DOI:10.28974/idojaras.2025.3.1

IDŐJÁRÁS

Quarterly Journal of the HungaroMet Hungarian Meteorological Service
Vol. 129, No. 3, July – September, 2025, pp. 241–263

Homogenized and gridded daily surface air pressure data series in Hungary from 1901 to 2023

Olivér Szentes[1,2,*], **Rita Pongrácz**[3],and **Mónika Lakatos**[1]

[1]*Climate Research Department*
HungaroMet Hungarian Meteorological Service
Kitaibel Pál u.1, Budapest 1024, Hungary

[2]*ELTE Faculty of Science, Doctoral School of Earth Sciences*
Budapest, Hungary

[3]*ELTE Department of Meteorology*
Pázmány Péter st. 1/A, Budapest 1117, Hungary

**Corresponding Author e-mail: szentes.o@met.hu*

(Manuscript received in final form February 25, 2025)

Abstract—To describe and study the climate and its changes more accurately, climate databases are needed that are representative in time and spatial coverage, and that are based on sufficiently long measurement data series. In Hungary, air pressure measurements have a long history, similar to temperature and precipitation, but a homogeneous gridded database of Hungarian air pressure measurements over a century, with a daily resolution covering the whole 20th century, has not yet been produced. Therefore, the main aim of this research was to produce a homogenized gridded daily air pressure database from the beginning of the 20th century, which is currently available from 1961 only. In addition, in the period after 1961, and especially in the last few decades, station data series are used in much greater numbers than before. This will produce a more accurate interpolation, i.e., a more accurate grid point database than at present, which can be updated annually in the future, as for temperature and precipitation.

In this paper, we describe the methods used, discuss the station systems used for homogenization and interpolation of air pressure in different time periods, analyze the main verification statistics of the homogenization, and also analyze the results of the interpolation, examine the annual, seasonal, and monthly surface air pressure data series and their extremes, including the daily extremes for the period 1901–2023.

Key-words: climate data, station level air pressure, 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-term data series of high quality. A detailed analysis of global and regional climate change, which is already clearly detectable today, therefore requires the longest possible reliable meteorological data series. This is the main goal of the current research, which aimed to create a long, homogenized station database, and hence a gridded air pressure database instead of the existing shorter and fewer station-based datasets. The resulting data will serve as an excellent basis for the further analysis of complex extreme meteorological and climatological events. In addition to the long-term analysis of air pressure for Hungary, the resulting air pressure database will also be used to check for erroneous/suspicious data for other meteorological elements (e.g., temperature data for cold air pool weather situations), thus helping to verify archive data during periods when measurements and observations are scarce.

Air pressure is a meteorological element whose spatial variability is essentially determined by altitude, so unlike, e.g., precipitation, where many stations with long time series are needed (*Szentes et al.,* 2023, 2024), for air pressure significantly fewer stations are sufficient to create a good quality climate database. However, the data series contain so-called inhomogeneities, for example due to station relocations, instrument changes or environmental changes, therefore, homogenization is needed (*Izsák* and *Szentimrey*, 2020). In the last decades, several methods and software were developed to homogenize meteorological data (*Venema* et al, 2012, 2020), such as MASH (*Szentimrey*, 1999, 2017, 2023, 2024a), standard normal homogeneity test (SNHT) (*Alexandersson*, 1986), and HOMER (*Joelsson* et al., 2021).

For data series homogenization, quality control and filling missing values, the MASH (Multiple Analysis of Series for Homogenization) procedure is used at the Climate Research Department of HungaroMet Nonprofit Zrt. (*Szentimrey*, 1999, 2008a, 2017). Using the MASHv3.03 software, homogenized and quality controlled data series without missing data are available for further analysis. The MASH method is based on hypothesis testing. An additive model with a significance level of 0.05 was used to homogenize the air pressure data series. Inhomogeneities were estimated from monthly data series. Monthly, seasonal, and annual inhomogeneities were harmonized in all MASH systems (taking into account different station networks). The homogenization of daily data is based on the detected monthly inhomogeneities.

Stations do not cover the country uniformly, so spatial interpolation is necessary to ensure spatial representativity. For such spatial interpolation, at HungaroMet we use the MISH (Meteorological Interpolation based on Surface Homogenized Data Basis) method, which was developed specifically for the interpolation of meteorological elements (*Szentimrey* and *Bihari*, 2007, 2014; *Szentimrey* 2024b).

2. Applied methods

In this chapter, we discuss the main features of the MASH and MISH methods used.
The MASH (*Szentimrey*, 1999, 2008b, 2017) procedure is used to homogenize the data sets, check the data and fill in missing data. Using the MASHv3.03 software, we have homogenized and quality controlled data sets filled with missing data, while the MISH method, MISHv1.03 software, is used to generate gridded data series.

2.1. The main properties of the 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 according to the meteorological element,
- 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.

For the air pressure data series, a normal distribution is assumed. In this case, an additive model can be used for homogenization (*Szentimrey*, 2008a). The general form of the additive model for additional monthly series for the same month in a small climatic region can be expressed as follows:

$$X_j(t) = C(t) + IH_j(t) + \varepsilon_j(t) \quad (j = 1,2,\dots,N;\ t = 1,2,\dots,n), \qquad (1)$$

where X is the data series, C is climate change, IH is inhomogeneity, ε is noise, N is the total number of data series, and n is the total number of time steps.

2.2. The main properties of the 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 statistics (local and stochastic) are as follows:

- it is based on long-term homogenized data series and supplementary deterministic model variables (elevation, 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 applied interpolation,
- 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 of 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) with different approaches (*Szentimrey et al.*, 2011). According to the interpolation problem, the unknown predictand $Z(\mathbf{s}_0, t)$ is estimated by the use of the known predictors $Z(\mathbf{s}_i, t)$ $(i = 1, \dots, M)$, where the location vectors $\mathbf{s}$ are the elements of the given space domain, M is the total number of predictors, and t is time. The type of the adequate interpolation formula depends on the probability distribution of the meteorological element.

In the case of air pressure, an additive model can be used because of the assumed normal distribution:

$$\hat{Z}(\boldsymbol{s}_0, t) = \lambda_0 + \sum_{i=1}^{M} \lambda_i \cdot Z(\boldsymbol{s}_i, t), \quad (2)$$

where $\sum_{i=1}^{M} \lambda_i = 1$, $\lambda_i \geq 0$ $(i = 1, \dots, M)$, and λ_0, λ_i $(i = 1, \dots, M)$ are the interpolation parameters (*Szentimrey* and *Bihari*, 2014).

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

$$RMSE(\boldsymbol{s}_0) = \sqrt{E\left(\left(Z(\boldsymbol{s}_0, t) - \hat{Z}(\boldsymbol{s}_0, t)\right)^2\right)}, \tag{3}$$

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

$$REP(\boldsymbol{s}_0) = 1 - \frac{RMSE(\boldsymbol{s}_0)}{D(\boldsymbol{s}_0)}, \tag{4}$$

where E is the expected value and $D(\boldsymbol{s}_0)$ 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 spatio-temporal variances (*Szentimrey* and *Bihari*, 2014; *Izsák et al.*, 2022).

