Communication Open Access

Asok K. Sen and Zoltán Kern*

Wavelet analysis of low-frequency variability in oak tree-ring chronologies from east Central Europe

DOI 10.1515/geo-2016-0044
Received Nov 15, 2015; accepted May 12, 2016

Abstract: This study investigates the low-frequency (interannual and longer period) variability in three hydroclimatic records from east Central Europe. Two of these records consist of climate proxies derived from oak-tree rings in Bakta forest, and Balaton Highlands in Hungary, for the time interval 1783-2003. The third record consists of homogenized instrumental precipitation data from Budapest, Hungary, from 1842 to 2003. Using wavelet analysis, the three time series are analyzed and compared with one another. It is found that all three time series exhibit strong interannual variability at the 2-4 years timescales, and these variations occur intermittently throughout the length of each record. Significant variability is also observed in all the records at decadal timescales, but these variations persist for only two to three cycles. Wavelet coherence among the various time series is used to explore their time-varying correlation. The results reveal significant coherence at the 2-4 years band. At these timescales, the climatic variations are correlated to the tree-ring signal over different time intervals with changing phase. Increased (decreased) contribution of large-scale stratiform precipitation offers a potential explanation for enhanced (faded) coherence at the interannual timescale. Strong coherence was also observed occasionally at decadal timescales, however these coherences did not appear uniformly. These results reinforce the earlier assertion that neither the strength nor the rank of the similarity of the local hydroclimate signals is stable throughout the past two centuries.

Keywords: Central Europe; Hydroclimate; Oak; Tree ring; Wavelet analysis

Asok K. Sen: Richard G. Lugar Center for Renewable Energy and Department of Mathematical Sciences, Indiana University Purdue University, 402. North Blackford Street, Indianapolis, IN 4602, USA; Email: asen@iupui.edu
***Corresponding Author: Zoltán Kern:** Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences MTA, Budaörsi út 45, H-1112 Budapest, Hungary; Email: kern@geochem.hu

1 Introduction

By virtue of their high resolution, climate sensitivity, and widespread availability, tree rings are often used as a proxy for reconstructing past climate. Tree-ring records of past climate are precisely dated, annually resolved, and can be well calibrated and verified [1]. Oak (*Quercus* sp.) among the species that is most frequently used for dendrochronological studies because of its longevity and relatively well crossdatable ringwidth pattern [2, 3]. In many regions, radial oak growth has been found to depend mainly on moisture availability from the southern to the northern edge [4–8] of its distribution area. In line with this pattern, oak chronologies are among the most valuable proxy records of past hydroclimatic variability also in east Central Europe [9].

Spatial correlation studies have pointed out the rather local character of tree-ring derived hydroclimate signals from Central Europe [10]. In view of this, a dense proxy network is expected to provide a solid basis for a seamless Europe-wide reconstruction. Thus the moisture-sensitive oak tree-ring proxies are good candidates to play a significant role in the future European hydroclimate reconstructions, and in improving our understanding of past changes of the moisture regime. Improved understanding of the hydroclimatic variability, and in particular, disentangling the high and low frequency variability is important since extreme hydroclimatic situations such as water shortage [11, 12], and excess water [13, 14] periods repeatedly affected large parts of the Central European plains. In addition, significant drying is projected in the region, especially in summer [15] and drought hazards on arable lands are envisaged to increasingly affect the productivity of agriculture in the region [16].

The purpose of this study is to investigate the interannual and longer period hydroclimatic variability in

