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Teleconnections of Inter-Annual Streamflow Fluctuation in Slovakia with Arctic Oscillation, North Atlantic Oscillation, Southern Oscillation, and Quasi-Biennial Oscillation Phenomena

Pavla PEKAROVA[1] and Jan PEKAR*[2]

[1] *Institute of Hydrology, Slovak Academy of Sciences, Racianska* 75, 831 02 *Bratislava* 3, *Slovak Republic*

[2] *Department of Applied Mathematics and Statistics, Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava, Mlynska dolina,* 842 48 *Bratislava, Slovak Republic*

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ABSTRACT

The aim of the paper is to analyze a possible teleconnection of Quasi-Biennial Oscillation (QBO), Southern Oscillation (SO), North Atlantic Oscillation (NAO), and Arctic Oscillation (AO) phenomena with long-term streamflow fluctuation of the Bela River (1895–2004) and Cierny Hron River (1931–2004) (central Slovakia). Homogeneity, long-term trends, as well as inter-annual dry and wet cycles were analyzed for the entire 1895–2004 time series of the Bela River and for the 1931–2004 time series of the Cierny Hron River. Inter-annual fluctuation of the wet and dry periods was identified using spectral analysis. The most significant period is that of 3.6 years. Other significant periods are those of 2.35 years, 13.5 years, and 21 years. Since these periods were found in other rivers of the world, as well as in SO, NAO, and AO phenomena, they can be considered as relating to the general regularity of the Earth.

Key words: inter-annual discharge fluctuation, spectral analysis, teleconnection, Quasi-Biennial Oscillation, Southern Oscillation, North Atlantic Oscillation, Arctic Oscillation

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1. Introduction

While analyzing the impact of climate change on hydrological regime changes of rivers, it is necessary to evaluate changes of hydrological characteristics of the basins that are uninfluenced by human activity. Dams and artificial reservoirs dramatically change the natural flow regime. Next, the analyzed time series must be as long as possible, and homogeneous. The time series of average annual discharge measured in the mountainous basins of the Vah and Hron Rivers in Central Slovakia satisfy these conditions.

The aim of the study is to analyze a possible teleconnection of Quasi-Biennial Oscillation (QBO), Southern Oscillation (SO), North Atlantic Oscillation (NAO), and Arctic Oscillation (AO) phenomena with long-term streamflow fluctuation in two uninfluenced mountainous basins in Slovakia (Central Europe): (1) the Bela River (Podbanske, Vah River basin, 1895–2004); and (2) the Cierny Hron River (Hronec, Hron River basin 1931–2004).

In recent years, many scientists have studied the relationships between atmospheric phenomena (such as AO, SO and NAO) and some hydroclimatic characteristics (such as total precipitation, air temperature, discharge, snow and ice cover, flood risk, sea level series, coral oxygen isotope records, dendrochronological series etc). For example, Jevrejeva and Moore (2001) and Jevrejeva et al. (2003) studied the variability in time series of ice conditions in the Baltic Sea within the context of NAO and AO winter indices using the singular spectrum analysis (SSA) and wavelet approach. According to these authors, cross-wavelet power for the time series indicates that the times of largest variance in ice conditions are in excellent agreement with significant power in the AO at 2.2–3.5-, 5.7–7.8-, and 12–20-yr periods. Similar patterns are also seen with the Southern Oscillation index (SOI) and the Niño-3

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*Corresponding author: Jan PEKAR, pekar@fmph.uniba.sk

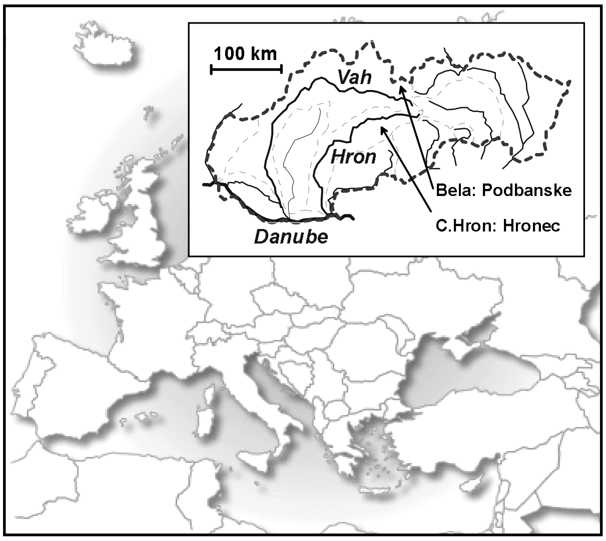

Fig. 1. Locations of the Bela River (Vah basin) and the Cierny Hron River (Hron basin), central Slovakia.

