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ORIGINAL PAPER

Analysis of monthly, winter, and annual temperatures in Zagreb, Croatia, from 1864 to 2010: the 7.7-year cycle and the North Atlantic Oscillation

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Abstract Long instrumental records of meteorological variables such as temperature and precipitation are very useful for studying regional climate in the past, present, and future. They can also be useful for understanding the influence of large-scale atmospheric circulation processes on the regional climate. This paper investigates the monthly, winter, and annual temperature time series obtained from the instrumental records in Zagreb, Croatia, for the period 1864–2010. Using wavelet analysis, the dominant modes of variability in these temperature series are identified, and the time intervals over which these modes may persist are delineated. The results reveal that all three temperature records exhibit low-frequency variability with a dominant periodicity at around 7.7 years. The 7.7-year cycle has also been observed in the temperature data recorded at several other stations in Europe, especially in Northern and Western Europe, and may be linked to the North Atlantic Oscillation (NAO) and/or solar/geomagnetic activity.

1 Introduction

For climatological studies, it is useful to have long instrumentally observed records of temperature, precipitation, and other meteorological variables in the region of interest. Such records are valuable for many reasons. They can be used for investigating the past regional climate, making future predictions, and understanding the influence of large-scale atmospheric circulation processes. However, in many parts of the world, the instrumental records are available only since the 1950s. For these regions, climate proxies such as ice cores, corals, ocean and lake sediments, tree rings, and speleothems are often used by researchers to reconstruct the climate in the pre-instrumental era. At several stations in Europe, environmental variables have been instrumentally monitored for more than a century. In Croatia, the Zagreb- Grič observatory has been continuously recording local temperature, pressure and other variables since around 1862 (Penzar et al. 1992).

In this paper, we examine the variability in the instrumental records of monthly, annual, and winter temperatures in Zagreb for the time period 1864–2010. These temperature data were recorded at the Zagreb-Grič observatory, and we retrieved the data from the archives at the Meteorological and Hydrological Institute of Croatia. Using wavelet analysis, we identify the dominant modes of variability in these temperature series and delineate the time intervals over which these modes may persist. We also explore possible teleconnections of the temperature variability with the North Atlantic Oscillation (NAO).

Our presentation is organized as follows. In section 2, we briefly describe the wavelet analysis methodology. This is followed in section 3 by a discussion of the results. Finally, in section 4, a few concluding remarks are given.

2 Wavelet analysis methodology

Wavelet analysis is a powerful tool for analyzing multiscale non-stationary oscillatory processes. It has been used for time series analysis in a wide variety of applications including geophysical time series (Addison 2002). For wavelet analysis of the Zagreb temperature time series, we have used a continuous wavelet transform (CWT). The CWT maps the spectral-temporal characteristics of a time series onto a time-frequency (time-period) plane from which the dominant

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periodicities and their duration can be discerned by visual inspection. The CWT uses a variable-size window that narrows when focusing on the small-scale or high-frequency features of a signal, and widens when focusing on the large-scale or low-frequency features, analogous to a zoom lens (Kumar and Foufoula-Georgiou 1997). Thus, it provides an elegant way to adjust the time and frequency resolutions in an adaptive fashion. For a time series, the CWT is defined as the convolution of the time series with a basis function called the analyzing wavelet or the mother wavelet. The wavelet power spectrum (WPS) is defined as the squared modulus of the CWT. The WPS represents the signal energy at a specific scale (period) and time. From the WPS, the various periodicities and the time intervals of their occurrence are determined. The details of the CWT methodology and its implementation can be found in the paper by Torrence and Compo (1998). In our recent work, we have applied CWT to the analysis of multiscale variability in hydrological and climatological time series (Sen 2009; Sen and Fang 2014).

For a time series $\{x_n\}$, with $n = 1, 2, 3,\ldots, N$, the CWT is given by:

$$W_n(s) = \sum_{n'=1}^{N} \left(\frac{\delta t}{s}\right)^{1/2} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s}\right]. \quad (1)$$

Here, $W_n(s)$ are the wavelet coefficients, n is the time index describing the location of the wavelet in time, s is the wavelet scale, and δt is the sampling interval. The function ψ is called the mother wavelet, and an asterisk denotes its complex conjugate The wavelet power spectrum (WPS) is given by $|W_n(s)|^2$. By plotting the WPS on a time-frequency (time-period) plane, the dominant modes of variability can be observed.