Notations:

$Z(\boldsymbol{s}_j, t)$ $(j = 1, \dots, N; t = 1, \dots, n)$ – gridded data series $(\boldsymbol{s}_j\text{: location}, t\text{: time})$,

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

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

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

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

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

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

Partitioning of total variance (Theorem):

$$\widehat{D}^2 = \frac{1}{N}\sum_{j=1}^{N}(\hat{E}(\boldsymbol{s}_j) - \hat{E})^2 + \frac{1}{N}\sum_{j=1}^{N}\widehat{D}^2(\boldsymbol{s}_j) = \frac{1}{n}\sum_{t=1}^{n}(\hat{E}(t) - \hat{E})^2 + \frac{1}{n}\sum_{t=1}^{n}\widehat{D}^2(t).$$

The analysis of these terms is recommended to characterize the spatio-temporal variability.

Spatial terms:

spatial variance of temporal means: $\frac{1}{N}\sum_{j=1}^{N}(\hat{E}(\boldsymbol{s}_j) - \hat{E})^2$,

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

Temporal terms:

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

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

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

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

spatial standard deviation of temporal means: $\sqrt{\frac{1}{N}\sum_{j=1}^{N}(\hat{E}(\boldsymbol{s}_j) - \hat{E})^2}$,

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

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

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 HungaroMet. Nowadays, the meteorological measurements of the automatic meteorological stations are continuously added to the database, where air pressure measurements are also recorded. The records of older, pre-automation (before 1990s) periods are kept in the climatology books. The digitization of the old data into the climate database is still in progress today. Since the 1960s, most of the air pressure data are available in digital format, while most of the data from earlier decades are still only available on paper. At the same time, air pressure is a much less variable meteorological element than, for example, precipitation, so that data from a few stations are sufficient. The digital climate database already contains a sufficient number of air pressure records from the early 20th century for different areas of the country, so that a homogenized gridded air pressure database covering the whole 20th century can be established. Prior to the complete renewal of the air pressure database, homogenization of air pressure data series was done in one step, starting in 1961 with 22 station data series homogenized and interpolated to a regular grid of 0.1°. As part of the research, the climate database on air pressure has been completely renewed. Similarly to temperature and precipitation, daily homogenized and gridded data series are now available for air pressure from the beginning of the 20th century. The previous one-step homogenization has been replaced by a three-step homogenization: from 1901 onwards, 10 stations are used for daily data, from 1951 onwards 25 stations, and from 1997 onwards 41 stations. It is important to note that the homogenization of air pressure is based on the instrumental air pressure data series, i.e., station-level pressure values, and not on the sea-level pressure values, which is a derived, non-measured quantity. The design of the station systems used for homogenization is essentially determined by the fact that, on the one hand, a larger number of digitized data sets are available since the 1950s and, on the other hand, the number of air pressure stations increased significantly due to the automation that started in the second half of the 1990s. *Fig. 1* shows the amount of monthly air pressure data available in the different MASH systems from January 1901 to December 2023.

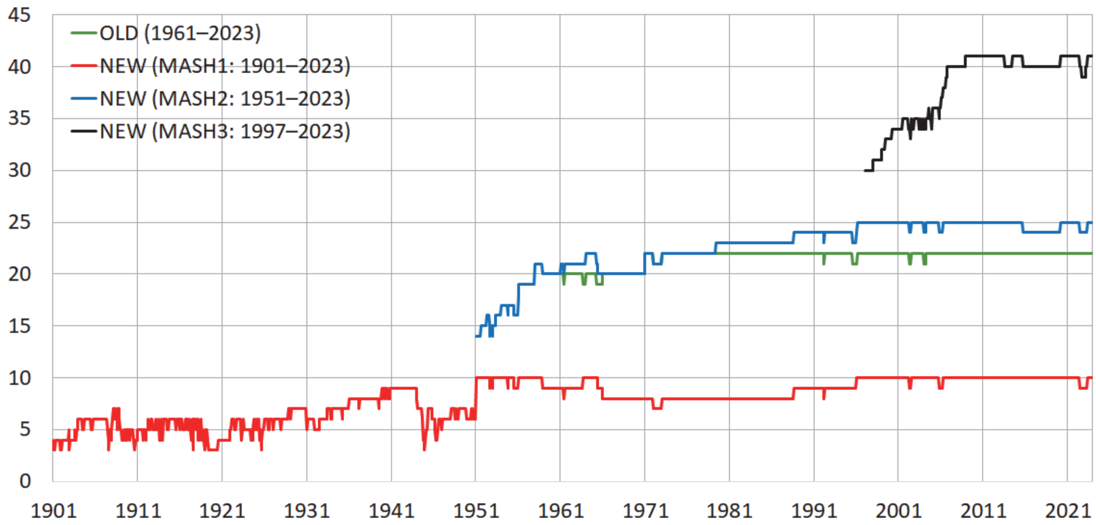

Fig. 1. Number of air pressure data used in the three MASH systems between 1901 and 2023, by month.

The location of air pressure stations in Hungary is shown in *Fig. 2*.

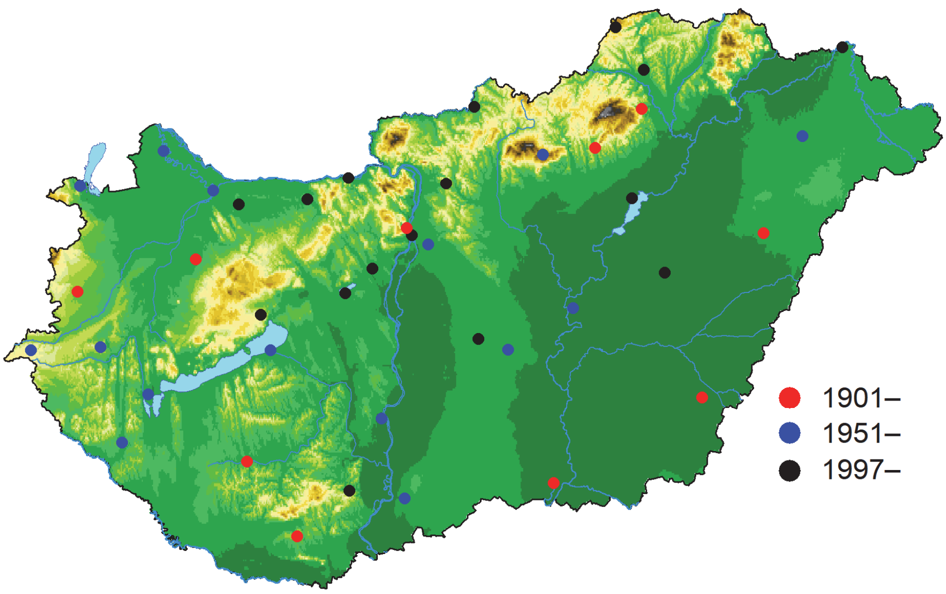

Fig. 2. Location of the stations used in the three MASH systems in Hungary.

