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Precipitation conditions in Hungary from 1854 to 2022

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Abstract— In Hungary, the regular precipitation measurements began in the 1850s under the direction of the then Austrian Meteorological Institute based in Vienna, and from 1870 onwards continued under the Budapest-based "Meteorológiai és Földdelejességi Magyar Királyi Központi Intézet", now HungaroMet Hungarian Meteorological Service. Over the decades, the measurements have undergone many changes, including changes in instrumentation and relocation of stations, which cause inhomogeneities in the data series. In addition, the number of stations and the density of the station network have also changed significantly. As a result, the data series need to be homogenized and interpolated to a uniform grid in order to study the climate and its changes over the long term. In this paper, we present the methods used, discuss the station systems used for precipitation homogenization and interpolation in different periods, analyze the main verification statistics of homogenization and also the results of interpolation, and examine the annual, seasonal, and monthly precipitation data series and their extremes for the period 1854–2022.

Key-words: climate data, precipitation changes in Hungary, homogenization, interpolation, MASH, MISH, verification statistics, gridded data series

1. Introduction

To better understand the climate system and its changes, we need to analyze long data series with high quality. Precipitation is a highly variable element in space and time, so long time series and many more stations are needed to describe the spatial characteristics of precipitation compared to, for example, temperature. Climate research and studies on precipitation conditions in Hungary, based on precipitation measurements, can typically be found from the beginning of the 20th century. There are few analyses dating back to the 19th century (*Izsák et al.*, 2022). Most of the precipitation data are digitized from the mid-20th century, from 1951 onwards. Precipitation measurements from the earlier period are mostly available on precipitation data sheets and in climatological books. It is, therefore, important to collect these data series, which have not yet been digitized, in order to have as accurate knowledge as possible of precipitation conditions and their changes.

The data series contain inhomogeneities due to, for example, station relocations, instrument changes, or changes in the environment, and therefore, homogenization is necessary. Several methods and software have been developed in recent decades to homogenize meteorological elements (*Venema et al.*, 2012, 2020). These include, for example, the MASH (*Szentimrey*, 1999, 2017, 2023), the standard normal homogeneity test (SNHT) (*Alexandersson*, 1986; *Alexandersson* and *Moberg*, 1997), the HOMER (*Mestre et al.*, 2013; *Joelsson et al.*, 2021), and the ACMANT (*Domonkos*, 2015) methods.

For homogenization of data series, quality control, and filling in the missing values, we use the MASH (Multiple Analysis of Series for Homogenization) procedure at the Climate Department of the Hungarian Meteorological Service (OMSZ) (*Szentimrey*, 1999, 2008a, 2017). By applying the MASHv3.03 software, homogenized and quality-controlled data series become available without missing data for further analysis. The MASH method is based on hypothesis testing. To homogenize the precipitation series, we used a multiplicative model with a significance level of 0.01. Inhomogeneities are estimated from the monthly data series. The monthly, seasonal, and annual inhomogeneities are harmonized in all MASH systems (considering different station networks).

There are several interpolation methods that are used to produce gridded climate data series (*Sluiter*, 2009). For the spatial interpolation of precipitation, the MISH (Meteorological Interpolation based on Surface Homogenized Data Basis) method, specifically developed for the interpolation of meteorological elements, is used at the Hungarian Meteorological Service (*Szentimrey* and *Bihari*, 2007, 2014).

2. Applied methods

For homogenization of data series, quality control and filling in the missing data, we use the MASH (*Szentimrey*, 1999, 2008b, 2017) procedure at the Climate Department of HungaroMet Hungarian Meteorological Service. By applying the MASHv3.03 software we have missing data filled, homogenized, and quality-controlled data series.

2.1. The main properties of MASH procedure

The homogenization of monthly series includes:

- a relative homogeneity test procedure,
- a step-by-step iteration procedure,
- additive (e.g., temperature) or multiplicative (e.g., precipitation) models that can be selected,
- quality control and missing data completion,
- homogenization of seasonal and annual series,
- metadata (probable dates of breakpoints) that can be used automatically,
- automatically generated verification files.

The homogenization of daily series is:

- based on the detected monthly inhomogeneities,
- quality controlled and containing the completion of missing data for each day.

If the data series are lognormally distributed (e.g., precipitation), then the multiplicative model can be used (*Szentimrey*, 2008a). In the case of relative methods, a general form of multiplicative model for additional monthly series belonging to the same month in a small climate region can be expressed as follows:

$$X_j^*(t) = C^*(t) \cdot IH_j^*(t) \cdot \varepsilon_j^*(t) \quad (j = 1,2,\ldots,N;\ t = 1,2,\ldots,n), \tag{1}$$

where X^* indicates the candidate series, C^* is the climate change, IH^* is the inhomogeneity, ε^* is the noise, N is the number of stations, and n is the total number of time steps.

Logarithmization for additive model gives the following equation:

$$X_j(t) = C(t) + IH_j(t) + \varepsilon_j(t) \quad (j = 1,2,\ldots,N;\ t = 1,2,\ldots,n), \tag{2}$$

where

$$X_j(t) = \ln X_j^*(t) \quad , \quad C(t) = \ln C\,(t),$$

$$IH_j(t) = \ln IH_j^*(t) \quad , \quad \varepsilon_j(t) = \ln \varepsilon_j^*(t).$$

A problem occurs if $X_j^*(t)$ values are near or equal to 0. This problem can be solved by a transformation procedure that slightly increases the small values. Consequently, the multiplicative model can be transformed into the additive model (*Szentimrey*, 1999, 2017). Once homogenization is complete, the data series are retransformed.

2.2. The main properties of MISH method

By using the MISHv1.03 software (*Szentimrey* and *Bihari*, 2007, 2014), spatially representative data series are obtained. MISH consists of a modeling and an interpolation subsystem.

The main features of the modeling subsystem for climate statistical (local and stochastic) are as follows:

- it is based on long term homogenized data series and supplementary deterministic model variables (height, topography, distance from the sea etc.),
- additive (e.g., temperature) or multiplicative (e.g., precipitation) models can be selected,
- the modeling procedure should be executed only once before the interpolation applications,
- it uses a high resolution grid (e.g., 0.5'×0.5').

The main characteristics of the interpolation subsystem are as follows:

- use of the modeled parameters for the interpolation of the meteorological elements to any point or grid,
- use of background information (e.g., satellite, radar, forecast data),
- data series completion (missing value interpolation for daily or monthly station data) during the interpolation process,
- capability for interpolation, gridding of monthly or daily station data series.

In practice, many kinds of interpolation methods exist (e.g., inverse distance weighting (IDW), kriging, spline interpolation), therefore the question is the difference between them (*Szentimrey et al.*, 2011). According to the interpolation problem, the unknown predictand $Z(\mathbf{s}_0, t)$ is estimated by use of the known predictors $Z(\mathbf{s}_i, t)$ $(i = 1, \ldots, M)$, where the location vectors $\mathbf{s}$ are the elements of the given space domain, M is the total number of predictors, and t is the time. The type of the adequate interpolation formula depends on the probability distribution of the meteorological element.

In the case of precipitation, a multiplicative model can be applied for a quasi-lognormal distribution:

$$\hat{Z}(s_0,t) = \vartheta \cdot \left(\prod_{q_i \cdot Z(s_i,t) \geq \vartheta} \left(\frac{q_i \cdot Z(s_i,t)}{\vartheta}\right)^{\lambda_i}\right) \cdot \left(\sum_{q_i \cdot Z(s_i,t) \geq \vartheta} \lambda_i + \sum_{q_i \cdot Z(s_i,t) < \vartheta} \lambda_i \cdot \left(\frac{q_i \cdot Z(s_i,t)}{\vartheta}\right)\right), \quad (3)$$

where $\vartheta > 0, q_i > 0, \sum_{i=1}^{M} \lambda_i = 1$, and $\lambda_i \geq 0$ $(i = 1, \ldots, M)$, q_i, λ_i $(i = 1, \ldots, M)$ are the interpolation parameters (*Szentimrey* and *Bihari*, 2014).

The root mean squared interpolation error (RMSE) is defined as follows:

$$RMSE(s_0) = \sqrt{E\left(\left(Z(s_0,t) - \hat{Z}(s_0,t)\right)^2\right)}, \quad (4)$$

and the representativity of the station network can be defined as follows:

$$REP(s_0) = 1 - \frac{RMSE(s_0)}{D(s_0)}, \quad (5)$$

where E is the expected value and $D(s_0)$ is the standard deviation of the predictand.