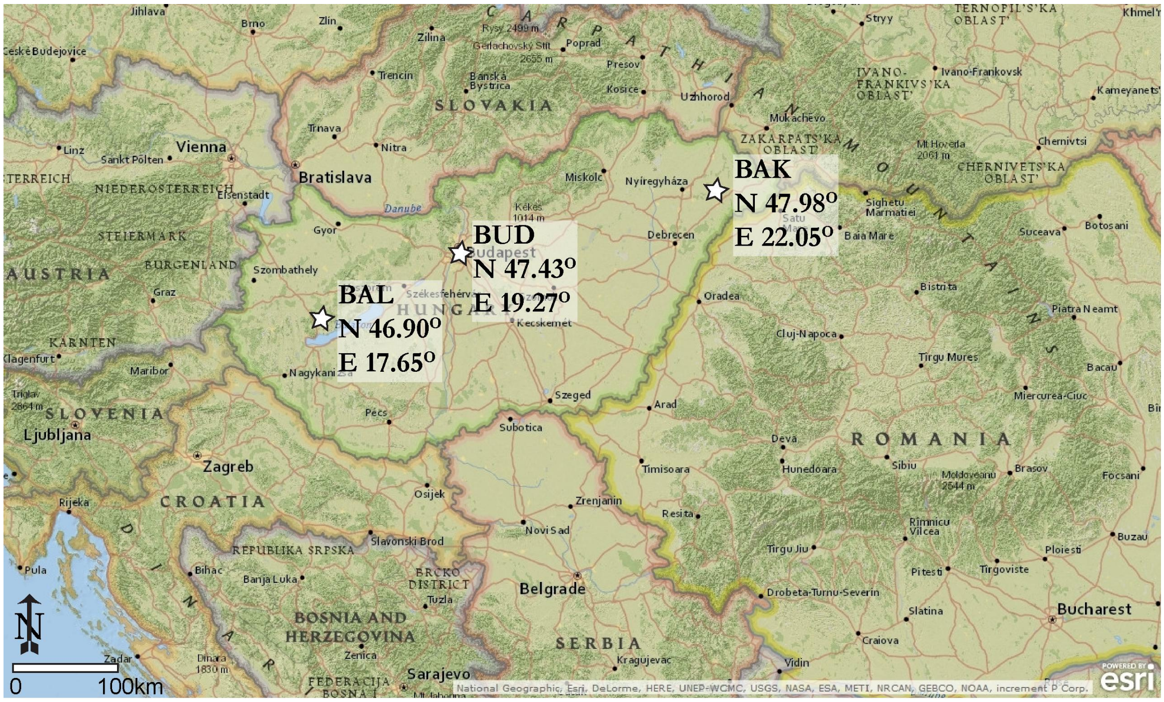

Figure 1: Topographic map showing the sites (stars) of the moisture-sensitive oak chronologies (BAK and BAL), and the location of the longest homogenized regional instrumental precipitation record (BUD). Geographical coordinates are displayed below each site code.

east Central Europe using moisture-sensitive annually-resolved oak tree-ring time series and the longest regionally available instrumental rain-gauge record from Budapest, Hungary. Using wavelet analysis, these three records are analyzed and compared with one another. In particular, we use continuous wavelet transform (CWT) to analyze oak tree-ring data from Bakta forest and Balaton Highlands in Hungary, and homogenized regional precipitation record from Budapest, Hungary. We also explore the time-varying correlation between the tree-ring data and the precipitation record using wavelet coherence. The paper is organized as follows. In Section 2, we describe the data and the methodology used. In Section 3, we present and discuss the results. Finally, in Section 4, a few concluding remarks are given.

2 Materials and methods

2.1 Data

In the recent past multicentennial precipitation reconstructions have been derived from oak tree rings in east Central Europe recently using (i) pedunculate oak (*Quercus robus* L.) trees from Bakta forest [17], and (ii) sessile oak (*Quercus petrea*) trees from the Balaton Highlands [18] in Hungary. Details of processing the tree-ring samples and chronology development are given in the original papers. Authors of the original papers compared their tree-ring chronologies with the local precipitation records and found a strong correlation (Pearson's) with the precipitation total from prior autumn to end of August of the current vegetation period. In this study, we analyze the above tree-ring time series for their common period spanning from 1783 to 2003 AD. The time series from Bakta forest and Balaton Highlands will hereafter be referred to as BAK and BAL, respectively. We also examine the relationships of these time series with the November-August precipitation totals derived from the longest regionally available homogenized precipitation record of Budapest, Hungary [19]. This precipitation series begun at 1842, and will be referred to as BUD. The locations of Bakta forest, Balaton Highlands, and Budapest are shown in the topographic map of Hungary (Figure 1). Each of the time series is normalized to have zero mean and unit variance over the twentieth century.

