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Annual and seasonal ANOVA and trend analysis of sub-daily temperature databases in Hungary

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Abstract— Commonly studying climate is gaining more and more space thanks to the expansion of the tools of statistical climatology and the development of the informatical background. Trend analyses of annual and seasonal mean temperature values clearly show that the Hungarian values are mostly in line with the global trend, and in some cases exceed it. Since a sufficient number of measurements are only available from the 1970s, we used hourly temperature values (03 UTC, 09 UTC, 15 UTC, 21 UTC) of the period 1971–2020 for station data series in Hungary for the trend analysis. In order to make the examined datasets sufficiently representative, we homogenized the station data series, filled in data gaps, and performed quality control using the MASH software. To ensure spatial representativeness, we interpolated the homogenized station data onto a dense, regular grid network with the MISH system. In addition, we used the ANOVA method to examine the expected values, standard deviations assigned to the hourly values, and we analyzed on maps how the values within the day changed in each region over 50 years.

Key-words: ANOVA, trend analysis, sub-daily temperature data, MASH software, MISH software, Hungary

1. Introduction

Climate change and its corresponding professional background knowledge have now become especially important. The examination of the past and present climate also plays an important role worldwide, especially with regard to investigations related to the process of climate change. In order to get an adequate picture of the detected changes, we can work with six-hourly temperature datasets. It is quite important that when modeling hourly values compared to daily data, we had to determine the regression coefficients, since we cannot interpolate in the same way within a day, since the expected values differ for example at dawn and at noon, and it can also be seen that there is a strong stochastic relation between the daily and hourly values. The hourly values were homogenized, the missing data were filled in, and then the available values were interpolated into the points where no measurements were taken. The purpose of this research is to examine the database of four hourly values within a day to see how much they changed overall during the research period, i.e., between 1971–2020. We used linear trend analysis for this comparing the changes that took place by area between the databases. Moreover, we also examined the databases and their differences and similarities using the ANOVA methodology.

2. Data

Six-hourly UTC (03 UTC, 09 UTC, 15 UTC, 21 UTC) measurements were used for the analysis. First, we did a homogenization process by applying the MASH system (*Szentimrey,* 2017) in order to fill in all the data gaps, followed by interpolation. The interpolation method was done by MISH (*Szentimrey* and *Bihari,* 2007*,* 2014). In the case of 03 UTC 47, 09 UTC 49, 15 UTC 49, and 21 UTC 55 station data series were available for this study. After the homogenization we interpolated the homogenized station data series to 1233 grid points which corresponds to 0.1° resolution (*Fig. 1*). Then we chose a much more detailed 0.5' resolution grid for interpolation to produce the trend maps. Due to the large number of missing data, we had to leave the very incomplete stations during the homogenization (*Szentimrey et al.,* 2014a).

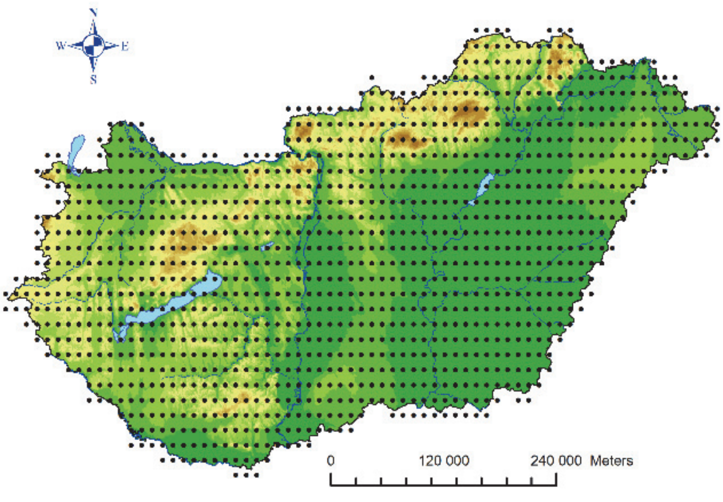

Fig. 1. The geographical location of the 1233 grid points in Hungary (EPSG:4326: WGS 84).

3. Interpolating sub-daily values with MISH, description of the methodology

Applying the MISH interpolation system compared to other methods used in climate research has a much smaller interpolation error in the interpolated data series, so its use is much more recommended for meteorological data compared to other interpolation methods (*Barna et al.,* 2023; *Izsák et al.,* 2023). This is due to the fact that in meteorology we cannot assume that there is no spatial trend, as the complex orography of the country means that different regions have different expected values.

Fig. 2 shows the montly difference of the six-hourly temperature values from the daily mean, and according to that we can declare that at 09 and 15 UTC the values are higher than the daily mean, furthermore, for 03 UTC and 21 UTC the daily mean value is higher than this two hourly value during the whole year. This can help in the decision when determining the regression parameters for interpolating the sub-daily hourly values (*Izsák,* 2023). Below we describe the metodology of interpolating hourly temperature values (*Szentimrey,* 2019).

Fig. 2. Monthly difference of the six-hourly temperature values from the daily mean values (°C).

The following interpolation formula (additive model) is applied for the daily mean temperature data (*Szentimrey et al.,* 2011, 2014b):

$$\hat{Z}(\boldsymbol{s}_0) = \sum_{i=1}^{M} \lambda_i \big(E(\boldsymbol{s}_0) - E(\boldsymbol{s}_i)\big) + \sum_{i=1}^{M} \lambda_i Z(\boldsymbol{s}_i) \,, \qquad (1)$$

where $Z(\boldsymbol{s}_0)$ (*s*: location) is a predictand, $Z(\boldsymbol{s}_i)$ $(i = 1, \ldots, M)$ are predictors (observations), and the weighting factors $\sum_{i=1}^{M} \lambda_i = 1$ and λ_i $(i = 1, \ldots, M)$ depend on the stochastic relations, while $E(\boldsymbol{s}_i)$ $(i = 0, \ldots, M)$ are the daily spatial trend values (*Szentimrey,* 2019).

The optimal interpolation parameters λ_i $(i = 1, \ldots, M)$ minimize the root-mean-square error, and these are known functions of the climate statistical parameters (*Szentimrey,* 2019, 2020).

Based on the daily interpolation formula, the following formula is applied to the $t = 03, 09, 15, 21$ UTC values, accepting the weighting factors:

$$\hat{Z}(\boldsymbol{s}_0, t) = \sum_{i=1}^{M} \lambda_i \big(E(\boldsymbol{s}_0, t) - E(\boldsymbol{s}_i, t)\big) + \sum_{i=1}^{M} \lambda_i Z(\boldsymbol{s}_i, t) \, , \quad (t = 03, 09, 15, 21) \qquad (2)$$

where $E(\boldsymbol{s}_i, t)$ $(i = 0, \ldots, M)$ represents the spatial trend values for the given times.