2.3. ANOVA (analysis of variance)

To compare gridded data sets interpolated from different numbers of data series, ANOVA is performed to examine the estimated spatiotemporal variances (*Szentimrey* and *Bihari*, 2014; *Izsák et al.*, 2022).

Notations:

$Z(s_j,t)$ $(j = 1, \ldots, N; t = 1, \ldots, n)$ – gridded data series $(s_j$: location, t: time),

$\hat{E}(s_j) = \frac{1}{n}\sum_{t=1}^{n} Z(s_j,t)$ (j=1,…,N) – temporal mean at location s_j,

$\hat{D}(s_j) = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(Z(s_j,t) - \hat{E}(s_j))^2}$ (j=1,…,N) – temporal standard deviation at location s_j,

$\hat{E}(t) = \frac{1}{N}\sum_{j=1}^{N} Z(s_j,t)$ (t=1,…,n) – spatial mean at moment t,

$\hat{D}(t) = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(Z(s_j,t) - \hat{E}(t))^2}$ (t=1,…,n) – spatial standard deviation at moment t,

$\hat{E} = \frac{1}{N \cdot n}\sum_{j=1}^{N}\sum_{t=1}^{n} Z(s_j,t) = \frac{1}{N}\sum_{j=1}^{N}\hat{E}(s_j) = \frac{1}{n}\sum_{t=1}^{n}\hat{E}(t)$ – total mean,

$\hat{D}^2 = \frac{1}{N \cdot n}\sum_{j=1}^{N}\sum_{t=1}^{n}(Z(s_j,t) - \hat{E})^2$ – total variance.

Partitioning of Total Variance (Theorem):

$$\widehat{D}^2 = \frac{1}{N}\sum_{j=1}^{N}\left(\widehat{E}(s_j) - \widehat{E}\right)^2 + \frac{1}{N}\sum_{j=1}^{N}\widehat{D}^2(s_j) = \frac{1}{n}\sum_{t=1}^{n}\left(\widehat{E}(t) - \widehat{E}\right)^2 + \frac{1}{n}\sum_{t=1}^{n}\widehat{D}^2(t).$$

The analysis of these terms is recommended to characterize the spatiotemporal variability.

Spatial terms:

spatial variance of temporal means: $\frac{1}{N}\sum_{j=1}^{N}\left(\widehat{E}(s_j) - \widehat{E}\right)^2$,

and temporal mean of spatial variances: $\frac{1}{n}\sum_{t=1}^{n}\widehat{D}^2(t)$.

Temporal terms:

spatial mean of temporal variances: $\frac{1}{N}\sum_{j=1}^{N}\widehat{D}^2(s_j)$,

and temporal variance of spatial means $\frac{1}{n}\sum_{t=1}^{n}\left(\widehat{E}(t) - \widehat{E}\right)^2$.

We do not show the variances but the standard deviations instead, to make the values easier to interpret, especially in the case of precipitation:

total standard deviation: $\widehat{D} = \sqrt{\frac{1}{N \cdot n}\sum_{j=1}^{N}\sum_{t=1}^{n}\left(Z(s_j, t) - \widehat{E}\right)^2}$,

spatial standard deviation of temporal means: $\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(\widehat{E}(s_j) - \widehat{E}\right)^2}$,

root spatial mean of temporal variances: $\sqrt{\frac{1}{N}\sum_{j=1}^{N}\widehat{D}^2(s_j)}$,

temporal standard deviation of spatial means: $\sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\widehat{E}(t) - \widehat{E}\right)^2}$,

root temporal mean of spatial variances: $\sqrt{\frac{1}{n}\sum_{t=1}^{n}\widehat{D}^2(t)}$.

3. Data

The meteorological measurements in Hungary are stored in the climate database of the HungaroMet. Today, meteorological measurements from automatic meteorological stations are continuously entered into the database. Records of older, pre-automation times are contained in climatological books and precipitation data sheets. The digitization of old data into the climate database is still ongoing. Most of the precipitation data from the 1950s are available in digital form also, whereas most of the precipitation data from earlier decades are still available only on paper. Recently, all monthly precipitation data from the beginning of the measurements in

Hungary have been collected, and these precipitation data can now be used also to create a homogenized and gridded climate database.

Before including data that has not yet been digitized, the existing daily precipitation database was renewed, and a study was published about this (*Szentes et al.*, 2023). That paper describes the changes in the station systems used and the main results of the homogenization. The renewal of the station networks was necessary because of the increasing lack of data, especially for the long series (due to the closure of stations), and therefore, the main objectives were (i) to minimize the missing data and (ii) to keep the old data series with long measurements by creating new merged station series. There is no significant change in the data set consisting of 131 stations used in the first half of the 20th century, the old and new systems are almost identical. However, in the last 10–20 years, several stations were discontinued and, in several cases, new station series were merged with nearby stations to have more data in years close to the present. In the shorter period (from 1951) we use 500 stations instead of the 461 stations previously used. From the previously used 461 stations, ~20 stations were deleted due to too much missing value and ~60 new stations, previously not used during the homogenization were added. The 500 data series for the shorter period (from 1951) includes the 131 data series which are available for the long period. The amount of missing data is not zero in the present either, because we use data from areas with higher spatial variability of precipitation (mountainous areas), where we have found stations that have been in operation for several decades then have stopped and there are no other stations in the vicinity to merge with.

3.1. Expansion of the station system before 1951

As shown above, the Hungarian precipitation climate database is currently based on two station systems: 131 stations from 1901, and 500 stations from 1951 (marked as different MASH systems later). The large jump in the number of data series from 1951 is explained by the fact that the majority of data series in the database were digitized from the mid-20th century. Extensive precipitation measurements in Hungary began in the 1850s. Recently, as a new achievement, all the monthly precipitation data have been collected from the beginning of measurements to 1950 (*Fig. 1*), which have not yet been digitized. This allowed a significant expansion of the station systems used for homogenization of data from the first half of the 20th century and the second half of the 19th century. In the last year, the monthly precipitation totals of all precipitation stations in Hungary were collected and digitized since the beginning of the measurements. Following this, new station systems were established, homogenized, and interpolated, which provided the first insight into the precipitation conditions in Hungary since the beginning of the measurements. *Figs. 2* and *3* show the number of available precipitation data series for the first half of the 20th century and the second half of the 19th century.

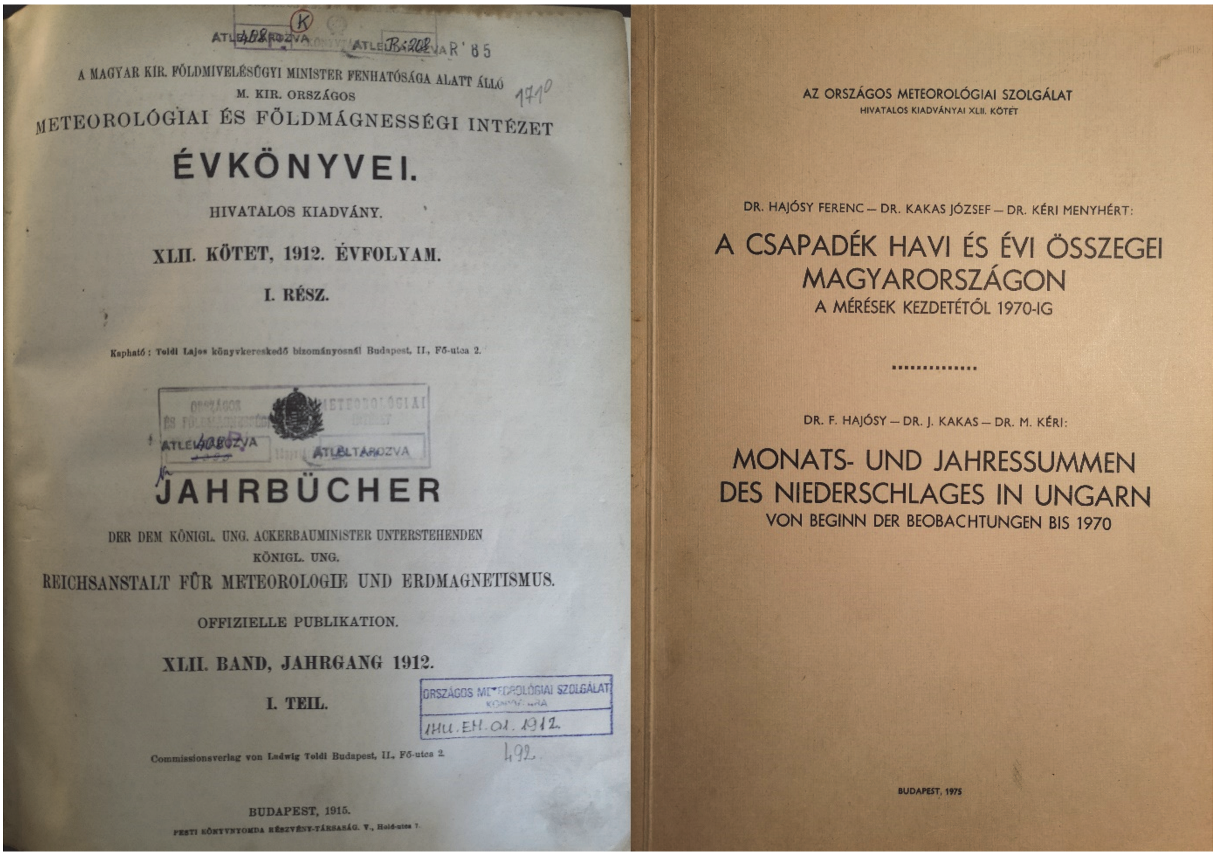

Fig. 1. Example for climatological books containing monthly precipitation data for Hungary.