sea surface temperature series. Wavelet coherence shows in-phase linkages between the 2.2−7.8- and 12−20-yr period signals in both tropical and Arctic atmospheric circulation, and also with ice conditions in the Baltic Sea. Anctil and Coulibaly (2003) described the local inter-annual variability in southern Québec streamflow based on wavelet analysis, and identified plausible climatic teleconnections that could explain these local variations. The span of available observations (1938–2000) allowed depicting the variance for periods of up to around 12 years. The most striking feature, in the 2–3-yr band, in the 3–6-yr band, and the 6–12-yr band (dominated by white noise and not considered any further) was a net distinction between the timing of the inter-annual variability in local western and eastern streamflows, which may be linked to the local climatology. Turkes and Erlat (2003) and Uvo (2003) studied teleconnection of NAO variability with precipitation variability in Turkey, and in Northern Europe, respectively. Felis et al. (2000) studied a 245-yr coral oxygen isotope record from the northern Red Sea in bimonthly resolution. A close to 70-yr oscillation of probably North Atlantic origin dominates the coral time series. Inter-annual to interdecadal variability was correlated with instrumental indices of the NAO, the El Niño-Southern Oscillation (ENSO), and North Pacific climate variability. The results suggested that these modes have consistently contributed to Middle East climate variability since at least 1750, predominantly at a period of close to 5.7 years. Yang et al. (2000) investigated the ENSO teleconnection with annual precipitation series (Tibetian Plateau, China) from 1690 to 1987 (nearly 300 years). The results showed that negative precipitation anomalies are significantly associated with El Niño years. Tardif et al. (2003) studied variations in periodicities of the radial growth response of black ash exposed to yearly spring flooding in relation to hydrological fluctuations at Lake Duparquet in northwestern Québec. They detected approximate 3.5-, 3.75- and 7.5-yr periodicities in all the dendrochronological series. According to the authors, the 3.75- and 7.5-yr components are harmonics of a 15-yr periodicity. Youn (2005) quantified major periodicities in surface air temperature variations over the Korean Penisula. Using spectral analysis it was found that the most dominant pattern centered at 2.3 years.

2. Data description

In our analyses we used the annual average discharge time series from two mountainous basins in the Carpathian region of Slovakia, namely from the Bela River basin and the Cierny Hron River basin. The former, as a part of the upper Vah River basin, is located inland—about 600 km from the Baltic Sea, 850 km from the Atlantic Ocean, and 700 km from the Adriatic Sea (see Fig. 1). The basin lies within the most precipitated region of Slovakia; average annual total precipitation in the basin is 1473 mm. The long-term average specific runoff of the Bela River at Podbanske is 37 $\mathrm{dm}^3\ \mathrm{s}^{-1}\ \mathrm{km}^{-2}$.

The Cierny Hron River lies in the upper Hron River basin and is a left-hand tributary of the Hron River. The distance of the basin from both the Baltic Sea and the Adriatic Sea is approximately the same −650 km. The basic hydrological characteristics of both considered basins are given in Table 1. Even though the Cierny Hron River basin is twice as large as the Bela River basin, the average annual discharge of the Cierny Hron River is lower than that of the Bela River due to its lower specific runoff (Skoda et al., 2005; Pekarova and Szolgay, 2005).

In Figs. 2a and 2b, the average monthly discharges (Q_a) for the periods 1931–1960, 1961–1990, and 1991–2000 are displayed. As these figures show, no change of runoff distribution occurred in either of the two basins during the period 1931–2000. The last decade of the 20th Century (1991–2000) in the Cierny Hron River was dryer due to lower precipitation totals in Slovakia, however the regime of the mean monthly discharge did not get changed.