To model the $E(\boldsymbol{s}, t)$ $(t = 3{,}9{,}15{,}21)$ hourly spatial trend values, the following linear model was chosen:

$$E(\boldsymbol{s}, t) = \alpha(t) + \beta(t) \cdot E(\boldsymbol{s}) \qquad (t = 03, 09, 15, 21). \qquad (3)$$

In this case, the interpolation formula for hourly values is given as follows:

$$\hat{Z}(\boldsymbol{s}_0, t) = \beta(t) \cdot \left(\sum_{i=1}^{M} \lambda_i \big(E(\boldsymbol{s}_0) - E(\boldsymbol{s}_i)\big)\right) + \sum_{i=1}^{M} \lambda_i Z(\boldsymbol{s}_i, t) \quad (t = 03, 09, 15, 21). \qquad (4)$$

Thus, the modeled daily spatial trend values $E(\boldsymbol{s}_i)$ $(i = 0, \ldots, M)$ and the estimated $\beta(t)$ $(t = 03, 09, 15, 21)$ hourly regression coefficients can be used to interpolate the hourly values (*Szentimrey*, 2019).

Looking at the average test statistics it is clear, that the correlation differs significantly from zero assumed in the null hypothesis. Moreover, these correlations allow us to conclude that there is a strong relationship between the daily and the six-hourly values. For example, if we choose a significance level of 0.05 considering a t-test statistic for a 50-year data series, the critical value for an individual station is 2.01. Summarizing the results of *Table 1*, the model for gridding of the daily values can be used to produce the gridded hourly values. According to *Table 1*, there is a large difference between the regression coefficients (β) related to measurements at 03 UTC, 09 UTC, 15 UTC, and 21 UTC. *Table 2* illustrates that hourly spatial trends can be well determined by linear regression on daily spatial trend (*Szentimrey,* 2019).

Table 1. Alpha and beta regression parameters for 12 months and for the 4 hourly values

	T03		**T09**		**T15**		**T21**	
	alpha	**beta**	**alpha**	**beta**	**alpha**	**beta**	**alpha**	**beta**
1	-1.34	0.91	-0.18	0.92	2.00	1.24	-0.48	1.01
2	-1.82	0.90	0.23	0.97	2.77	1.32	-0.60	0.95
3	-1.90	0.77	0.95	1.00	2.58	1.28	-0.74	0.94
4	-1.00	0.69	0.92	1.08	1.50	1.27	-0.01	0.86
5	0.34	0.66	0.73	1.07	-0.23	1.28	0.39	0.85
6	2.16	0.63	1.19	1.05	-0.75	1.27	0.24	0.87
7	2.34	0.63	0.31	1.09	-1.19	1.28	0.17	0.88
8	2.22	0.65	1.57	1.03	-1.89	1.35	-0.29	0.90
9	1.09	0.68	0.35	1.10	-2.01	1.43	-1.48	0.97
10	0.22	0.68	0.45	1.10	-0.72	1.47	-0.52	0.91
11	-0.59	0.80	0.69	0.97	0.64	1.35	-0.85	1.00
12	-0.73	0.95	-1.15	0.89	1.90	1.07	0.07	1.08

Table 2. Correlations (corr) and t-test statistics (tstat) for 12 months and for the 4 hourly values

	T03		**T09**		**T15**		**T21**	
	corr	**tstat**	**corr**	**tstat**	**corr**	**tstat**	**corr**	**tstat**
1	0.94	18.18	0.97	28.90	0.93	17.19	0.95	23.05
2	0.89	12.81	0.95	20.50	0.90	14.20	0.94	20.11
3	0.84	10.55	0.90	13.97	0.88	13.02	0.89	14.32
4	0.75	7.72	0.88	12.51	0.90	14.03	0.82	10.25
5	0.78	8.34	0.91	14.60	0.93	17.86	0.85	11.78
6	0.74	7.35	0.91	14.79	0.93	17.48	0.84	11.39
7	0.66	5.96	0.90	13.78	0.90	14.15	0.78	9.13
8	0.69	6.34	0.86	11.65	0.88	12.60	0.77	8.91
9	0.71	6.74	0.85	11.25	0.88	13.01	0.84	11.47
10	0.71	6.68	0.85	11.28	0.86	11.70	0.81	9.95
11	0.82	9.48	0.91	14.59	0.90	14.27	0.93	19.07
12	0.95	19.71	0.96	23.87	0.93	16.77	0.95	22.81

Next, we examined the data series using linear trend analysis and the ANOVA method for comparison of the hourly datasets to each other (*Szentimrey,* 1989). The applied methodology is the same as described for the analysis of the six-hourly databases (*Barna et al.,* 2021*,* 2022). In detailing the results using

ANOVA method, we present a comparison of the six-hourly datasets produced and examine the expected values and standard deviations for the extended area of Hungary. ANOVA methodology can also be used to examine the anomaly values. As a result it can be concluded that in the warmer years (1992, 2003, 2007) of the period under study (1971–2020), the anomaly relative to the mean is larger for 09 and 15 UTC than for 03 and 21 UTC. The highest positive anomaly values can be associated to the southern Great Plain areas, and the lowest (negative) values can be assigned to the extensive surroundings of our mountains and lakes.

4. Results

4.1. ANOVA

Turning to the results, *Fig. 3* illustrates the spatial expected values between 1971–2020 for the four hourly values, and *Fig. 4* represents the temporal expected values where the examination period is also 1971–2020. In accordance to our expectations, the 21 UTC values are below the average daily temperature values, but the 09 UTC values can already be related to the 18 UTC data series examined earlier *Barna et al.* (2021). The 15 UTC data clearly have the highest values among the shown data series. Looking at the spatial distribution of the values in Hungary, the central part of Transdanubia and the southern Great Plain region can be characterized by higher values in the morning, Similar spatial trend can be observed at 09 UTC, where higher values can be attributed to the southern areas of the country, particularly the Körös-Maros region (12–14 °C). Also for 15 UTC, lower values are obtained in the northern part of Hungary. The 21 UTC data series are lower values in the Northern Central Mountains and the Transdanubian Central Mountains, compared to the rest of the country.