4. Results

4.1. Results of homogenization

The homogenization is based on a total of three different station systems, where the monthly, seasonal, and annual inhomogeneities detected in each station system are harmonized during the homogenization process. Naturally, the MASH systems with shorter periods include stations with longer series (e.g., MASH2 includes MASH1 series from 1951 onwards). The homogenization process automatically produces verification statistics. *Table 1* summarizes the main verification statistics for the homogenization of annual air pressure averages for each station system.

Table 1. Main verification statistics of homogenization for annual air pressure means

	MASH1	**MASH2**	**MASH3**
Number of series	10	25	41
Critical value (significance level: 0.01)	21.93	21.40	20.53
Test statistics before homogenization	18359.40	18016.62	3711.91
Test statistics after homogenization	21.74	19.34	16.04
Relative modification of series	1.17	0.78	0.27
Representativity of station network	0.93	0.93	0.93

Before homogenization, the average test statistics for all station systems were well above the critical value, while the test statistics after homogenization were below the critical value, so the air pressure database can be considered homogeneous, with a representative station dataset in time after homogenization. The extremely high test statistic values before homogenization are mainly caused by the fact that air pressure is a meteorological element with a very small temporal variance, and therefore significant breaks, so-called inhomogeneities, can be caused by station relocations in the data series. The changes in the data series are of course larger for longer data series, because longer data series contain more inhomogeneities, for example due to more instrument changes and relocations. The representativity of the station network is similar in all three MASH systems, indicating that a few stations can be used to provide a good substitute for the meteorological element.

The significant inhomogeneities due to relocations are illustrated by the annual air pressure data series for Miskolc (*Fig. 3*), where the three most significant inhomogeneities were caused by the known relocations of the station.

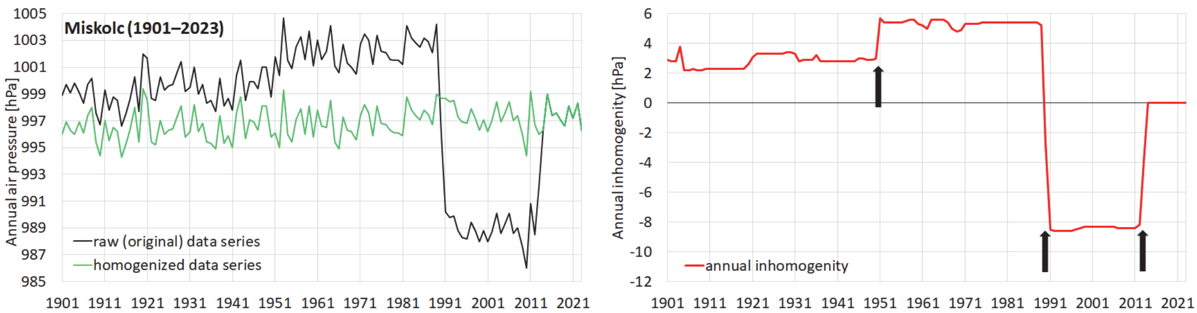

Fig. 3. Raw and homogenized annual air pressure means (left) and annual inhomogeneities (right) in Miskolc between 1901 and 2023, where black arrows indicate well-documented station relocations.

In the mid-20th century, measurements were taken at the airport in the lower part of the city, from where the station was moved to the Avas hill in 1990, more than 100 m higher than the previous measuring site. This resulted in a 14 hPa decrease in the air pressure data. Later, in 2013, the meteorological station together with the air pressure measurements were moved to the western part of Miskolc, to the valley of Diósgyőr, causing another significant inhomogeneity in the air pressure data series.

4.2. Results of interpolation

After homogenization, the data series were interpolated to a regular grid of 0.1° using the MISHv1.03 software. The mean of the values in grid points represents the country average.

The question arises, how similar the grid point data series produced from different numbers of data series are. Our aim is to create a grid point air pressure database in which grid point data series interpolated from 10 stations (MISH1), 25 stations (MISH2), and 41 stations (MISH3) show similar spatiotemporal characteristics. ANOVA was performed on the grid point data series interpolated from three different station systems for the period 1997-2023 for all station systems. *Table 2* shows the main results of the ANOVA for the annual air pressure means.

Table 2. The main ANOVA results for the gridded annual mean air pressure data series for different station systems over the period 1997-2023 (all values are expressed in hPa)

	MISH1	**MISH2**	**MISH3**
Total mean	998.52	998.52	998.52
Total standard deviation	9.85	9.84	9.85
Spatial standard deviation of temporal means	9.79	9.78	9.79
Root spatial mean of temporal variances	1.05	1.05	1.05
Temporal standard deviation of spatial means	1.05	1.05	1.05
Root temporal mean of spatial variances	9.79	9,79	9.79

The ANOVA results clearly show that the total (spatial) mean is the same for all MISH systems over the period 1997–2023. In addition, the spatial variance of the temporal averages and the temporal variance of the spatial averages are almost exactly identical, which shows that air pressure is a very well interpolated meteorological element, and that a few data series is sufficient to create a good quality air pressure climate database.

As far as the annual air pressure averages and the spatial variance of the annual air pressure averages over the period 1997–2023 are concerned, the interpolation results do not show significant differences, with only a few hundredths of a hPa difference (*Fig. 4*).

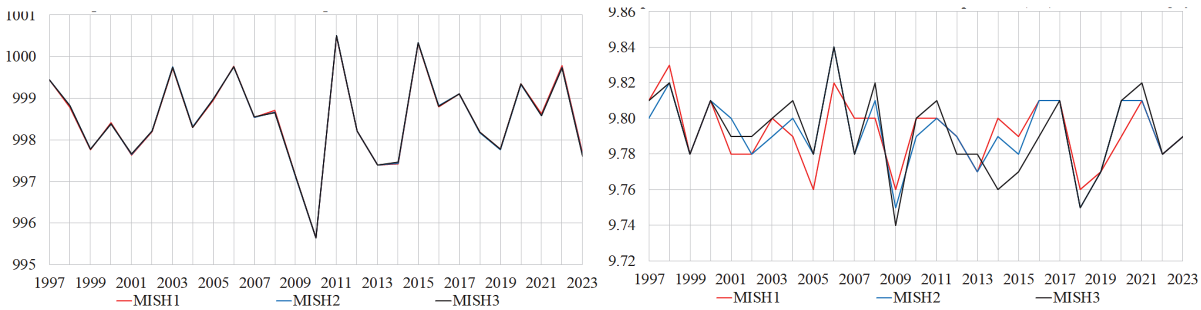

Fig. 4. Annual mean air pressure (left) and spatial standard deviations of annual means (right) for different station systems in Hungary, for the period 1997–2023.

When comparing the spatial means from the MISH1 and MISH2 station systems with the interpolation from MISH3 of 41 stations, it can be seen (*Fig. 5*) that the mean error in absolute value is within 0.01 hPa in each month, and the RMSE values are also within 0.05 hPa in each month. This implies that the spatial mean produced from a smaller set of stations can also be considered representative for Hungary. After interpolation, a spatially representative surface air pressure database becomes available.