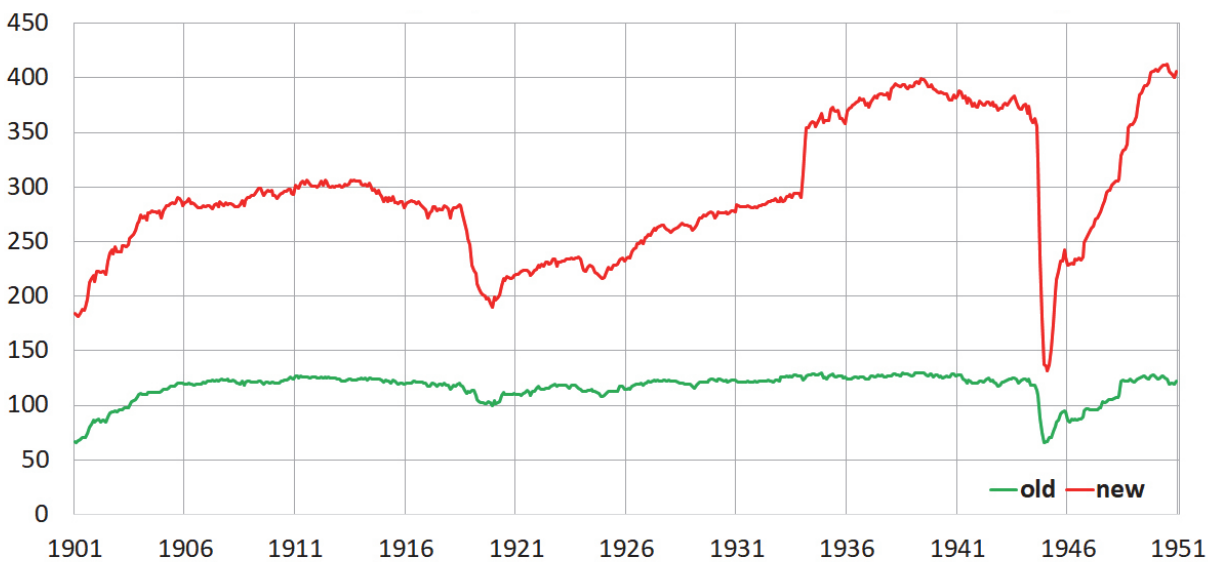

Fig. 2. Number of monthly precipitation station data series in Hungary (within today's border) during the first half of the 20th century.

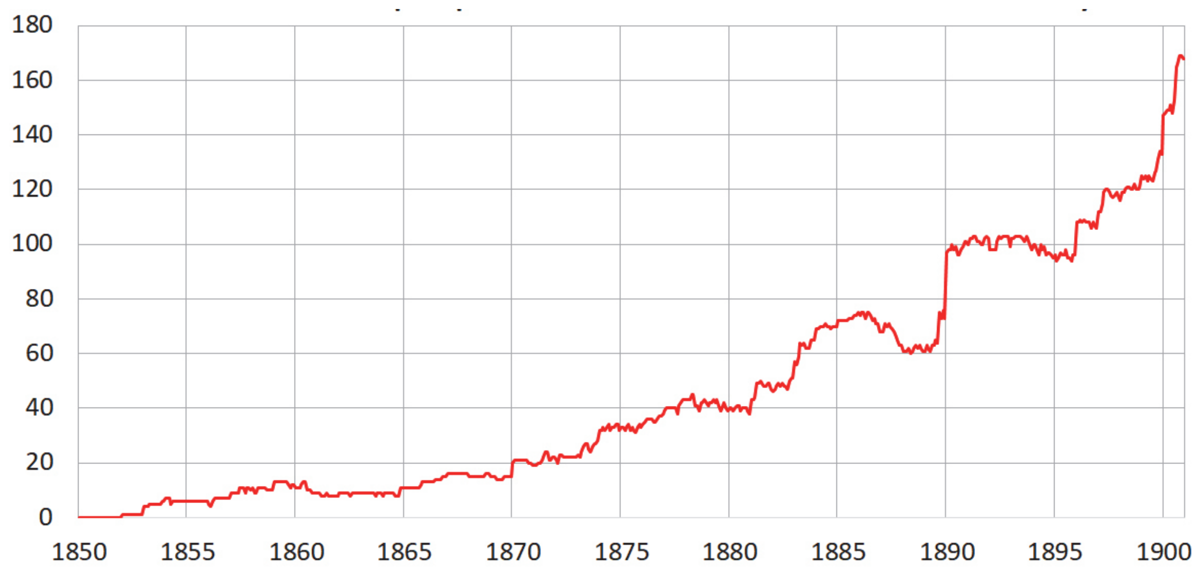

Fig. 3. Number of monthly precipitation station data series in Hungary (within today's border) during the second half of the 19th century.

Major station network expansions took place in the early 20th century and in the 1930s, so that the previous homogenization from 1901 onwards in one step was replaced by a two-step homogenization in the first half of the 20th century. The devastation of World War II is reflected in the temporary cessation of measurements at about 70% of the precipitation stations by 1945.

In the second half of the 1800s, the expansion of the network of stations was relatively continuous with an accelerating trend from the 1870s onwards. Regular measurements in different parts of the country started in 1854, under the control of the then Austrian Meteorological Institute (now GeoSphere Austria), so that 1854 can be considered as the beginning of precipitation measurements in Hungary. For the second half of the 19th century, the homogenization took place in three steps.

So, in total, there are six steps in the homogenization of precipitation, from 1854 to the present: from 1854 30, from 1870 50, from 1881 124, from 1901 318, from 1931 402, and from 1951 500 station data series (*Fig. 4*) are homogenized, any missing data is completed, and the overall resulting time series are quality controlled.

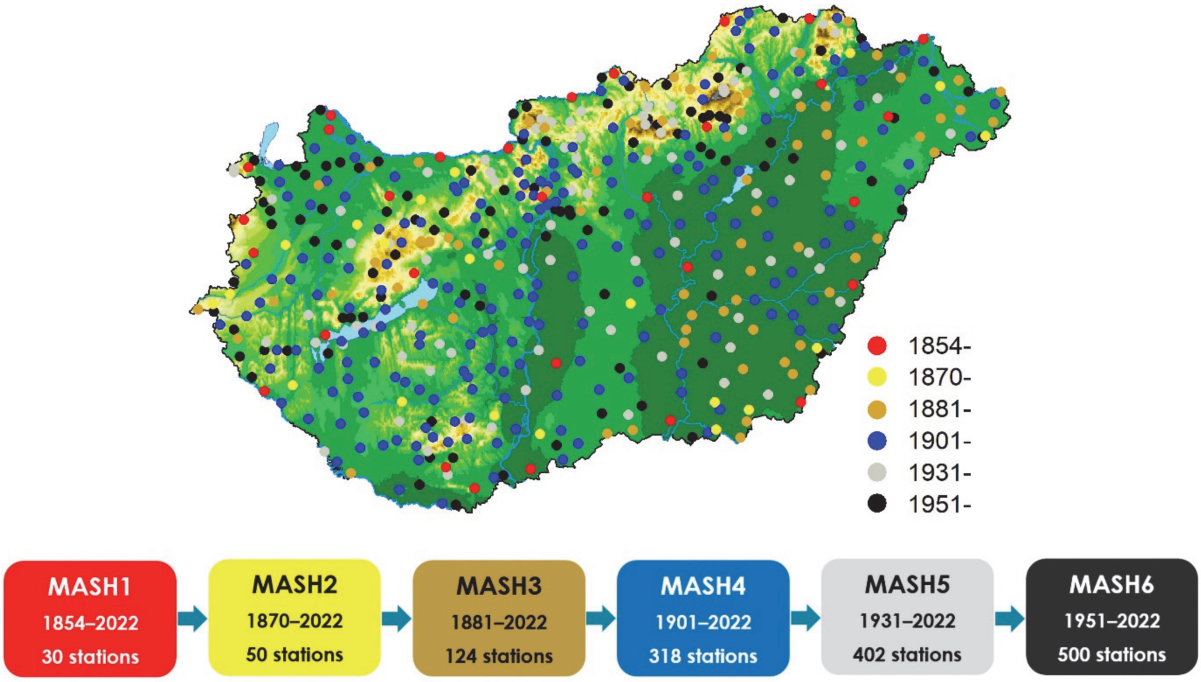

Fig. 4. The six MASH systems and the location of the precipitation stations used within them.

