanied by a rise in the mean and in SD. From 1952, the mean and SD are lower than in the preceding segment. Between 1985 and 2018, a significant increasing trend can be identified as the reason for the change-point. In spring, all three segments display a significant increasing trend, and between 1925 and 1951, a higher mean and SD are observable. A cooling period can be found in summers between 1871 and 1926, while from 1927 the mean and SD are higher than previously. This is probably the reason for the change-point in 1927. The last period of the examined time series displays a significant rising trend. The change-point in autumn, 1924, may be the consequence of a rise of the mean and decline in the SD, implying a lower degree of autumn temperature variability compared with warmer years. The period 1969–2018 shows a significant increasing trend according to the MK trend test. In the three segments of the winter, an upward shift in the mean followed by a downward shift can be seen. In case of SD, the opposite pattern can be detected.

For the ETCW period, significant rising trends can be detected in the annual mean temperature and in spring. The mean temperature is higher than the previous or subsequent periods' average in the case of the annual data,

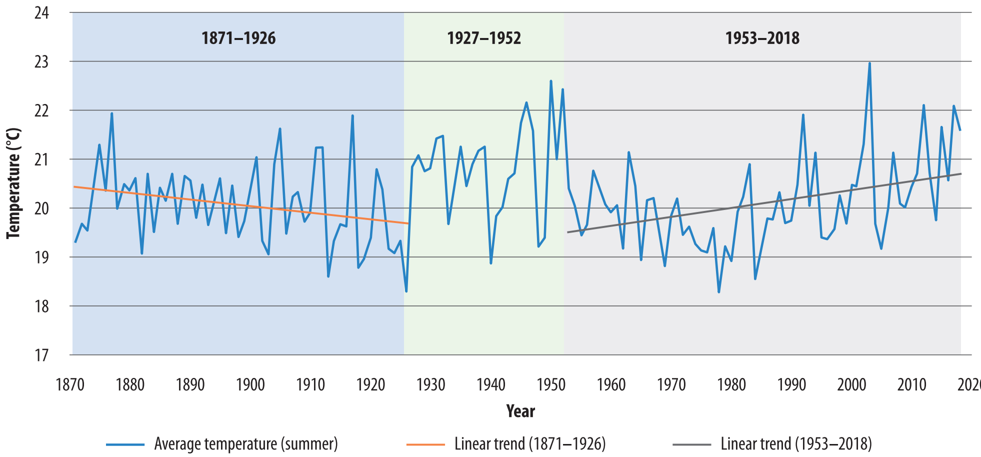

Fig. 5. Trends within segments in the summer season. *Source*: Authors' own elaboration.

Table 2. Mean (M) and standard deviation (SD) of the segments defined in Table 1

Seasons	M ºC /SD ºC/ (Period)				
Annual	*10.023 /0.707/ (1871–1894)*	*10.513 /0.509/ (1895–1930)*	*10.852 /0.893/ (1931–1951)*	*10.360 /0.642/ (1952–1984)*	*10.740 /0.803/ (1985–2018)*
Spring	10.644 /1.011/ (1871–1924)		11.036 /1.464/ (1925–1951)	10.860 /1.071/ (1952–2018)	
Summer	20.053 /0.818/ (1871–1926)		20.829 /0.943/ (1927–1952)	20.009 /0.897/ (1953–2018)	
Autumn	10.469 /1.215/ (1871–1923)		11.344 /1.009/ (1924–1968)	10.560 /1.194/ (1969–2018)	
Winter	-0.975 /2.094/ (1872–1895)	0.715 /1.583/ (1896–1923)	0.367 /1.856/ (1924–2018)		

and also individually in spring, summer and autumn, too. In comparison, the last part of the 20th century (i.e., well within the current warming period) displays significant warming tendencies for spring, summer and autumn, while the mean temperatures of these periods are slightly lower than those in the ETCW period. These facts suggest that in the ETCW period a shift in the mean was observable, while in the current warming period, a slow but significant increasing tendency is occurring.