Our goal is to identify inter-annual dry and wet periods in the Bela and Cierny Hron basins. As already stated, the discharge fluctuations should be analyzed using time series of maximum possible lengths. This is why the average annual discharge time series of the

Table 1. Basic hydrological characteristics of the selected basins.

River	Station	Area (km^2)	L_{max}	L_{min}	Period	Q_{a}	q_{a}	c_{s}	c_{v}	r_1	r_2	r_6
Bela	Podbanske	93.5	2494	922	1895–2003	3.50	37.3	0.18	0.20	0.06	−0.19	−0.32
C. Hron	Hronec	239.0	1338	480	1931–2003	2.94	12.3	0.32	0.32	0.25	0.04	−0.08

L_{max} and L_{min}, maximum and minimum altitude (m a.s.l.); Q_{a}, average annual discharge (m^3 s^{-1}); q_{a}, mean annual specific yield (dm^3 s^{-1} km^{-2}); c_{s}, coefficient of asymmetry; c_{v}, coefficient of variation; r_1, r_2, and r_6, auto correlation coefficients of lags (−1, −2 and −6 years, respectively).

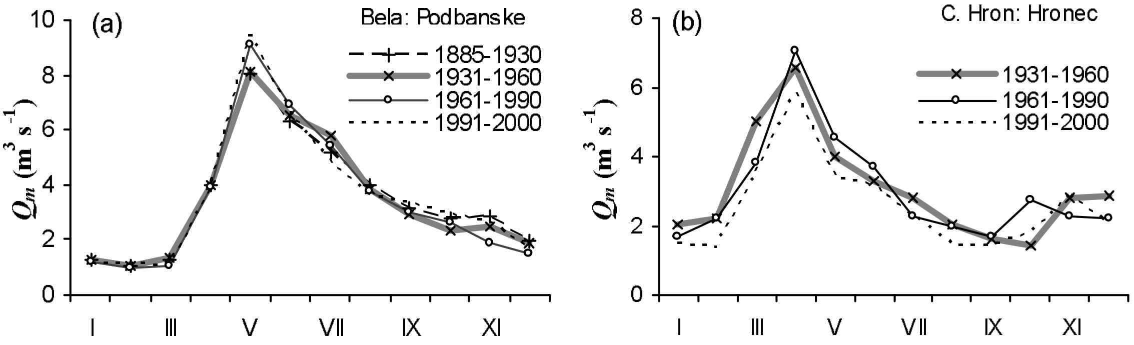

Fig. 2. Average monthly discharge (Q_{m}) for the periods 1931–1960, 1961–1990 and 1991–2000: (a) Bela River (including an historical data reconstruction for the period 1885–1930); (b) Cierny Hron River.

