Appearance of climatic cycles and oscillations in Carpathian Basin precipitation data

Csaba ILYÉS[1], Péter SZŰCS[1] and Endre TURAI[2]

Abstract

A number of climatic cycles and teleconnections are known on the Earth. By definition, the cycles can have a periodic effect on the global climate, while teleconnections can influence the weather at large distances. At the same time, it is overwhelmingly assumed that the hydrological cycle is permanently intensifying all over the world. In this study, we determine and quantify some connections among these climatic cycles and precipitation data from across Hungary. By using cross-correlation and cross-spectral analysis, the connections of the climatic patterns and oscillations with the precipitation of different Hungarian areas have been defined. We used the 1950–2010 timeframe in order to be able to detect effects of several climatic patterns, such as the El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the Pacific/North American teleconnection pattern (PNA) and the Atlantic Multidecadal Oscillation (AMO) on the rainfall events of the Carpathian Basin. Data from four different precipitation measurement sites and oscillation indexes from several databases were used. The results help to understand the patterns and regularities of the precipitation, which is the major source of natural groundwater recharge, and a handy tool for future groundwater management measures. Because of the defined connections, any changes in these teleconnections will probably influence the future utilization of the Hungarian groundwater resources.

Keywords: hydrological cycle, climatic anomaly, precipitation, groundwater recharge, oscillations

Received October 2021, accepted February 2022.

Introduction

Extreme weather conditions influence the hydrological cycle (Szűcs, P. *et al.* 2015). The observed effects are varied (Jakab, G. *et al.* 2019). In the measurement-based hydro-meteorological datasets both periodic as well as stochastic components can be observed. Teleconnections can influence the local weather conditions over large physical distances. In spite of the huge amount of available monitoring data, the patterns and periodicities, especially the latter, are still unsolved problems in hydrology (Böschl, G. *et al.* 2019).

The hydrological cycle is defined as the circulation and flow of water on Earth. As previously written (IPCC 2012): „The cycle in which water evaporates from the oceans and the land surface is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, and/or discharges into streams and flows out into the oceans, and ultimately evaporates again from the oceans or land surface. The various systems involved in the

[1] Institute of Environmental Management, Faculty of Earth Science and Engineering, University of Miskolc; MTA-ME Geoengineering Research Group, H-3515 Miskolc, Egyetemváros, Hungary. E-mails: hgilyes@uni-miskolc.hu, hgszucs@uni-miskolc.hu
[2] Institute of Geophysics and Geoinformatics, Faculty of Earth Science and Engineering, University of Miskolc. Egyetemváros, H-3515 Miskolc, Hungary. E-mail: gfturai@uni-miskolc.hu

hydrological cycle are usually referred to as hydrological systems."

One of the hypothetical consequences of the common scientific consensus of the climate change is that specific humidity increases with rising temperatures, and increased evaporation is associated with more precipitation.

It is normal to be expected that there will be approximately 3.8 percent more precipitation per additional degree of temperature. This hypothetical phenomenon is called the intensification or "acceleration" of the hydrological cycle (Del Genio, A. *et al.* 1991). Huntington, T. (2006) provided the first experimental support for the hypothesis. The study concluded, despite a number of uncertainties, that the behaviour of most hydrological variables is consistent with the assumed intensification of the hydrological cycle. The study (Huntington, T. 2006) was supported by others with additional data sets, to the extent that the intensification of the hydrological cycle has become almost universally accepted. However, in a comprehensive analysis, (Koutsoyiannis, D. 2020) refuted the claims about one-way trends in the elements of the hydrological cycle. Instead of monotonous tendencies, he showed all kinds of fluctuations in the hydrological cycle (from strengthening to weakening and *vice versa*), and in the 21st century, he showed the prevalence of weakening. A one-way trend was observed only in the increase in groundwater use, which leads to a small increase in sea level on a global scale.

The peculiarities of (Koutsoyiannis, D. 2020)'s approach are as follows: (1) he ignored what the models indicate for the future; (2) he used the longest possible time series available instead of shorter, selected periods; (3) he did not focus on certain limited areas (because it is a common experience that a hydrological indicator that becomes more intense in one place may simultaneously weaken in another); (4) he used a well-defined, transparent processing method; (5) he embraced the Aristotle principle "It is the mark of educated man to look for precision in each class of things just so far as the nature of the subject admits", which also has the necessary consequence that (Huntington, T. 2006) the estimated 2 percent increase in precipitation for the entire 20th century is below the error of definition.

The very first test point of the hypothesis of accelerating the hydrological cycle would normally be to test claims for an increase in atmospheric water vapor content itself. Long data sets (radiosonde measurements) are available from the troposphere alone; surface GPS, solar photometer and satellite data used to measure integrated water vapor of the atmosphere (IWV) go back too short a period of time. The question, of course, is how much definitional certainty the Aristotelian principle allows. According to the proponents of the intensification of the hydrological cycle, global warming can cause more uneven rainfall distribution, more devastating storms, torrential rains and unexpected flash floods, regardless of changes in atmospheric water vapour content (Szöllősi-Nagy, A. 2018). The hypothesis of accelerating the hydrological cycle becomes so complex and untraceable that it is less and less possible to check their truthfulness based on Feyman's scientific method (Feynman, R. 1964). In Feynman's interpretation we could address this by easily saying that such hypotheses are no longer scientific. The situation is even more complicated: it is quite likely that the arguments needed for an exact refutation may be lost in the Aristotelian swamp. On the one hand, it is necessary to analyse the most accurate and longest time period available in a local, regional and global context (e.g. Ilyés, C. *et al.* 2016) from Hungary), and on the other hand, it is necessary to analyze the in-depth theoretical studies on the characteristics of natural time series.

The main objective of this paper is to determine how various global climatic cycles and oscillations can influence the local precipitation, thus, all the other components of the hydrological cycle in the Carpathian Basin.

Sustainable utilization of groundwater resources in Hungary

Groundwater resources play a major role in Hungary's drinking water supply system.

Hydrogeologists have a responsible role in safeguarding the groundwater resources and managing their sustainable utilization in quantitative and qualitative terms (Szűcs, P. *et al.* 2013). During the past few years hydrogeologist experts had to face numerous global or local environmental challenges that may have significant effect on environmental elements, especially on groundwater (Kohán, B. and Szalai, J. 2014).

