THE IMPACT OF MEDITERRANEAN OSCILLATIONS ON PERIODICITY AND TREND OF TEMPERATURE IN THE VALLEY OF THE NISAVA RIVER – A Fourier and Wavelet Approach

by

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Periodicity of temperature on three stations in the Nisava River valley in period 1949-2014, has been analyzed by means of Fourier and wavelet transforms. Combined periodogram based on fast Fourier transform shows considerable similarity among individual series and identifies significant periods on 2.2, 2.7, 3.3, 5, 6-7, and 8.2 years in all datasets. Wavelet coherence analysis connects strongest 6-7 years spectral component to Mediterranean oscillation, starting in 1980s. Combined periodogram of Mediterranean oscillation index reveals 6-7 years spectral component as a dominant mode in period 1949-2014. Wavelet power spectra and partial combined periodograms show absence of 6-7 years component before 1975, after which this component becomes dominant in the spectrum. Consistency between alternation in temperature trend in the Nisava River valley and change in periodicity of Mediterranean oscillation was found.

Key words: *temperature, Nisava River valley, Mediterranean oscillation, wavelet transformation, periodogram*

Introduction

Climatologic time series (temperature, precipitation, *etc.*) have complex non-stationary and non-linearity characteristics under multiple temporal scales. They are generated by complex climate system, of which we very often know very little. Therefore, predictability in behavior such as trends and periodicities is very important. This characteristic limits traditional spectral and correlation analysis, as an important approach for finding periodicities and detecting association between two or more of climatologic phenomena. Fourier analysis is widely used to examine periodicities in the frequency domain, where we implicitly assume that the underlying processes are stationary in time. In climate system this assumption is correct just in limited time intervals. On the other side wavelet transform expands time series into time-frequency space, and therefore has the ability to find localized intermittent periodicities [1]. Ma-

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jor disadvantages of traditional correlation analysis are that it is suitable only for series with linear and ergodic properties, and can not reveal and describe series cross-correlations under certain temporal scale [2]. The wavelet cross-correlation analysis methods (XWT) and wavelet coherence (WTC) analysis method, based on both continuous wavelet transform (CWT), and discrete wavelet transform, are more suitable for analyses of cross-correlations among different climatologic variables.

This study was initiated in order to examine the existence of a common periodicity for investigated temperature time series in the Nisava River valley. Since we found it, we have tried to find a connection with some of the climate indices, such as AO, NAO, ENSO, *etc.* Applying selected methodology we have failed to find significant connections, so we tried to find a connection with regional Mediterranean oscillation (MO). This time not only did we find the connection between the periodicity of phenomena, but it paved the way for us to find the connection to temperature trend and anomaly in the behavior of the MO itself.

The MO is a regional circulation pattern related to the activity of cyclogenesis in the Mediterranean, mainly in the bay of Genoa [3]. In the positive phase of MO, the cyclogenesis is anomalously intense while in the negative phase it is anomalously weak. The Mediterranean oscillation index (MOI) is defined originally by Conte [4] as the normalized pressure difference between Algiers (36.4°N, 3.1°E) and Cairo (30.1°N, 31.4°E). A second version of the index, which is used in this study, is calculated from Gibraltar's Northern Frontier (36.1°N, 5.3°W) and Lod Airport in Tel Aviv, Israel (32.0°N, 34.5°E) [5]. An overview of different influences on climate variability in the Mediterranean Basin has been attributed to the MO given in [6]. Maheras and Kutiel [7] found favorable circulation for high temperatures in the western basin (southerly flow) associated with unfavorable circulation in the eastern basin (northerly flow) and vice versa. Piervitali *et al.* [8] found high negative correlation between the eastern Iberian and Italian rainfall and MO, exceeding the relationship with the NAO through the year. Palutikof [5] found a significant negative relationship between the MO and rainfall over the western and central Mediterranean in winter, higher than the relationship between the NAO and rainfall in these locations. Burić *et al.* [9] found a connection between the MO and precipitation extremes in Montenegro. Dunkeloh and Jacobeit [10] have used a canonical correlation analysis to identify main coupled circulation-rainfall patterns and relate to recent variability and trends of Mediterranean precipitation to large-scale circulation dynamics. They found that the circulation patterns do not coincide completely with the ordinary NAO, and the most important pattern recurring with dynamical adjustments throughout the whole year reflects the seasonal cycle of the MO. Similar results were found by Corte-Real *et al.* [11] for the case of whole-year analysis on monthly scale. These results seem to imply that the MO is not an independent phenomenon, but is associated with the NAO.