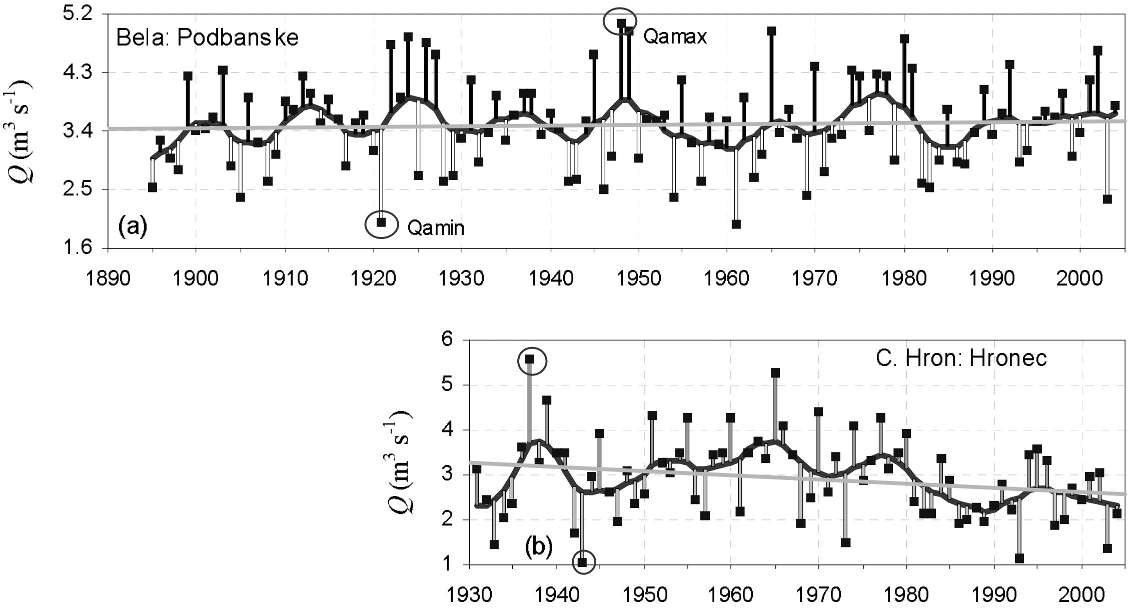

Fig. 3. Course of the average annual discharge time series (Q_{a}) (differences from 5-yr moving average values): (a) Bela River (1895–2004); (b) Cierny Hron River (1931–2004).

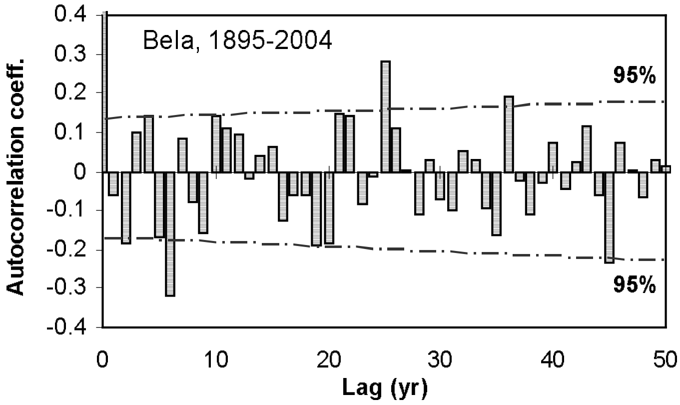

Fig. 4. Auto-correlogram of the annual discharge time series of the Bela River.