The natural replenishment of groundwater resources is a key factor concerning the future aspects of sustainable utilization (Szűcs, P. *et al.* 2015). The demand for groundwater resources is continuously increasing in Hungary as well as all over the world. Besides the drinking water supply, thermal water production is also significant in Hungary, which also underlines the importance of sustainability issues (Buday, T. *et al.* 2015). Extreme weather conditions can affect some components of the hydrological cycle, e.g. groundwater replenishment or natural recharge (Fehér, Z.Z. and Rakonczai, J. 2019).

Patterns and periodicities

Patterns and periodicities, especially the latter, have been still unsolved problems in hydrology (Böschl, G. *et al.* 2019). The pattern approach is relatively new. Looking back to the history, the weather predictability was based, from the beginning, on various – either observed or just assumed – periodicities. Examples: Indian and Chinese traditional calendars, based on a 60-year cycle known in the Indian tradition as the Brihaspati ("Jupiter") cycle, the biblical fourteen-year periodicity (Genesis 41: 18–30), and English folklore ("There is no debt so surely met as wet to dry and dry to wet"). Below we provide insight into the documented history of the periodicities.

A brief history of periodicity studies

A solar-weather connection was raised by Meldrum, C. (1873), followed by much discussion. (Marvin, C.F. 1921) introduced the term "periodocrite", in order to be able to separate obscure and hidden periodicities.

The mechanism of world-weather was found exceedingly complex (W. W. B. 1920). Even some bibliography collections were made on the possible influence of weather on crops. C. E. P. B. (1925) found a 28-month periodicity in weather and solar phenomena. (Abbot, C.G. 1939) discovered a 23-year periodicity. Priston, W.R. (1939) corrected it to 274 months and confirmed the existence of the quasi-biannual periodicity of 27 months.

Atmospheric processes take place through spatial waves (i.e. patterns) and/or of temporal periods as units (Zhang, J-C. 1981). In this paper, a 10 years cyclicity in yearly rainfall values in Beijing was revealed.

In Burroughs, W.J. (1992), the history of cycle-searching was summarized, and a mathematical treatment was provided, illustrated with plenty of examples. An insight into extra-terrestrial aspects, including celestial mechanics, was given, too. It was assumed (C. E. P. B. 1925) that if there is no plausible physical earthbound process, the cause should be looked for outside Earth. Moreover, perturbations propagate downwards from high in the stratosphere.

Due to satellite observations, significant oscillations (patterns and periods) were (and have been) found, having regional or global weather and climate impacts. Various climate indices were defined, and a number of teleconnections were revealed. Below we provide a brief summary of the most significant ones.

A brief summary on oscillations

The Southern Oscillation Index (SOI) is one of the world most important climate indices. It is a common measurement of the El Niño/La Nina (ENSO) teleconnection (Power, S.B. and Kociuba, G. 2011), and is a standardized index based on the observed sea level pressure differences between Tahiti and Darwin, Australia (PSL 2020). During the El Niño event, the SOI tends to be negative, and the changes in the ENSO drive major changes in rainfall, agricultural production and river flow all across the world (Power, S.B. and Kociuba, G. 2011). ENSO typically lasts from 6 to 18 months (Chen, S. *et al.* 2020), with a 2–7-year cycle (Kuss, A.J.M. and Gurdak, J.J. 2014).

The Atlantic Multidecadal Oscillation (AMO), believed to be caused by the North Atlantic thermohaline circulation, is defined by the Sea Surface Temperature (SST) anomaly over the Atlantic from 0°N to 70°N (Enfield, D. *et al.* 2001), characterized by a 50–70-year period (Dijkstra, H.A. *et al.* 2006). Its effect on the climate of Europe was examined in the UK (Knight, J. *et al.* 2006) and in Romania (Ionita, M. *et al.* 2012), as well as several other areas around the Atlantic (Folland, C. *et al.* 2001; Knight, J. *et al.* 2005).

The North Atlantic Oscillation – along with the AMO – is the most important phenomenon influencing the weather variability over Europe (Ionita, M. *et al.* 2012; Dvoryaninov, G.S. *et al.* 2016), with the periodicity of 3–6 years (Kuss, A.J.M. and Gurdak, J.J. 2014). The NAO index is defined as the difference of the normalized sea-level pressure at the Azores and Iceland (Mokhov, I. and Smirnov, D. 2006) at inter-annual and inter-decadal time scales. The changes in circulation associated with changes in the NAO index are determined from the difference in sea-level pressure (SLP) between winters with an index value greater than 1.0 and those with an index value less than -1.0 (Hurrel, J. 1995).

The Arctic Oscillation (AO) is defined as an opposing pattern of pressures between the Arctic and northern mid-latitudes (Chen, S. *et al.* 2020). When the pressure is high in the Arctic, it tends to be low in the northern latitudes. That is called a negative phase, while the opposite is called a positive phase. When positive, it causes a wetter weather in Alaska, Scotland and Scandinavia, and a drier weather in the US and Mediterranean. If reversed, it brings stormy weather to the more temperate climates (Mokhov, I. and Smirnov, D. 2006).

The Pacific/North American teleconnection pattern (PNA) is one of the most recognized, influential climate patterns in the Northern Hemisphere mid-latitudes beyond the tropics. It consists of anomalies in the geopotential height fields (typically at 700 or 500 mb) observed over the western and eastern United States. It varies from intra-seasonal (2–90 days) to inter-annual time scales (2–20 years) (Allan, A.M. and Hostetler, S.W. 2014). The PNA influences the climate in autumn and winter in the whole Northern Hemisphere (Soulard, N. and Lin, H. 2017).

The relationship of these teleconnections was also thoroughly examined, with the relation of the ENSO and the AMO (Mokhov, I. and Smirnov, D. 2016), and the PNA (Song, J. *et al.* 2009), while all of the major teleconnections were found to have a relation with the ENSO. The NAO (Mokhov, I. and Smirnov, D. 2006) and the AO (Chen, S. *et al.* 2020) are also closely linked to each other (Rogers, J. and McHugh, M. 2002), and the connection between the PNA and the NAO was also investigated (Soulard, N. and Lin, H. 2017). A clear interconnection among them was detailed by Lüdecke, H-J. *et al.* (2021) while investigating African rainfall.

Connection with regional hydrological data

The global and regional effects on precipitation and groundwater levels have been examined thoroughly across the globe. The influence of NAO on temperature and precipitation is a widely studied subject (Hurrel, J. 1995; Slonosky, V. and Yiou, P. 2001). The global effect of ENSO, as examined in (Sun, X. *et al.* 2015), varies substantially by seasons, and the extreme precipitation is only affected by one phase, and is asymmetric in most of Europe.