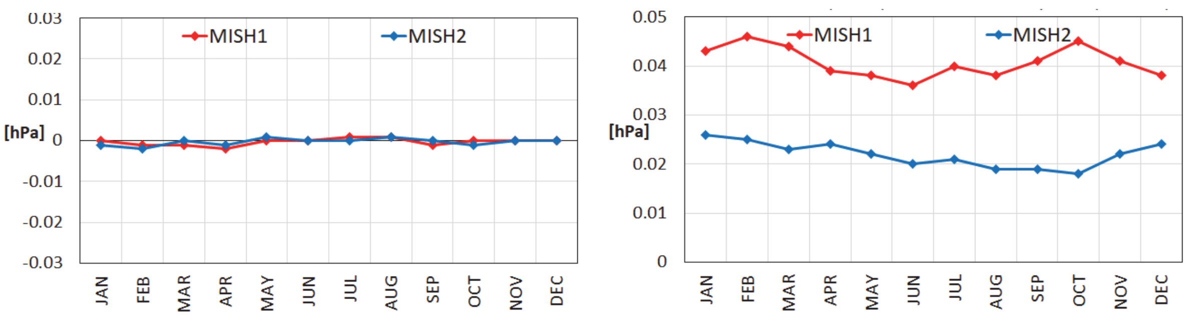

Fig. 5. Monthly mean errors (left) and RMSE values (right) of spatial means of surface air pressure for the period 1997–2023 compared to interpolation from 41 stations in different MISH systems.

4.3. Annual air pressure

Fig. 6 shows the spatial means of annual air pressure values from the beginning of the 20th century. The annual average surface air pressure in Hungary is generally between 997 and 1000 hPa.

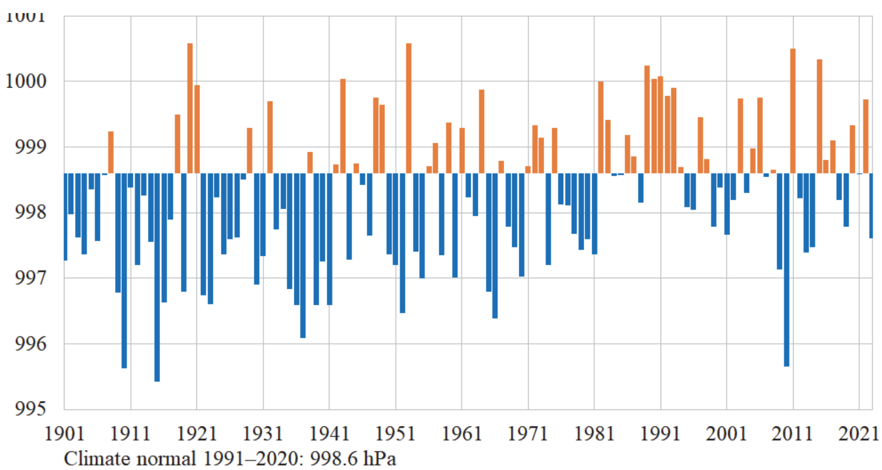

Fig. 6. Spatial means of annual surface air pressure in Hungary from 1901 to 2023.

The annual mean air pressure values show a reverse relationship with annual precipitation totals. Although the extremes do not coincide, in years with higher precipitation (e.g., early 20th century), more cyclones occur, resulting in lower pressure means, while in drier years, when more anticyclones dominate the weather, the pressure means is higher. The wettest year on average in Hungary since the beginning of the 20th century was 2010, and the driest year was 2011. This is also reflected in the annual mean air pressure, which was below 996 hPa in 2010, while it exceeded 1000 hPa in 2011. Considering the long averaging time period and a relatively small overall variance, this difference of 4–5 hPa is quite substantial between years.

4.4. Seasonal and monthly air pressure

Winter

Among the seasons, the greatest variability in air pressure occurs in winter (*Fig. 7*). In some years, winter weather in Hungary is mostly determined by Mediterranean cyclones, while there are winters when northern European anticyclones are more dominant.

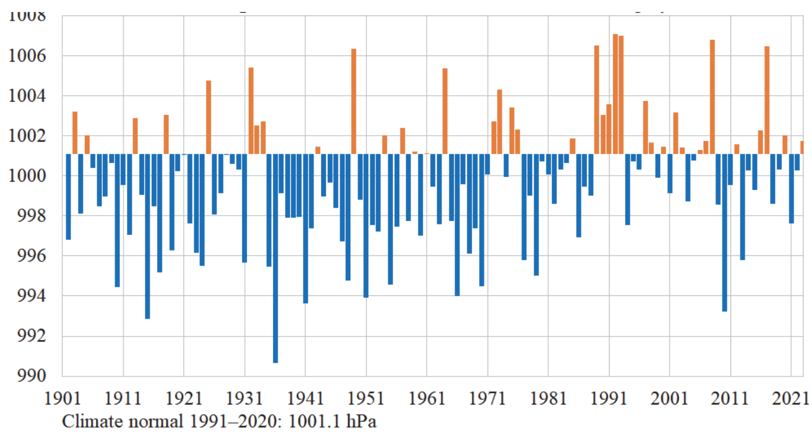

Fig. 7. Spatial means of winter surface air pressure in Hungary from 1901/1902 to 2022/2023.

Looking at the individual winter months within the season, it can be observed that spatial means below 990 hPa and above 1010 hPa can occur in all the three months (*Fig. 8*). January and February show both higher and lower air pressure values in each decade, while December exhibits a higher frequency of higher monthly air pressure means compared to the 1991-2020 average since the 1970s than in the first half of the 20th century.