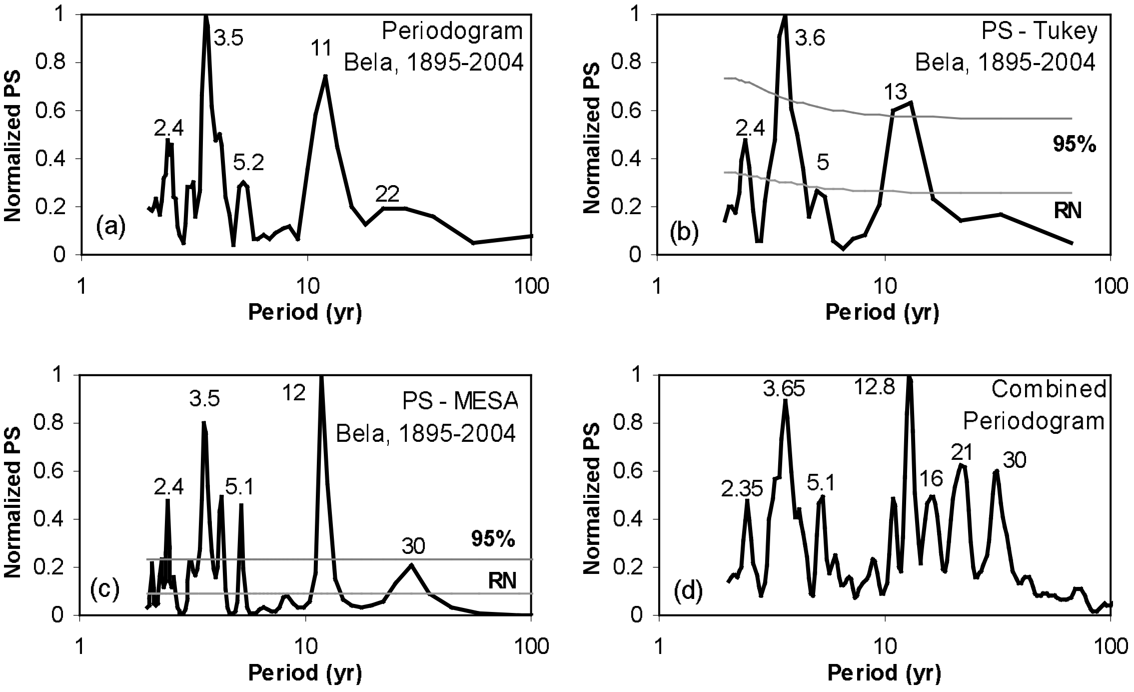

Fig. 5. Spectral analysis of the mean annual discharge of the Bela River for the period 1895–2004: (a) periodogram; (b) PS Tukey; (c) PS MESA (software AnClim, Stepanek, 2003); (d) combined periodogram (Pekarova et al., 2003). Values were normalized. (RN, red noise; 95%, the 95% confidence level).

Bela River from the period 1895–2003 was used in order to analyze the multi-annual variability.

In this station, the water levels have been regularly measured since 1928, while discharges have been reguregularly determined since 1931. In order to complete omitted data, the period 1895–1928 was derived from historical materials, namely from monthly precipitation measured at one station within the basin and two stations in its neighborhood, by Pekarova et al. (2005). For the period 1928–1931 daily discharges were estimated using mean daily water levels. Homogeneity of the derived time series was verified using the Alexandersson test (Alexandersson, 1986; Alexandersson and Moberg, 1997).

3. Interannual fluctuation analysis

The occurrences of dry and wet periods in both considered basins can be tracked in Fig. 3. The driest year in the Bela River basin was that of 1921, a year that was extremely dry in the whole of Central Europe. It is interesting that on the other hand this year