In the US, it was found that the ENSO has a significant effect in case of precipitation and groundwater level fluctuations, with the higher frequency climate models showing greater ENSO effect (Velasco, E.M. *et al.* 2017). Other results indicate that the groundwater levels are partially controlled by interannual to multidecadal climate variability, and ENSO has a greater effect than NAO or AMO (Kuss, A.J.M. and Gurdak, J.J. 2014). In Canada, the effects of ENSO and NAO on streamflow and precipitation were examined, and the results show that a positive phase reflected drier conditions, with lower amount of precipitation, whereas the negative phase reflected wetter conditions, and higher amount of streamflow (Nalley, D. *et al.* 2019).

Concerning European groundwater well data, it was found, that there are significant correlations between NAO, AMO and ENSO (Liesch, T. and Wunsch, A. 2019). The average coherence for AMO is higher than for NAO, while it was the highest for ENSO, meaning a larger influence (Lüdecke, H-J. *et al.* 2021). Also, several year-long periods were calculated, namely, periods of: 4 and 13–14 for NAO; 15, 23–25 and 60–80 for AMO; and 2–5, 15–18, 31 and 56 for ENSO (Liesch, T. and Wunsch, A. 2019). In the case of AO, in the positive phase, higher pressure at mid-latitudes drives ocean storms farther north, while changes in the circulation pattern bring drier conditions to the Mediterranean (Thompson, D.W.J. and Wallace, J.M. 1998). It is known that the winters of 2009–2010 and 2015–2016 were affected by the NAO (Seager, R. *et al.* 2010).

According to (Domonkos, P. 2003), the winter precipitation in Hungary decreases significantly when the NAO index increases. (Matyasovszky, I. 2003) showed a nonlinear relationship between the climate of Hungary and the ENSO.

Periodicities in stochastic time series, such as precipitation, were also examined, with several local, regional deterministic components defined in rainfall data covering 110 years (Ilyés, C. *et al.* 2017). In the study annual, monthly and daily precipitation time series were calculated using spectral analysis to find deterministic patterns in them. With this method several regional/countywide periods were defined. Detailed studies revealed further local cyclic parameters (Ilyés, C. *et al.* 2018).

With this research the main objective was to find connections between these climatic patterns and the periods defined before, in order to better understand the main factors behind the periodicity of the precipitation in Central Europe. These atmospheric oscillations vary in their time scales and locations, and the impacts on local precipitation is complex. In this research paper a correlation and spectral analysis were used for determining the nature of the connection.

Methods and materials

To implement the investigation, the precipitation data were downloaded from the Hungarian Meteorological Service's online database (HMS 2019), containing 5 different monitoring sites, over the timescale of 1950–2010. As the calculations require equidistant sampling, the monitoring site Szeged needed to be dropped from one of the calculations due to missing data in the 1940s.

The collected precipitation data resembles the climatic patterns of the Carpathian Basin, as seen in *Figure 1.* Budapest is located at the banks of the Danube River, in the middle of the basin, while Szombathely lies at the foothills of the Alps mountain range. The Debrecen monitoring site represents the Hungarian Great Plain and the eastern part of the basin, while the climate of the southwestern monitoring site, Pécs, is somewhat influenced by the Mediterranean. The Szeged monitoring site represents the southern area of the basin, with the smallest annual rainfall and the warmest climate.

For the calculations, monthly precipitation data were used, with an equidistant one-month sampling rate.

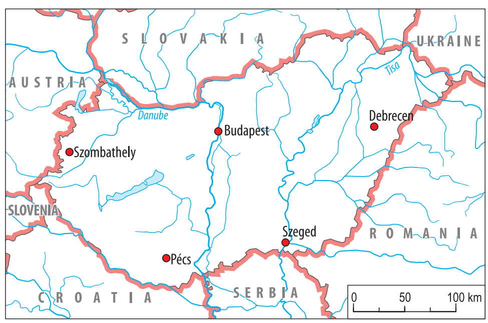

Fig. 1. The location of the monitoring sites in Hungary

The climatic data of the patterns and oscillations were collected from several open-source databases. The AMO data come from the Physical Sciences Laboratory at NOAA (PSL 2020), while the AO, NAO, PNA and SOI data were downloaded from the National Centres for Environmental Information at NOAA (NCEI 2020). The data has the January 1950 – December 2010 time frame in the cases of AO, PNA, NAO, and January 1951 – December 2010 in the case of SOI, while the AMO data are available from January 1901.

The method for examining a linear connection uses the following expressions to obtain the coefficients for correlation and cross-spectral analysis results. These methods were used to examine the connection between precipitation and karst water levels in several studies (Padilla, A. and Pulido-Bosch, A. 1995; Darabos, E. 2018) and the relation between teleconnections and streamflow (Pekarova, P. and Pekar, J. 2007).

Assume two discrete time series (x_t, and y_t), with n samples in each series. The cross-correlation function r obtained with the two series is not symmetrical, where k = 0, 1, 2, … m, the shift of the two series.

$$r_{+k} = r_{xy}(k) = \frac{C_{xy}(k)}{\sqrt{C_x^2(0)C_y^2(0)}}$$

$$r_{-k} = r_{yx}(k) = \frac{C_{yx}(k)}{\sqrt{C_x^2(0)C_y^2(0)}},$$

where

$$C_{xy}(k) = \frac{1}{n}\sum_{t=1}^{n-k}(x_t - \bar{x})(y_{t+k} - \bar{y})$$

$$C_{yx}(k) = \frac{1}{n}\sum_{t=1}^{n-k}(y_t - \bar{y})(x_{t+k} - \bar{x})$$

$$C_x(0) = \frac{1}{n}\sum_{t=1}^{n}(x_t - \bar{x})^2$$

$$C_y(0) = \frac{1}{n}\sum_{t=1}^{n}(y_t - \bar{y})^2,$$

where $\bar{x}$ and $\bar{y}$ are the averages of the two series of x_t and y_t.

The t significance level of the calculated time lag can be examined with the following equation (MT18 2019):

$$t = \frac{2}{\sqrt{n-|k|}},$$

where n is the number of samples, and k is the time lag. If t is smaller than the calculated cross-correlation value, it has a significance level (α) of approximately 5 percent.