Wavelet analysis can also be used to identify the interrelationship between two time series. This can be done using the concept of wavelet coherence. Wavelet coherence reveals local similarities between two time series and may be considered a local correlation coefficient in the time-frequency (time-period) plane. It can display the relative phase between the time series, and thus locally phase-locked behavior can be detected. If the two time series are physically related, one would expect a consistent or slowly varying phase lag (Grinsted et al. 2004). For climatological time series, wavelet coherence can be used to identify their possible teleconnection with large-scale atmospheric processes. Wavelet coherence can find significant coherence even where the common power in the CWTs of the two times series is low.

The wavelet coherence between two time series can be computed by normalizing and smoothing their cross wavelet spectrum. The cross wavelet spectrum between two time series is given by the product: $W_n^{XY}(s) = W_n^X(s)\, W_n^{Y*}(s)$, where $W_n^X(s)$ and $W_n^Y(s)$ represent the WPS of the time series $\{x_i\}$ and $\{y_i\}$, respectively, and the asterisk denotes a complex conjugate.

3 Results and discussion

First, we examine the monthly temperature time series. As we would expect, this time series has a very pronounced annual cycle. In order to investigate the low-frequency variability, the annual cycle was removed by subtracting the seasonal means from the time series. The resulting time series is shown in the upper panel of Fig. 1. This time series was analyzed using a continuous wavelet transform (CWT) with a Morlet wavelet of order 6 as the mother wavelet. The Morlet wavelet consists of a complex sinusoid with a Gaussian envelope. This mother wavelet is chosen because it provides a good balance between time and frequency resolutions. The Morlet wavelet has been used successfully by many researchers for identifying quasi-periodic fluctuations in a variety of geophysical time series. The wavelet power spectrum (WPS) of the monthly temperature time series shown in the upper panel of Fig. 1 is depicted in the lower panel in Fig. 1. In the WPS, the dark contour lines denote 95 % confidence level with respect to a red-noise background spectrum, and the region below the U-shaped curve represents the cone of influence (COI). Inside the COI, the edge effects become important, and so the results in this region may not be reliable, and should therefore be used with caution (Torrence and Compo 1998). We will consider an oscillatory mode a true periodicity if it encompasses at least two full cycles of oscillation. Within the 95 % confidence level, the WPS shown in Fig. 1 clearly reveals the presence of the 7.7-year cycle as a dominant period of variability persisting approximately from 1931 to 1972, encompassing more than five cycles of oscillation. The WPS also indicates strong variability at the decadal timescale of about 12.4 years, spanning the time interval from 1935 to 1960, consisting of two oscillatory cycles.

Many geophysical time series can be modeled as a red-noise process. Accordingly, the statistical significance of the wavelet power spectrum (WPS) of the temperature time series analyzed here is assessed using the spectrum of a red-noise process as the background spectrum. We used a lag-1 autoregressive (AR1) process for red noise. If a peak in the WPS is significantly above this background spectrum, then it can be assumed to be a true feature of the time series with a certain percent confidence. We have used a significance level of 5 % or a confidence level of 95 % (see Torrence and Compo 1998 for details).

Next, we examine the winter (DJF) temperature time series. This time series is plotted in the upper panel of Fig. 2, with its WPS shown in the lower panel. The 7.7-year cycle is also evident from this WPS as the most dominant periodicity persisting approximately from 1946 to 1971, with more than