Keszthely has local importance as a tourist destination and as a biodiversity reservation in Hungary. The high dependence of Keszthely weather on lakeshore conditions determines its characteristics, and this is likely to continue. The significant declining precipitation trend, together with rising temperature trends, may cause declining lake water levels, disturbing tourist activities. The specialty of its meteorological dataset lies in its unique uninterrupted length of 150 years (Kocsis, T. and Anda, A. 2006), and its particular importance in the assessment of the water quality of the largest shallow freshwater lake in Central Europe, Lake Balaton (Hatvani, I.G. *et al*. 2022), including its semi-constructed water protection system. Worldwide, wetlands cover 5–8 percent of total land surface (Mitsch, W.J. *et al.* 2013), including the Kis-Balaton wetland in the neighbourhood of Keszthely, and these wetlands constitute 20–30 percent of the total global carbon pool. They therefore play a crucial role in climate change mitigation (Dang, A.T.N. *et al.* 2021). The release of a wetland's CO_2 may also augment the local impacts of global warming.

Similar to global trends, the ETCW period can be detected between 1931 and 1951 in the annual mean temperature time series of Keszthely: between 1925 and 1951 a significant increasing trend is observed for spring mean temperature, and although in the case of summer and autumn, this period cannot be described as displaying any significant trends, an upward shift in the mean can be observed.

Similar to the regional results presented in this paper, evidence of significant increments in temperature between 1920 and 1950, then starting from 1985 until nowadays, are also reported in Italy (Herrera-Grimaldi, P. *et al*. 2018). Brunetti, M. *et al*. (2000) analysed the time series of annual mean temperature for the period of 1866–1995 and reported that the Italian climate has become warmer and drier, especially in the South, since about 1930. In the continental mid-latitudes of the Northern Hemisphere warm anomalies are often accompanied by dry conditions. So, besides warming trends during the ETCW, southeast of the present study area, in Bulgaria, several dry periods were detected in the 1940s by Alexandrov, V. *et al.* (2004). Moreover, in the 1930s the East European Plain was affected by intense long-lasting droughts (Popova, V. *et al.* 2022), and these are also considered to be connected to the ETCW. While the previously mentioned studies report droughts linked to the ETCW period, in Hungary Makra, L. *et al.* (2005) detected significant wet periods in the first part of the 20th century (between 1901 and 1940), while dry periods were found in the second half of the century, that is, including under the current warming period. Unfortunately, no literature could be found on investigations of the ETCW and its effects on the Central European region, nor on the Carpathian-Basin, nor on Hungary itself.

Conclusions

This paper wanted to fill the gap between the wide number of studies about the effects of ETCW in the Artic and limited investigations concerning its impact on Europe. Keszthely, with its uninterrupted temperature records since 1871, serves as a focal point for analysing long-term temperature trends. The research uncovers evidence of ETCW in Keszthely's annual, spring, and summer temperatures, but its indicators remain elusive during fall and winter. Furthermore, the study notes that the characteristics of ETCW in Central Europe slightly differ from those reported for the broader region. Unfortunately, due to a lack of studies on ETCW in the Carpathian Basin, comparisons could not be made, highlighting a critical area for future research.

***Acknowledgements*:** The dataset was provided by the Department of Meteorology and Water Management, Georgikon Campus, Hungarian University of Agriculture and Life Sciences (Keszthely). The authors thank Eric Ruggieri for his constructive comments on the methodology description.

REFERENCES

Alexandrov, V., Schneider, M., Koleva, E. and Moisselin, J.-M. 2004. Climate variability and change in Bulgaria during the 20th century. *Theoretical and Applied Climatology* 79. (3): 133–149. https://doi.org/10.1007/s00704-004-0073-4

Allan, R., Brohan, P., Compo, G.P., Stone, R., Luterbacher, J. and Brönnimann, S. 2011. The international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative. *Bulletin of the American Meteorological Society* 92. (11): 1421–1425. https://doi.org/10.1175/2011BAMS3218.1

Anda, A., Simon, Sz. and Simon-Gáspár, B. 2023. Impacts of wintertime meteorological variables on decomposition of Phragmites australis and Solidago canadensis in the Balaton System. *Theoretical and Applied Climatology* 151. 1963–1979. https://doi.org/10.1007/s00704-023-04370-y

Béll, B. and Takács, B. (eds.) 1974. *A Balaton éghajlata* (Climate of the Lake Balaton). Budapest, OMSZ. (in Hungarian)