Because of the asymmetrical cross-correlation function, the spectral-density function must be expressed with a complex number:

$$\Gamma_{xy}(f) = |\alpha_{xy}(f)| exp[-i\Phi_{xy}(f)],$$

where i represents $\sqrt{-1}$, the $\alpha_{xy}(f)$ and the $\varphi_{xy}(f)$ are the values of the cross-amplitude in the phase functions with f frequency, in details:

$$\alpha_{xy}(f) = \sqrt{\Psi_{xy}^2(f) + \Lambda_{xy}^2(f)}$$

$$\phi_{xy}(f) = arctan\frac{\Lambda_{xy}(f)}{\Psi_{xy}(f)},$$

where the cross-spectrum, $\Psi_{xy}(f)$ and the quadrate spectrum, $\Lambda_{xy}(f)$ are:

$$\Psi_{xy}(f) = 2\left\{r_{xy}(0) + \sum_{k=1}^{m}[r_{xy}(k) + r_{yx}(k)]D_k \cos(2\pi f k)\right\}$$

$$\Lambda_{xy}(f) = 2\left\{\sum_{k=1}^{m}[r_{xy}(k) - r_{yx}(k)]D_k \sin(2\pi f k)\right\},$$

where D_k is the weighting function which is necessary to overcome the distortion caused by the two coefficients $Y_{xy}(f)$, and $L_{xy}(f)$.

For the calculations a custom-made python software was developed, featuring the equations (GH 2020).

Results and discussion

Our hypothesis was that the teleconnections mentioned above have a mathematically calculable effect on the rainfall events of the Carpathian Basin. A few important teleconnections were chosen to represent a major part of the Earth. Our hypothesis for the direction of the connection was that the x_t teleconnection – calculated with its respective index – influences the precipitation time series y_t measured at five different monitoring sites.

The teleconnections are happening on a global scale, and in most cases, they represent climatic patterns far away from Central Europe. That means that instead of high correlation coefficients, only minor but calculable effects are expected.

AMO effects on precipitation in the Carpathian Basin

In the case of the AMO, a longer time interval was available, so precipitation data from the monitoring point of Szeged was not used because of missing values.

The Atlantic Multidecadal Oscillation seems to have an immediate effect on the precipitation data of the Carpathian Basin. In *Figure 2*, the maximum value is at around the 0-month mark for most monitoring sites. A clear one-year cycle is present, too. Although the correlation coefficient is not larger than 0.1, a clear connection can be identified in the graph.

In *Figure 3* a strong maximum amplitude is visible at frequency 0.083, corresponding to a time period of 1 year. There is another maximum value at a frequency of 0.021, corresponding to a period of 4 years. The other cyclic components are much less intense.

The results for Szombathely differ from those for three other ones. The reason for that is probably the slightly different precipitation pattern of Szombathely, detected in differences in the case of deterministic components calculated with spectral analysis of the same rainfall data (Ilyés, C. *et al.* 2017).

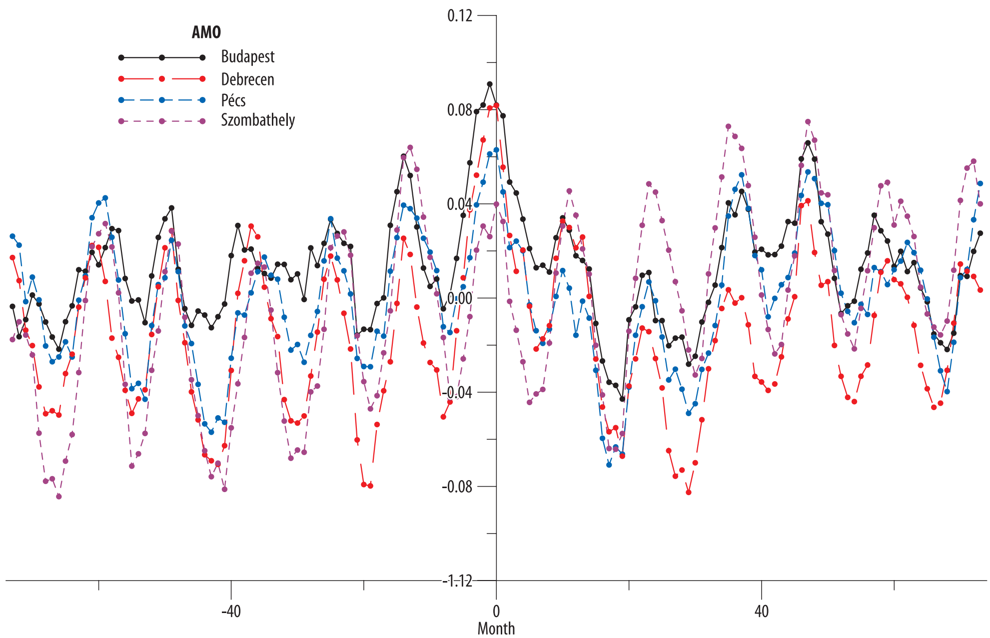

Fig. 2. Cross-correlation between AMO and the precipitation of the Carpathian Basin