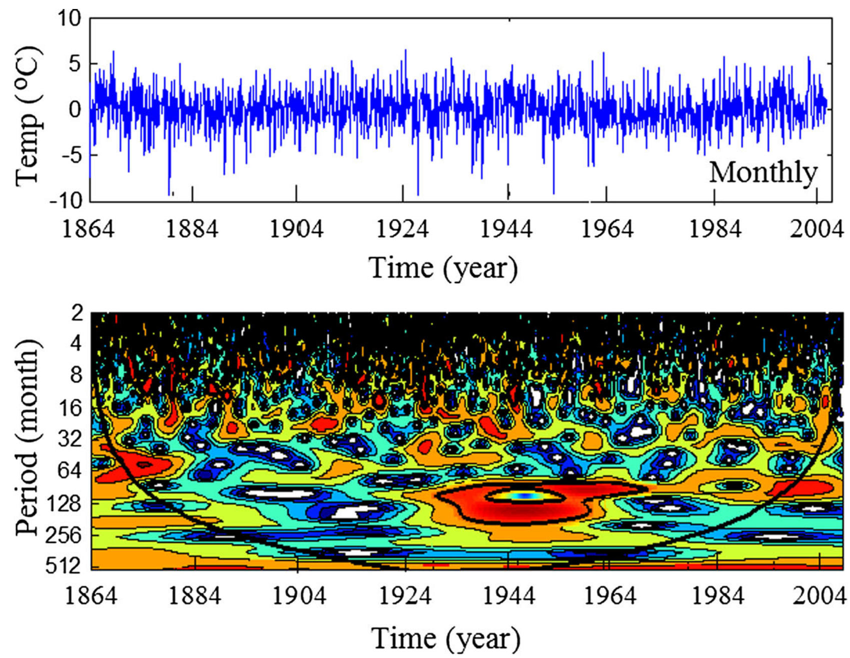

Fig. 1 *Upper panel*: The monthly temperature time series from 1864 to 2010, with the annual cycle removed. *Lower panel*: Wavelet power spectrum (WPS) of the time series shown in the *upper panel*

three cycles. Finally, the annually averaged temperature series is shown in the upper panel of Fig. 3. The WPS of this series is illustrated in the lower panel. It is apparent from Fig. 3 also that the most dominant periodicity is the 7.7-year cycle which occurs between 1949 and 1970, spanning more than two cycles.

In a recent study, Radić et al. (2004) used the Zagreb-Grič observatory data to analyze the annual and seasonal averages of temperature, pressure, cloudiness, and precipitation in Zagreb for the time interval 1862–2002. Using the method of empirical mode decomposition (Huang et al. 1998), they investigated the trends and periodicities in these variables and studied their relationships. In their analysis, they focused on the low-frequency variability at decade-to-century timescales and excluded periodicities at timescales of a few years or less. Accordingly, they did not report the presence of the interannual 7.7-year cycle in the Zagreb temperature data.

The 7.7-year cycle has been detected in a few other temperature records from different parts of Europe. Several researchers have examined the instrumental and documentary records of central England temperature (CET) from 1659 until the end of the twentieth century, using a variety of

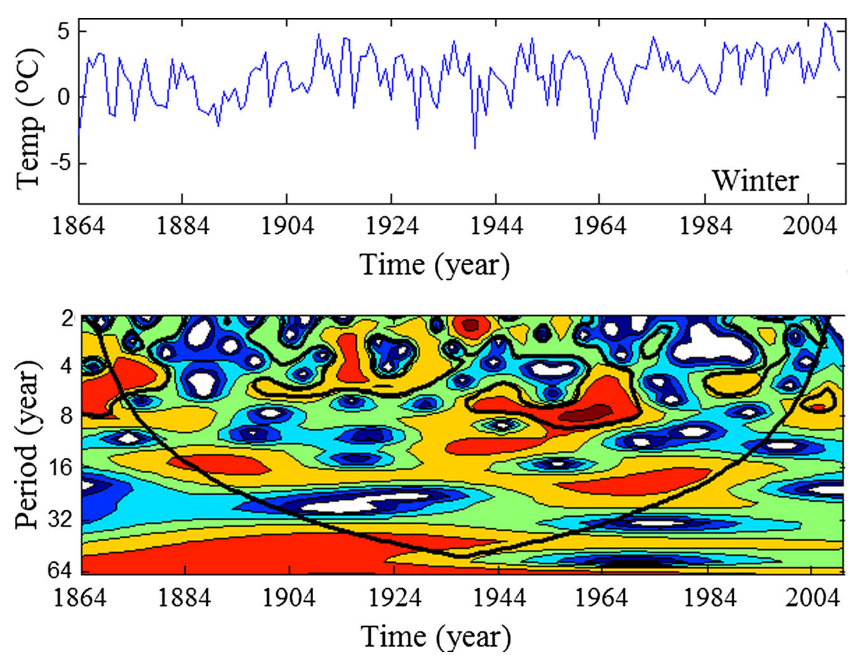

Fig. 2 *Upper panel*: The winter (DJF) temperature time series from 1864 to 2010. *Lower panel*: Wavelet power spectrum (WPS) of the time series shown in the *upper panel*