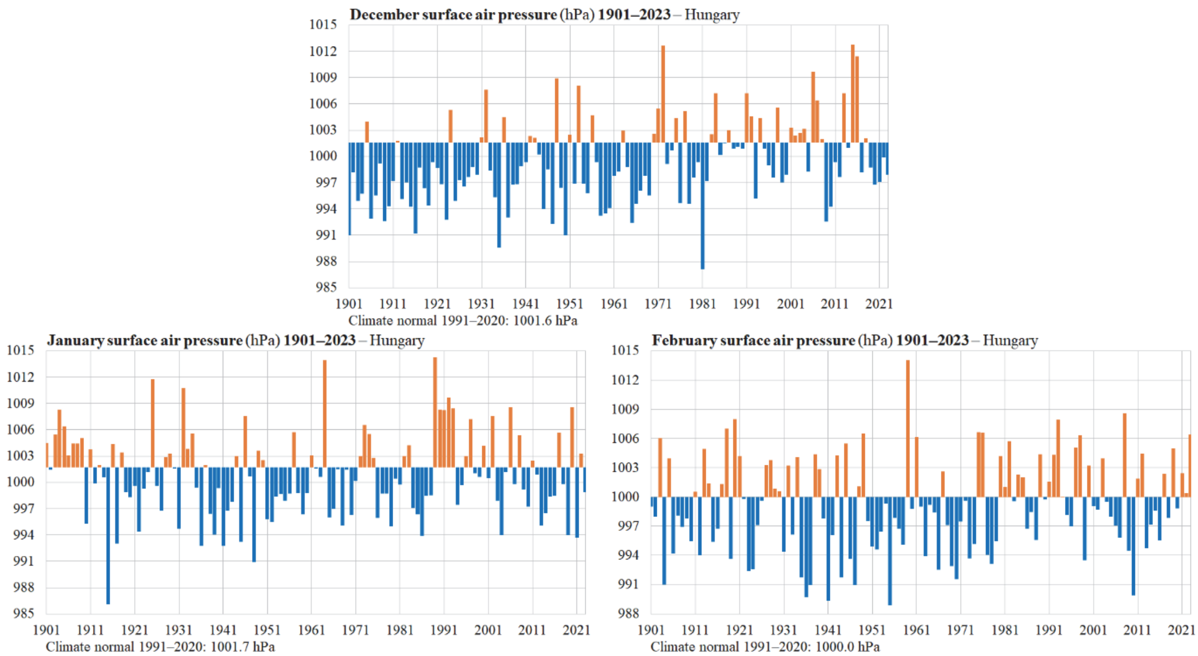

Fig. 8. Spatial means of surface air pressure in the winter months in Hungary from 1901 to 2023.

Spring

In spring, the entire pressure range is much smaller than in winter, mostly between 994 and 1000 hPa. Among the seasonal averages for 1991–2020, the mean spring pressure is the lowest. Averages are lower in the first three decades of the 20th century, when springs were wetter, while higher pressure averages occurred more frequently in the mid-20th century and in the last two decades (*Fig. 9*).

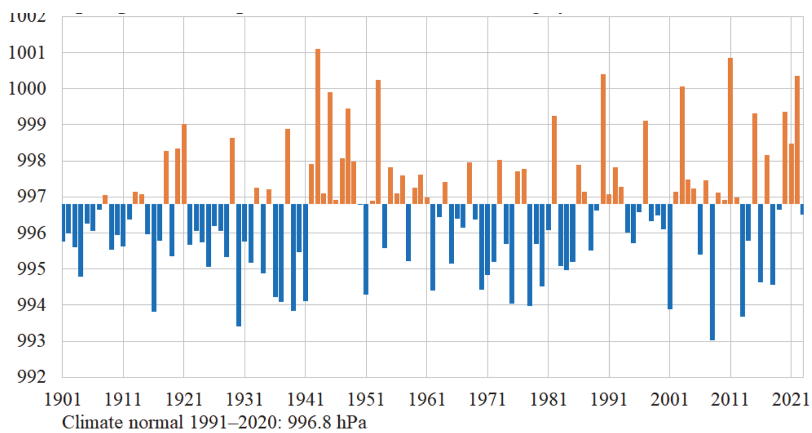

Fig. 9. Spatial means of spring surface air pressure in Hungary from 1901 to 2023.

Of the spring months, March is the most variable. Lower air pressures in April were recorded in the 1920s, 1930s, and 1970s, while higher values were recorded in the mid-20th century and the last 20 years (*Fig. 10*). Nevertheless, the mean air pressure in April is the lowest of all months over the period 1991–2020. In May, the mean reaches 1000 hPa less frequently, and there is no spatial means below 990 hPa.

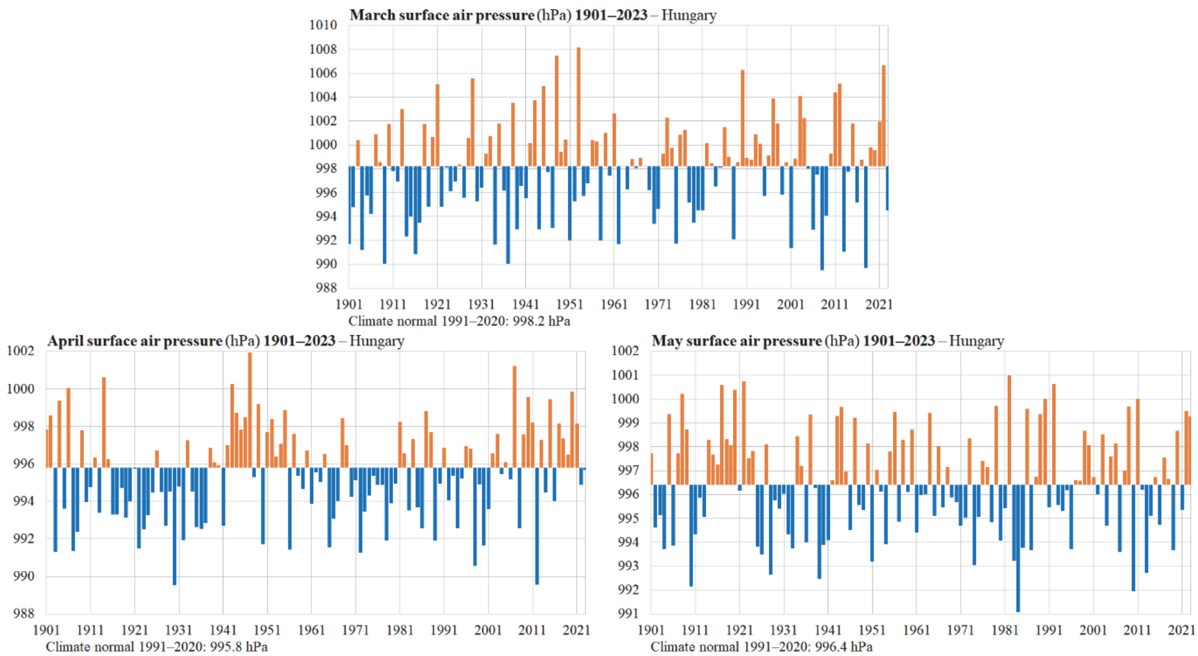

Fig. 10. Spatial means of surface air pressure in the spring months in Hungary from 1901 to 2023.

Summer

The mean air pressure in summer is very similar to spring, only 0.1 hPa higher on average. However, the least variability of all seasons occurs in summer, with the spatial mean summer air pressure typically remaining within a range of 3 hPa, between 995 and 998 hPa (*Fig. 11*).

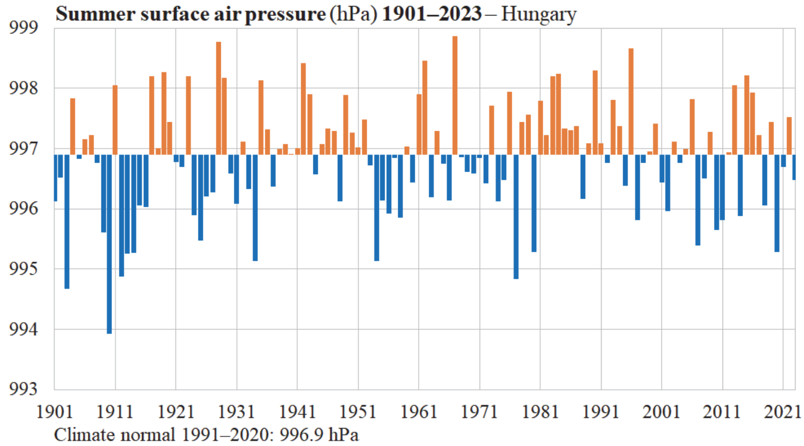

Fig. 11. Spatial means of summer surface air pressure in Hungary from 1901 to 2023.