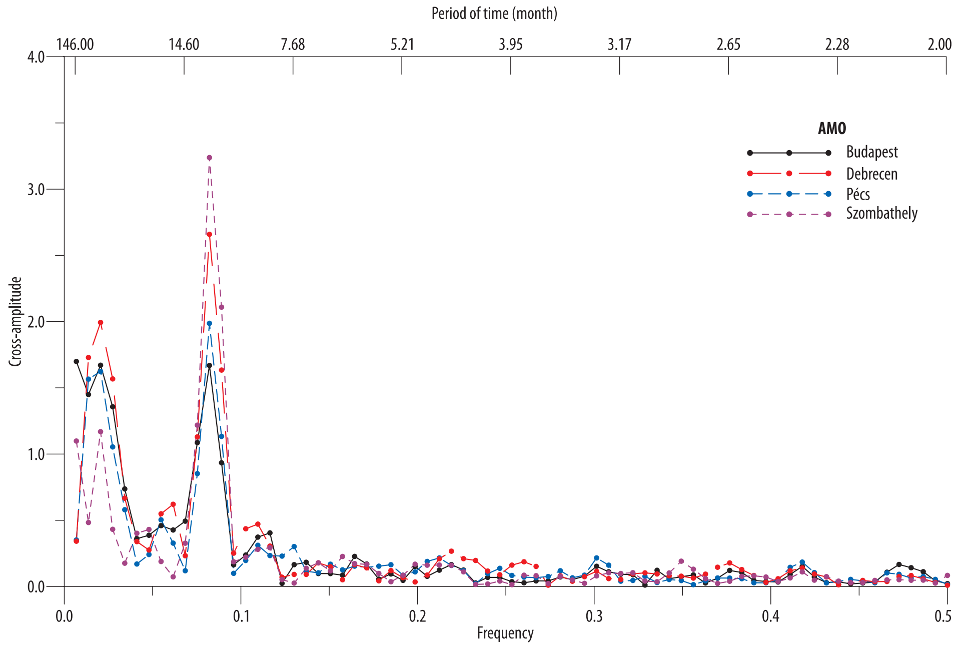

Fig. 3. Cross-amplitudes of AMO and precipitation of the Carpathian Basin

AO effects on precipitation in the Carpathian Basin

In the case of the Arctic Oscillation, most of the correlation coefficient has a negative peak at the 0 month mark, but at 37 month a positive peak can be detected, as seen in *Figure 4.* The negative significant peak may suggest that the direction of the effect is reverse, that is, the precipitation and the Arctic Oscillation have a negative linear connection, which would mean that an increase in AO causes a decrease in the amount of precipitation. An alternative, less probable explanation could be that the local time lag for the Carpathian Basin is 37 months. Similar to the case of AMO, for the monitoring site of Szombathely somewhat different results can be seen.

As for the cross-spectral analysis, there are clear patterns of periodicity. A strong one-year long cycle can be detected from the data, with maximum amplitude values at frequency 0.083, as well as a half-year long one (at frequency 0.166). The 6-month long periodicity has a larger amplitude than the 12-month long one, meaning a stronger cyclic pattern. Other major cycles are the 36, 7.7 and 9 month long ones, as shown in *Figure 5.*

NAO effects on precipitation in the Carpathian Basin

For the North-Atlantic Oscillation data, the 1950–2010 time interval was used. The cross-correlation coefficients *(Figure 6)* are again very low, but the connection can clearly be seen. As in the case of the AO, the direction of the effect is the opposite of what would have been guessed: for the correlation coefficient values of each of the five monitoring sites significant negative peaks with a larger than 0.1 amplitude were obtained at the 0 month mark. That refers to a negative linear connection. In *Figure 6*, a great volatility can also be seen, with no clear sign of periodicity. In the case of increasing NAO, precipitation in the Carpathian Basin seems to decrease.

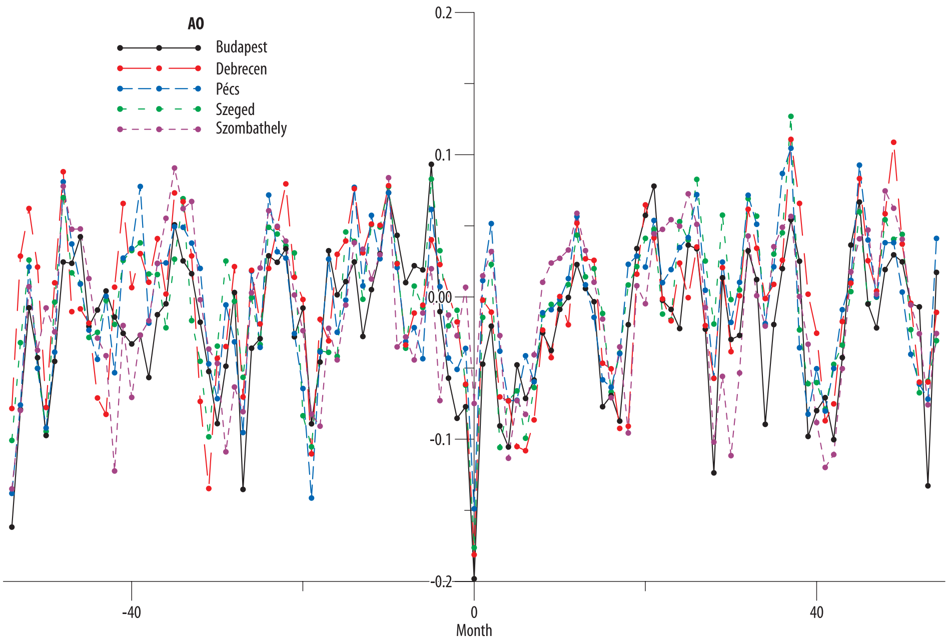

Fig. 4. Cross-correlation between AO and the precipitation of the Carpathian Basin