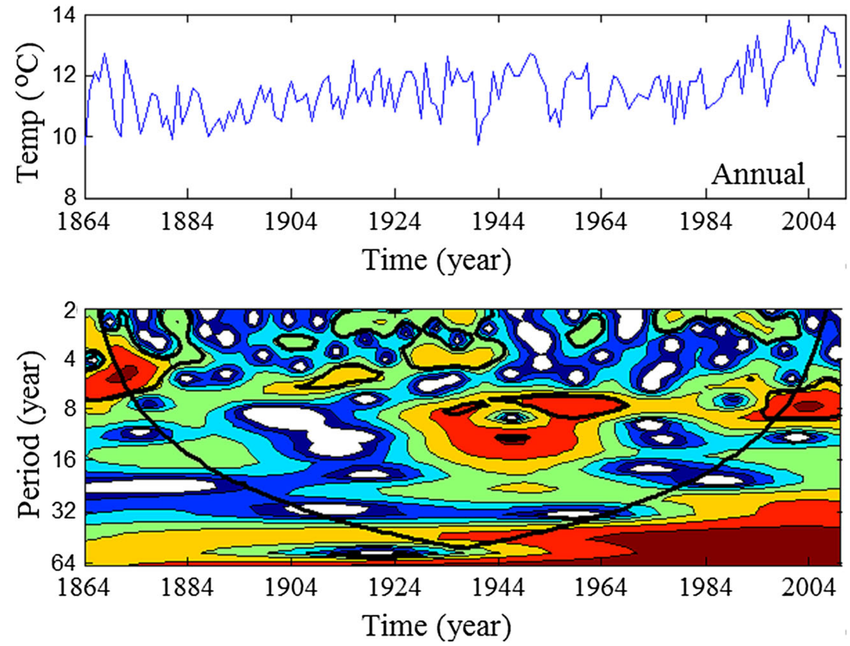

Fig. 3 *Upper panel*: The annual temperature time series from 1864 to 2010. *Lower panel*: Wavelet power spectrum (WPS) of the time series shown in the *upper panel*

mathematical and statistical techniques (Balinus et al. 1997; Plaut et al. 1995; Benner 1999). All these methods confirm that there is a pronounced oscillatory mode of variability at the period of 7–8 years in the CET. In addition, using the monthly averages of CET from 1659 to 1997 and the NAO index of Hurrell et al. (1995); Benner (1999) has shown that the dominant 7.7-year variability in CET may be driven by the North Atlantic oscillation (NAO). The occurrence of the 7–8-year cycle in other climatic records and its synchronization with the NAO has also been discussed by Feliks et al. (2010) and Feliks et al. (2011) and more recently by Palus (2014). The latter paper also gives a new important role to the 7–8-year cycle by the finding that it modulates temperature variability on short time scales in large areas of Europe.

Grieser et al. (2002) examined the monthly mean temperature data from several stations distributed throughout Europe, for the past 100 years. Their statistical analysis also reveals the 7.7-year cycle as the most dominant mode of variability in temperature mainly in the northern and western parts of Europe. It is appropriate to point out that their study sites did not include Zagreb, Croatia. Paluš and Novotná (2004, 2007) examined the monthly surface air temperature at several mid-latitude European stations and also observed the 7.7-year cycle as a dominant oscillatory mode of variability. In addition, they have shown that this mode is phase-synchronized with the 7.7-year cycle of the NAO. In another paper, Paluš and Novotná (2009) investigated the effect of solar/geomagnetic activity on climate variability at the mid-latitude European stations. They observed statistically significant phase coherence between the monthly mean temperature, NAO, and solar/geomagnetic activity at the timescales of 7–8 years. Furthermore, Paluš and Novotná (2011) studied the effect of solar/geomagnetic activity on the northern hemisphere near-surface air temperature. For this purpose, they analyzed the NCEP/NCAR and ERA40 temperature data and detected dominant variability in the periods of 7–8 years. They also found evidence of coupling between the climate variability based on the northern hemisphere near-surface air temperature, and NAO, and the solar/geomagnetic activity around the 7–8-years timescales.