Territory and data

The Nisava River valley is located in the central part of the Balkan Peninsula. It covers the area of east and southeast Serbia, and part of the territory of western Bulgaria. The valley is of a composite type, with the direction of northwest-southeast. Direction is caused by tectonic and morphological evolution of the Balkan Serbia relief. It is located between the parts of the Eastern zone of young fold mountains in the north and east, and parts of the Serbian-Macedonian mass in the south and southwest. The confluence of the Ginska and Vrbnica Rivers near Toden, Bulgaria, at 640 m above sea level, creates the Nisava River, with total length of 202 km (with Ginska) [12], fig. 1.

Monthly temperature time series used for analysis from three meteorological stations were provided by Republic Hydro-Meteorological Service of Serbia. Two synoptic (Nis, Dimitrovgrad) and one climate (Pirot) station are located at the bottom of the Nisava River valley, in the hypsometric belt of 200-450 m above sea level, tab. 1.

Monthly temperature series have very strong spectral component of one year, which is a consequence of the Earth's revolution. The strength of this component masks all the other spectral components, and therefore it is necessary to remove it, or to deseasonalizate data. All time series are deseasonalized removing monthly averages from the series [13].

The MOI daily records have been obtained from the Climate Research Unit, University of East Anglia, Norwich, UK [14].

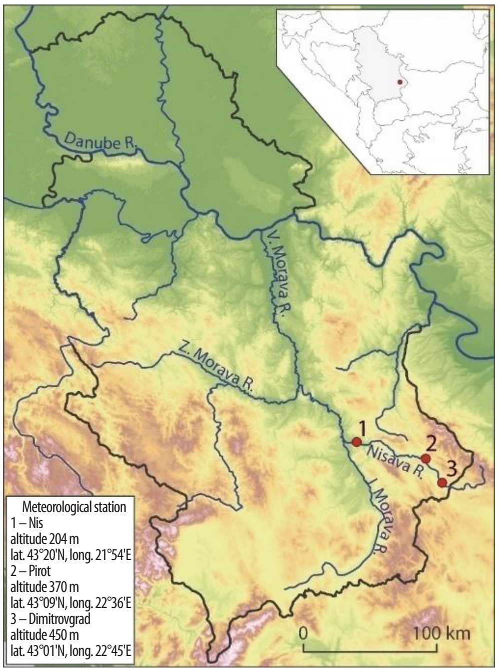

Figure 1. Geographical position of meteorological station in the Nisava River valley

Methodology

Combined periodogram

The basic tool in spectral analysis is Fourier transform, the process of decomposing a signal into oscillatory components. In most cases, the signal is given as a finite series of random variable, and in that case the discrete Fourier transform (DFT) is used eq. (1). Most common implementation of DFT is highly efficient fast Fourier transform (FFT) algorithm [15].

Table 1. Meteorological stations

Location	Latitude	Longitude	Altitude	Period
Nis (1)	43°20′N	21°54′E	204 m	1949-2014
Pirot (2)	43°09′N	22°36′E	370 m	1949-2014
Dimitrovgrad (3)	43°01′N	22°45′E	450 m	1949-2014

The DFT of observing temperature time series $\{x_n\}$, $n = 0, \ldots, N-1$ is given as:

$$X_n = \sum_{n=0}^{N-1} x_n e^{-2\pi i k \frac{n}{N}} \quad k \in \mathbb{Z} \tag{1}$$

The simplest technique to estimate the spectrum, in order to find signal periodicity, is the periodogram. The periodogram is given by the modulus squared of DFT:

$$S(f) = \left| \sum_{n=0}^{N-1} x_n e^{-2\pi f n i} \right|^2 \tag{2}$$

where $f = k/N$ is frequency. Physical meaning of frequency is the number of cycles per unit of time. Climatology instead of frequency it is common to use period $T = 1/f = N/k$.

Most of statistical software has embedded FFT as a function, which makes it easy to draw periodogram from eq. (2) and find periods [16]. The problem with the periodogram is the inability to precisely determine periods, especially longer periods. This is due to the limited number of representations of periods, given as N/k. For example, if we have 100 years of measurements, the longest period that can be detected is 100/2 = 50 years, next periods are 100/3 = 33.3, 100/4 = 25, *etc.* We see that if there was a periodicity of 40 years, it would be impossible to represent it correctly, the nearest value would be used instead, in this case 33.3 years.