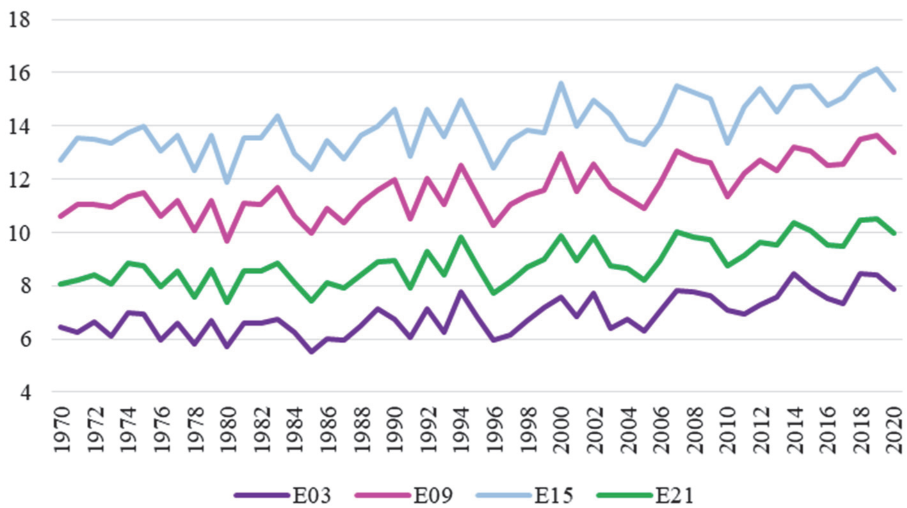

Fig. 3. Yearly spatial expected values for hourly values (03 UTC, 09 UTC, 15 UTC, 21 UTC) (1971–2020) (^{0}C).

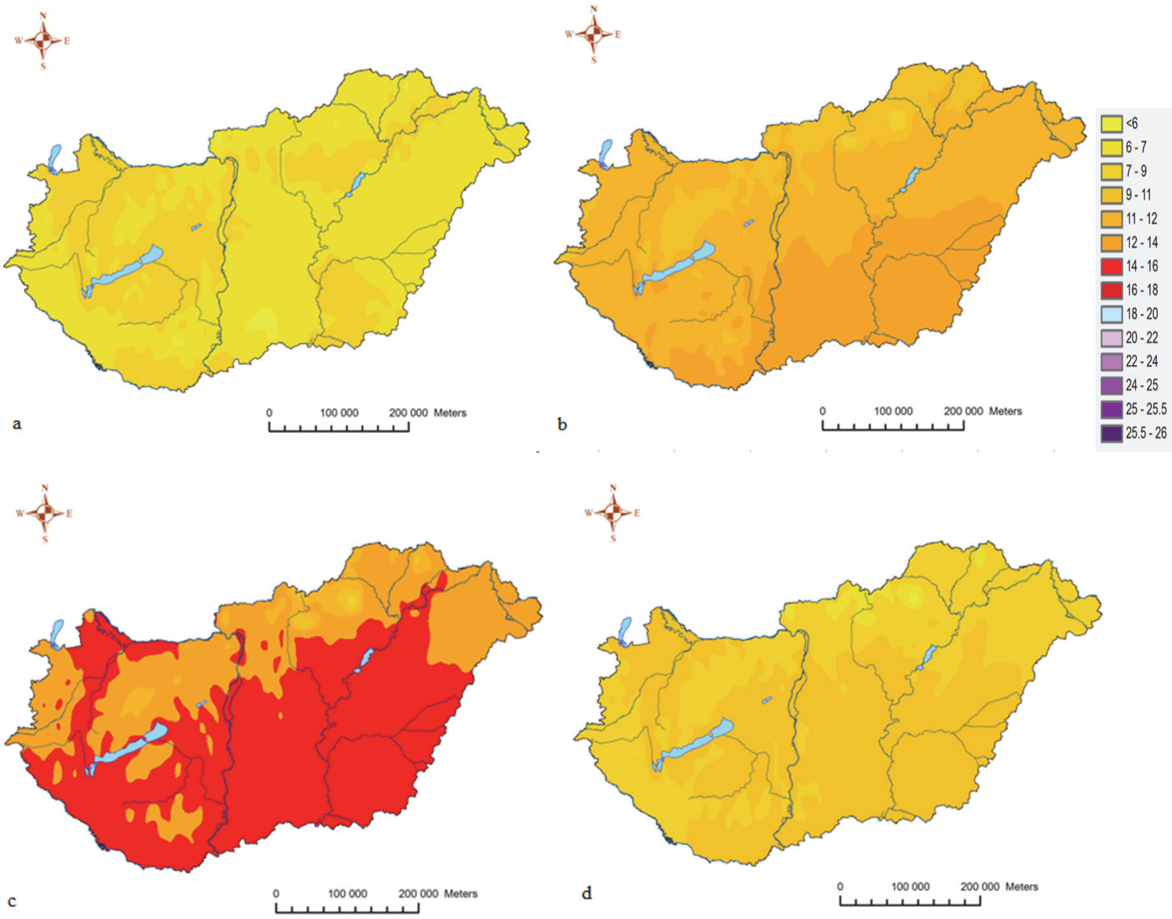

Fig. 4. Yearly temporal expected values for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)) (1971–2020) (ºC).

Examining the spatial distribution of the standard deviation values, it can be said that the 03 UTC database is the least variable, and the 15 UTC database is considered the most variable according to *Fig. 5*. Compared to the analyses for the main terminus measurements (*Barna et al.,* 2021), here we can already assign higher standard deviation values to the data series. Looking at the maps comparing temporal standard deviations, the 03 UTC case is the least variable (*Fig. 6*). *Fig. 6* shows that the southern regions of the country exibit the lowest standard deviation, with minimum values below 0.6. Compared to 09 UTC, higher standard deviations can be assigned to the central parts of the country. In case of the 15 UTC, two contiguous areas with standard deviation above 1.15 can be seen, which was not seen previously the border areas between Körös-Maros and the northwestern borderside of the country. The 21 UTC case also proves to be less variable with higher values in the southwestern part of the country.