In summer, the pressure field is often uncharacteristic, with cyclones and anticyclones much less dominant than in other seasons, especially compared to winter. This is also reflected in the air pressure values during the summer months. The highest monthly spatial means rarely reach 1000 hPa, while values below 993 hPa are also seldom (*Fig. 12*).

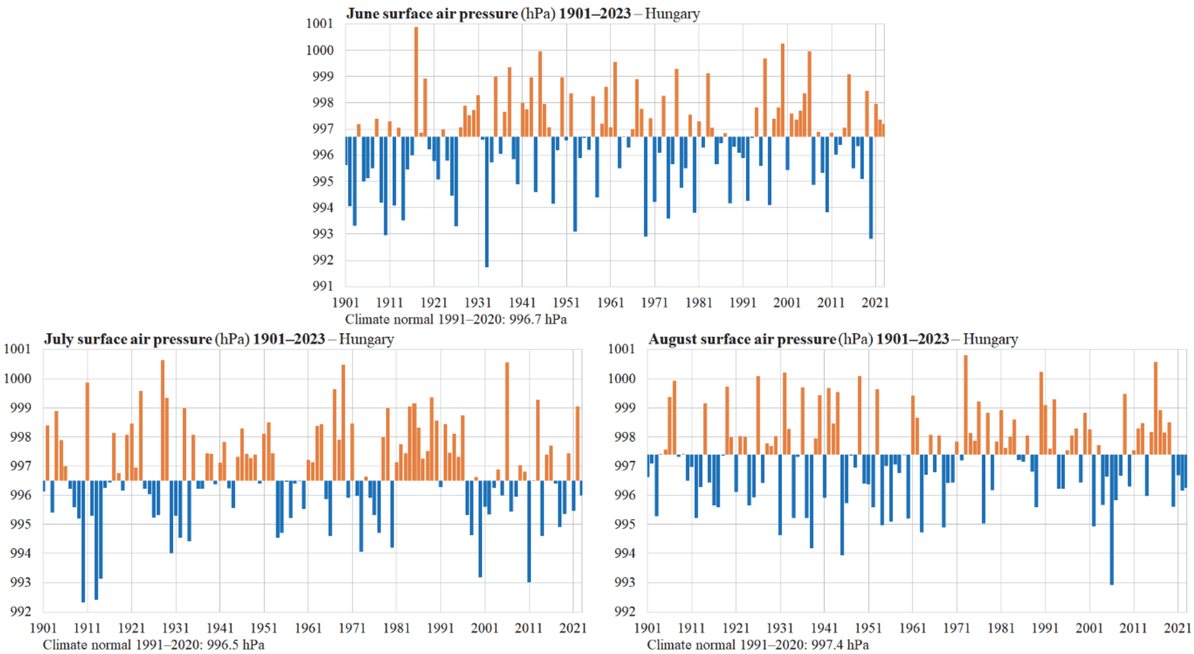

Fig. 12. Spatial means of surface air pressure in the summer months in Hungary from 1901 to 2023.

Autumn

The spatial mean for autumn air pressure was mostly below the 1991–2020 average in the first four decades of the 20th century, and then more consistently above the 1991–2020 average in the following four decades. Autumn surface air pressure is generally around 1000 hPa, typically between 997 and 1003 hPa (*Fig. 13*).

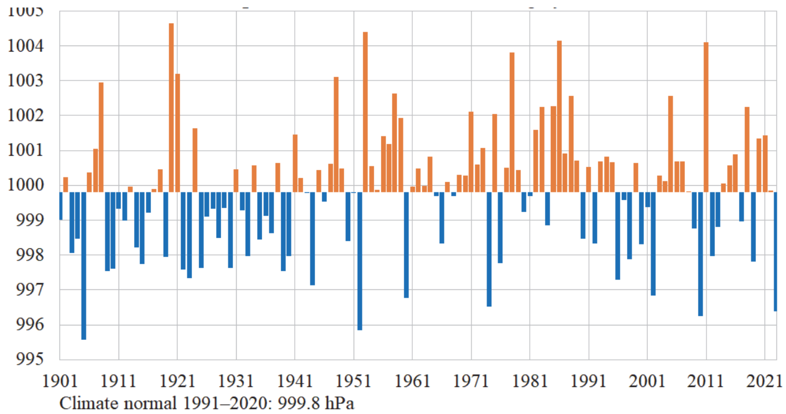

Fig. 13. Spatial means of autumn surface air pressure in Hungary from 1901 to 2023

As in the seasonal mean, September and October are dominated by lower air pressure in the first four decades of the 20th century, and then higher pressure until the 1980s (*Fig. 14*). September also shows a clear decline in the 1990s, when cyclonic circulation conditions became more frequent in September. As we approach winter, there is an increasing variability in air pressure values. The November surface air pressure is more similar to the winter months than to the other two autumn months, with monthly mean values above 1010 hPa.

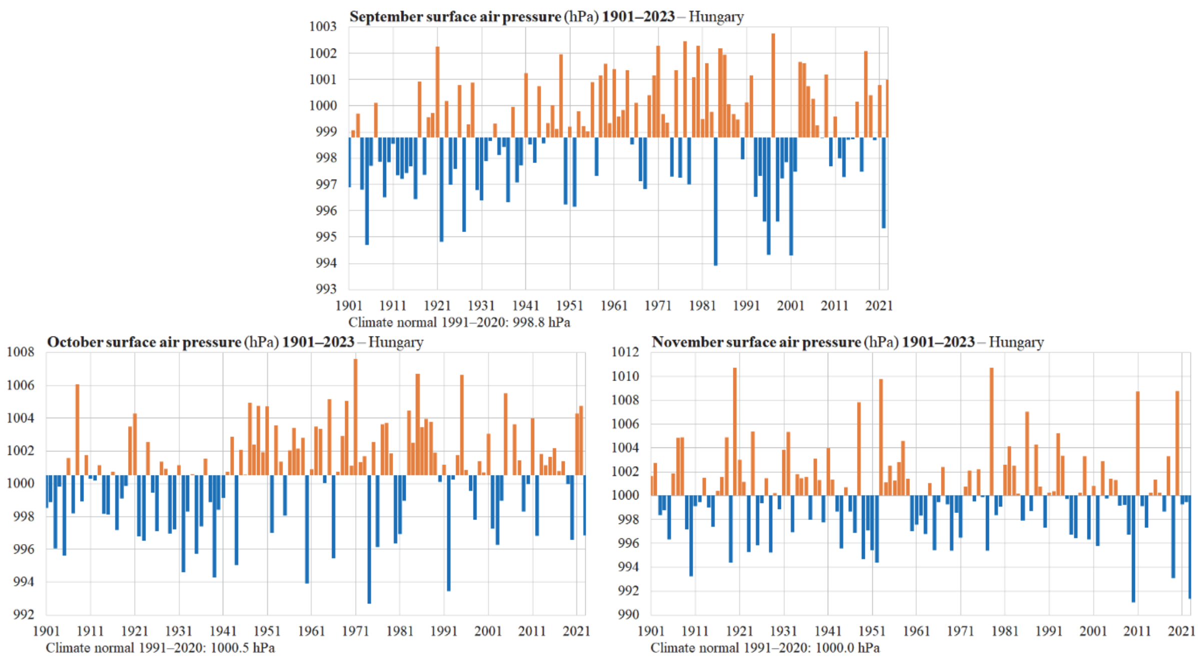

Fig. 14. Spatial means of surface air pressure in the autumn months in Hungary from 1901 to 2023