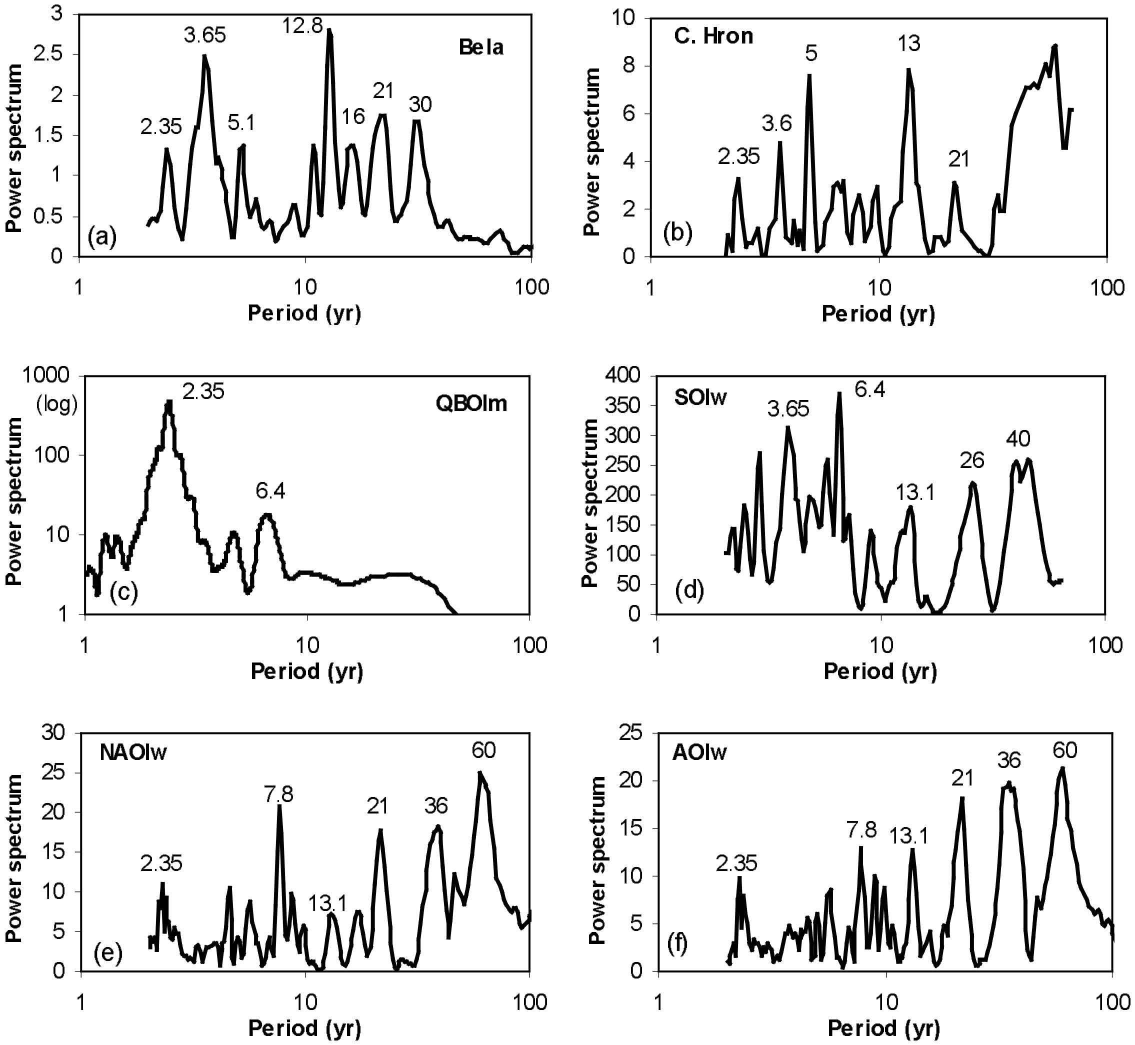

Fig. 6. Combined periodogram of (a) the annual discharge time series of the Bela River (1895–2003); (b) the annual discharge time series of the Cierny Hron River (1930–2003); (c) the Quasi-Biennial Oscillation Index (QBOIm)—monthly time series for the period 1953–2001 according to Marquardt and Naujokat (1997); (d) the Winter Southern Oscillation Index (SOIw), 1866–2004 (Ropelewski and Jones, 1987; Allan et al., 1991); (e) the Winter NAO Index (NAOIw) from Li and Wang (2003a)—long-term trend removed; and (f) the Winter NAM(AOIw) Index from Li and Wang (2003a)—long-term trend removed.

was wet in the region of the Amazon River in South America. To identify lengths of dry and wet periods it is necessary to apply spectral analysis.

3.1 *Autocorrelation and spectral analyses*

Time series analysis includes many useful methods that help us to identify periodicity in time series, e.g. Autocorrelation Analysis (AC), Power Spectrum Analysis (PSA), Singular Spectrum Analysis (SSA), Maximum Entropy Spectrum Analysis (MESA), Empirical Orthogonal Functions Method (EOFs)/Fourier Analysis (FA), Method of Main Components (MMC) etc. (Nobre and Shukla, 1996; Jevrejeva and Moore, 2001; Rao and Hamed, 2003; Liritzis and Fairbridge, 2003; van Gelder et al., 2000; Prochazka et al., 2001). In this study we used the AC method, SSA method, MESA method, and the combined periodogram method (described by Pekarova et al., 2003) to identify inter-annual dynamics patterns of the annual discharge time series, and of the AO, NAO, SO, and QBO time series.

In Fig. 4, the auto-correlogram of the average annual discharge time series (1895–2003) of the Bela River is shown. From this graph it follows that there exists a significant correlation between the data of the time series (negative ones for 2, 6 and 9 year lags, and positive ones for 22, 25 and 36 year lags).

The most significant period in the Bela River's annual discharge at the Podbanske station identified by