Combined periodogram proposed by Pekarova [17], Pekarova *et al.* [18], and Pekarova and Pekar [19] brings significant improvements regarding this problem. The algorithm consists in gradually reducing the length of the analyzed series, calculating periodogram (2) for each single series, and then displaying it as a unified periodogram. In this way, number of possible representations of period is increased. If we cut down the series from the previous example from 100 to 80 years, we would have correct representation of 40 years period as 80/2. Resulting combined periodogram is much better interpreted by spectral peaks than periodogram (2), and it is possible to determine the period more precisely.

Wavelet transform

The wavelet transform can be used to analyze non-stationary time series at many different time scales. While at the Fourier transform as an analytic function uses the sine function, wavelet transform's analytical function is wavelet. A wavelet is a function with zero mean, localized in frequency, and time. Wavelet is not strictly defined function, but there are some conditions for its construction. These conditions are described in detail by Percival and Walden [20], for example.

The CWT, eq. (3), of a time series with uniform time steps δt is defined as the convolution of $\{x_n\}$ with the scaled and normalized wavelet [21]:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{i=0}^{N-1} x_i \psi_0 \left[(i-n+1) \frac{\delta t}{s} \right] \quad (3)$$

where ψ_0 is *mother wavelet*. Mother wavelet chosen for this study is Morlet, consisting of a sine wave modulated by Gaussian envelope, given as:

$$\psi_0(\eta) = \pi^{-\frac{1}{4}} \mathrm{e}^{-\mathrm{i}\omega_0 \eta} \mathrm{e}^{-\frac{\eta^2}{2}} \quad (4)$$

where ω_0 is dimensionless frequency. Varying ω_0 changes the width of the Gaussian envelope and thus adjusts the time-scale resolution. Morlet wavelet with $\omega_0 = 6$ has been found as a good choice for climate signals property extraction, since it provides a good balance between time and frequency localization.

The real strength of wavelet analysis lies in the possibility of comparing two time series, finding the common power, phase, and coherence. The cross wavelet transform (XWT) of two time series $\{x_n\}$ and $\{y_n\}$ is defined as $W^{XY} = W^X W^{Y*}$ where * denotes complex conjugation [1]. Cross wavelet power $|W^X W^{Y*}|$ can be interpreted as common power, while the complex argument arg (W^{XY}) can be interpreted as the local relative phase between $\{x_n\}$ and $\{y_n\}$ in time-frequency space.

Another measure is how coherent XWT is in time-frequency space. The WTC of two time series is defined:

$$R_n^2(s) = \frac{\left| S[s^{-1} W^{XY}(s)] \right|^2}{S[s^{-1} W^X(s)] S[s^{-1} W^Y(s)]} \quad (5)$$

where S is empirical smoothing operator [22]. Wavelet coherence can be treated as a localized correlation coefficient in time-frequency space.

More mathematical details of wavelet transform can be found in [1, 21-25]. A MATLAB software package by the Grinsted *et al.* [1] for performing XWT and WTC can be found at site of National Oceanography Centre, Southempton, UK, [26].

Results and discussion

Mean annual temperature in Dimitrovgrad, Pirot, and Nis with related quadratic polynomial interpolation and trend for all the stations is shown in fig. 2. As comparison, observation period has been split on two equal 33-year period. Graphic shows that temperatures had trend of falling in the first half of observational period, and trend of rising in the second half. Results of Mann-Kendall test in [27] are shown in tab. 2.

Table 2. Trend statistic – Mann-Kendall test (*α* – significance, ↓ – falling, ↑ – rising trend)

Location	1949-2014	1949-1981	1982-2014
Dimitrovgrad	–	0.01↓	0.001↑
Pirot	0.01↑	0.05↓	0.001↑
Nis	0.01↑	0.05↓	0.001↑

As we can see, resulting trend of temperatures in the Nisava River valley, fig. 2 is consistent with global temperature trend shown in fig. 3 [22].

Without intention to engage in a deeper analysis of trends and controversies related to the problem of global warming [30], we will show that the time of alternation in the trend in the Nisava River valley could be linked to oscillatory regime change in MO.

