Examination of the cyclic properties of 110-year-long precipitation time series

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In the hydrological cycle of the Earth, the periodic components play an important role in that process. It could be a great importance for groundwater management reasons to get to know better the cyclic properties of the meteorological extremes, affecting the hydrological cycle. The cyclic parameters of the annual, monthly and daily precipitation values have been calculated from precipitation data from four different meteorological stations in Hungary. The cycle parameters of these datasets have been determined using a period of 110 years of precipitation data, through the determination of the frequency, amplitude and phase angle with an analytic version of Discrete Fourier-Transformation (Meskó 1984). The values obtained from the four stations have been compared, and the regional or the national cycles have been defined for the Carpathian-basin. Using the daily datasets, examination of the changes in the 1-year cycle and the changing of the longest cycle (cycle with the longest period of time) have been carried out. In our examination, we showed the presence of the one-year-long and the half year long cycle as well as the third most dominant 5-year-old one, and the 12-year-old, the longest period of time. According to our research, the period of time and the amplitude of the longest cycle has significantly decreased, which is important new information.

Keywords: *precipitation, cycles, cyclic parameters, spectral analysis, climate change*

Introduction

On the Earth, approximately 400 000 km^3 volume of water is being transported annually in the dynamic water cycle, which is affected by the changing climate (Hartai, 2014) and the meteorological extremities present in recent years (Szűcs, 2012).

In Hungary, 95 % of the drinking water is produced from groundwater aquifers. Therefore, the effects of a changing climate and even the slightest changes in the water cycle can have a strong effect to these aquifers. Therefore, these are important task-related questions in the Carpathian Basin. The changes in the nature of precipitation have an impact on the groundwater resources through the recharge, so it is important to understand better the nature of the precipitation and the hydrologic cycle.

In recent years, the World Water Council showed in several studies that the hydrologic cycle is accelerating, the number of meteorological extremities increased the ratio of wet and dry seasons are becoming much more diverse. Now the wet seasons will have almost the same amount of precipitation as previously, but it will fall within a short time period. It increases the runoff and causes a decrease in the groundwater recharge, and the dry seasons will have a longer period without any measurable rainfall. Thus, less amount of water will reach the water table, so the decrease in groundwater resources is predictable (Szöllösi-Nagy, 2015).

At the University of Miskolc, several types of research were carried out examining the climate change, and its effect on groundwater resources on several sample areas. This effect is mostly present in the recharge of these aquifers. The recharge of shallow groundwater was previously examined with environmental isotopes in a time span of 60 years of data (Szűcs et. al., 2015), as well as measurements of precipitation and karst water level in the Bükk Mountains. It showed that the range of the maximum and minimum values of precipitation values and karst water levels have become broader (Szegediné et. al., 2015).

There are several methods to examine the periodicity of a time series based on the Fourier-transformation, such as the Lomb-Scargle periodogram (Nason et. al., 1999), the Wavelet Time Series Analysis (Kovács et. al., 2010). These two methods were used before in several studies to examine precipitation in California (Sangdan, 2004), at the Sanjiang Plain (Liu et al., 2009) and in Gannan County, China (Zheng et al., 2014). In this paper, we used an analytic version of the discrete Fourier-transformation, which was used previously to examine precipitation in the Bükk and Mátra Mountains of Hungary (Kovács et. al., 2015) and the rainfalls of Central-America (Hastenrath, 1964).

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Based on former studies, this paper examined 110-year-old precipitation time series from four Hungarian cities. Discrete Fourier-Transformation method was used to examine the annual, monthly and daily precipitation datasets from Budapest, Debrecen, Pécs and Szombathely (Fig. 1).

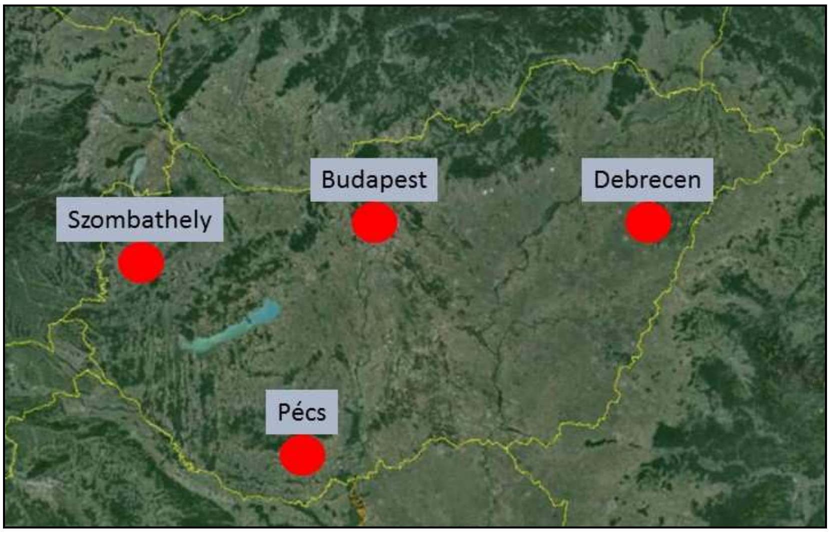

Fig.1. The location of the examined cities in the Carpathian-basin.

Theoretical Background

The long term hydrometeorological data sets are considered to be time series so that we can apply time series analysis via mathematical methods.