4. Results

4.1. Results of homogenization

The homogenization is carried out in a total of six separate station systems, where the inhomogeneities (monthly, seasonal, and annual) detected in each station system are harmonized during the homogenization procedure. Of course, MASH systems with shorter periods include the stations with longer data series (e.g., MASH2 system includes MASH1 data series from 1870). *Table 1* presents a summary of the main verification statistics for the annual precipitation sum for each station system.

Table 1. Main verification statistics of homogenization for annual precipitation sum

	MASH1	MASH2	MASH3	MASH4	MASH5	MASH6
Number of series	30	50	124	318	402	500
Critical value (significance level: 0.01)	28.00	28.00	28.00	28.00	29.00	29.00
Test statistics before homogenization	87.62	87.57	122.67	73.19	53.17	46.27
Test statistics after homogenization	28.42	28.16	30.74	29.11	25.58	25.18
Relative modification of series	0.30	0.28	0.25	0.19	0.15	0.12
Representativity of station network	0.55	0.56	0.61	0.67	0.69	0.70

Before homogenization, the average test statistics for all station systems is well above the critical value, while the test statistics after homogenization are close to or below the critical value, so the precipitation database can be considered homogeneous at the end. The modification of the data series is of course greater for longer data series, as longer data series contain more inhomogeneities, for example due to the more instrument changes and relocations.

The inhomogeneities due to relocations are illustrated well by the annual precipitation data of Budapest belterület (inner city) station (*Fig. 5*). This station is located at the headquarters of the HungaroMet. The largest breaks at this station were caused by relocations. Precipitation is currently measured on the roof of the meteorological observation tower, where the precipitation gauge was installed in 1985. The current location is much windier than before, which caused a reduction of about 6% in the annual precipitation.

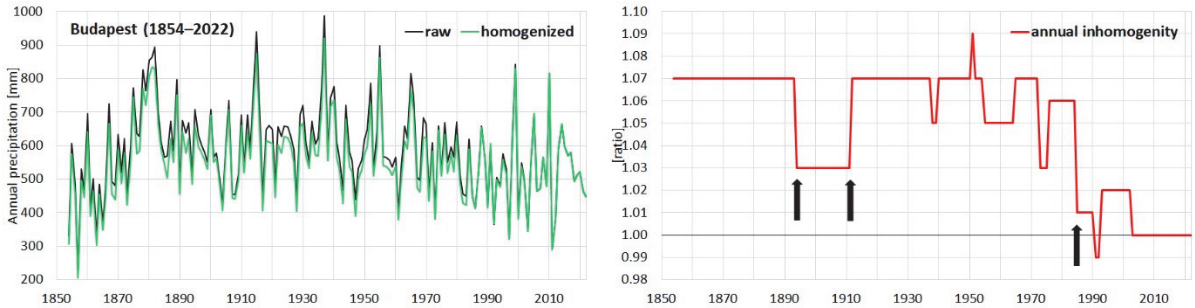

Fig. 5. Raw and homogenized annual precipitation sum (left) and annual inhomogeneities (right) of Budapest from 1854 to 2022, black arrows indicate the relocations.

4.2. Results of interpolation

After homogenization, the data series were interpolated with the MISHv1.03 software to a grid of 0.1°. The average of the grid points means the country average.

The question arises, how similar are the gridded data sets produced from different numbers of data series? We aim to produce a gridded precipitation database, where gridded data series interpolated from 30 stations (MISH1) and 500 stations (MISH6) show similar spatiotemporal characteristics. An ANOVA was carried out on the gridded datasets interpolated from six different station systems for the period 1951–2022 for all MISH systems. *Table 2* shows the main ANOVA results for the annual precipitation.

Table 2. The most important ANOVA results for the gridded annual precipitation series for the different station systems in the time period 1951–2022

	MISH1	MISH2	MISH3	MISH4	MISH5	MISH6
Total mean	597.87	598.40	600.30	601.46	601.19	602.05
Total standard deviation	131.72	131.73	133.14	135.20	135.19	135.72
Spatial standard deviation of temporal means	66.54	68.17	67.95	68.69	67.96	68.38
Root spatial mean of temporal variances	113.17	112.02	113.99	115.79	116.23	116.58
Temporal standard deviation of spatial means	97.50	96.53	97.55	98.80	99.04	99.11
Root temporal mean of spatial variances	85.94	87.20	88.21	89.65	89.49	90.15

The ANOVA results show that the total (spatial) mean for all MISH systems is around 600 mm, and the deviations are within 1%. The spatial standard deviations of temporal means and the temporal standard deviations of spatial means are also very similar.

Regarding the spatial standard deviation series of temporal means and the temporal standard deviations series of spatial means for the years 1951–2022 (*Fig. 6*), the interpolation results do not show significant differences from year to year. The ANOVA results are also very similar for the drier and wetter years.

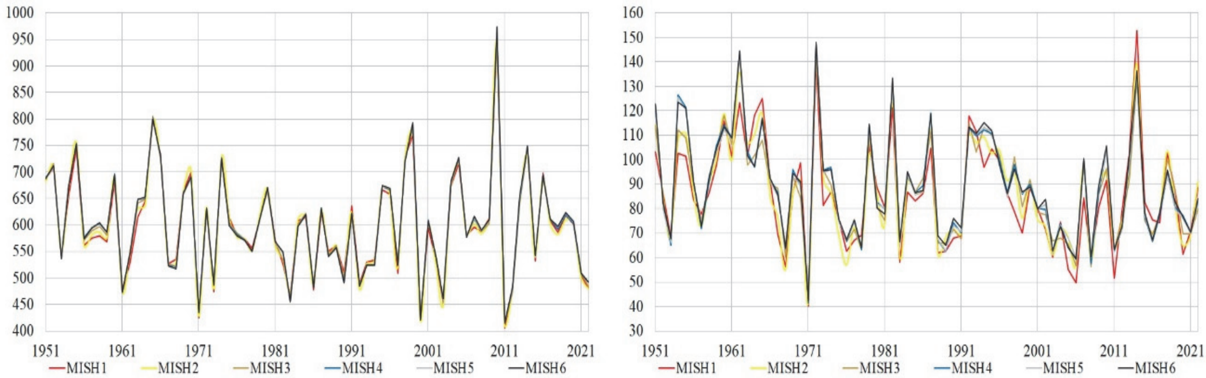

Fig. 6. Spatial mean series (left) and spatial standard deviation series (right) of annual precipitation (in mm) for the different MISH systems (indicated by different colors) from 1951 to 2022.

Comparing the grid point data series produced from fewer stations with the densest grid using 500 stations, we find that the absolute values of the mean errors (ME) for the spatial means are below 1 mm for all months in the period 1951–2022, and furthermore, the RMSE values are below 5 mm (*Fig. 7*). Therefore, also the spatial mean (country average) produced from a small number of station data sets can be considered representative for Hungary. These small deviations are due to the very good MISH-modeled climate statistical parameters, which are used in the interpolation procedure. In summer, much of the precipitation is convective, and therefore, there is much more spatial variability, which explains the slightly higher values in summer.