2.2 Methodology

Wavelet analysis is a powerful tool for investigating multiscale phenomena that are localized in both frequency and time. It is particularly useful for analyzing quasiperiodic

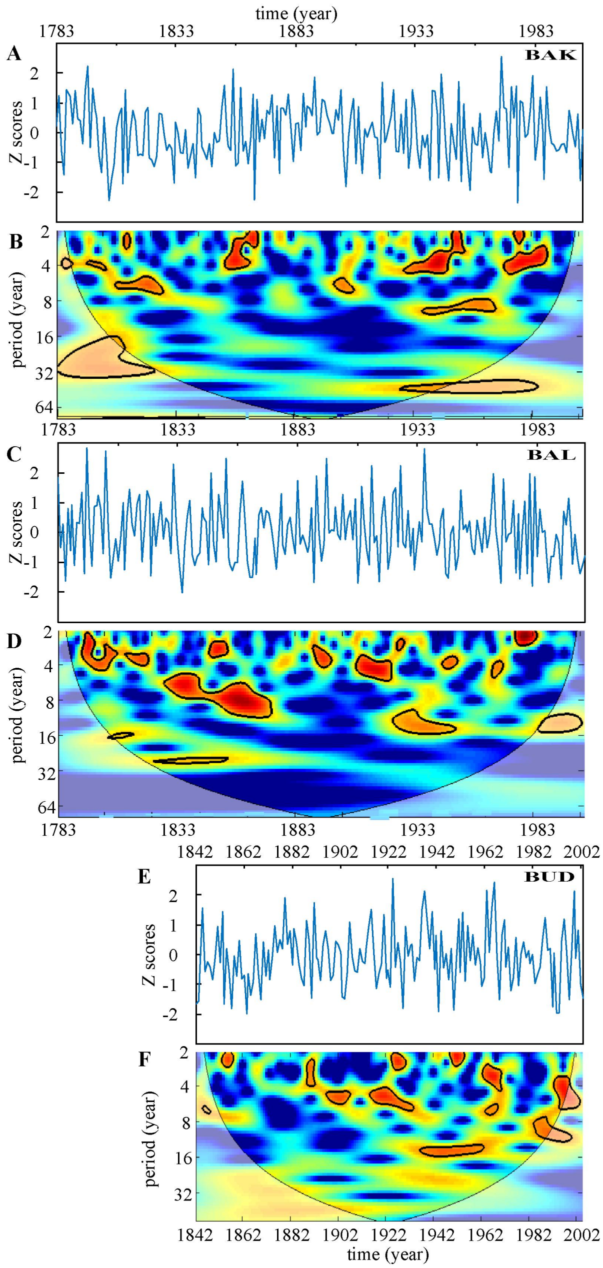

Figure 2: Wavelet power spectrum (WPS) of the three hydroclimatic records from east Central Europe. Latewood width time series of pedunculate oak (*Quercus robur* L.) from Bakta forest (BAK) (A) and the corresponding WPS (B). Total ringwidth time series of sessile oak (*Quercus petrea*) from Balaton Highlands (BAL) (C) and the corresponding WPS (D). Homogenized precipitation time series (BUD) from Budapest (E) and the corresponding WPS (F). In the WPS, the color red (blue) denotes high (low) power, respectively, with the other colors denoting intermediate power levels. The dark contour lines designate 95% confidence level with respect to a red-noise background spectrum, and the region below the U-shaped curve indicates the cone of influence (COI). Inside the COI, the WPS may be unreliable and therefore the results in this region should be used with caution [22].

and intermittent fluctuations. Wavelets have been used for time series analysis in a wide variety of applications including geophysical processes [20]. For wavelet analysis of the time series considered here, we used a CWT. It is able to map the spectral-temporal characteristics of a time series onto a time-frequency (time-period) plane. 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 [21]. 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 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 over which they persist can be identified by visual inspection. The details of the CWT methodology and its implementation can be found in the paper by Torrence and Compo [22]. In our recent work, we have applied CWT to the analysis of multiscale variability in hydrological and climatological time series [23–25].

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 closely resembles the behavior of a traditional correlation coefficient in the time-frequency (time-period) plane [26] thus in the paper we will refer to coherence as correlation. 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 [26]. For climatological time series, wavelet coherence can be used to detect their possible teleconnection with large-scale atmospheric processes [24, 27, 28]. Wavelet coherence can find significant coherence even where the common power in the CWTs of the two time series is low.