There are two ways to examine a time series, the classical statistical method is the trend analysis (Monsteller et. al., 1977), and the other way is the spectral analysis. These two methods complement each other; the trend analysis examines the long-term linear components of a time series, while the spectral analysis searches for the periodic components in a dataset. In the spectral examination, we use harmonic functions to define the periodicity of a time series.

These precipitation datasets contain several of periodic components. Therefore, we chose to examine it with spectral analysis, based on the Fourier-Transformation (Meskó, 1984; Panter, 1965). Working with harmonic functions in the analytic Fourier Transformation, a complex Fourier-spectrum *F(f)* is obtained, which can be divided into a real and an imaginary part. The Re[*F*(*f*)] real part of the spectrum can be written as:

$$\mathrm{Re}\left[F(f)\right] = \int_{-\infty}^{+\infty} f(t)\cos(2\pi ft)dt \qquad (1)$$

The imaginary part as:

$$\mathrm{Im}[F(f)] = -\int_{-\infty}^{+\infty} f(t)\sin(2\pi ft)dt \qquad (2)$$

The complex Fourier-spectrum can be written as with the two spectra:

$$F(f) = \mathrm{Re}[F(f)] + j \times \mathrm{Im}[F(f)] \qquad (3)$$

The *F*(*f*) complex spectrum can also be defined in an exponential form, by introducing two other real spectra:

$$F(f) = A(f)e^{j\Phi(f)} \qquad (4)$$

where the *A*(*f*) spectrum is called the amplitude, while the *Φ*(*f*) spectrum is called the phase spectrum. The amplitude and phase spectrum are defined by the real and imaginary spectra:

$$A(f) = \sqrt{\mathrm{Re}^2[F(f)] + \mathrm{Im}^2[F(f)]} \quad (5)$$

$$\Phi(f) = arctg\,\frac{\mathrm{Im}[F(f)]}{\mathrm{Re}[F(f)]} \quad (6)$$

The amplitude spectrum gives the weight in the formation of the signal of the harmonic component falling into a frequency band unit around any frequency. The phase spectrum shows, what part of the period length the maximum of this harmonic component shifts in relation to the maximum of base function $\cos(2\pi ft)$.

The relative amplitude spectrum defined as the local maximum value of the amplitude compared to the absolute maximal amplitude found in the time series.

In spectral analysis, there are two different ways to examine the time series. The first is the deterministic way; the other is the stochastic way, where we presume there are various random effects in the series (Candy, 1985).

Basically, these meteorological processes are stochastic, but in this paper, we searched for deterministic components in our datasets with the criteria, that the time series has no significant trend and the sampling rate is equidistant.

For these analyses, a self-made software for cyclic components was used, the graphs were made by OriginPro.

Results

To determine the cyclic, parameters we used the data from the OMSZ (Hungarian Meteorological Service) online database (HMS 2015), which contains 110 years of meteorological parameters for five cities of Hungary. The locations of the chosen meteorological stations properly represent the weather of the Carpathian-basin. Budapest represents the middle part of the country, on the banks of the Danube River, Debrecen shows the weather of the eastern part of the Great Plain and the country. Pécs was chosen to represent the southern part of the country, close to the Adriatic Sea. Szombathely located on the western side of the basin, at the foothills of the Alps Mountains. The database contains the city of Szeged, but because of missing data, it had to be dropped, not fulfilling the criteria of equidistance.

After defining the cyclic parameters, the amplitude, the phase angle and the frequency, the cycles with the relative amplitude spectrum over 50 % were defined as major (dominant) cycles and cycles with relative amplitude spectrum between 20 % (in some cases 10 %) and 50 % were defined as additional (minor) cycles.

Annual Precipitation

At first, we chose to examine the annual precipitation. The registration period is 1901 – 2010. Thus the length of the registration period, T_{reg}=110 years, the sampling rate is 1 year, and the numbers of samples are 110 from each city. The Nyquist frequency is 2 years (Meskó 1984). The Nyquist-frequency shows the minimal length of the period of time that can be calculated correctly by this examination method. The results of the spectral analysis, the cycles, and its relative amplitude are shown in Table 1.

The graphs show the amplitude (left) and the relative amplitude (right) at different period of time values. To show the dominance of a cycle, the relative amplitude can be used. Most of the graphs show an increasing part at the end of the graph without reaching a local maximum value, meaning there can be even longer periods in the dataset, but not measurable with these registration periods and methods.

In Budapest, 21 cycles were detected (Fig. 2), most of them (15) are major cycles, and 6 of them are additional cycles. The most dominant cycle was the 5-year-long with almost 100 % relative amplitude spectrum ($AY(T)_{max}$), followed by the 3.6-year-old with the second largest amplitude.

Tab. 1. Cycles in precipitation from four different cities of Hungary.