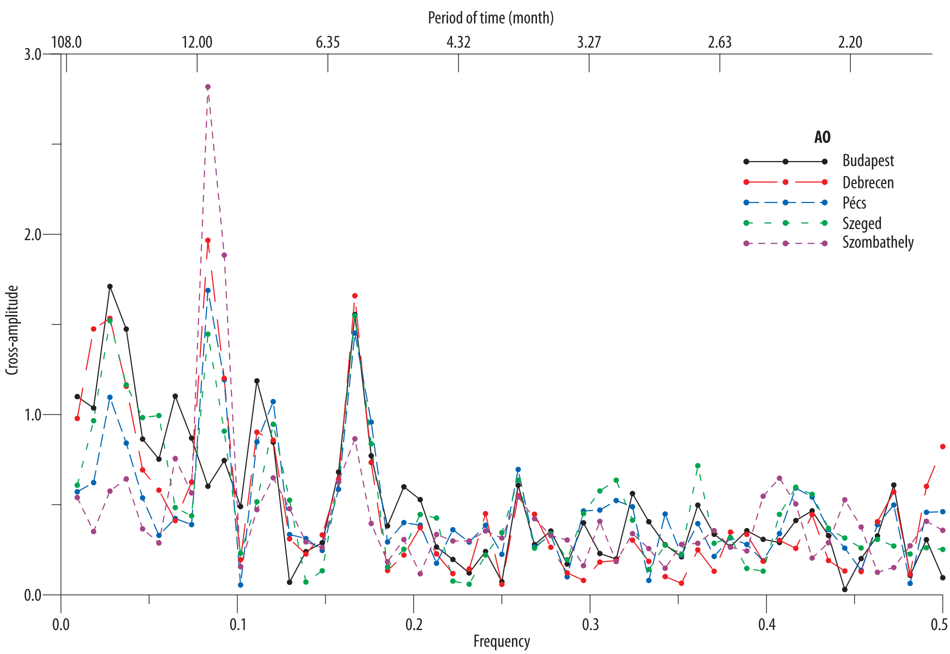

Fig. 5. Cross-amplitudes of AO and precipitation of the Carpathian Basin

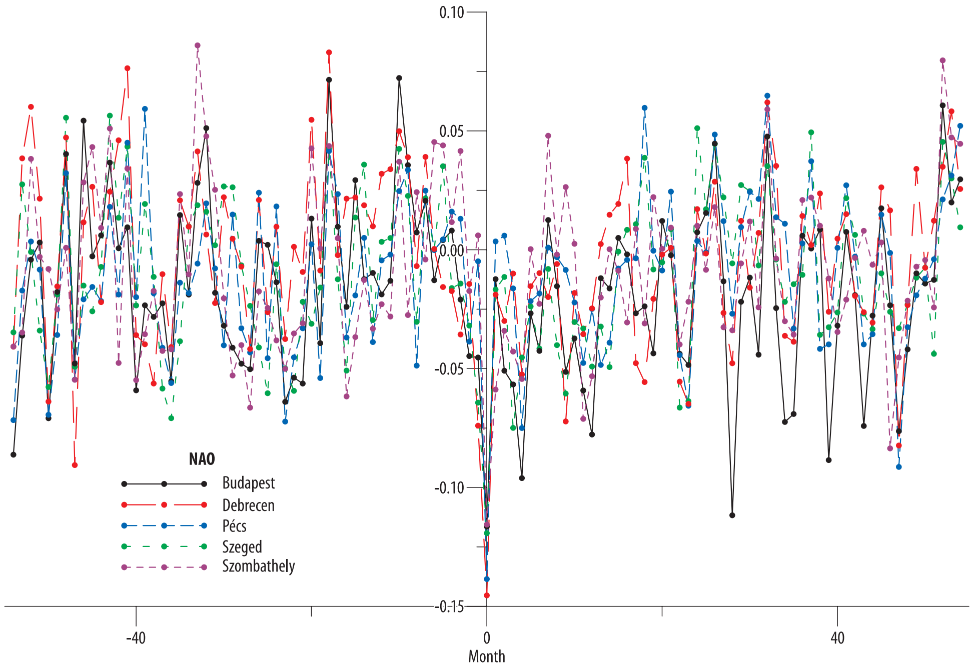

Fig. 6. Cross-correlation between NAO and the precipitation of the Carpathian Basin

The cross-spectral analysis *(Figure 7)* also shows irregular or random maximum values. Nevertheless, there are some similarities among the 5 cross-amplitude datasets. In four of the time series, a 3-year long cycle (at frequency 0.027) is seen, besides the one-year period (frequency 0.083), and the 6-month long one (frequency 0.166). A 8.3-month long period (frequency 0.12), and 4.9–5.1 month long periods (frequency 0.19–0.2) also occur. Szombathely again delivers an outlier result, because of a stronger local influence in its rainfall events.

PNA effects on precipitation in the Carpathian Basin

The Pacific/North American teleconnection influences the climate patterns in the Northern Hemisphere mid-latitudes beyond the tropics. As had been assumed, it does not have a significant effect on the precipitation of the Carpathian Basin.

The figure of the cross-correlation values *(Figure 8)* is the most volatile one. Time lag cannot be calculated, as the correlation coefficients have no common peaks.

The results of the cross-spectral analysis are shown in *Figure 8*. A few local cycles are seen, with some similarities: three of the monitoring stations showed a 12–13.5 month long cycle (frequency 0.08), as well as a 36-month long one (frequency 0.027). From the data a 6.5–7.2 month long period and a 5.6–6 month long period were calculated.

As seen in *Figure 9*, the data are too volatile to let one estimate a connection. The correlation coefficients are very low, and the effect on precipitation is negligible.

SOI effects on precipitation in the Carpathian Basin

The Southern Oscillation is the most well-known teleconnection index, measuring the