3 Results and discussion

3.1 Wavelet spectrum analysis

From the obtained WPS for the BAK time series (Fig. 2a) it became evident that there is strong variability at interannual timescales in the 2-4 years band, and these variations are intermittent throughout the length of the record. Significant variations are also observed around the 5.8-year

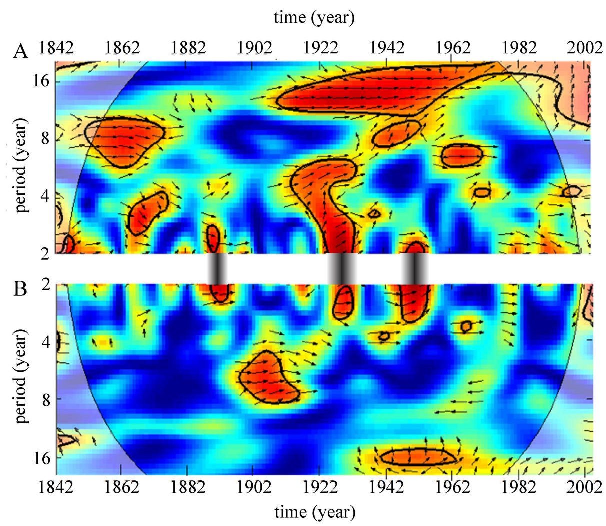

Figure 3: Squared wavelet coherence between tree-ring proxy and instrumental precipitation records. Squared wavelet coherence between BAL and BUD (A) and BAK and BUD (B) time series. As in Figures 2 the dark contours represent 95% confidence level with respect to a red-noise background spectrum, and the faded area shows the COI. The arrows indicate the phase difference between the two signals. A horizontal right (left) pointing arrow indicates in-phase (anti-phase) relationship. A vertically upward (downward) pointing arrow means that the BUD times series lags (leads) the oak tree-ring proxy by 90° in panel B. However, the wavelet coherence plot reflected horizontally for illustration purpose in panel A so here a vertically downward (upward) pointing arrow means that the BUD times series lags (leads) the oak tree-ring proxy by 90°. Grey shaded stripes between the panels indicate the three most characteristic periods when significant coinciding in-phase coherency have been found in the interannual variability among the three hydroclimatic records from east Central Europe.

period spanning the time interval 1808–1827, and around the 8.8-year period over the time interval 1937-1969. However these variations are weaker than those at the 2-4 years timescale (Fig. 2b).

The BAL time series (Fig. 2c) and its WPS (Fig. 2d) exhibit strong variability at both interannual and decadal timescales. As for the BAK time series, the BAL time series also undergoes intermittent fluctuations in the 2–4 years periodic band. Significant variations are also seen to occur around the 5.8-year periodic band from 1828 to 1843, followed by the 7.8-year band from 1847 to 1882. Somewhat weaker variability is observed around the 13.6-year period over the time interval 1925–1951 (Fig. 2d).

Figure 2e shows the BUD time series, and its WPS depicted in the Figure 2f. Intermittent variations in the 2–4 years periodic band are also seen in this WPS. In addition, there are significant variations around the 5.8-year band from approximately 1888 to 1936 with a waning interval of 1907–1917. Decadal-scale variability is also observed around the 13.9-year band over the time interval from 1936 to 1963 (Fig. 2f).

Similar power peaks were recognized in early spectral analysis studies with periods of 2–4 years and 10–16 years for the annual precipitation sums over Central Europe [29]. In addition, there are very good agreement among the significant power peaks found in another tree-ring derived hydroclimate record at around 15, 7.5, 5.8, and 2.7 years from the northern edge of the present study region [30]. Our results reinforce these previous findings. The wavelet decomposition, however, revealed that these periodicities are not stable throughout the past centuries.

3.2 Wavelet coherence

In order to examine the time-varying correlation between the tree-ring (BAK and BAL) time series and the precipitation (BUD) record, we used wavelet coherence. Squared wavelet coherence pattern between the BAK and BAL time series for the interval 1842 to 2003 revealed significant correlation between the BAK and the BUD time series in the 2–3 year periodic band (Fig. 3b). Within this band, the two time series appear to be nearly in phase over certain time intervals. Strong coherence is also observed in the 5.6–6.9 years periodic band, with the two time series being nearly in phase around the 6.2-year period from approximately 1898 to 1911.