Budapest		Debrecen		Pécs		Szombathely	
T [year]	$\frac{AY(T)^{lok}_{\max}}{AY(T)^{abs}_{\max}}$ [%]	T [year]	$\frac{AY(T)^{lok}_{\max}}{AY(T)^{abs}_{\max}}$ [%]	T [year]	$\frac{AY(T)^{lok}_{\max}}{AY(T)^{abs}_{\max}}$ [%]	T [year]	$\frac{AY(T)^{lok}_{\max}}{AY(T)^{abs}_{\max}}$ [%]
2.8	45.65	3.1	41.11	2.9	88.95	2.8	50.20
3	48.83	3.4	56.89	3.2	61.44	3	44.10
3.3	47.93	3.6	100.00	3.6	95.02	3.5	71.06
3.6	90.15	4.3	71.45	3.9	64.36	3.9	54.00
3.9	29.79	4.6	28.36	4.1	82.77	4.2	55.97
4.3	41.42	5	77.45	4.5	100.00	4.5	21.06
4.5	40.03	5.6	55.18	5	99.50	5	52.84
5	90.88	6.1	61.87	5.6	55.28	5.5	30.80
5.3	32.98	6.5	49.59	6.1	66.19	6.3	47.78
5.7	41.75	7	30.45	6.7	32.68	6.8	32.11
6.2	33.63	7.7	24.24	7.6	60.27	7.8	40.63
6.6	33.23	10.4	26.52	9.9	67.53	8.5	51.41
7.5	30.02	13.5	69.34	12	54.49	9.5	47.53
8.3	40.12	21.8	43.45	14.3	65.71	10.4	49.95
10.6	53.15	31.6	77.77	18.1	43.87	11.8	80.05
12.4	60.56	51	27.46	31.6	73.43	13.3	61.30
14	57.74			51	55.10	15.6	72.15
19.8	59.76					26.7	100.00
24.4	40.03					36	80.94
31.3	17.05					59	65.26
47	47.17						

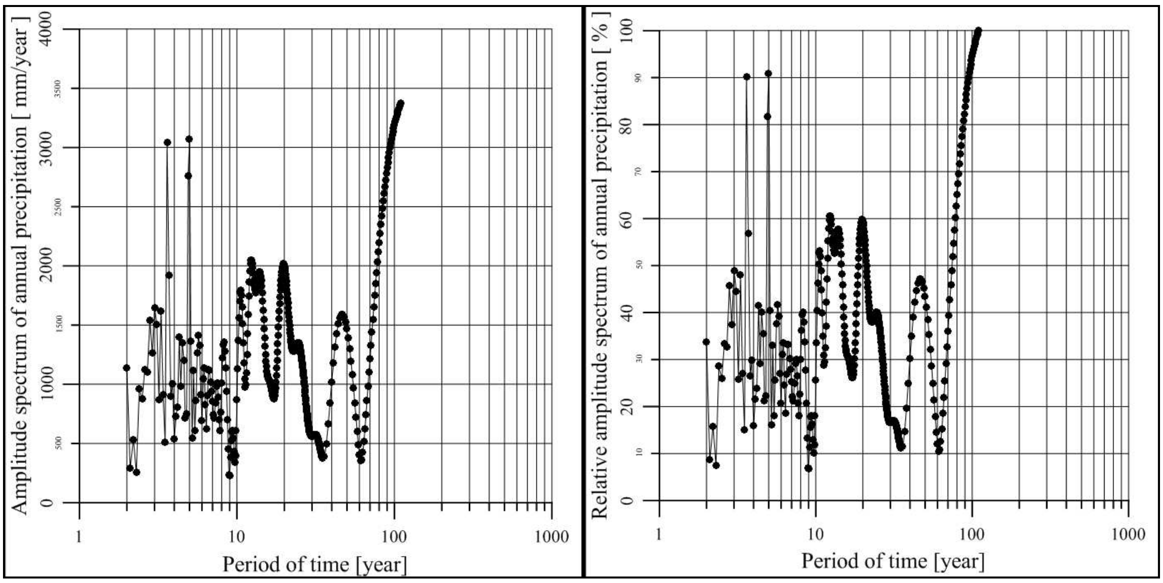

Fig. 2. The amplitude and relative amplitude in Budapest between 1901 and 2010.

In Debrecen, 16 cycles were calculated (Fig. 3), 11 major cycles, and 10 additional cycles. In this city the 3.6-year-long cycle was the most dominant, with exactly 100 % relative amplitude, the other cycles have a smaller amplitude between 77 - 27 %.