Bokuchava, D.D. and Semenov, V.A. 2021. Mechanisms of the early 20th century warming in the Arctic. *Earth-Science Reviews* 222. 103820. https://doi.org/10.1016/j.earscirev.2021.103820

Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T. and Schöner, W. 2001. Regional temperature variability in the European Alps: 1760–1998 from homogenized instrumental time series. *International Journal of Climatology* 21. (14): 1779–1801. https://doi.org/10.1002/joc.689

Brázdil, R., Zahradníček, P., Pišoft, P., Štěpánek, P., Bělínová, M. and Dobrovolný, P. 2012. Temperature and precipitation fluctuations in the Czech Republic during the period of instrumental measurements. *Theoretical and Applied Climatology* 110. (1): 17–34. https://doi.org/10.1007/s00704-012-0604-3

Brönnimann, S. 2009. Early twentieth-century warming. *Nature Geoscience* 2. (11): 735–736. https://doi.org/10.1038/ngeo670

Brunetti, M., Maugeri, M. and Nanni, T. 2000. Variations of temperature and precipitation in Italy from 1866 to 1995. *Theoretical and Applied Climatology* 65. (3): 165–174. https://doi.org/10.1007/s007040070041

Camuffo, D. and Jones, P.D. 2002. Improved understanding of past climatic variability from early daily European instrumental sources. In *Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources*. Eds.: Camuffo, D. and Jones, P., Dordrecht, Springer Netherlands, 1–4. https://doi.org/10.1007/978-94-010-0371-1_1

Camuffo, D. 2018. Evidence from the archives of societies: Early instrumental observations In *The Palgrave Handbook of Climate History*. Eds.: White, S., Pfister, C. and Mauelshagen, F., London UK, Palgrave Macmillan, 83–92. https://doi.org/10.1057/978-1-137-43020-5_7

Dang, A.T.N., Kumar, L., Reid, M. and Anh, L.N.T. 2021. Modelling the susceptibility of wetland plant species under climate change in the Mekong Delta, Vietnam. *Ecological Informatics* 64. 1–15. https://doi.org/10.1016/j.ecoinf.2021.101358

Da Silva, R.M., Santos, C.A.G., Moreira, M., Corte-Real, J., Silva, V.C. and Medeiros, I.C. 2015. Rainfall and river flow trends using Mann-Kendall and Sen's slope estimator statistical tests in the Cobres River basin. *Natural Hazards* 77. 1205–1221. https://doi.org/10.1007/s11069-015-1644-7

Dee, D., Thorne, P., Noone, S., Baddour, O. and Tassone, C. 2021. The critical role of observations in informing climate science, assessment and policy. *Boletín-Organización Meteorológica Mundial* 70. (2): 27–33.

Delworth, T.L. and Knutson, T.R. 2000. Simulation of early 20th century global warming. *Science* 287. (5461): 2246–2250. https://doi.org/10.1126/science.287.5461.2246

Ducré-Robitaille, J.-F., Vincent, L.A. and Boulet, G. 2003. Comparison of techniques for detection of discontinuities in temperature series. *International Journal of Climatology* 23. (9): 1087–1101. https://doi.org/10.1002/joc.924

Gilbert, R.O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. London, John Wiley & Sons.

Hamed, K.H. and Rao, A.R. 1998. A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology* 204. 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X

Hatvani, I.G., de Barros, V.D., Tanos, P., Kovács, J., Kovács, I.S. and Clement, A. 2020. Spatiotemporal changes and drivers of trophic status over three decades in the largest shallow lake in Central Europe, Lake Balaton. *Ecological Engineering* 151. 105861. https://doi.org/10.1016/j.ecoleng.2020.105861

Hatvani, I.G., Topál, D., Ruggieri, E. and Kern, Z. 2022. Concurrent changepoints in Greenland ice core & delta: 180 records and the North Atlantic Oscillation over the past millennium. *Atmosphere* 13. (1): 93. https://doi.org/10.3390/atmos13010093

Hegerl, G.C., Brönnimann, S., Schurer, A. and Cowan, T. 2018. The early 20th century warming: Anomalies, causes, and consequences. *WIREs Climate Change* 9. (4): e522. https://doi.org/10.1002/wcc.522

Herrera-Grimaldi, P., García-Marín, A., Ayuso-Muñoz, J.L., Flamini, A., Morbidelli, R. and Ayuso-Ruíz, J.L. 2018. Detection of trends and break points in temperature: The case of Umbria (Italy) and Guadalquivir Valley (Spain). *Acta Geophysica* 66. (3): 329–343. https://doi.org/10.1007/s11600-018-0118-1

Hipel, K.W. and McLeod, A.I. 1994. *Time Series Modelling of Water Resources and Environmental Systems*. Amsterdam, Elsevier.