The squared wavelet coherence pattern illustrates the relationship between the BAL and BUD time series (Fig. 3a). There are several regions exhibiting strong coherence. In particular, in the 6.6–9.3 years periodic band over the time interval 1857–1871, during which the two time series are nearly in phase. The time series are also nearly in phase around the 5.8–7.4 years band from approximately 1960 to 1972, and around the 15-year period from 1912 to 1962 (Fig. 3a).

An excellent correspondence can be observed among in-phase coherency patterns detected for the interannual variability between tree-ring proxy and instrumental precipitation records (Fig. 3). The most characteristic periods for this correspondence are around 1950, around 1930, and around 1890. A multiple coherence pattern in the regional hydroclimate variability suggests spatially more homogenous hydroclimatological changes over extended areas in certain periods, while more local hydrological patterns can be prevailing between these large-scale coherencies. A simple triggering mechanism for these variations could be the temporal changes in the relative contribution of frontal and convective precipitation over the region. When enhanced cyclonic activity affects east Central Europe increased relative contribution of frontal precipitation is expected. A mid-latitude frontal system typically extends over ~1000 km hence frontal systems deliver precipitation over the entire region. However, if diminished cyclonal activity prevails then weather fronts reach east Central European more occasionally and the relative contribution of precipitation from related large-scale systems to the annual precipitation total is reduced. As a result the relative contribution of the typically more local convective precipitation increased.

To test the validity of this explanation the temporal trend of the cloud types typically accompanied with convective (Cumulus, Cumulonimbus) and stratiform (Nimbostratus, Stratus) clouds can be compared with the results of wavelet coherence analysis.

A recent study has reported statistically significant decreasing trends for stratiform precipitation, while the frequencies of rain shower and snow shower (convective precipitation) were increasing; correspondingly, cloud types showed decreasing trends for stratiform clouds and increasing trends for Cumulonimbus since 1961 in Eastern Romania [31]. Similar observations were reported also from central Poland for the period from 1951 to 2000 [32]. Thus the observed lack of coherence in the interannual variability among the three east Central European hydroclimate records over the past ~50 years is in line with the late-20th century regional cloud-type changes.

An exceptionally long and homogenous nephological record on cloud types is available from Cracow, southern Poland [33]. This record similarly points to a pronounced decline in stratiform clouds over the second half of the 20th century accompanied with an increase in the convective clouds. However, the Cracow nephological record allows an extension for a detailed comparison. The characteristic drop in stratiform cloud observations before 1920 matches fairly well with the lack of coherence period in the interannual variability and the periods of coherence corresponds to higher frequency in stratiform cloud observations in southern Poland (Fig. 3). This interaction might partially explain the weak spatial correlation of the hydroclimate records in the region [17] and also for a boarder Central Europe [10].

On the contrary, a complementary relation can be observed between the two wavelet coherence plots over the lower frequencies. When an in-phase coherency detected between BAL and BUD no any coherence could be seen with BAK and vice versa. This suggests that the hydroclimatic variability may be under different control at the multiannual/decadal scales.

4 Conclusions

Using wavelet analysis, we have found that the dominant low-frequency variations in the latewood width time series of pedunculate oak and ringwidth time series of sessile oak in Hungary occur at the 2–4 years timescales. These interannual variations are intermittent and may be correlated with the regional hydroclimatic variability over different time intervals with changing phase. The periods of coherent and in-phase variability of precipitation have not been reported earlier from this region. Increased (decreased) proportion of frontal precipitation offers a plausible explanation for enhanced (faded) coherence at the interannual timescale in large scale hydroclimate signal. These results emphasize the great potential of proxy climate data, owing to their longer span, to contribute novel information impossible to retrieve otherwise from shorter instrumental observation records. These findings, however, not only corroborate the earlier assertion that neither the strength nor the rank of similarity of the local hydroclimate signals is stable throughout the past centuries in east Central Europe but also contribute to the explanation of the more localized information of the hydroclimate proxy records in the region.