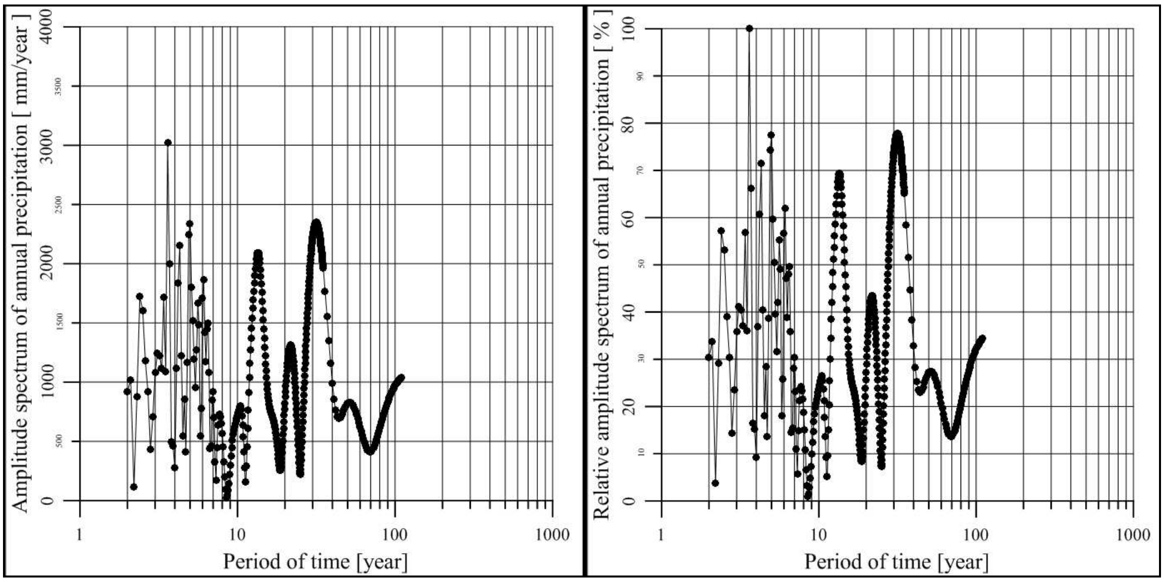

Fig. 3. The amplitude and relative amplitude in Debrecen between 1901 and 2010.

In Pécs, 17 cycles were determined (Fig. 4), 16 of them are major, and only 1 is an additional cycle. This means that the cycles are much more dominant in the precipitation time series in Pécs than in any other city. We can describe the precipitation in Pécs with few, but dominant cycles. The most dominant 4.5-year-long cycle followed by the 5-year-long, with almost the same relative amplitude value, and the third is the 3.6-year-long with more than 90 % relative amplitude.

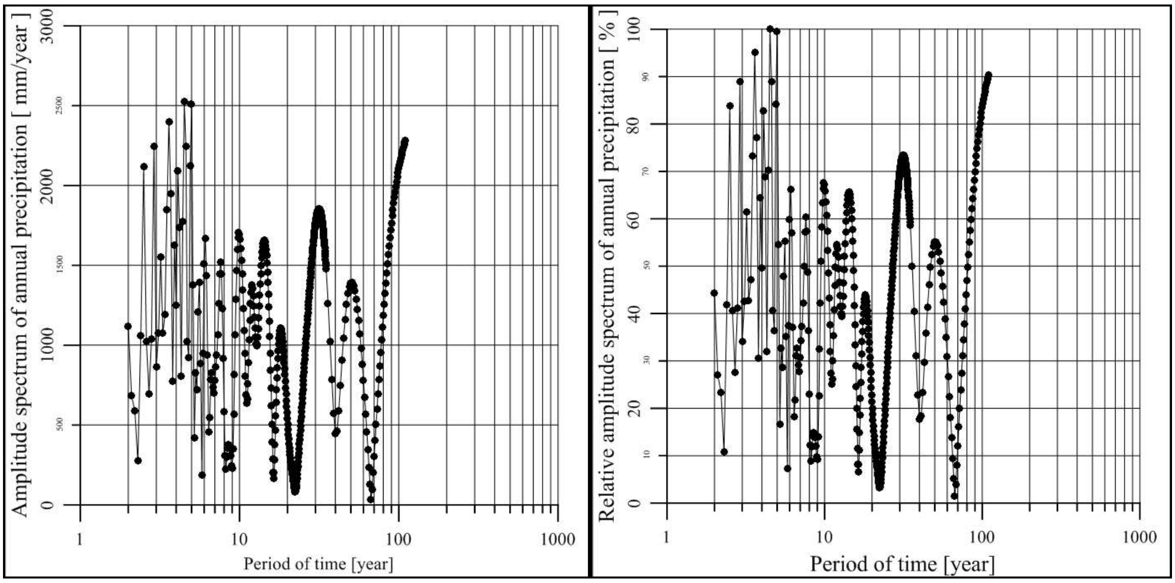

Fig. 4. The amplitude and relative amplitude in Pécs between 1901 and 2010.

In Szombathely, 20 cycles were determined (Fig. 5). Most of them cannot be compared to the other 3 cities, mostly because of its geographical location (close to the Alps). This area has the most precipitation in the country. Therefore, its cyclic parameters differ from the other ones. The most dominant cycle is the 26.7-year-long, and as seen in Table 1. All the cycles with higher relative amplitude are in the range of 10 to 60 years. This means that the longer cycles determine the weather of the city, and because of the different meteorological parameters of the area, the short term cycles are less dominant, the variability is dominant.