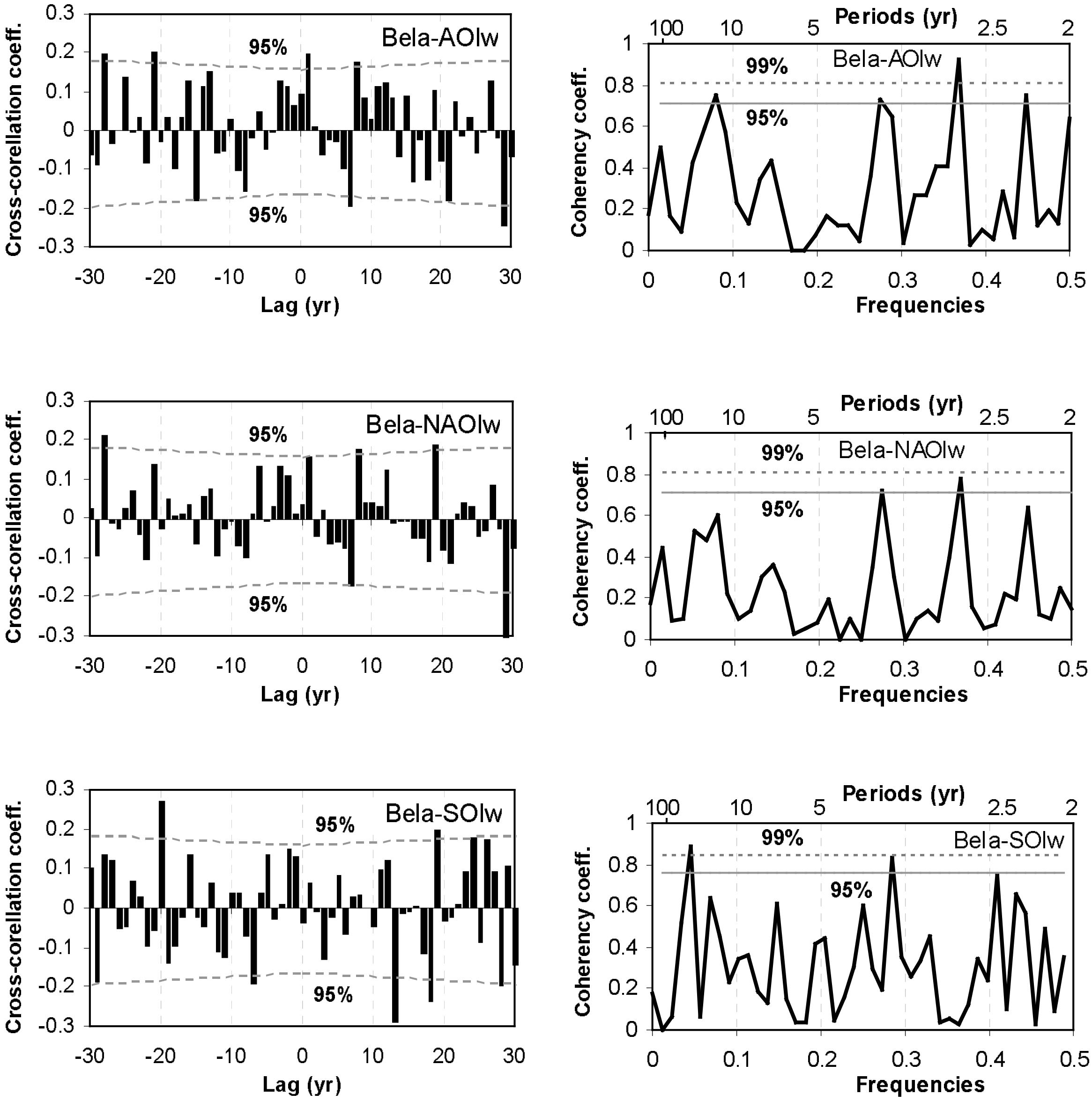

Fig. 7. Crosscorrelograms (left) and coherency coefficients (right) of the discharge of the Bela River and of AO, NAO and SO phenomena for the period 1895–2004.

periodogram and power spectrum—Tukey—was of 3.6 years, while that identified by maximum entropy spectrum analysis and the combined periodogram method was of 12 years (see Figs. 5c and 5d). Moreover, periods of 5.1, 4.2, 2.35, 21, and 30 years were also identified as significant. In Figs. 6a and 6b, the combined periodograms (Pekarova et al., 2003) of yearly Bela and Hron discharge time series are presented. The most significant period in the Hron River is that of 13 years. Other significant periods in the Hron River are those of 3.6 years, 5 years, 21–22 years, and 2.35 years.

Since the lengths of the discovered periods are not integers, it is not possible to identify them by the auto-correlogram method. For example, the most significant period—3.6 years—is reflected in the auto-correlogram only slightly by an increase of the third and fourth auto-correlation coefficients. This defect can be partially eliminated if we use the monthly discharge time series after removing the cycle of 12 months (Compagnucci et al., 2000).