Applied combined periodogram on the monthly temperature anomaly at all the stations is graphically presented in fig. 4. High level of agreement between the obtained results at all three measuring stations is obvious. The characteristic peaks of the spectrum mostly match in all the periodograms.

This analysis implies that the temperature series are non-stationary and a deterministic multi-annual cycle has been discovered. The spectral analysis confirmed that the occurrence of multi-annual cycles exhibits the following durations: 2.2, 2.7, 3.3, 5, 6-7, and 8.2 years. Separation between the periodicity of 4.7 and 5 years is found in Pirot and Dimitrovgrad, which does not exist in Nis. Periodicity at 13-14 years was found

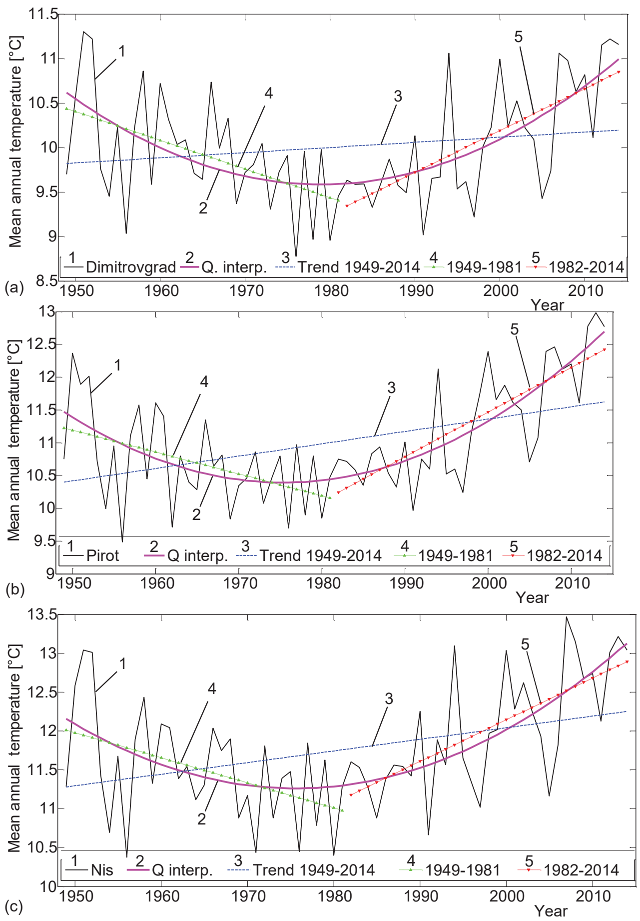

Figure 2. Mean annual temperature, 2nd degree polynomial interpolation and trend: (a) Dimitrovgrad, (b) Pirot, and (c) Nis