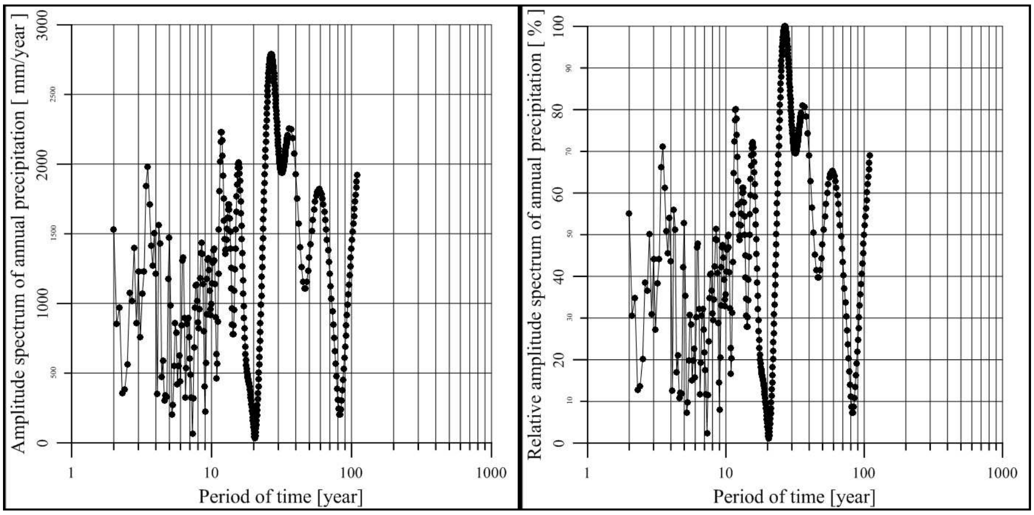

Fig. 5. The amplitude and relative amplitude in Szombathely between 1901 and 2010.

After the spectral analysis, the four results were examined together. We found 7 cycles that were present in all datasets, which are the following with the average relative amplitude spectrum:

5-year-long	$AY(T)_{max}$ = 80.17 %
3.5 – 3.6-year-long	$AY(T)_{max}$ = 71.25 %
11.8 – 13.5-year-long	$AY(T)_{max}$ = 66.11 %
2.8 – 3.1-year-long	$AY(T)_{max}$ = 57.27 %
6.1 – 6.3-year-long	$AY(T)_{max}$ = 52.36 %
4.5 – 4.6-year-long	$AY(T)_{max}$ = 47.36 %
7.5 – 7.8-year-long	$AY(T)_{max}$ = 38.79 %

The geographical location of these meteorological stations represents the whole country, so these cycles can be called national, or Central-European regional cycles, because the collected data from the four cities can be representative for the whole Carpathian Basin.

Monthly Precipitation

The registration period is January 1901 – December 2010, the length of the registration period, T_{reg}=1320 months, the sampling rate is 1 month, and the numbers of samples are 1320 from each city, the Nyquist frequency is 2 months.

In Budapest, 71 cycles were detected (Fig. 6). The most dominant was the half year long, with a relative amplitude spectrum of 100 %, the second was the 1-year-long with 76,63 % relative amplitude value. In the 71 cycles, 3 were major cycles, with relative amplitude over 50 %, and the other were additional cycles. The additional dominant cycles were the 3, the 13.7, 16.2 month long ones, along with 43 others with relative amplitude range between 20 and 50 %.

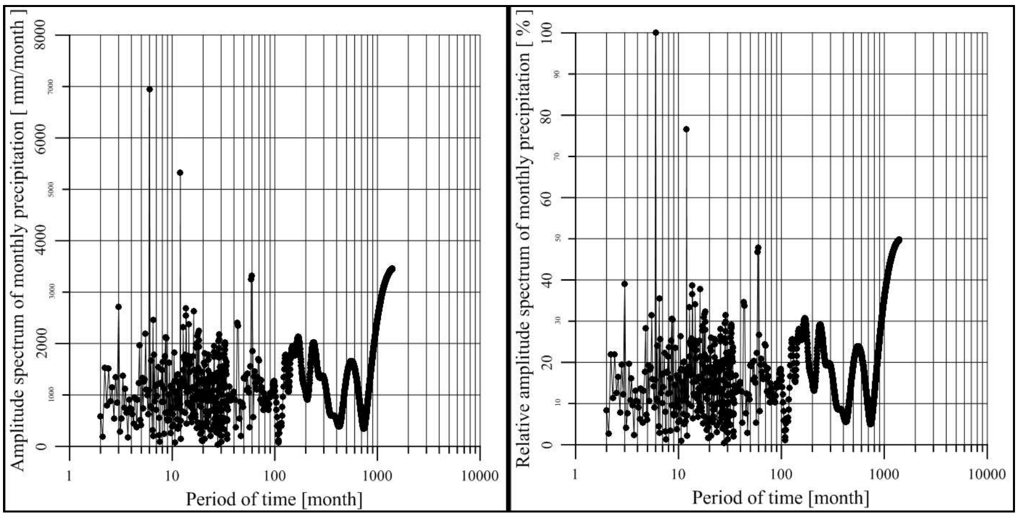

Fig. 6. The amplitude and relative amplitude in Budapest between January 1901 and December 2010.

In Debrecen, 43 cycles were detected (Fig. 7). In this case, the 1-year-long cycle had the 100 % relative amplitude spectrum, and the half year long had the relative amplitude spectrum of 57.64 %. The other cycles were additional cycles. The additional dominant cycles were the 59, 14.7, 378 month long ones, most of the minor cycles have the relative amplitude range under the 20 % value but were considered as important ones in the precipitation dataset.