Horváth, Sz., Makra, L. and Mika, J. 2005. 20th century variations of the soil moisture in East Hungary. *Acta Climatologica et Chorologica, Universitatis Szegediensis* Tom. 38–39. 85–95.

Hungarian Meteorological Service – on its homepage www.met.hu: https://www.met.hu/eghajlat/eghajlatvaltozas/megfigyelt_hazai_valtozasok/hosegindexek/, and https://www.met.hu/eghajlat/eghajlatvaltozas/megfigyelt_hazai_valtozasok/hidegindexek/(in Hungarian)

IPCC 2021. Summary for policymakers. In *Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Eds.: Masson-Delmotte, V. *et al.*, New York–Cambridge UK, Cambridge University Press, 3–32. https://doi.org/10.1017/9781009157896.001

Izsák, B. and Szentimrey, T. 2020. To what extent does the detection of climate change in Hungary depend on the choice of statistical methods? *GEM – International Journal on Geomathematics* 11. (1): 17. https://doi.org/10.1007/s13137-020-00154-y

Jones, P.D. 2001. Early European instrumental records. In *History and Climate*. Eds.: Jones, P.D., Ogilvie, A.E.J., Davies, T.D. and Briffa, K.R., New York, Springer Science, 55–77. https://doi.org/10.1007/978-1-4757-3365-5_4

Kendall, M. 1975. *Rank Correlation Methods*. London, Charles Griffin.

Kocsis, T. and Anda, A. 2006. *A keszthelyi meteorológiai megfigyelések története* (The history of the meteorological measurements at Keszthely). Keszthely, Hungary, PE-GMK Nyomda. (in Hungarian)

Kocsis, T., Kovács-Székely, I. and Anda, A. 2020. Homogeneity tests and non-parametric analyses of tendencies in precipitation time series in Keszthely, Western Hungary. *Theoretical and Applied Climatology* 139. (3): 849–859. https://doi.org/10.1007/s00704-019-03014-4

Makra, L., Mika, J. and Horváth, Sz. 2005. 20th century variations of the soil moisture content in East Hungary in connection with global warming. *Physics and Chemistry of the Earth* 30. 181–186. https://doi.org/10.1016/j.pce.2004.08.035

Mann, H.B. 1945. Nonparametric tests against trend. *Econometrica* 13. (3): 245–259. https://doi.org/10.2307/1907187

Meyers, S.R. 2014. Astrochron: An R package for astrochronology. https://cran.r-project.org/package=astrochron

Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, C.J., Jørgensen, J.E. and Brix, H. 2013. Wetlands, carbon, and climate change. *Landscape Ecology* 28. 583–597. https://doi.org/10.1007/s10980-012-9758-8

Moberg, A., Jones, P.D., Barriendos, M., Bergström, H., Camuffo, D., Cocheo, C., Davies, T.D., Demarée, G., Martin-Vide, J., Maugeri, M., Rodriguez, R. and Verhoeve, T. 2000. Day-to-day temperature variability trends in 160- to 275-year-long European instrumental records. *Journal of Geophysical Research: Atmospheres* 105. (D18): 22849–22868. https://doi.org/10.1029/2000JD900300

Popova, V., Matveeva, T. and Bokuchava, D. 2022. The early 20th century warming in the East European plain climate: Extreme drought in 1920–1940, atmospheric circulation anomalies and links with the sea ice variability. *Environmental Sciences Proceedings* 19. (1): 57. https://doi.org/10.3390/ecas2022-12864

Przybylak, R. 2010. Instrumental observations. In *The Polish Climate in the European Context: An Historical Overview*. Ed.: Przybylak, R., Dordrecht, Springer Netherlands, 129–166. https://doi.org/10.1007/978-90-481-3167-9_5