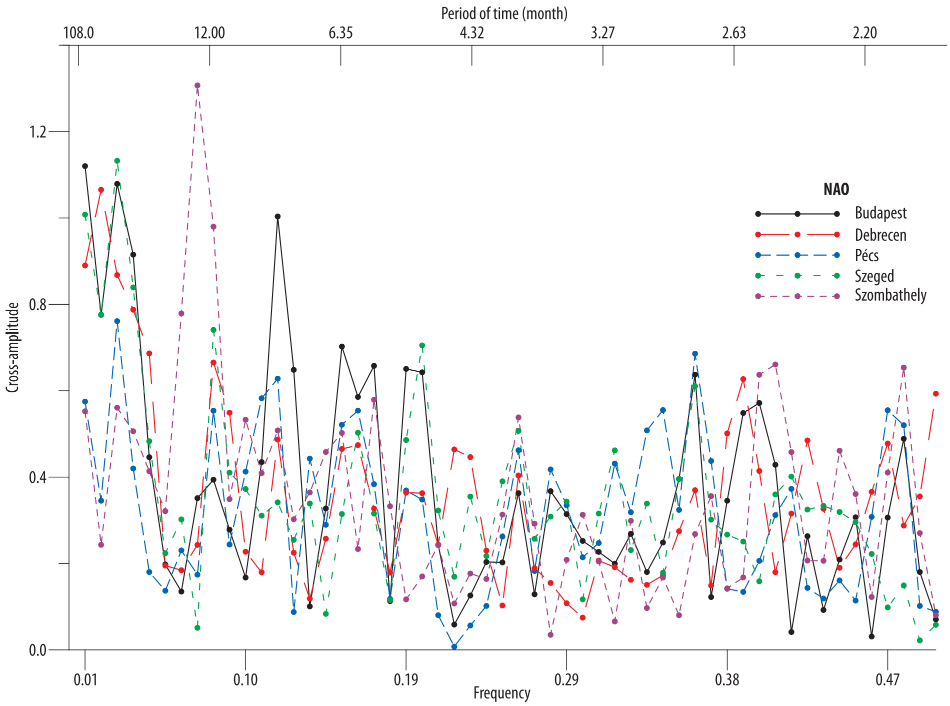

Fig. 7. Cross-amplitudes of NAO and precipitation of the Carpathian Basin

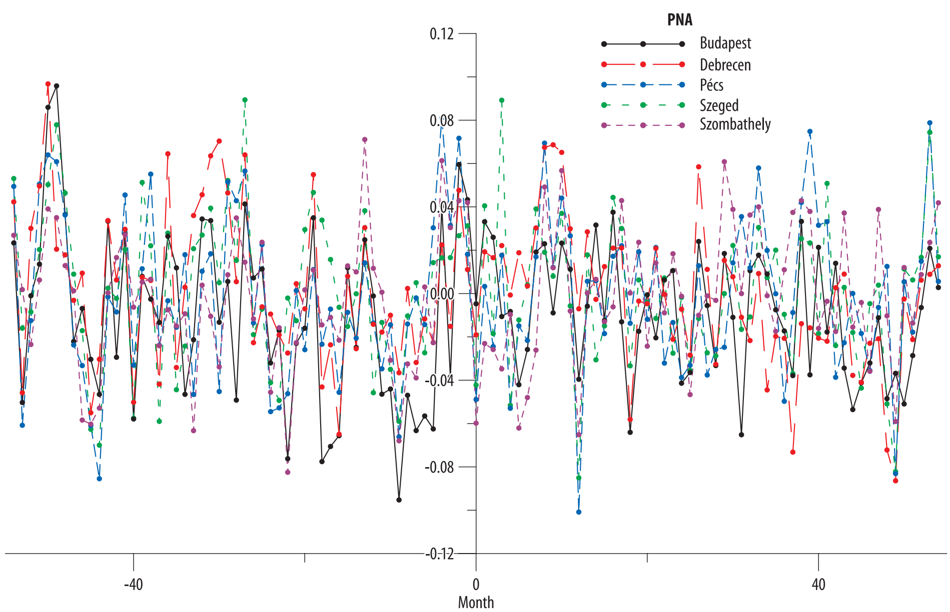

Fig. 8. Cross-correlation between PNA and the precipitation of the Carpathian Basin

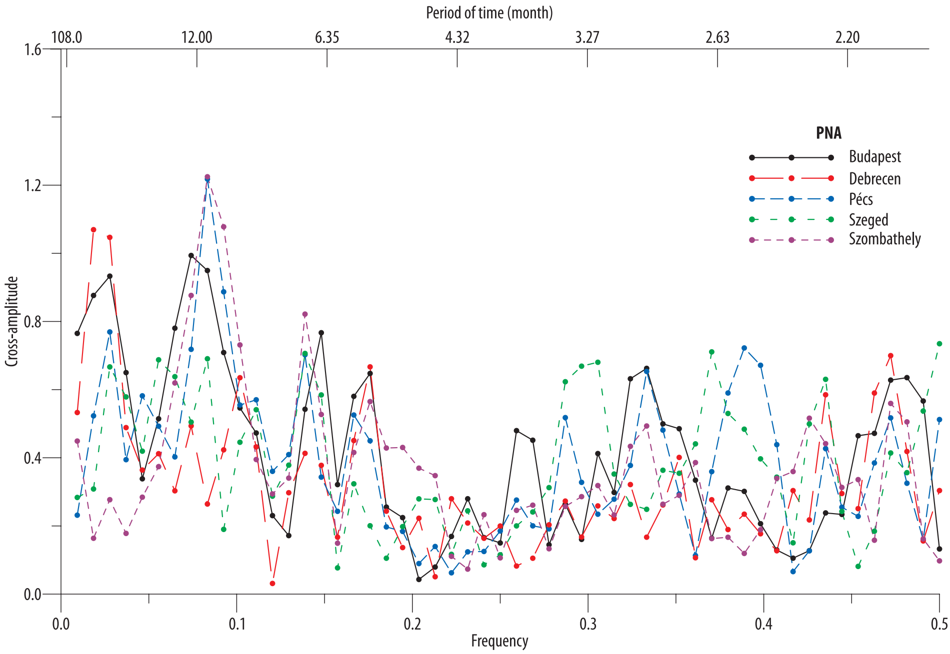

Fig. 9. Cross-amplitudes of PNA and precipitation of the Carpathian Basin

intensity of the El Niño or La Nina effects in the Pacific.

The cross-correlation calculations show inconclusive results, with low coefficients, although 3 of the 5 monitoring stations show a minimum value at 22-month time lag. According to *Figure 10*, neither a clear linear relation nor any periodicity is visible.

The cross-spectral analysis shows some similarities among the 5 monitoring sites. As seen in *Figure 11*, for most of the monitoring sites, there is a 1-year long period (frequency 0.083). Data for 3 sites seems to have a 4.5-year long period (frequency 0.018), and a 1.9–2.2 year long period (frequency 0.04), with a 5.4 and 2.5 month long cycle in them. Other periods were defined locally with 9–10 periods in each dataset, respectively.

From all these results it is clearly seen that the teleconnections have a minimal, but calculable effect on the precipitation patterns of the Carpathian Basin. Most of the studied climatic patterns showed some periodicity when compared to the precipitation time series.

The teleconnections not far from Central Europe have an immediate effect on the rainfall events, while the Pacific/North Atlantic, and the Southern Oscillation index data showed no clear relationship. Events happening in the Pacific area have minimal effect on this side of the planet. It is important to keep in mind that teleconnections are interconnected. The PNA has been found to be strongly influenced by the El Niño-Southern Oscillation (ENSO) phenomenon, which itself is measured by the SOI.

The SOI and PNA results have similarities in case of the cross-spectral analysis. In both calculations 4.5, 1.5–1.8, 1.1–1.2 year long periods were defined, along with the one and half year long period, which was calculated from all of the parameters. The AO, NAO and PNA datasets had a 3 year long period, too.

The AO and NAO data also show similarities, with the 3.0, 1.1–1.2, and 0.69 year-long cycles in both of them.

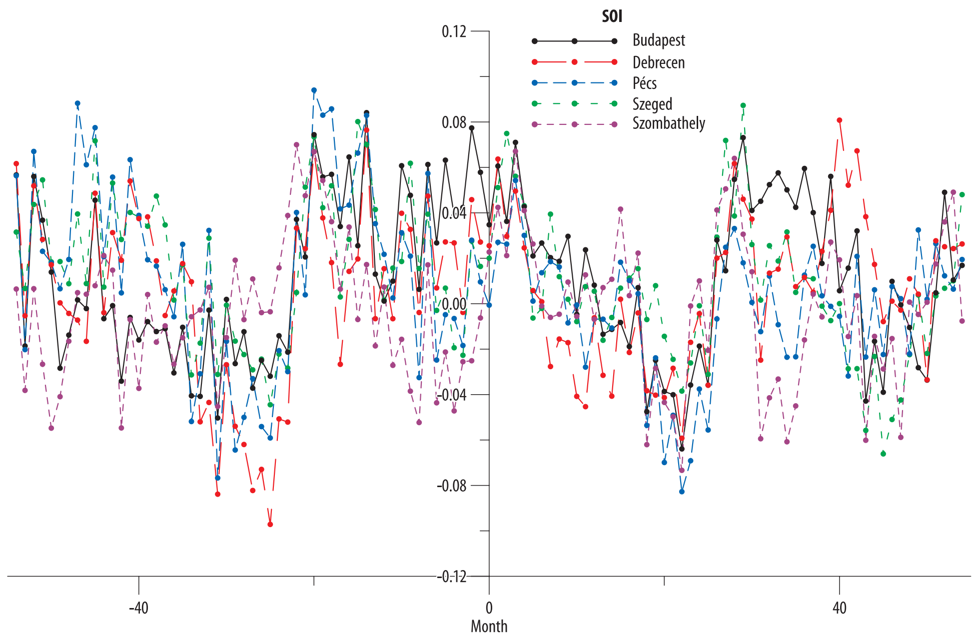

Fig. 10. Cross-correlation between SOI and the precipitation of the Carpathian Basin