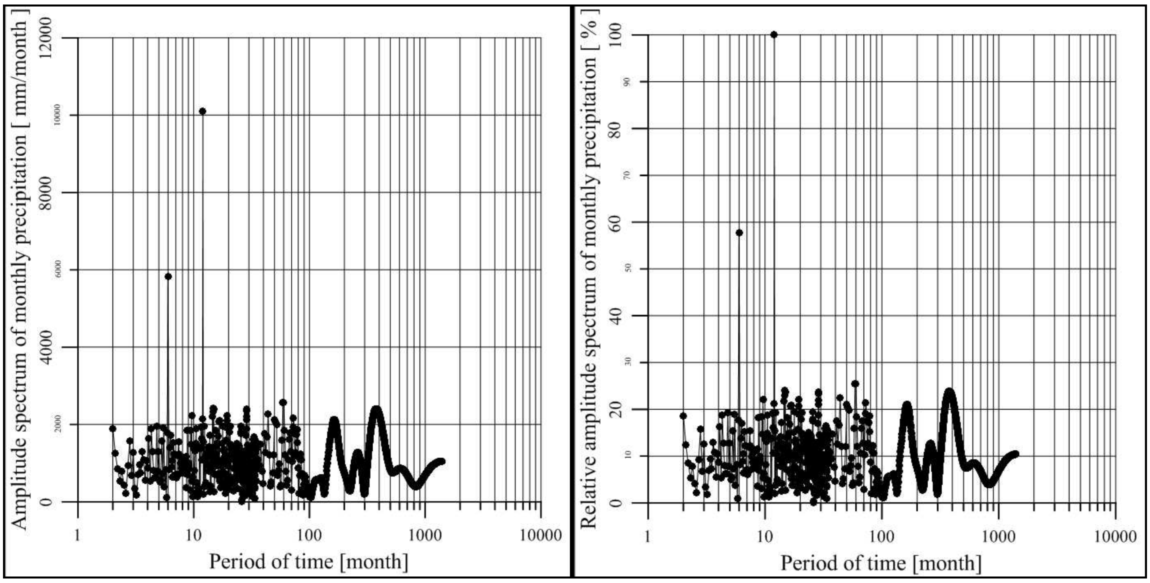

Fig. 7. The amplitude and relative amplitude in Debrecen between January 1901 and December 2010.

In Pécs, 65 cycles were detected (Fig. 8). The 1-year-long cycle had the relative amplitude of 100 %; the half year long had 66.53 %. All of the other ones were additional cycles, with relative amplitude range between 14-50 %. The dominant minor cycles are the 5.5, 54, 12.2, 60 month long ones, with 22 others with the relative amplitude values between 20 and 50 %.

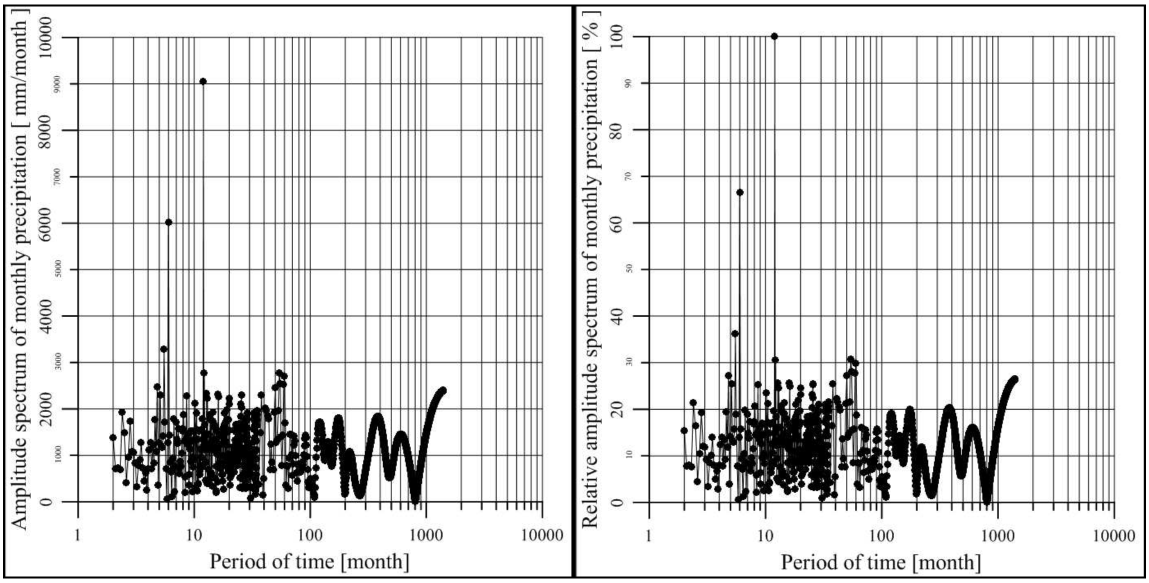

Fig. 8. The amplitude and relative amplitude in Pécs between January 1901 and December 2010.

In Szombathely, only 19 cycles were detected (Fig. 9.), and the only major cycle is the 1-year-long one, with 100% relative amplitude value. The half year long cycle had only 23.71 % relative amplitude, which means the 6 month long cycle of the weather is not as dominant as seen in the other 3 stations, and all the other minor cycles have a relative amplitude value less than 20 %.