The North Atlantic Oscillation (NAO) is the most important mode of atmospheric variability over the North Atlantic Ocean and plays a major role in influencing the weather and climate variations over Eastern North America, the North Atlantic, and the Eurasian continent (Hurrel 1995; Greatbatch 2000; Wanner et al. 2001; Hurrell et al. 2003). The NAO is described by an index which measures the difference in sea level pressure between Stykkisholmur, Iceland, and Ponta Delgada, Azores (Hurrell 1995). Through fluctuations in the strength of the Icelandic low and the Azores high, it controls the strength and direction of westerly winds and storm tracks across the North Atlantic. The NAO swings from one phase to another, producing large changes in surface air temperature, winds, storminess, and precipitation over the Atlantic as well as the adjacent continents. Although the NAO is evident in all seasons, it is most pronounced in the winter. During winters, when the NAO index is high, the westerly winds are stronger than normal. The moderating influence of the North Atlantic Ocean then leads to warmer-than-normal conditions over the Eurasian continent, while the eastern Canadian Arctic is colder than normal (Hurrell 1995). High NAO index winters are also associated with drier conditions over much of central and southern Europe and wetter-than-normal conditions over Iceland and Scandinavia (Trigo et al. 2002).

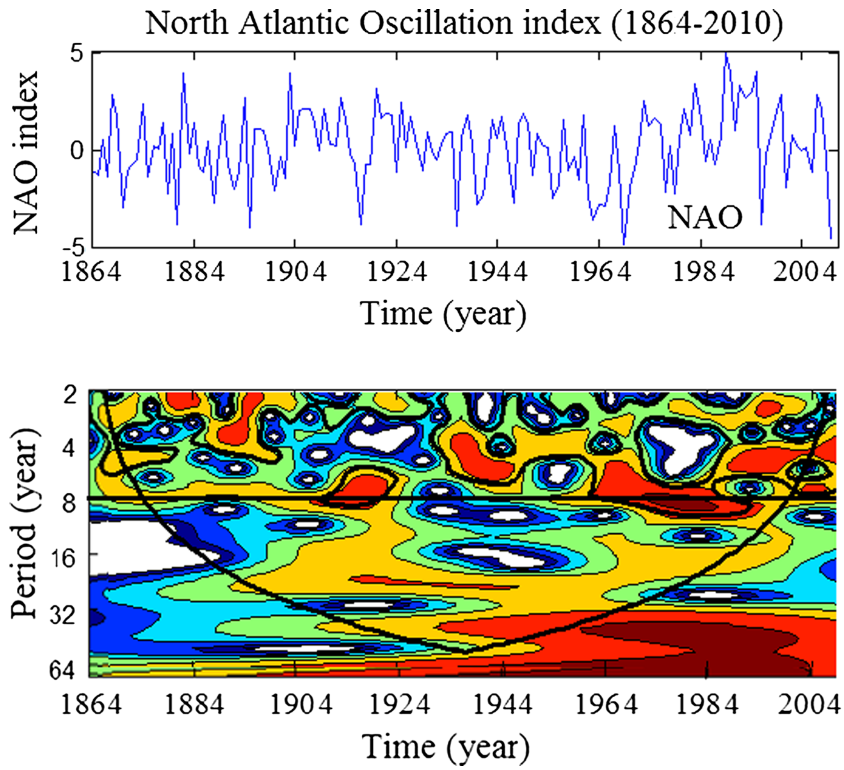

Fig. 4 *Upper panel*: Winter NAO index time series of Hurrell et al. (2014) from 1864 to 2010. *Lower panel*: Wavelet power spectrum (WPS) of the NAO index time series shown in the upper panel

Strong variations in the NAO index at interannual timescales have been observed by several investigators. Among others, Hurrell and van Loon (1997) examined a 130-year record of winter NAO index from 1865 to 1994 and found significant variability between the periods of 6 and10 years. They also analyzed the winter temperature variability in Northern Europe and found strong coherence with the NAO at the 6–10-year timescales. Using singular spectrum analysis, Gámiz-Fortis et al. (2002) analyzed the winter NAO index from 1826 to 2000 and found the 7.7-year cycle as a dominant mode of oscillation. In an effort to investigate ocean–atmosphere coupling in the North Atlantic region, Da Costa and de Verdiere (2002) analyzed a 136-year long sea-level pressure (SLP) and sea-surface temperature SST) dataset and found the 7.7-year cycle as the statistically significant mode of coupled oscillation associated with the NAO.