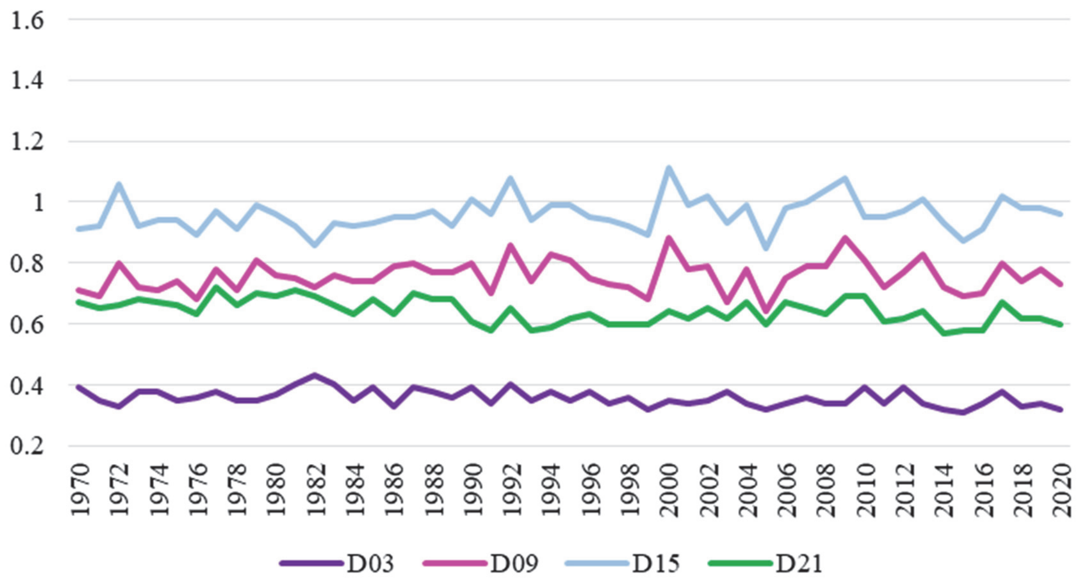

Fig. 5. Yearly spatial standard deviation values for hourly values (03 UTC, 09 UTC, 15 UTC, 21 UTC) (1971-2020) (^{0}C).

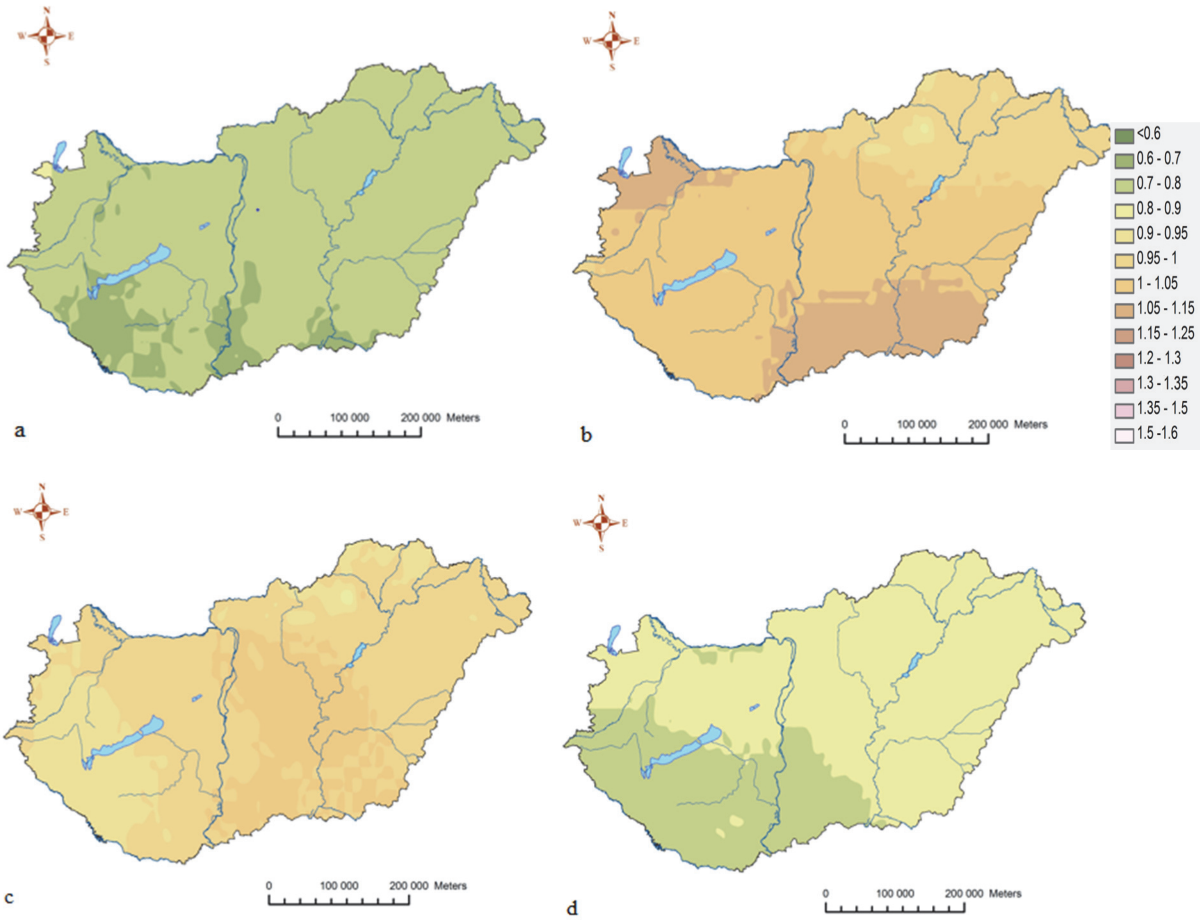

Fig. 6. Yearly temporal standard deviation values for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)) (1971–2020) (^{0}C).

All in all, the diagrams above show the spatial standard deviations and the maps show the average of the temporal standard deviations in the whole area of Hungary. If we examine the average temperature, the average of the variances over time is the largest (*Barna et al.,* 2021). The consequence is that since the temporal variance are higher (*Table 3*), longer data series are needed for each test. If the spatial variability were greater, many more station data series would be required to conduct the desired analyses. For example, when examining the 15 UTC data series based on *Fig. 6*, we need a much denser spatial coverage than the 03 UTC data, because the values are much more variable due to the greater spatial dispersion. On the other hand, if the variance in time is larger, a long sample is required for accurate estimates.