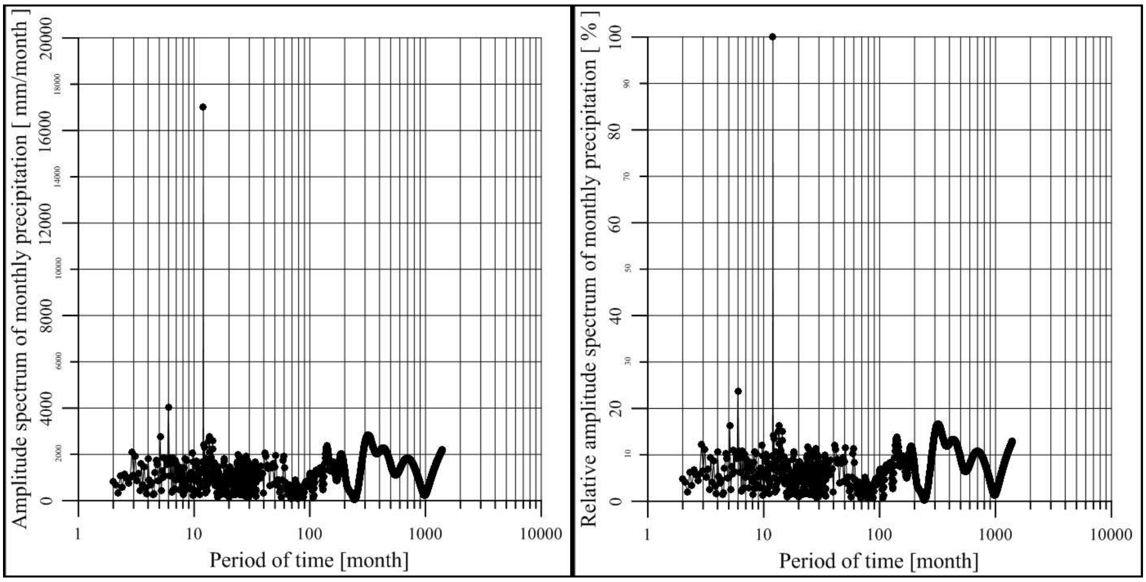

Fig. 9. The amplitude and relative amplitude in Szombathely between January 1901 and December 2010.

As it is seen in the graph, only two-three higher value can be seen in this case. This can be caused by the special climate situation of the city; it lies in the area which has the most precipitation in the country caused by the closeness of the Alps. In this climate, the cycles are not as dominant as seen in Budapest.

To examine the four results together, we found 13 cycles that were present in all of the datasets, which are the following, with the average relative amplitude values:

1-year-long	$AY(T)_{max}$ = 94.16 %
0.5-year-long	$AY(T)_{max}$ = 61.97 %
4.92 – 5.00-year-long	$AY(T)_{max}$ = 28.61 %
1.13 – 1.15-year-long	$AY(T)_{max}$ = 23.14 %
1.2 – 1.21-year-long	$AY(T)_{max}$ = 23.08 %
3.42 – 3.67-year-long	$AY(T)_{max}$ = 22.83 %
0.4 – 0.43-year-long	$AY(T)_{max}$ = 22.76 %
2.36 – 2.39-year-long	$AY(T)_{max}$ = 21.85 %
4.17 – 4.5-year-long	$AY(T)_{max}$ = 20.88 %
11.75 – 13.67-year-long	$AY(T)_{max}$ = 19.34 %
2.8 – 3.17-year-long	$AY(T)_{max}$ = 17.35 %
6.08 – 6.25-year-long	$AY(T)_{max}$ = 15.21 %
7.58 – 7.67-year-long	$AY(T)_{max}$ = 10.56 %

As it can be seen in the results, the most dominant is the yearly precipitation cycle with almost 100 % relative amplitude value, with the half year long cycle being the second one. At the examination of the annual precipitation, the 5-year-long cycle was the most dominant, which is the third most dominant according to the monthly precipitation. Cycles slightly longer than one year have a relative amplitude above 20 %. The longest cycle found in all of the four datasets is the 12-year-long one. The longer cycles have more differences in the data for each city, so it could not be called the same in every result.

According to other measurements in the region, most of the cycles can be found in other examinations. The long period time cycles from the annual precipitation data can be found in previous studies examining the long-term precipitation datasets in the Bükk-Mátra Region of Hungary (Kovács et. al. 2015) the 5, 3.6, 6.4-6.5, 7.4 and 14.3-year-long cycles were also found. These similarities with the previous research can confirm that these cycles represent most of the countries nature of precipitation.

The cycles from the monthly precipitation datasets show similarities with the results of another study examining the Nyírség Region of Hungary (Ilyés et. al. 2015). In that paper, we used precipitation data from two small towns, from East-Hungary with the registration period of 52 years. The 1, 0.5, 0.4-0.43, 1.13-1.15, 2.38-year-long cycles were also found in that area.

Daily Precipitation

To examine the long-term changes in the cyclic parameters, we used the daily precipitation datasets to answer the question, how the yearly cycle changes, and how the cycle with the longest period of time changes. If there is any change in the hydrologic cycle of the Earth, it has an effect of the cycles in the precipitation. In recent studies, professionals say that this hydrologic cycle is speeding up, the climate of the planet is getting more diverse and the distribution of the annual precipitation within the year is changing (Stocker et. al., 2013), (Bates et. al., 2008), increasing the danger of flooding of an area.

We used the 110-year (40 177 days) long data sets, dividing it into four time periods, and examining it simultaneously. The periods are the following:

1. January 1901. – 2. July 1928.
2. July 1928. – 1. January 1956.
1. January 1956. – 2. July 1983.
2. July 1983 – 31. December 2010.