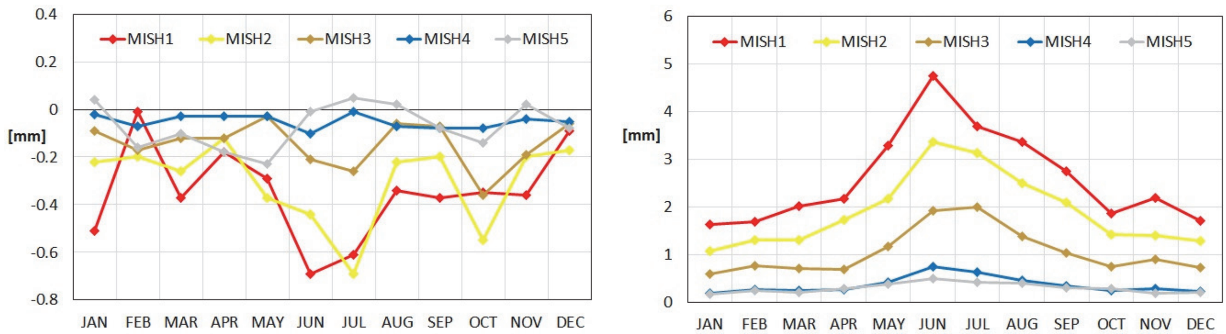

Fig. 7. Monthly mean errors (left) and Root Mean square errors (right) in spatial means of precipitation for the period 1951–2022 compared to interpolation from 500 stations in different MISH systems.

4.3. Annual precipitation

Before the seasonal and monthly precipitation, we first analyze the annual precipitation sum. *Fig. 8* shows the spatial means of annual precipitation for Hungary from 1854 to 2022.

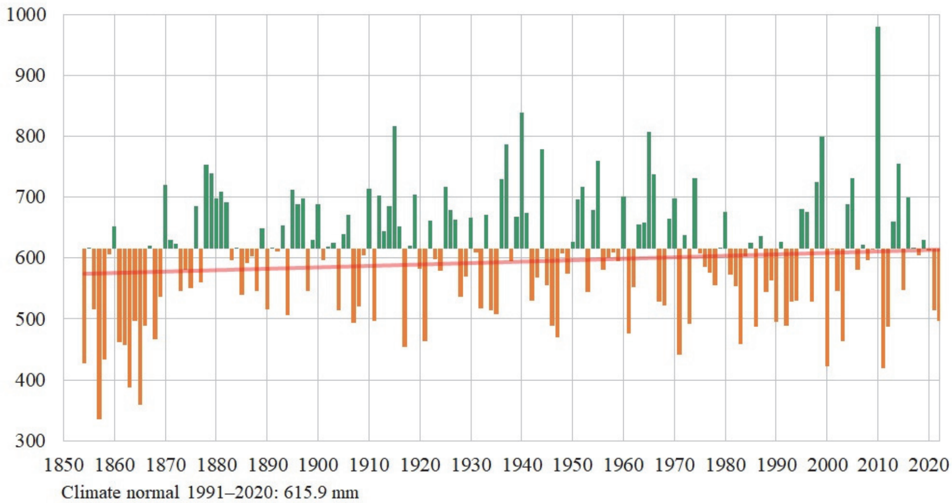

Fig. 8. Spatial means of annual precipitation in Hungary from 1854 to 2022, with the fitted exponential trend.

As a result of this work, precipitation conditions in Hungary can be analyzed from the beginning of precipitation measurements to the present day for the first time, including the very dry period around the 1860s. The year 2011 was the driest year since 1901, however, starting from 1854, there were three drier years around the 1860s: 1857, 1863, and 1865. In the period 1861–1866, rainfall was below 500 mm on average for the country in each year. This drought is also illustrated by the fact that Lake Fertő, for example, last dried up in the 1860s. The wettest year in Hungary since 1854 was 2010, while the wettest consecutive period of several years occurred around 1880, between 1878 and 1882. Over the whole period, the annual precipitation shows a slight increase of 6.9%, but this change is not significant at the 0.1 significance level.

Climate normals

The mean annual precipitation in Hungary is close to 600 mm as a countrywide average. However, there are larger variations in different parts of the country, but independent from the chosen climate normal period, a similar pattern of spatial distribution of precipitation is obtained (*Fig. 9*). The wettest areas of Hungary are the mountainous regions and the western and southwestern counties. These areas also receive mean annual precipitation of more than 700–750 mm. The driest part of the country is the central region of the Great Hungarian Plain, furthest from the mountains. In the central part of the Great Hungarian Plain, the least mean annual precipitation is below 550 mm for all climate normal periods, with variable spatial extent (*Szentes*, 2023).

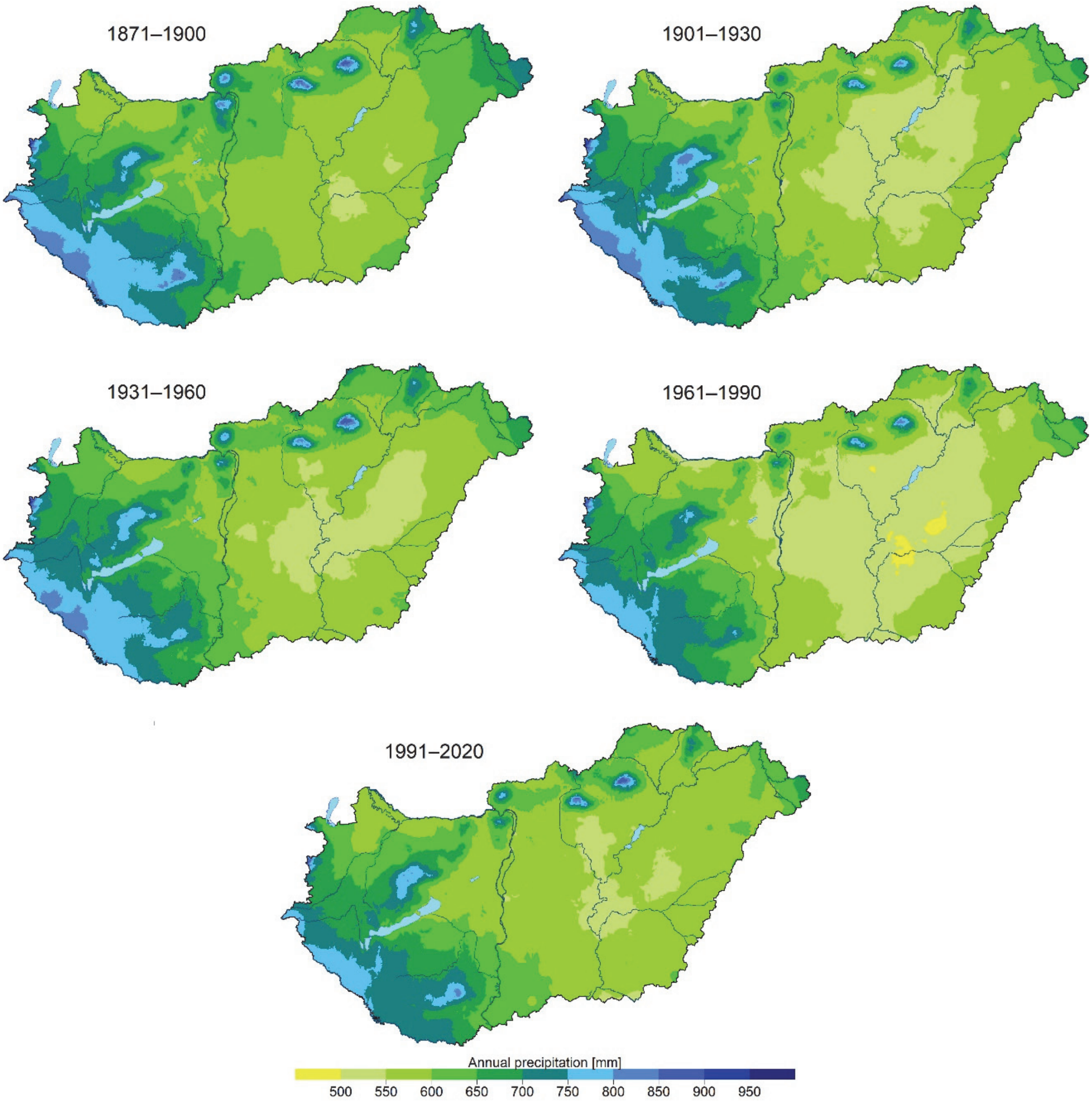

Fig. 9. Distribution of mean annual precipitation in Hungary in different climate normal periods.

4.4. Seasonal and monthly precipitation

Winter

In Hungary, the driest season is winter. The temporal mean of the spatial mean precipitation for the period 1991–2020 is 115.2 mm. Of all the seasons, only winter shows a significant change in precipitation, with an increase of 31.3% over the whole period. In the second half of the 19th century, extreme dry winters were common, with a few years of winter precipitation below 70 mm, while only a few wet winters occurred (*Fig. 10*). The wettest winters (above 150 mm) occurred in the 1950s, 1960s, and the last decade.