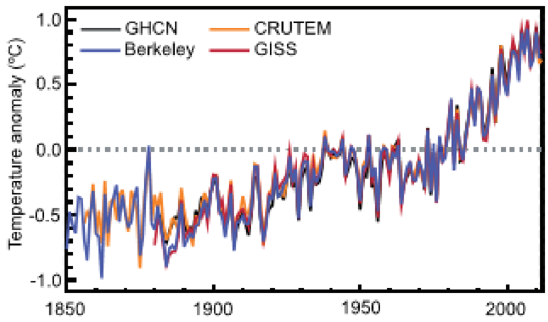

Figure 3. Global annual land-surface air temperature relative to 1961-1990 climatology from the latest version of four different data sets (Berkeley, CRUTEM, GHCN, GISS). Source: IPCC AR5 [28]
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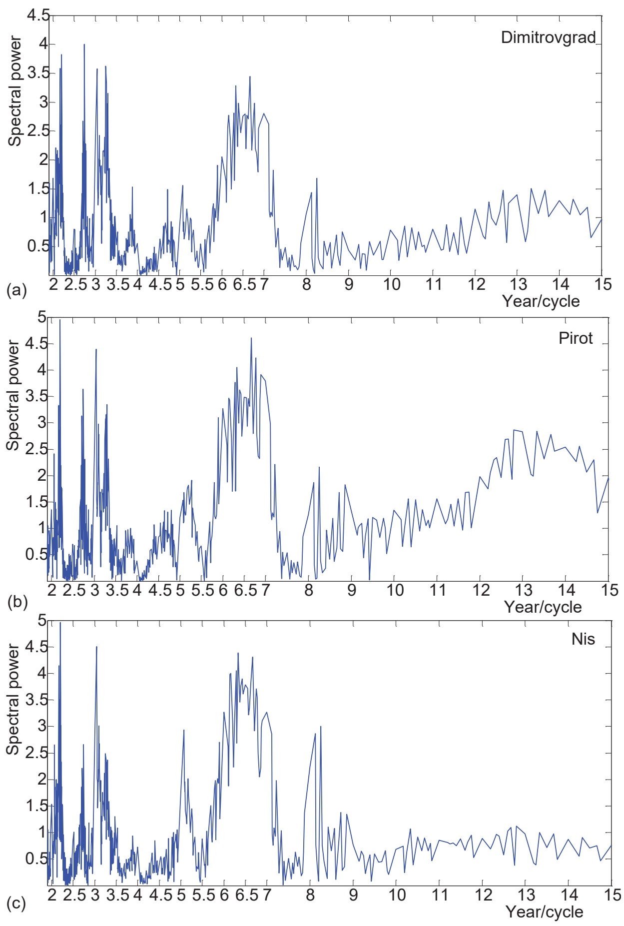

Figure 4. Combined periodogram of monthly time series: (a) Dimitrovgrad, (b) Pirot, and (c) Nis

in Pirot, there is an indication of it in Dimitrovgrad, while in Nis there is no indication at all. The most significant period in temperature cyclicality found on all three stations was 6-7 years.

We were looking at large scale atmospheric patterns for the causes of the periodicity in the time series, known as atmospheric oscillations or teleconnections. It is well known that the global atmospheric patterns such as NAO and ENSO strongly influence the climate of some areas [30]. Testing of the effects of the NAO, ENSO, AO, EA/WR, and NSC on the temperature of the Nisava River valley using WTC method has shown that there is no significant coherence between the phenomena.

The WTC cross-scalogram reveals significant coherence between MO and temperatures in Dimitrovgrad, Pirot, and Nis (fig. 4). Most significant coherence was found on scale 5-8 years, in the period after 1984.

The accuracy of determination of the scale and the time of coherence is not arbitrary, but rather conditioned by the nature of mother wavelet and time-frequency uncertainty principle [15]. Better time resolution leads to worse frequency resolution, and vice versa. Scale for Morlet wavelet ($\omega_0 = 6$) is almost identical to Fourier period ($T_{\text{scale}} = 1.033\ T_{\text{Fourier}}$), so we can easily identify that scale of coherence corresponds to dominant 6-7 years period on combined periodograms, fig. 4. In order to investigate behavior of temperature in frequency domain as a function of chosen time interval, we have split time series in two identical 33 years long intervals (1949-1981, 1982-2014). On fig. 6 we presented combined periodograms for split time series and scalogram for Nis. Results for the other two sites are similar. Combined periodograms, fig. 6, reveal shift in frequency domain between two intervals. For the first period investigated dominant peak is on 8 years, while in second it is 6-7 years. Wavelet power reveals the same shift as combined periodogram, placing it in between 1970 and 1980. Statistical significant (black contour) oscillations on 8 years only exist in period 1952-1960, outside of cone of influence [1], but colors on scalogram and peak on periodogram give us reason to believe that this oscillation started before start of measurement and lasting till the beginning of 1970s. After that there is a gap until the beginning of 1980s, where new oscillation starts, now with the period shifted to 6-7 years. As we can see on cross-scalograms, fig. 5, this oscillation is coherent with MO, they co-vary with some phase shift between them (black arrows), which is considerably constant.