The 4 registration periods contain 10 045 samples respectively from each city, and the sampling rate is 1 day.

In Debrecen, the yearly cycle's change is minimal, it stays the same for a period of time at 366.6 days in the first and last period, and in the middle of the century, it becomes slightly shorter - 364.4 days. The amplitude spectrum of the yearly cycle also shows minimal changing; it increases with 12 %.

In Budapest, a small increase can be found from 366.5 to 366.9, but the second period has the longest cycle with 368 days. Also four quite different amplitudes were calculated, which shows the diversity of the precipitation in the 20th Century in Budapest.

In Pécs, a minor decrease can be found from 366.8 to 365.7. The third period has the longest yearly cycle, a 366.9 long one, and the second has the shortest with 363.7 days. Also, there is a slight increase in amplitude.

In Szombathely, the same results were found. The yearly cycle is the longest in the last period (365.9 days), shortest in the second (364.4 days). In this city, a decrease in the amplitude was calculated.

The results showed that the changes in the period of time of the yearly cycle are not strongly monotonic, the four datasets showed four different results. In most of the cases, there were minor increases in the amplitude, but in Szombathely, a decrease was calculated. According to these results, it can be said that the changes of the yearly cycle are minimal, it stays within a 365 - 366-day-long period of time.

The examination of the longest cycle found in the datasets showed a different result. In Debrecen, the longest cycle decreases from 5576 days to 4386 days, but in the second period, it has a 5930-day-long period of time. Also, the same change can be found in the amplitude, it doubles from the first to the second period, but after it decreases to a minimum value if 306.4225 mm/365 days. In Budapest, the period of time of the longest cycle halved during the century, but it was the longest in the third quarter of the 100 years. In Pécs, the results have similarity with the results from Debrecen in the case of period of time, but the amplitude has a minimal increase from 356.408 mm/365 days to 470.0534 mm/365 days. In Szombathely, the period of time halved during the 110 years, and the amplitude decreased from 1208.7170 mm/365 days to 378.6933 mm/365 days.

Tab. 2. The changes of the period of time in the cycle with the longest period of time.

Time periods	Longest cycle [days]			
	Budapest	Debrecen	Pécs	Szombathely
1. January 1901. – 1. January 1956.	7998	5753	5157,5	3724
1. January 1956. – 31. December 2010.	6424	4654,5	3605	2789,5
Change in the period of time [days]	**-1574**	**-1098,5**	**-1552,5**	**-934,5**

Tab. 3. The changes of relative amplitude in the cycle with the longest period of time.

Time periods	Longest cycle [mm/365 days]			
	Budapest	Debrecen	Pécs	Szombathely
1. January 1901. – 1. January 1956.	1139.7566	795.8804	739.9553	724.1627
1. January 1956. – 31. December 2010.	581.1618	637.4869	597.1862	532.4286
Change in the relative amplitude spectrum (%)	**-49.01**	**-19.9**	**-19.29**	**-26.48**

As it is seen in Table 2. and Table 3., if we choose to examine the datasets divided into only two parts, the results are clearer. In all of the four cities, the period of time changes through the 110 years, and also the amplitude changes, decreasing about 20-25 % in Pécs, Szombathely and Debrecen, and almost halves in Budapest.

On the basis of the results, we can say that the longest cycles are changing, they become shorter, and most of the amplitudes also decreasing. This can be caused by the variability of the weather. In recent years the weather, and the meteorological parameters changing quickly, and there are no more long term cycles in the weather because of its increasing diversity. The changes of the amplitude can be explained by the same factors, the distribution of the precipitation changes, and with the longest period of time becomes smaller, and it becomes less dominant also.

Conclusion

In recent years, studies showed that the number of meteorological extremities increased. The future predictions forecast a changing in the hydrological cycle as well as in the geographical and temporal distribution of the precipitation (Szöllösi-Nagy 2015). In this study, we used spectral analysis based on Fourier-Transformation to get to know the cyclic properties of the precipitation in the Carpathian Basin.

The result showed that there are 13 cycles present in the 110-year-long data sets and many other cycles were determined locally. The daily datasets showed no major difference in the case of the one-year-long cycle of precipitation, but it showed that the cycle with the longest period of time became significantly smaller in the examined 110 years. These results mean that the diversity in the nature of precipitation and the variability is more dominant then was 50 years ago, and the long cycles found in the datasets are less significant.

It is important to know how we can describe the reason of these cycles. The 1-year-old cycle is caused by the location and movement of the Earth in the solar system, and researchers in Beijing revealed that the solar sunspot activity has a strong correlation with the annual precipitation (Hathaway 2015). The 12-year-long cycle in the annual rainfall datasets has a connection with the 11 - 13-year-long periodicity of the sunspot activity (Zhao et. al., 2004 and Bal-Bose, 2010)

For further examination, it is important to get to know the explanation of what can be the cause of these cycles, are there any meteorological processes that can explain the results, and with the calculation of the phase angle, we can make deterministic predictions for the future for this area.

***Acknowledgements**: The research was supported by the GINOP-2.3.2-15-2016-00010 "Development of enhanced engineering methods with the aim at utilization of subterranean energy resources" project in the framework of the Széchenyi 2020 Plan, funded by the European Union, co-financed by the European Structural and Investment Funds.*

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