Next, multi-annual cycles of QBO, AO, NAO and SO phenomena annual time series were analyzed. Different NAO index series were tested: according to Hurrell (1995), according to Jones et al. (1997), and according to Li and Wang (2003a,b). In this paper, results obtained from the last mentioned NAO series are used. In Figs. 6c–f combined periodogram indices are presented. In the Quasi-Biennial Oscillation Index (QBOI) monthly time series a significant 28-month (ca 2.35-yr) periodicity was found. This period occurs in both the Arctic Oscillation Index (AOI) and North Atlantic Oscillation Index (NAOI) time series. Similarly, in the NAOI time series there exists a significant 7.8-yr period, presented in the AO time series. Fourier analysis shows that all periods found in all other indices also occur in the AOI time series. The AO pattern covers variability of all mentioned oscillations around the Northern Hemisphere.

The cycle of about 3.6 years in the discharge time series could depend on the SO represented by the SO index. The cycle of about 7.8 years is connected with the NAO represented by the NAO index. This implies that the fluctuation of the Bela runoff can be influenced by both NAO and SO phenomena.

3.2 *Cross-correlation and cross-spectral analyses*

In order to verify possible relationships between significant periods in inter-anual streamflow fluctuation in Slovakia and those in the AO, NAO and SO, a cross-correlation analysis was performed. The independence between the data series for the period 1895–2004 with a lag time up to ±30 years was tested. For the same reason a cross-spectral analysis was performed for the same pairs of time series. The obtained crosscorrelograms and coherency coefficients are shown in Fig. 7, which demonstrates that at the 95% level of significance there exists a significant correlation between streamflow and the indices of interest.

Only a deeper understanding of the teleconnection between NAO, AO, SO, or QBO phenomena and precipitation, temperature, and discharge time series will allow us to explain the discharge multi-annual variability, as well as to consider an impact of climate change on runoff.

4. Conclusions

In the study, teleconnection between AO, SO, NAO, and QBO and inter-annual streamflow cycles in the Hron and Vah River basins (Central Europe) was found. The ca 2.35-, 3.6-, 7.8-, 13.5-, 21-, 30-, and 36-yr periods of SOI, NAOI and AOI time series were identified by the combined periodogram method. Such periods have also been found in other Slovak rivers, as well as in most European rivers (Pekarova, 2003; Pekarova et al., 2003).

The cycle of 3.6 years, found in discharge time series in Slovakia and the rest of Europe, is evidence that multi-annual discharge fluctuations through precipitation totals are affected by SO, i.e., by the well-known ENSO phenomena, the time series of which this cycle also contains. The mutual teleconnection between temperature, discharge, precipitation, ice cover, sea level, dendrochronological, and other time series and AO, NAO and SO is now sufficiently proven. There must be a reason why the lengths of the discovered inter-annual cycles coincide in all analyzed time series all over the world. They probably have an identical origin, but, unfortunately, the source of this inter-annual cyclicity is not yet known.

As a source of these cycles, the known fluctuations of solar activity (11- and 22-yr cycles of sunspot numbers) has been discussed in a lot of studies, e.g., Palus et al. (2000) demonstrated that there is a weak interaction between gravity and solar activity. Important results were also obtained by Charvatova and Strestik (1995, 2004), who employed the inertial motion of the Sun around the barycenter of the Solar System as the base in searching for possible influences of the Solar System as a whole on climatic processes, especially on the changes in surface air temperature in Central Europe. Charvatova (2000) explained a solar activity cycle of about 2400 years by solar inertial motion, and described the 178.7-yr basic cycle of solar motion. The longer cycle, over an 8000-yr interval, was found to average 2402.2 years. This corresponded to the Jupiter/Heliocentre/Barycenter alignments (9.8855-yr×243). Similarly, Esper et al. (2002), Vasiliev and Dergachev (2002), Fairbridge and Shirley (1987), and Liritzis and Fairbridge (2003) demonstrated that the multi-annual cycles probably have their origin in terrestrial motion in Space.

In future research it will be necessary to also take into account the impact of the natural variability of the climate on the hydrological cycle.

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