Table 3 summarizes the monthly, seasonal, and annual extremes and standard deviations for the period 1901–2023, as well as the averages for 1991–2020. Both the lowest and highest monthly air pressure were recorded in January. Monthly mean pressures above 1010 hPa averaged over the winter months in November, while monthly mean pressures below 990 hPa averaged over January to April and December since the beginning of the 20th century. The standard deviation of monthly values is close to 5 hPa in winter and less than 2 hPa in summer.

Table 3. Monthly, seasonal, annual extremes and standard deviations of spatial means of air pressure for the period 1901–2023 and the 1991–2020 averages

Month/ season	**Lowest**		**Highest**		**1901–2023 standard deviation [hPa]**	**1991–2020 average [hPa]**
	hPa	**year**	**hPa**	**Year**		
January	986.1	1915	1014.3	1989	4.9	1001.7
February	988.9	1955	1014.0	1959	4.9	1000.0
March	989.5	2008	1008.2	1953	4.2	998.2
April	989.5	1930	1002.0	1947	2.6	995.8
May	991.1	1984	1001.0	1982	2.3	996.4
June	991.7	1933	1000.9	1917	1.8	996.7
July	992.3	1910	1000.7	1928	1.7	996.5
August	992.9	2006	1000.8	1973	1.6	997.4
September	993.9	1984	1002.8	1997	2.0	998.8
October	992.7	1974	1007.6	1971	3.1	1000.5
November	991.0	2010	1010.7	1920	3.7	1000.0
December	987.1	1981	1012.8	2015	4.9	1001.6
Winter	990.7	1935/1936	1007.1	1991/1992	3.3	1001.1
Spring	993.0	2008	1001.1	1943	1.7	996.8
Summer	993.9	1910	998.9	1967	1.0	996.9
Autumn	995.6	1905	1004.7	1920	1.8	999.8
Year	995.4	1915	1000.6	1920	1.2	998.6

4.5. Daily air pressure

In the monthly and seasonal air pressure data, it was already shown that there is much more variability in air pressure in winter than in summer, and that both absolute maximum and minimum values occur in winter. In this chapter, the daily spatial means of surface air pressure is analyzed together with its annual pattern and its daily extremes.

The daily mean surface air pressure is above 1000 hPa for most of the winter months and below 1000 hPa from mid-March to mid-September (*Fig. 15*). For the

1991–2020 averages, the highest daily pressure occurred on January 15 (1004.5 hPa) and the lowest on April 18 (993.4 hPa). There is a distinct annual pattern of extremes, daily maximum and minimum values. The maxima and minima clearly occur in winter, with a substantially narrower interval of pressure values in summer, with higher minima and lower maxima. The mean daily minimum of spatial averages is 974.2 hPa in January and 985.8 hPa in July, while the corresponding mean maximum is 1023.2 hPa and 1006.1 hPa, respectively.

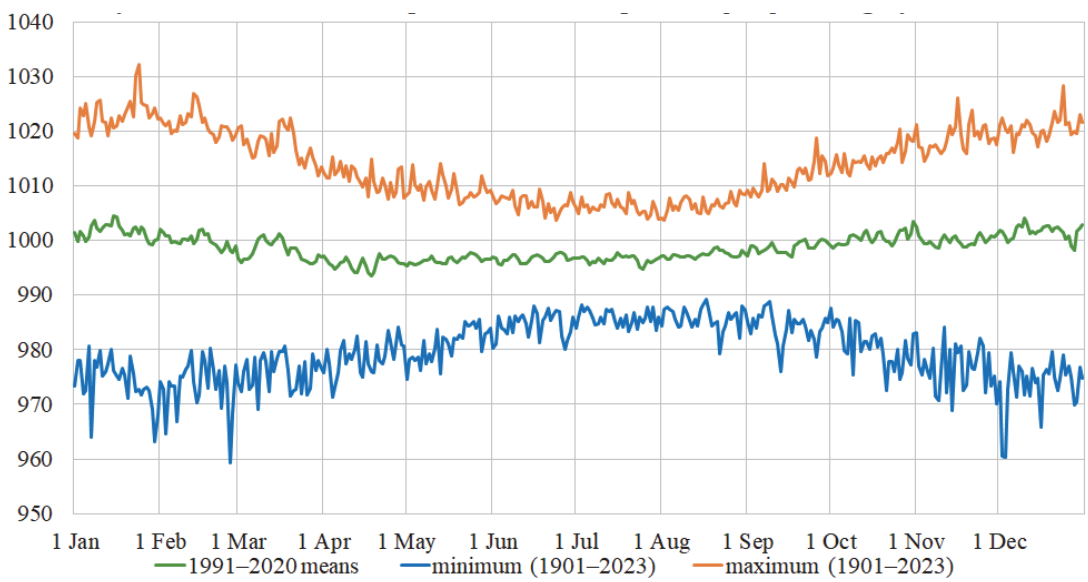

Fig. 15. Spatial means of daily surface air pressure 1991–2020 and daily extreme values for the period 1901–2023.

The daily spatial mean surface air pressure was the lowest on February 26, 1989 and the highest on January 24, 1907. The distribution of surface air pressure in Hungary on these days is shown in *Fig. 16*, while *Table 4* lists the ten lowest and ten highest values of spatial means of daily air pressure since the beginning of the 20th century.

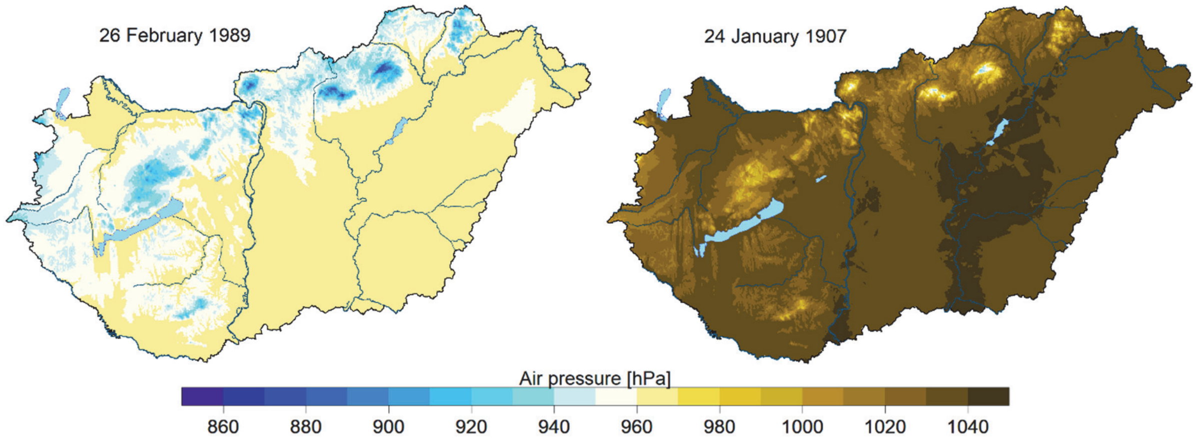

Fig. 16. Distribution of surface air pressure in Hungary on February 26, 1989 and January 24, 1907.