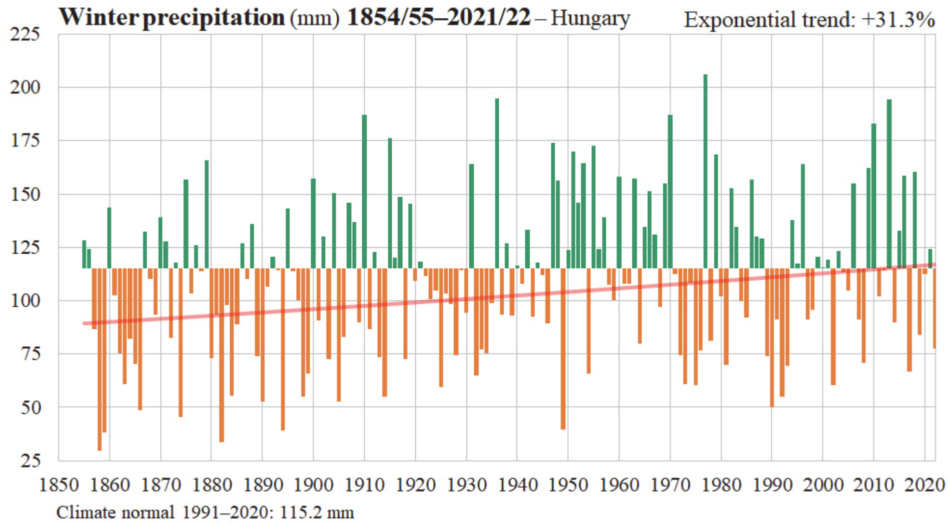

Fig. 10. Spatial means of winter precipitation in Hungary from 1854/1855 to 2021/2022, with the fitted exponential trend.

Regarding the precipitation for the winter months (*Fig. 11*), all three winter months show an increase, from which the change is significant only in February. Overall, the driest winter month is January, the wettest is December, but all three months remain below 50 mm on average.

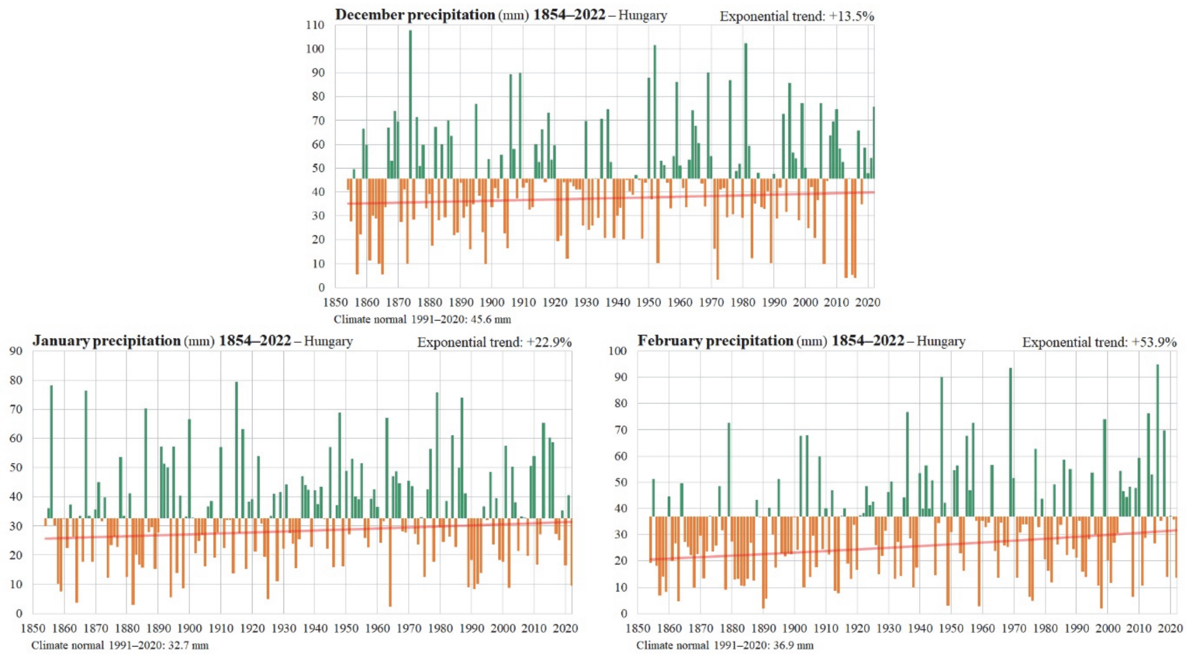

Fig. 11. Spatial means of precipitation in the winter months in Hungary from 1854 to 2022, with the fitted exponential trends.

Spring

The temporal mean of the spatial mean precipitation for the period 1991-2020 is 139.1 mm in spring. Over the whole period, spring precipitation shows a decrease, but this change is not significant. Several very dry springs occurred until the mid-1870s, as well as lately, since the 1990s (*Fig. 12*). In addition, dry springs were more frequent in the 1940s. However, from the late 1870s to the early 1940s, springs were mostly wetter than in the present day.

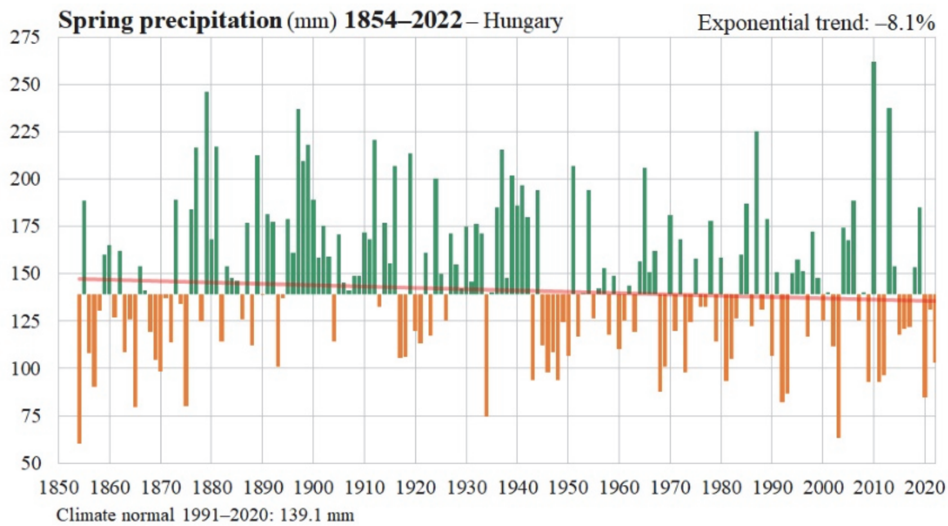

Fig. 12. Spatial means of spring precipitation in Hungary from 1854 to 2022, with the fitted exponential trend.

Among the spring months, there is a decrease in March and April and a slight increase in May. The decrease in March precipitation is significant. In average, March is the driest and May is the wettest spring month in Hungary, but April was drier than March several times in the last 15 years (*Fig. 13*).

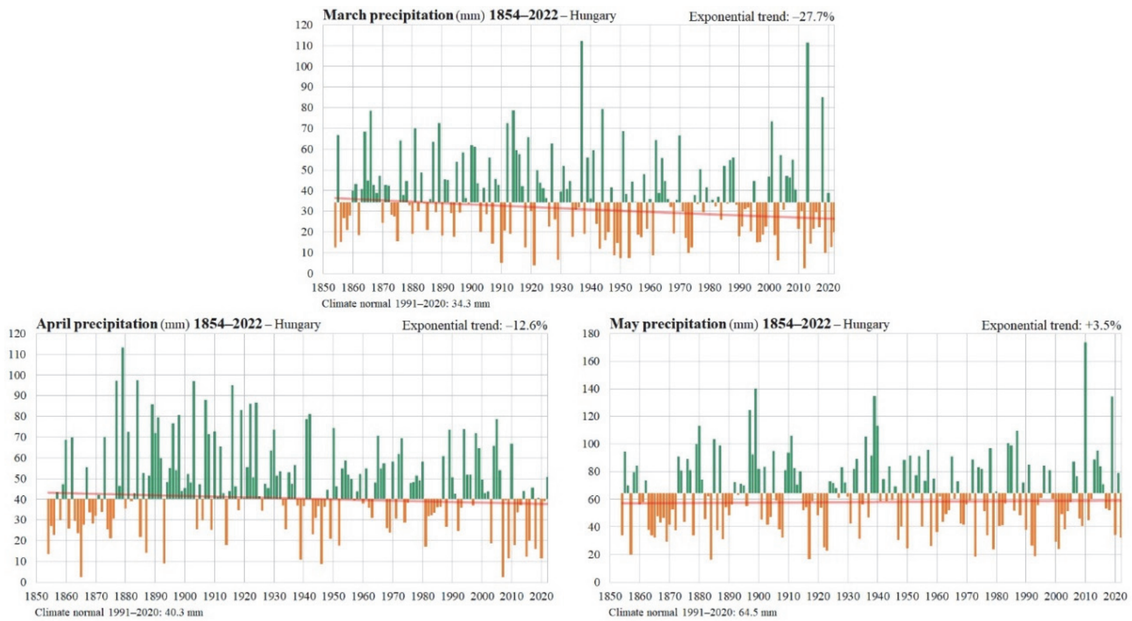

Fig. 13. Spatial means of precipitation in the spring months in Hungary from 1854 to 2022, with the fitted exponential trends.