Table 3. Yearly Anova statistics

Yearly Anova statistics	**T03**	**T09**	**T15**	**T21**
Total mean	6.88	11.62	14.03	8.86
Total variance	0.66	1.50	1.94	1.06
Spatial variance of temporal means	0.11	0.55	0.89	0.40
Spatial mean of temporal variances	0.55	0.95	1.05	0.67
Temporal variance of spatial means	0.53	0.93	1.02	0.65
Temporal mean of spatial variances	0.13	0.58	0.92	0.41

4.2. Trend analysis

In this section, we present the results of the trend analysis which looks at how the data series changed over time. It is important that the trend maps show the change over the entire period, not the direction tangent. We examined the hourly data series on an annual and seasonal scales. We fitted linear trend to the data series. Annual changes are presented first (*Fig. 7*). We tested the estimated trend at the significance level of 0.1. With the exception of winter, we identified significant change for the entire area of Hungary. Regarding the 03 UTC trend values, an area characterized by values below 1.5 °C can be observed. In case of 09 UTC, values above 2.5 °C occur in the central parts of the country. Even the trends for the 15 UTC database, values above 2 °C indicated across the country, lower values can be seen in the northeastern areas of the country. However, the spatial distribution of the 21 UTC trend values shows a very diverse pattern. Values below 1.75 °C are typical in the southeastern areas of the country. Moving eastwards, higher and higher values are visible, in the central part of the country the trend values ranging from 1.75–2.25 °C. Besides in the northeastern part of the country, values between 2.25 and 2.5 °C appear.

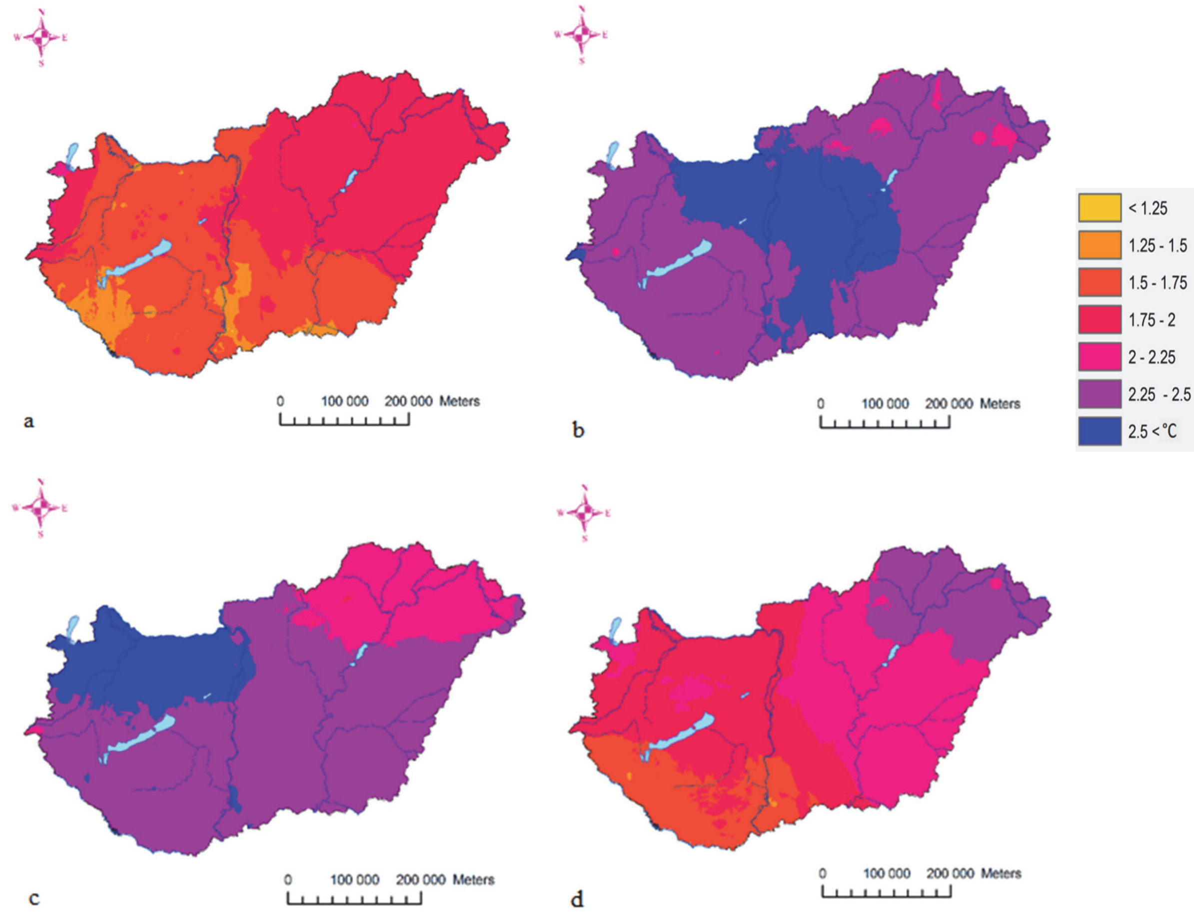

Fig. 7. The values of yearly change over the whole period (1971–2020), for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)), with linear trend estimation (ºC). The change is significant at the 0.1 significance level in the entire area of Hungary.

Let us have a look at how the spring trends are shaping up. Based on *Fig. 8* we can see that the spatial distribution of the 03 UTC trends has an area with the highest values appearing along the northwestern border. Apart from this, the trend values remain below 2 °C in the rest of the country. Values below 1 °C also appear in the extended area of the Danube and the Körös-Maros region. The largest area trends above 2.5 °C were obtained in the 09 UTC database. In addition, the southern Transdanubian region and the eastern area of the Great Plain can also be characterized by trends above 2 °C. A northwestern region can be characterized by values above 2.5 °C at 15 UTC. Going east these values decrease continuously, so in the areas south from the Danube and west from the Tisza, values above 2.25 °C appear and further east above 2 °C then above 1.75 °C. Examining the 21 UTC case it can be said, that the spatial distribution of the values can be best identified with the 18 UTC case examined in *Barna et al.* (2021). However, in terms of the order of magnitude of the values as a result of the trend analysis, this database is characterized by lower values. Trend values below 1 °C also appear in the southern areas of the country, and the highest values above 2 °C can be assigned to the northeastern area.