Table 4. Spatial means of daily surface air pressure lows and highs in Hungary, in period 1901-2023

	Lowest		Highest	
	hPa	**Date**	**hPa**	**Date**
1.	959.3	February 26, 1989	1032.3	January 24, 1907
2.	960.3	December 3, 1976	1030.2	January 23, 1907
3.	960.6	December 2, 1976	1028.3	December 24, 1963
4.	963.2	January 30, 2015	1026.9	February 13, 1959
5.	964.0	January 7, 1912	1026.3	February 14, 1959
6.	964.5	February 3, 1912	1026.0	November 16, 1908
7.	965.9	December 16, 1962	1025.7	January 10, 1929
8.	966.9	February 7, 1974	1025.5	January 21, 1925
9.	967.9	December 2, 1935	1025.4	January 9, 1929
10.	968.0	January 31, 2015	1025.3	January 25, 1932

The weather in the Carpathian Basin in winter, especially in November and December, is often humid and foggy, with low-level stratus clouds in the lower few hundred meters of the atmosphere, during which maximum temperatures remain near freezing and low daily temperature fluctuations are common. Such weather situations can develop with persistently anticyclonic, i.e., high atmospheric pressure, while the higher mountains stay above the cloud cover, where the anticyclone is responsible for sunny, clear weather, with maximum temperatures several degrees above the lowlands. Such a cold air pool situation is illustrated in *Fig. 17*, where, in addition to the maximum temperatures measured at Kékestető and Gyöngyös (i.e., at the top and foot of the Mátra, respectively) in November 1978, the anomalies of the daily air pressure are shown as spatial averages for the entire country.

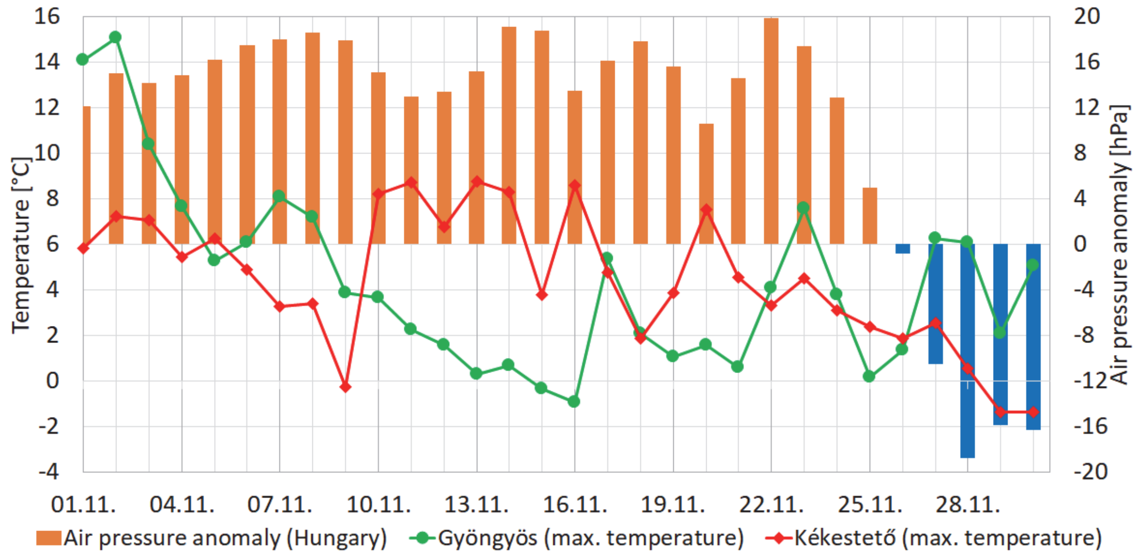

Fig. 17. Daily maximum temperatures at Kékestető and Gyöngyös and anomalies of daily surface air pressure anomalies of Hungarian spatial means in November 1978.

It can be seen that for most of the month, the air pressure was 12–20 hPa higher than usual. At the beginning and end of the month, the maximum daily temperature at the mountain station (Kékestető) was several degrees lower than normal. However, in the middle of the month, especially between November 10 and 16, maximum temperatures were lower at the foot of the mountain, in Gyöngyös, by 4–8 °C. Looking at the temperature data alone, one might therefore think that the values from Kékestető or Gyöngyös could be wrong, as the temperature should normally be several degrees lower on the mountain. However, considering the air pressure anomalies, it is clear that these reverse conditions occurred during a period of persistent high pressure in November, which suggests the formation of a cold air pool over Hungary. Nowadays, satellite imagery can also help in deciding on the temperature values in question in such weather situations, and the importance of daily air pressure data is enhanced when checking older suspicious data, especially before the mid-20th century, when there were fewer mountain stations to measure, as they can significantly help in checking archive data.

5. Summary

Within the framework of the present research, the surface air pressure database, which started in 1961, was completed from the beginning of the 20th century to the year 2024, thus, in addition to temperature and precipitation (*Szentes* et al., 2023), a daily climate database for surface air pressure was created, which is representative in time and space from the beginning of the 20th century to the present. In addition, station data series are used in much larger numbers in the period after 1961, especially in the last few decades. Homogenized station time series and interpolated gridded air pressure database are produced from station air pressure measurements and, like other meteorological elements, can be updated annually in the future. The station systems used for the homogenization were presented, which is now done in three steps instead of the previous one-step homogenization. The interpolation results were also subjected to an ANOVA test, where it was shown that barometric pressure is a meteorological element that can be interpolated with high accuracy. When analyzing the monthly, seasonal, and annual averages of air pressure, a correlation with precipitation is apparent, as lower air pressures are associated with more intense cyclonic activity, and thus, more precipitation, while persistently high air pressures are associated with the lack of precipitation, even drought. During the winter period, high air pressure often causes the formation of a low-level stratus cloud (so-called cold air pool), under which the air is humid and air pollution increases substantially, often to levels above the health limit. The development and frequency of these weather events, which can have a significant impact on our health, can now be studied in more detail over the long term by examining long air pressure data series. Moreover, the air pressure database, which has been compiled since the early 20th century, can be used to check suspicious data from other meteorological elements (e.g., temperature data from cold air pool weather situations), helping to verify archive data at times when measurements are scarce.

Acknowledgement: This paper was supported by the ÚNKP-23-1 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Found, the framework of the Széchenyi Fund Plus program with the support of the RRF-2.3.1-21-2022-00014 National Multidisciplinary Laboratory for Climate Change project.

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