Summer

In all climate normal periods in Hungary, summer is the wettest season. The temporal mean of the spatial mean precipitation for the latest climate normal period (1991–2020) is 203.1 mm in summer. A slight increase in summer precipitation is detected between 1854 and 2022, however, this is not significant. Dry summers were frequent during the dry period of the 1850s and 1860s, but extreme dry summers occur in Hungary in all decades (*Fig. 14*). In the wettest summers, the spatial means exceeds 250 mm, less frequently even 300 mm.

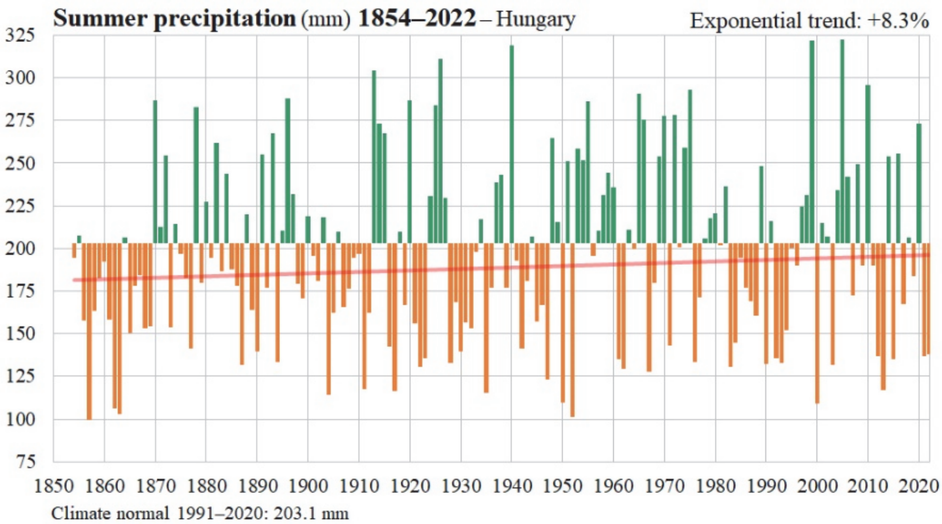

Fig. 14. Spatial means of summer precipitation in Hungary from 1854 to 2022, with the fitted exponential trend.

There is no significant change in precipitation for the summer months, with June and August showing near zero changes and July showing a slight increasing trend (*Fig. 15*). Previously, June was clearly the wettest month in Hungary, but the slightly higher increase in July precipitation resulted in the 1991-2020 averages for June and July being the same.

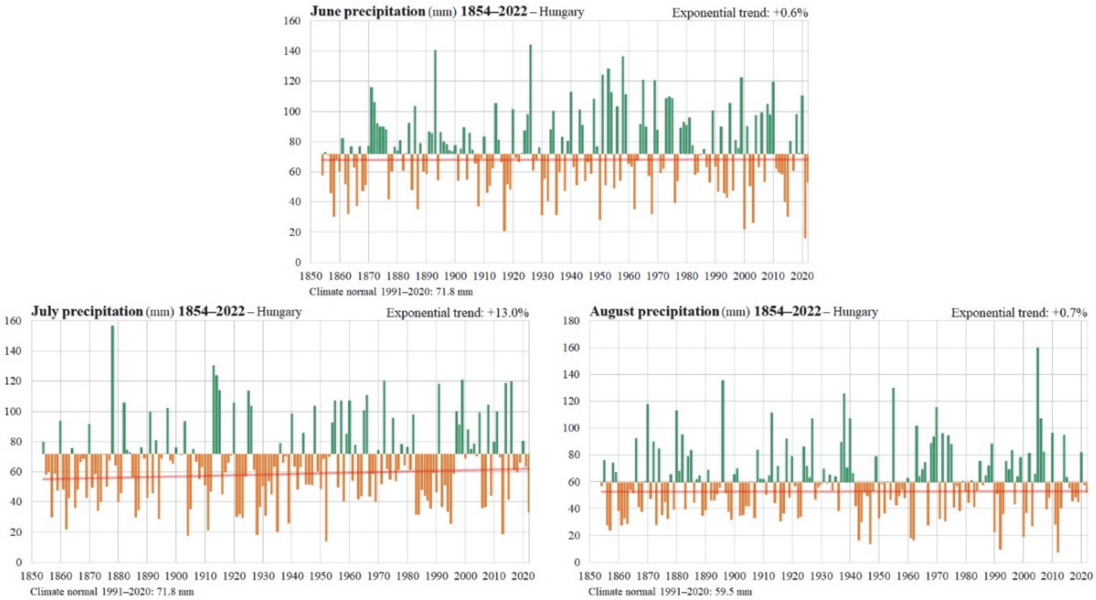

Fig. 15. Spatial means of precipitation in the summer months in Hungary from 1854 to 2022, with the fitted exponential trends.

Autumn

The temporal mean of the spatial mean precipitation for the period 1991-2020 is 158.5 mm in autumn. No significant trend in autumn precipitation amounts is detected over the whole period. Dry autumns were common in the 1850s, 1860s, 1970s, and 1980s. In spatial mean, autumns with higher precipitation (above 200 mm) occurred more frequently around 1880 and in the first half of the 20th century (*Fig. 16*).

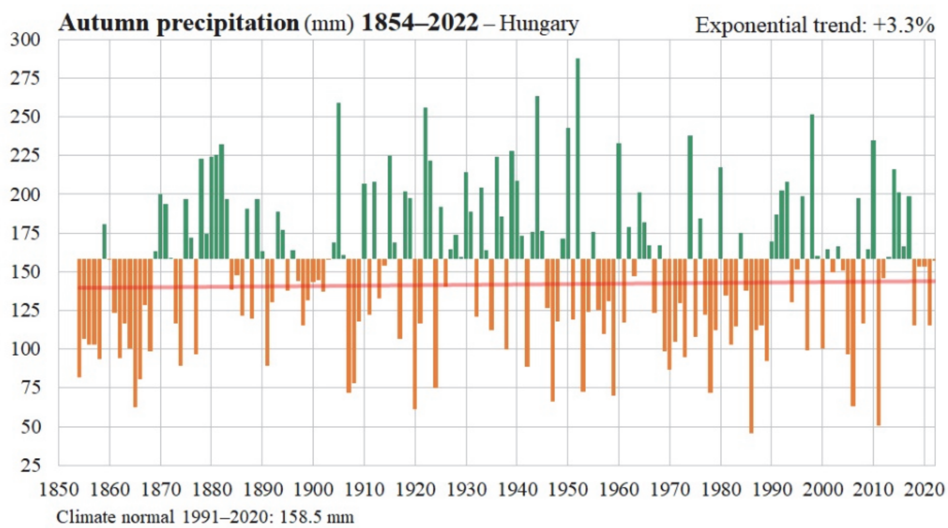

Fig. 16. Spatial means of autumn precipitation in Hungary from 1854 to 2022, with the fitted exponential trend.

The wettest autumn month in average is September in Hungary, while the driest is November. There is a slight increase in precipitation in September and November, but these are not significant changes. However, in October, there is a significant decrease in precipitation from 1854 to 2022 (*Fig. 17*).