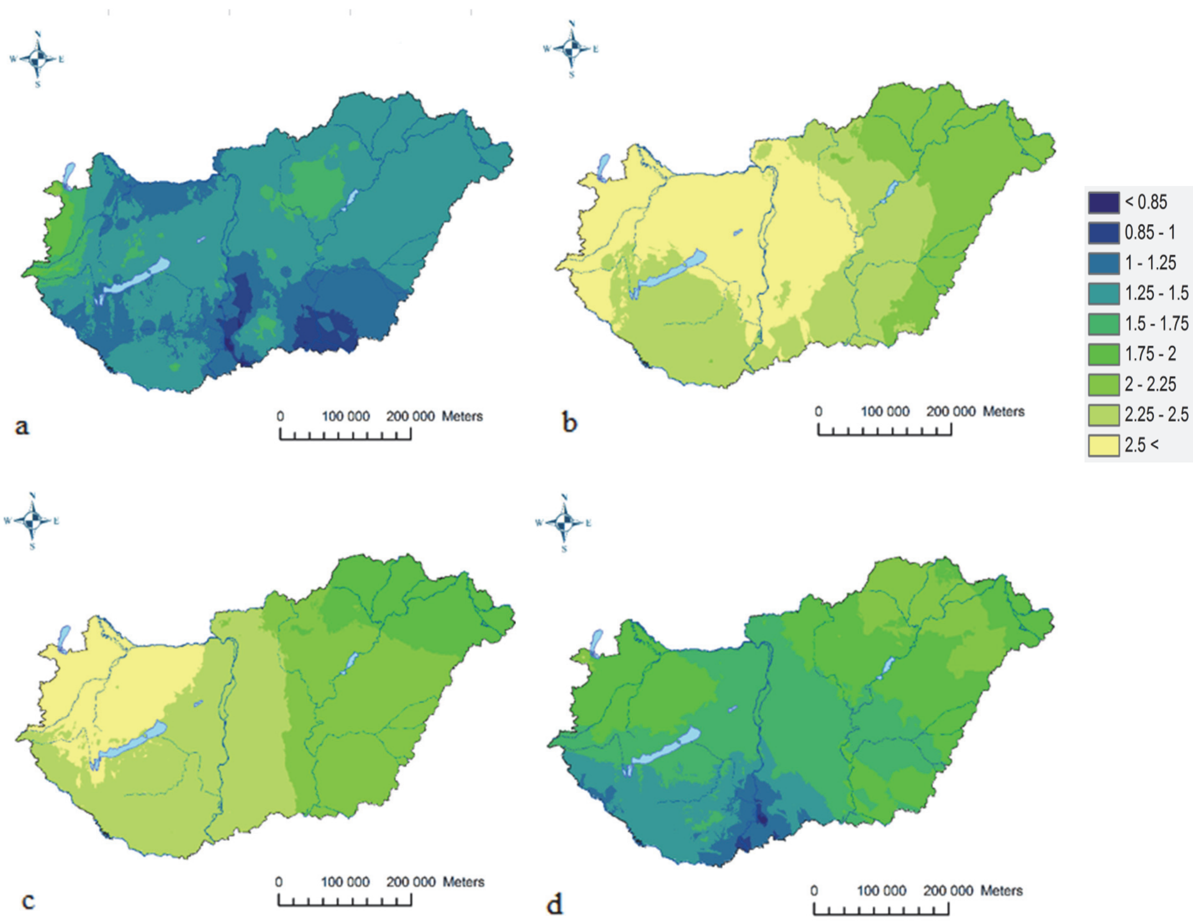

Fig. 8. The values of spring change over the whole period (1971-2020), for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)), with linear trend estimation (ºC). The change is significant at the 0.1 significance level in the entire area of Hungary.

Fig. 9 illustrates the results of the summer trend analysis. The lowest trend values can be assigned to the 03 UTC case. However, as we expect it, as they are summer tests, they are higher compared to the results of the other seasons and the 03 UTC database's annual results. The lowest values (<2.25 °C) appear in the Transdanubian areas and the Southern Great Plain region. Examining the trend values of 09 UTC, lower values appear in the southwestern and northeastern areas of the country compared to the central areas, but these are also above 3 °C. Comparing all the cases analyzed, it is clear that the highest values appear for 15 UTC. Along the northeastern border, where the lowest values also occurred, we can declare values above 3 °C. With the exception of this region temperature, values above 3.25 °C are typical throughout the country. For the 21 UTC dataset, the overall values are lower compared to the results of trend estimation for the 09 and 15 UTC data. The 21 UTC hourly trend values are the lowest along the southwestern border and continue to increase as we move towards the eastern half of the country. To the east from the Danube, except for the southern areas of the Danube-Tisza region, the typical estimated trends are already above 2.75 °C.