Przybylak, R., Svyashchennikov, P.N., Uscka-Kowalkowska, J. and Wyszyński, P. 2021. Solar radiation in the Arctic during the early twentieth-century warming (1921–50): Presenting a compilation of newly available data. *Journal of Climate* 34. (1): 21–37. https://doi.org/10.1175/JCLI-D-20-0257.1

Quiang, R. and Ruggieri, E. 2023. Autocorrelation and parameter estimation in a Bayesian Change Point Model. *Mathematics* 11. 1082. https://doi.org/10.3390/math11051082

R Core Team 2019. *R: A Language and Environment for Statistical Computing*. Vienna, Austria, R Foundation for Statistical Computing. https://www.R-project.org/

Reeves, J., Chen, J., Wang, X., Lund, R.B. and Lu, Q. 2007. A review and comparison of changepoint detection techniques for climate data. *Journal of Applied Meteorology and Climatology* 46. 900–915. https://doi.org/10.1175/JAM2493.1

Ruggieri, E. 2013. A Bayesian approach to detecting change points in climatic records. *International Journal of Climatology* 33. (2): 520–528. https://doi.org/10.1002/joc.3447

Ruggieri, E. 2018. A pruned recursive solution to the multiple change point problem. *Computational Statistics* 33. (2): 1017–1045. https://doi.org/10.1007/s00180-017-0756-9

Ruggieri, E. and Antonellis, M. 2016. An exact approach to Bayesian sequential change point detection. *Computational Statistics & Data Analysis* 97. 71–86. https://doi.org/10.1016/j.csda.2015.11.010

Semenov, V.A. and Latif, M. 2012. The early twentieth century warming and winter Arctic sea ice. *The Cryosphere* 6. (6): 1231–1237. https://doi.org/10.5194/tc-6-1231-2012

Sen, P.K. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of American Statistical Association* 63. 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Shapiro, S.S. and Wilk, M.B. 1965. An analysis of variance test for normality (Complete samples). *Biometrika* 52. (3–4): 591–611. https://doi.org/10.2307/2333709

Stott, P., Strangeways, I. and the Climate Science Communications Group, 2018. Measuring meteorological variables for studying the climate. *Weather* 73. (10): 332–332. https://doi.org/10.1002/wea.3369

Svendsen, L., Keenlyside, N., Bethke, I., Gao, Y. and Omrani, N.-E. 2018. Pacific contribution to the early twentieth-century warming in the Arctic. *Nature Climate Change* 8. (9): 793–797. https://doi.org/10.1038/s41558-018-0247-1

Szentimrey, T. 1999. Multiple analysis of series for homogenization (MASH). In *Proceedings of the Second Seminar for Homogenisation of Surface Climatological Data*. Budapest, Hungary, WMO, 27–46.

Szentimrey, T. 2006. Development of MASH homogenization procedure for daily data. In *Proceedings of the Fifth Seminar for Homogenization and Quality Control in Climatological Databases*, Vol. 29. Budapest, Hungary, 123–130.

Szentimrey, T. 2008. An overview on the main methodological questions of homogenization. In *Proceedings of the Fifth Seminar for Homogenization and Quality Control in Climatological Databases. Climate Data and Monitoring WCDMP.* No. 71. 1–6.

Szinell, C.S., Bussay, A. and Szentimrey, T. 1998. Drought tendencies in Hungary. *International Journal of Climatology* 18. 1479–1491. https://doi.org/10.1002/(SICI)1097-0088(19981115)18:13<1479::AID-JOC325>3.0.CO;2-P

Tokinaga, H., Xie, S.-P. and Mukougawa, H. 2017. Early 20th-century Arctic warming intensified by Pacific and Atlantic multidecadal variability. *Proceedings of the National Academy of Sciences* 114. (24): 6227–6232. https://doi.org/10.1073/pnas.1615880114

Topál, D., Matyasovszkyt, I., Kern, Z. and Hatvani, I.G. 2016. Detecting breakpoints in artificially modified- and real-life time series using three state-of-the-art methods. *Open Geosciences* 8. (1): 78–98. https://doi.org/10.1515/geo-2016-0009

Yamanouchi, T. 2011. Early 20th-century warming in the Arctic: A review. *Polar Science* 5. (1): 53–71. https://doi.org/10.1016/j.polar.2010.10.002