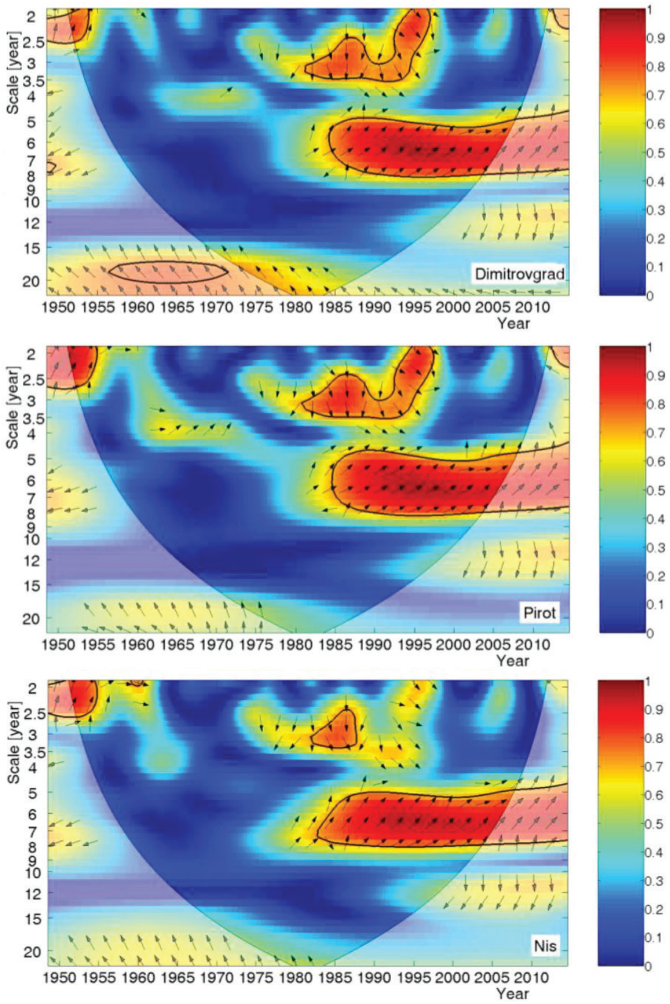

Figure 5. The WTC between MOI and temperature anomaly in Dimitrovgrad, Pirot, and Nis
(*for color image see journal web site*)

The MOI periodogram, fig. 7, shows dominant spectral component on 6-7 years, same as the temperatures. Although the statistical significance of the spectral components has been occurring since 1990, the color of the scalogram clearly shows that it started around 1975. The combined periodograms of split time series confirm this. According to cros-scalograms, scalograms, and periodograms, figs. 5-7, we can say that MO has been the main source of oscillatory behavior of temperature in dominant 6-7 year period, since 1980. Previous dominant 8 years period is not connected to MO. The temperature started to be coherent with MOI around 1980, while 6-7 year MOI fluctuations started around 1975, so there is around 5-year synchronization period between periodicity.

As we saw, the trend of mean annual temperature alternated in the beginning of 1980s from falling to rising, fig. 2. We calculated 2nd order interpolation polynomial in order to find the turning point. Temperature interpolation polynomial is given as $T_2 = p_2y^2 + p_1y + 0$, eq. (6), where y is the year. The turning point is found when we find the zero of the first derivative of

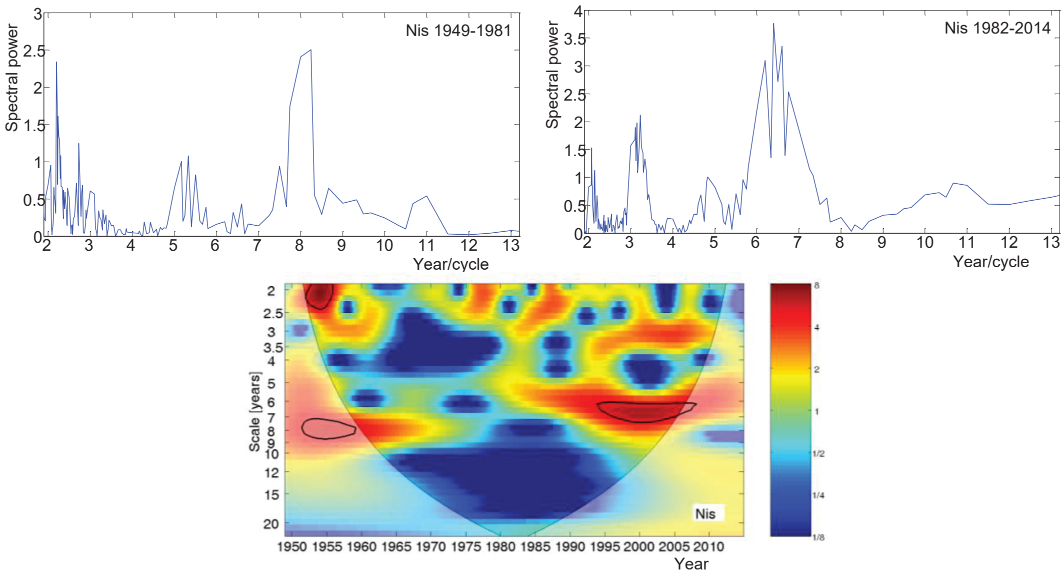

Figure 6. Temperature in Nis – combined periodogram; (a) 1949-1981, (b) 1982-2014, and (c) wavelet power scalogram 1949-2014
(*for color image see journal web site*)