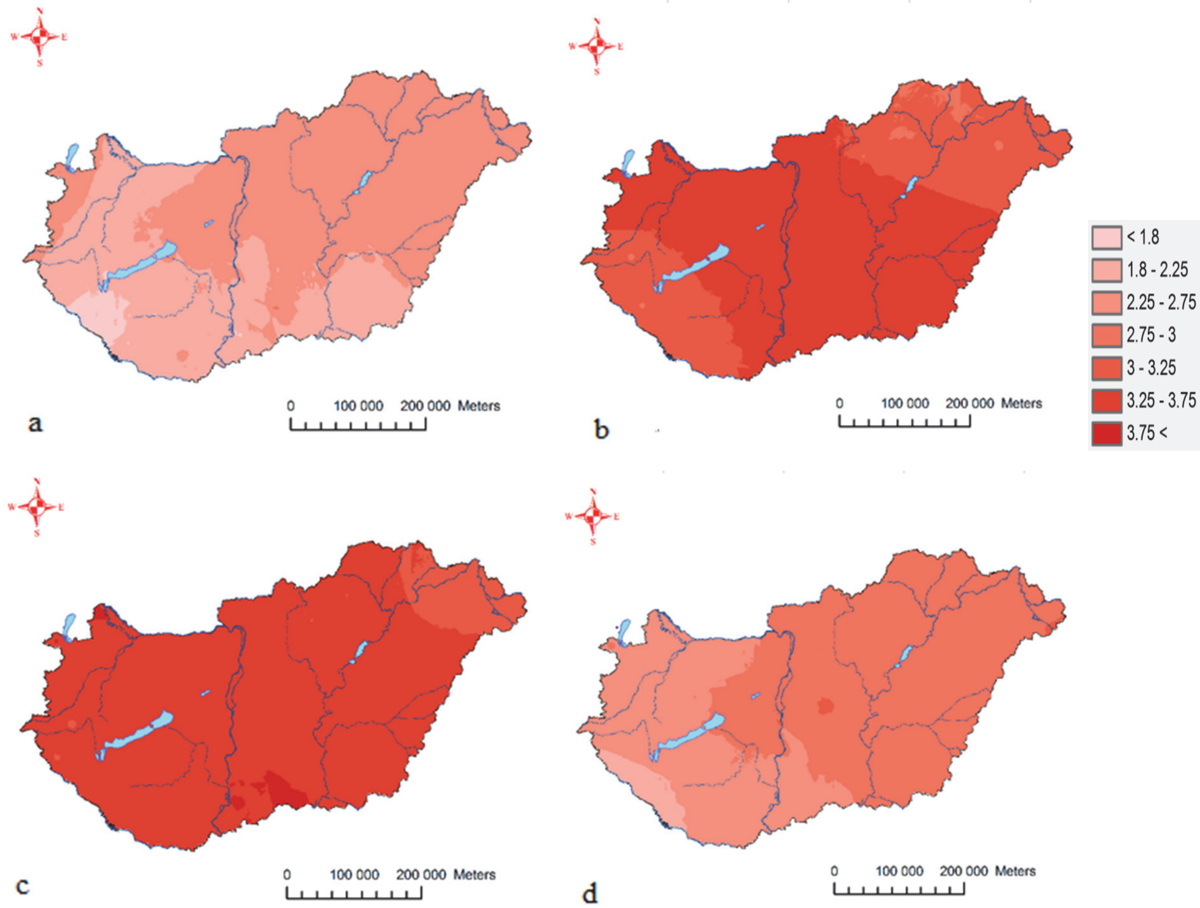

Fig. 9. The values of summer change over the whole period (1971-2020), for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)), with linear trend estimation (ºC). The change is significant at the 0.1 significance level in the entire area of Hungary.

Among the analyzed seasonal trends, autumn is illustrated by *Fig. 10*. In the case of the 03 UTC data, the highest values can be assigned to the region east from Tisza, and the lowest values obtained by linear trend estimation to the northern and southwestern areas of Transdanubia. Regarding the 09 UTC dataset, the Transdanubian region also shows lower values and even lower values can be highlighted in mountainous areas. When examining the 15 UTC database, the lowest trend values can be associated with the mountainous and southwestern areas, while the highest trend values can be located east from the line of the Tisza and in the extensive area of the capital city. Moreover, examining the entire area of Hungary, trend values above 2 °C appear in many places at 15 UTC data. Looking at the results for the 21 UTC database, we can see a similar tendency of the spatial distribution, i.e., the trend values obtained by fitting linear trend, continue to increase from west to east. Thus, lower values characterize the southwestern part of the country, and the greatest values appear in the northeastern part.

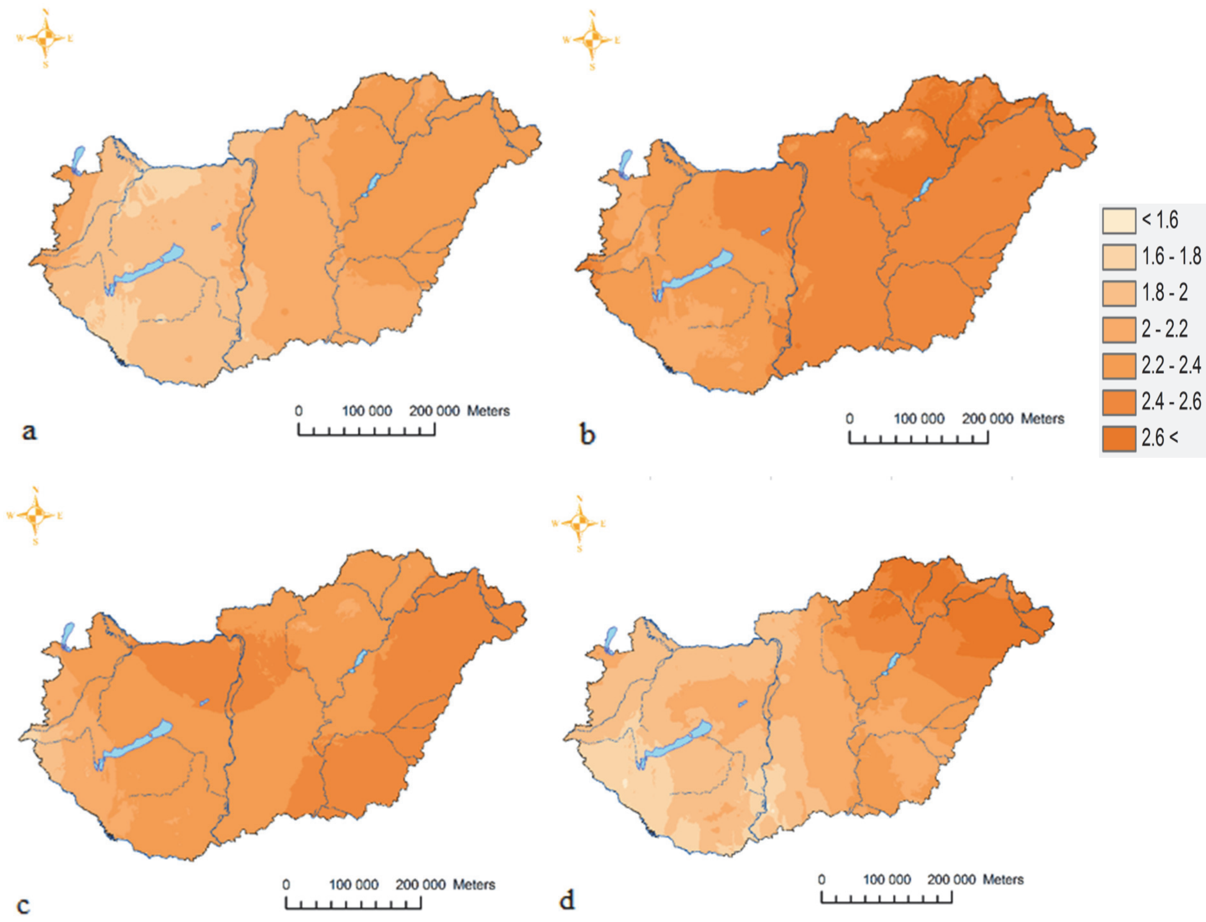

Fig. 10. The values of autumn change over the whole period (1971-2020), for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)), with linear trend estimation (ºC). The change is significant at the 0.1 significance level in the entire area of Hungary.