We now explore possible teleconnections of the temperature variability in Zagreb with the NAO. For this purpose, we consider the winter (DJF) Zagreb temperature time series and the winter NAO index of Hurrell et al. (2014) from 1864 to 2010. This winter NAO index time series is downloaded from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based and is plotted in the upper panel of Fig. 4. The WPS of this time series is shown in the lower panel. In the WPS, the 7.7-year period (marked by the dark horizontal line) appears as a dominant cycle with varying strength persisting from 1908 to 1924 and from 1961 to 1988. Figure 5 illustrates the squared wavelet

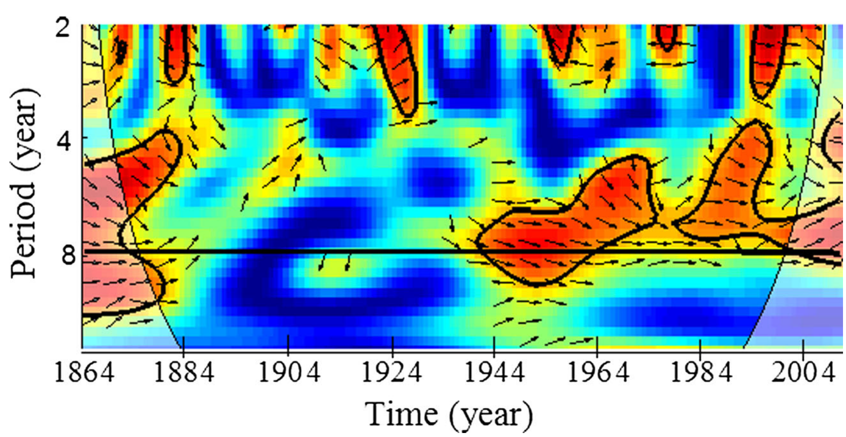

Fig. 5 Squared Wavelet coherence between the Zagreb winter temperature and the winter NAO index of Hurrell et al. (2014) over the time interval 1864–2010

coherence between the Zagreb winter temperature time series and the winter NAO index data. In this figure, as in the other figures above, the dark contour lines represent 95 % confidence level with respect to a red-noise background spectrum, and the U-shaped curve denotes the COI. The arrows indicate the relative phase between the two time series. In particular, a right (left) pointing arrow denotes in-phase (anti-phase) relationship, whereas a vertically up (down) arrow indicates that the second time series lags (leads) the first in phase by 90°. It is apparent from this figure that there are regions between the periods of 4.9 and 9.3 years where the relative phase between the two time series is nearly constant. In particular, around the 7.7-year period marked by the dark horizontal line, the relative phase is consistent from 1942 to 1964, indicating that the two time series are phase-locked over this time interval. This establishes a direct association between the Zagreb winter temperature and the winter NAO.

The statistical significance of the wavelet coherence is estimated with respect to a red-noise spectrum using Monte Carlo methods (Grinsted et al. 2004). For this purpose, we generate a large ensemble of surrogate data set pairs with the same AR1 coefficients as the input datasets. For each pair, we calculate the wavelet coherence. We then estimate the significance level for each scale using only values outside the COI. Empirical testing shows that the AR1 coefficients have little impact on the significance level. The specifics of the smoothing operator, however, have a large impact. For example, the resolution chosen when calculating the scale smoothing has a major influence on the significance level. The Monte Carlo estimation of the significance level requires of the order of 1000 surrogate data set pairs. The number of scales per octave should be high enough to capture the rectangle shape of the scale smoothing operator while minimizing computing time. Empirically, we find ten scales per octave to be satisfactory. Further details may be found in Torrence and Webster (1999), and Grinsted et al. (2004).

4 Concluding remarks

Using wavelet analysis, we have investigated the instrumental records of monthly, winter, and annual averages of temperature in Zagreb for the period 1864 to 2010. In all three records, the dominant mode of variability is found to be around the 7.7-year period. This interannual periodicity has been observed in the temperature records at other European stations, especially in northern and western Europe, and may be linked to the North Atlantic Oscillation. The 7.7-year cycle in Zagreb temperature may also be linked to solar/geomagnetic activity (Paluš and Novotná 2011).

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