eq. (6), $dT_2/dy = 0$, which leads us to $y = -p_1/2p_2$. Coefficients in eq. (6) are easy to find by using some of commercial software (Excell, MATLAB, *etc.*), wherefrom we find turning years: for Dimitrovgrad 1979, for Pirot 1977, and for Nis 1976. As we can see, the alternation of temperature trend in the Nisava River valley occurs just after changing dominant periodicity of MO. Methodology we used here can not prove the connection between temperature trend and MO,

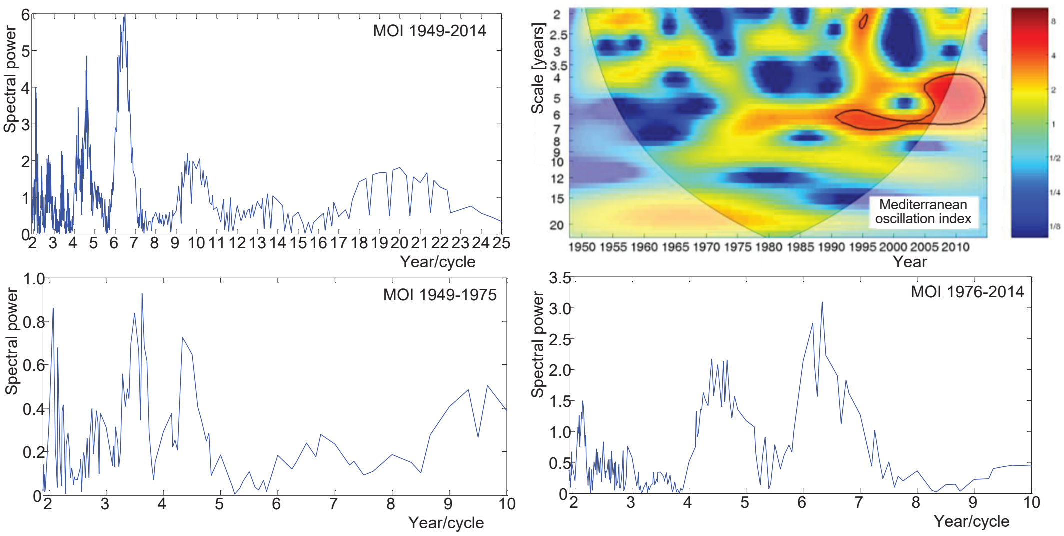

Figure 7. The MOI – combined periodograms and WT scalogram
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but we have reasonable doubt about it. During 5-year synchronization period of temperature periodicity with MO, periodicity at the other scales was changed too, fig. 6, which could lead to changes in the long-term tendency.

Conclusions

Three temperature time series in the Nisava River valley were analyzed. The spectral analysis discovers deterministic multi-annual cyclic components, with periodicity on: 2.2, 2.7, 3.3, 5, 6-7, and 8.2 years. The most significant period in temperature cyclicality found on all three stations was 6-7 years. We have shown that this periodicity is completely explained by the influence of MO.

We have found an anomaly in MOI signal, sudden occurrence of 6-7 year period was detected around 1975. Coherence of MOI with the Nisava River valley temperatures at that periodicity stars around 1980. During synchronization period 1975-1980, a change in the trend of temperatures was found, led us to the assumption of the connection between temperature trend and MO.

Detection of such behavior can not clarify the mechanisms underlying these phenomena, so that further research is required. Special emphasis is placed on the reasons for MO regime change.

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Nomenclature

f – frequency, [Hz]
$R^2_n(s)$ – wavelet coherence
$S(f)$ – periodogram
$W^X_n(s)$ – continuous wavelet transform of a time series $\{x_n\}$
W^{XY} – cross wavelet transform of a time series $\{x_n\}$ and $\{y_n\}$
X_n, Y_n – discrete Fourier transform of time series $\{x_n\},\{y_n\}$
$\{x_n\},\{y_n\}$ – observing time series

Greek symbols

ψ_0 – mother wavelet (Morlet)
ω_0 – dimensionless frequency

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