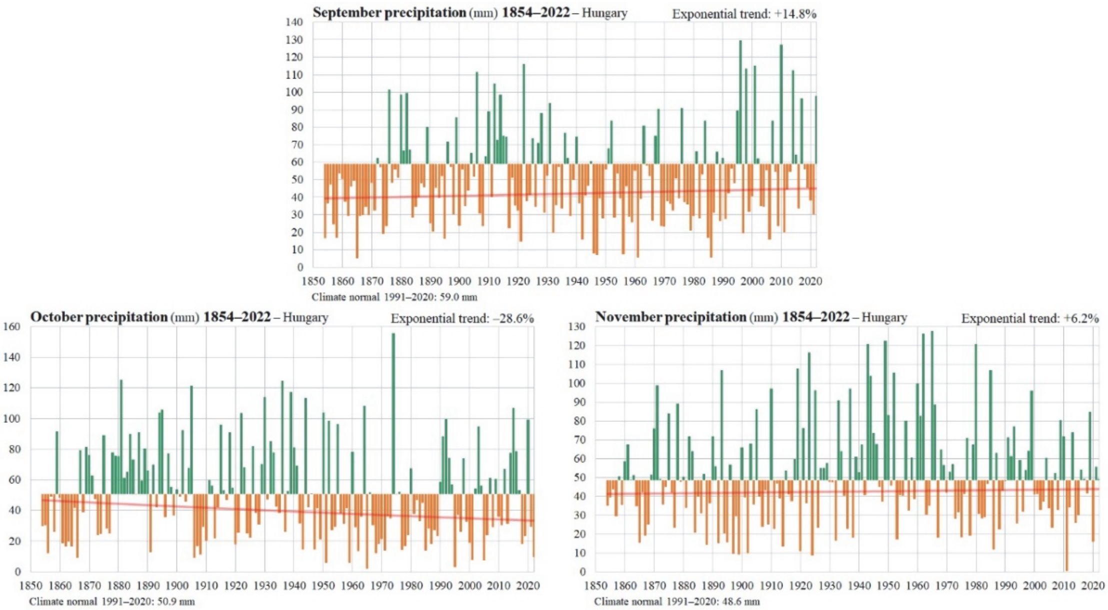

Fig. 17. Spatial means of precipitation in the autumn months in Hungary from 1854 to 2022, with the fitted exponential trends.

Fig. 18 summarizes the monthly, seasonal, and annual exponential trend estimates for the period 1854–2022. In most cases, non-significant precipitation increases are detected. Significant precipitation increases are detected only for February and winter, while significant precipitation decreases can be seen in March and October.

The driest month in Hungary since the beginning of precipitation measurements was November 2011 (0.3 mm). From October to April, the monthly minimum precipitations are below 5 mm and only in May, June, and July are above 10 mm (*Table 3*).

Overall, May 2010 was the wettest month since 1854 (the country mean is 173.8 mm). Moreover, July 1878, October 1974, and August 2005 also had over 150 mm in spatial mean precipitation. The only two months without any spatial mean above 100 mm, are January and February. The driest season between 1854 and 2022 was the winter of 1857/1858, while the wettest was the summer of 2005. The driest year since the beginning of precipitation measurements in Hungary occurred in 1857, and the wettest in 2010.

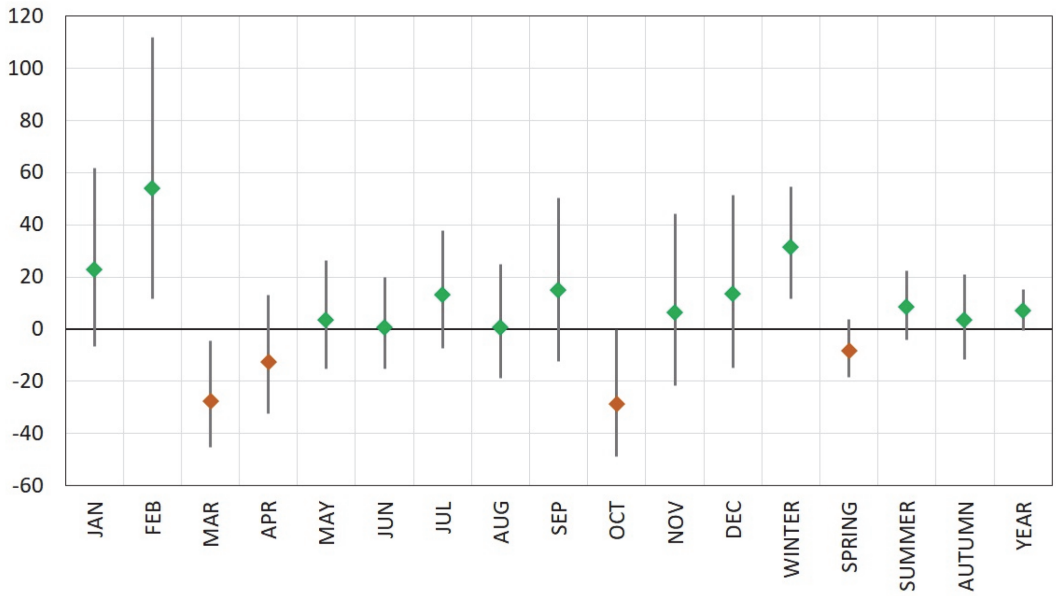

Fig. 18. Exponential trend estimation in % for the spatial means of monthly, seasonal and annual precipitation, over the total period of 1954–2022 in Hungary, with α=0.9 confidence level estimation.

Table 3. The monthly, seasonal, and annual extremes in spatial means from 1854 to 2022 with their year of occurrence, the means for the period 1991–2020, and the fitted exponential trends over the total period

Month/ Season	**Driest**		**Wettest**		**1991–2020 means** [mm]	**Exponential trend** [%] (and α=0.9 confidence level interval)
	mm	year	mm	year		
Jan	2.2	1964	79.6	1915	32.7	22.9 (–6.7 - 61.7)
Feb	1.8	1890	94.9	2016	36.9	53.9 (11.8 - 111.9)
Mar	2.4	2012	112.2	1937	34.3	–27.7 (–45.3 - –4.5)
Apr	2.4	1865	113.4	1879	40.3	–12.6 (–32.3 – 13.0)
May	16.3	1884	173.8	2010	64.5	3.5 (–15.2 - 26.3)
Jun	16.1	2021	144.3	1926	71.8	0.6 (–15.4 - 19.7)
Jul	13.8	1952	156.8	1878	71.8	13.0 (–7.4 - 37.8)
Aug	7.6	2012	160.0	2005	59.5	0.7 (–18.8 - 24.8)
Sep	5.2	1865	129.5	1996	59.0	14.8 (–12.4 - 50.4)
Oct	1.8	1965	155.9	1974	50.9	–28.6 (–48.8 - –0.2)
Nov	0.3	2011	127.8	1965	48.6	6.2 (–21.7 - 44.2)
Dec	3.4	1972	107.8	1874	45.6	13.5 (–15.0 - 51.5)
Winter	29.7	1857/1858	206.2	1976/1977	115.2	31.3 (11.6 - 54.4)
Spring	60.3	1854	262.1	2010	139.1	–8.1 (–18.6 - 3.7)
Summer	99.3	1857	322.6	2005	203.1	8.3 (–4.2 - 22.3)
Autumn	45.6	1986	287.6	1952	158.5	3.3 (–11.7 - 20.8)
Year	335.0	1857	980.4	2010	615.9	6.9 (–0.6 - 15.1)

5. Summary

Recently, significant changes have been made in the availability of the homogenized and gridded climate precipitation database produced by the Climate Department of the HungaroMet Hungarian Meteorological Service. The daily precipitation database was renewed, and all monthly precipitation data from the period before 1951 up to the beginning of the precipitation measurements were collected and used together with the existing station systems in the homogenization and interpolation procedure.

The MASH homogenization procedure of precipitation consists of six major steps from 1854 to the present: from 1854 30, from 1870 50, from 1881 124, from 1901 318, from 1931 402, and from 1951 500 station data series were homogenized, the missing data were completed, and the series were quality controlled.

After homogenization, the data series were interpolated with the MISH method to a 0.1° resolution grid. The average of the grid points gives the country average. Comparing the grid point data series produced from fewer stations with the densest grid using 500 stations, we found that the absolute values of the mean errors (ME) for the spatial means are below 1 mm for all months in the period 1951–2022, and furthermore, the RMSE values are below 5 mm. Therefore, also the spatial mean (country average) produced from a small number of station data sets can be considered representative for Hungary. These small deviations are due to the very good MISH-modeled climate statistical parameters, which were used in the interpolation procedure.

In this study, we also analyzed the spatial means of annual, seasonal, and monthly precipitation amounts for Hungary in the period 1854-2022, moreover, the extreme values and the detected precipitation trends were also calculated and shown.

With this new development of the Hungarian climatological precipitation database, a much more information-rich gridded precipitation dataset is available for climate studies, even for the first half of the 20th century. Finally, the most important result of this study is that we obtained a first insight into the precipitation conditions in Hungary from the very beginning of the precipitation measurements (i.e., from 1854) up to the present.

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