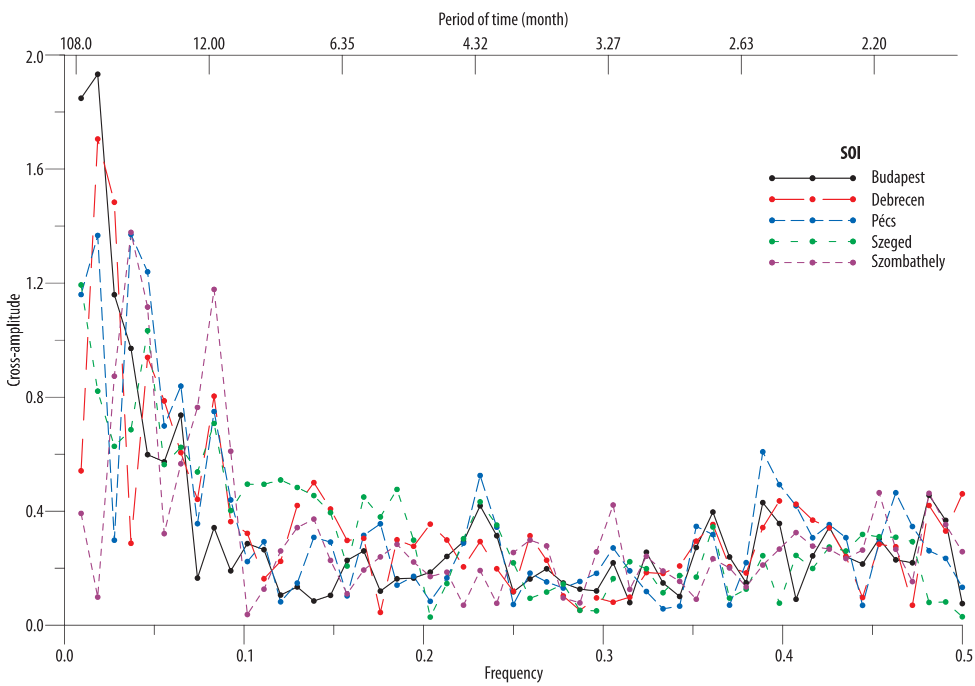

Fig. 11. Cross-amplitudes of SOI and precipitation of the Carpathian Basin

All the examined datasets have 0.69–0.71 and 1.1–1.2 year-long periodic components.

In previous research (Ilyés, C. *et al.* 2017), the cyclic components of these precipitation datasets were examined with spectral analysis, based on the Fast-Fourier transformation, with several deterministic components defined in them. Some of the cycles can be interpreted using the results of the present cross-spectral calculations. The 3 and 4–4.5 year-long periodicities with large amplitudes had been previously discovered using spectral analysis on annual precipitation data (Ilyés, C. *et al.* 2017).

The connection between the ENSO and NAO, and some meteorological parameters in Hungary, had been investigated previously, and a clear relation was found for both indices (Pongrácz, R. 2003). The main reason for the calculated results can be that the connection is not linear in case of these distant patterns.

Similar investigations (Pekarova, P. and Pekar, J. 2007) had been carried out for streamflow fluctuations in a neighbouring country (Slovakia). The effects of several teleconnections were calculated with the streamflow of two rivers in the country. Because of the different time intervals of the measurements, the longer periods couldn't be calculated for both of the research projects, but in the case of the AO and NAO, the ca. 3 year-long cycles were also determined along with the 2.25 year-long period from the AO data, meaning similarities can be found in the patterns of these data.

Conclusions

In the present study, relationships are detected between AO, NAO, PNA, SOI, AMO and precipitation cycles at five monitoring sites in the Carpathian Basin. With the applied method of cross-correlation and cross-spectral analysis, the correlation coefficient and deterministic components are revealed from the investigated datasets.

The results show that a minimal but calculable relation can be defined for climatic patterns taking place in the Northern Hemisphere, such as AO, NAO and AMO, although the method cannot quantify the connections with patterns from distant regions, such as SOI and PNA. The relationships for these climatic phenomena (AO, NAO and AMO) are quite immediate *(Table 1)* and can be connected to periods previously defined from the precipitations of the Carpathian Basin (Ilyés, C. *et al.* 2017). Several cycles, reported in previous studies, can be explained via teleconnections of these climatic patterns (Ilyés, C. *et al.* 2018). The results also show similarities to other results from Central Europe (Pekarova, P. and Pekar, J. 2007), and to a very recent cloud-pattern analysis (Sfica, L. *et al.* 2021).

Table 1. Summary of the findings relative to time lag, direction, and major detected cycles

Climatic phenomena	Time lag	Direction	Major cycles
AMO	~0	positive	1; 4 years
AO	0	negative	0.5; 0.6; 1; 3 years
NAO	0	negative	1; 3 years; 8.3; 4.9 month
PNA	No clear linear connection detected		
SOI			

With the calculated correlation and cyclic components, a clear interdependence has been revealed in the case of the Carpathian Basin rainfall events. As we have found, any change in the studied distant climatic patterns will have some precipitation effect in the Carpathian Basin, thus, affecting the recharge or natural replenishment of its groundwater aquifers. The obtained results highlight the importance of sustainability issues in the future utilization of groundwater resources.

For the future, a complex Wavelet coherence or partial Wavelet analysis with groundwater levels and streamflow data can help to better evaluate the nature of the defined connections of the oscillations and the hydrological cycle in Central Europe.

Acknowledgements: The research was carried out at the University of Miskolc both as part of the "More efficient exploitation and use of subsurface resources" project implemented in the framework of the Thematic

Excellence Program funded by the Ministry of Innovation and Technology of Hungary (Grant Contract reg. nr.: NKFIH-846-8/2019) and the project titled as "Developments aimed at increasing social benefits deriving from more efficient exploitation and utilization of domestic subsurface natural resources" supported by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund in line with the Grant Contract issued by the National Research, Development and Innovation Office (Grant Contract reg. nr.: TKP-17-1/PALY-2020).

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