Finally, turning to the analysis of winter trends, the change occurring during the entire test period cannot be considered significant trend for all examined stations. There are 11 stations at 03 UTC, 32 stations at 09 UTC, 16 stations at 15 UTC, and 19 stations at 21 UTC with significant change. Taking the hourly databases one by one, in case of 03 UTC, lowest trends can be observed in the southwestern areas of the country. Compared to this, the 09 UTC tend values are already particularly high with values above 1.2 °C across the country. However, this is still considered low, compared to the results obtained with the other three seasonal trend analysis. Regarding 15 UTC, Hungary can be separated into two parts according to the estimated trend, since the lowest values appear in the northeastern areas. Moving westward the trend values gradually increase. According to this, the highest change appear reaching the western border areas, and this is the area where the stations with significant change are located. Based on the tests of significance of trends for the 21 UTC data, *Fig. 11* indicates that the northwestern and northeastern areas of the country show higher values compared to the central and southern areas.

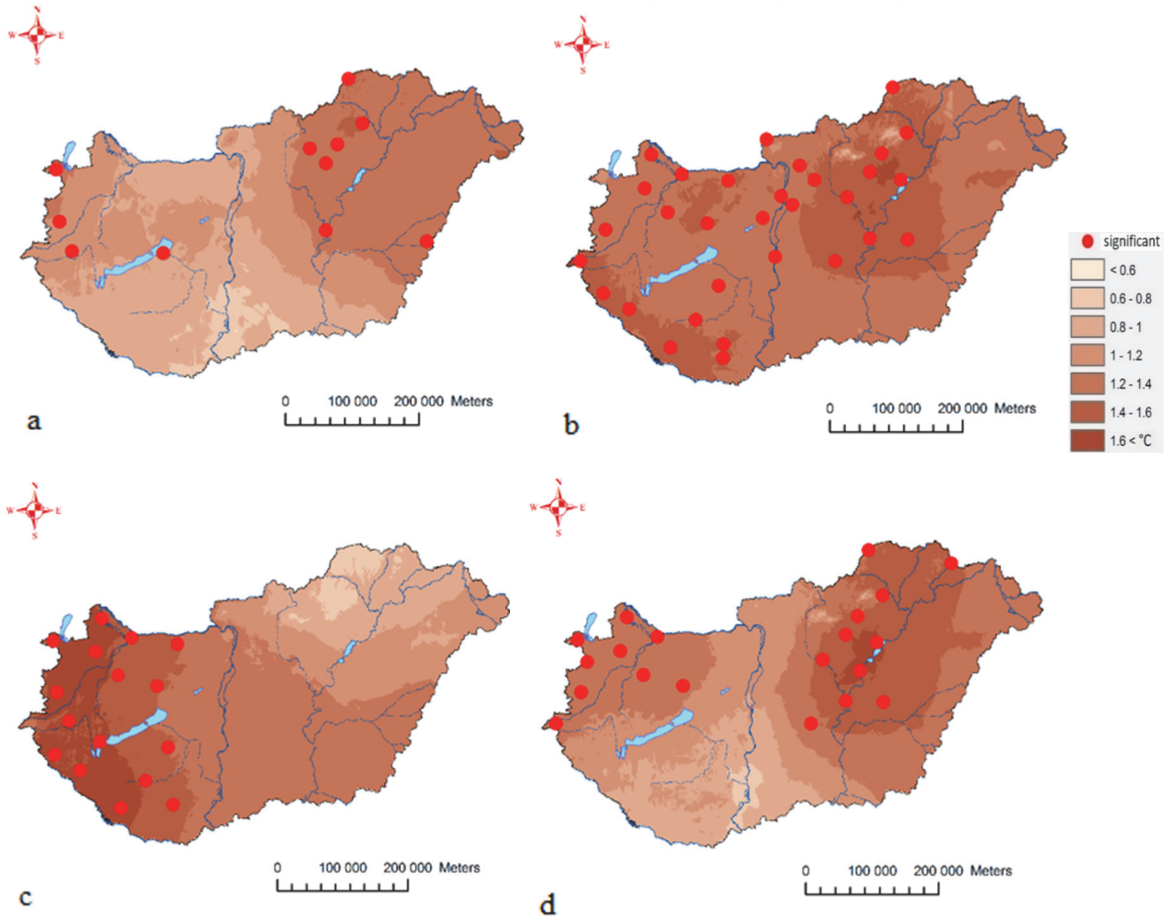

Fig. 11. The values of winter change over the whole period (1971-2020), for hourly values (03 UTC (a), 09 UTC (b), 15 UTC (c), 21 UTC (d)), with linear trend estimation (°C). Red points indicate the place of significant change at 0.1 significance level.

For the comparison from other point of view of the seasonal trends to each other, *Table 4* consists of the minimum, maximum, and average trend values appear in the country for each six-hourly data. Minimums are the highest at 09 UTC, the only exception is in summer, when the value belonging to the 15 UTC dataset is the highest. The same distribution appears when examining the means. However, in winter, spring, and summer the maximums are the highest at 15 UTC, and in autumn values are the highest at 09 UTC.

Table 4. Seasonal trend values over the whole period (1971–2020) of the six-hourly values obtained by linear trend estimation. Minimum, mean and maximum values are given as spatial values.

03 UTC trend	Min	Mean	Max
Winter	0.52	1.10	1.46
Spring	0.60	1.33	2.28
Summer	1.47	2.29	2.93
Autumn	1.56	2.07	2.44
09 UTC trend	**Min**	**Mean**	**Max**
Winter	0.75	1.37	1.79
Spring	2.00	2.42	2.84
Summer	2.90	3.35	3.79
Autumn	1.97	2.43	2.89
15 UTC trend	**Min**	**Mean**	**Max**
Winter	0.63	1.27	1.92
Spring	1.75	2.29	2.97
Summer	2.95	3.49	3.95
Autumn	1.65	2.34	2.63
21 UTC trend	**Min**	**Mean**	**Max**
Winter	0.58	1.23	1.67
Spring	0.46	1.71	2.34
Summer	1.99	2.77	3.12
Autumn	1.43	2.13	2.77

5. Main conclusions

According to our analysis, we can highlight that the results of the ANOVA method indicate the differences between the hourly databases regarding the expected values and standard deviations. The presented maps and diagrams illustrate that the 15 UTC database has the highest expected values. Considering the standard deviations, the difference of the datasets is not particularly large, but the temporal and spatial variability of the 03 and 21 UTC databases and the 09 and 15 UTC databases can be separated from each other. As a result of the trend analysis, it can be seen that the 15 UTC database shows the highest trends, as expected. We can conclude that the estimated annual and seasonal linear trends emerge in the 03 UTC and 21 UTC data series are similar, however, comparing the 09 UTC and 15 UTC trend values, the magnitude and spatial distribution of those differe too.

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