Acknowledgement: This research was supported by the “Lendület” program of the Hungarian Academy of Sciences (LP2012-27/2012). This is contribution No.28 of 2 ka Palæoclimatology Research Group.

References

[1] Fritts H.C., Tree Rings and Climate. Academic Press, London, 1976

[2] Čufar K, De Luis M, Eckstein D, Kajfez-Bogataj L, Reconstructing dry and wet summers in SE Slovenia from oak tree-ring series. Int. J. Biomet., 2008, 52, 607–615

[3] Haneca K, Čufar K, Beeckman H, Oaks, tree rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. J. Archaeol. Sci., 2009, 36, 1–11

[4] Akkemik U, Dagdeviren N, Aras A., A preliminary reconstruction (A.D. 1635–2000) of spring precipitation using oak tree rings in the western Black Sea region of Turkey. Int. J. Biomet., 2005, 49, 297–302

[5] Griggs CB, DeGaetano AT, Kuniholm PI, Newton MW., A regional high-frequency reconstruction of May-June precipitation in the north Aegean from oak tree-rings, A.D. 1089–1989. Int. J. Climatol., 2007, 27, 1075–1089

[6] Helama S, Läänelaid A, Raisio J, Tuomenvirta H., Oak decline in Helsinki portrayed by tree-rings, climate and soil data. Plant Soil, 2009, 319, 163–174

[7] Sohar K, Läänelaid, A, Eckstein, D, Helama, S, Jaagus J., Dendroclimatic signals of pedunculate oak (*Quercus robur* L.) in Estonia. Eur. J. Forest. Res., 2014, 133(3), 535–549

[8] Sohar K, Helama S, Läänelaid, A, Raisio, J, Tuomenvirta H., Oak decline in a southern Finnish forest as affected by a drought sequence. Geochronometria, 2014, 41(1), 92–103

[9] Nechita C, Popa I., The relationship between climate and radial growth for the oak (*Quercus robur* L.) in the western plain of Romania. Carpathian J. Earth Environ. Sci., 2012, 7, 137–144

[10] Büntgen U, Franke J, Frank D, Wilson R, Gonzales-Rouco F, Esper J., Assessing the spatial signature of European climate reconstructions. Clim. Res., 2010, 41, 125–136

[11] Pálfai I, Herceg Á., Droughtness of Hungary and Balkan Peninsula. Riscuri si Catastrofe, 2011, 9(2), 145–154

[12] Gosic M, Trajkovic S., Analysis of precipitation and drought data in Serbia over the period 1980–2010. J. Hydrol., 2013, 494, 32–42

[13] Vari A, Linnerooth-Bayer J, Ferencz Z., Stakeholder views on flood risk management in Hungary's Upper Tisza Basin. Risk Analysis, 2003, 23(3), 585–600

[14] Rácz RM., Outline of floods as well as flood prevention and flood protection activities in Hungary. AARMS, 2011, 10, 123–129

[15] Bartholy J, Pongrácz R, Hollósi B., Analysis of projected drought hazards for Hungary. Adv. Geosci., 2013, 35, 61–66

[16] Blanka V, Mezősi G, Meyer B., Projected changes in the drought hazard in Hungary due to climate change. Időjárás, 2013, 117(2), 219–237

[17] Kern Z, Patkó M, Kázmér M, Fekete J, Kele S, Pályi Z., Multiple tree-ring proxies (earlywood width, latewood width and δ^{13}C) from pedunculate oak (*Quercus robur* L.), Hungary. Quat. Int., 2013, 29, 257–267

[18] Kern Z, Grynaeus A, Morgós A., Reconstructed precipitation for Southern Bakony Mountains (Transdanubia, Hungary) back to AD 1746 based on ring widths of oak trees. Időjárás, 2009, 113, 299–314

[19] Auer I, Böhm R, Jurkovic A, Lipa W, Orlik A, Potzmann R *et al.*, HISTALP – Historical instrumental climatological surface time series of the greater Alpine region: 1760–2003. Int. J. Climatol., 2007, 27, 17–46

[20] Addison PS., The Illustrated Wavelet Transform handbook. Institute of Physics Publishing, Philadelphia, 2002

[21] Kumar P, Foufoula-Georgiou E., Wavelet analysis for geophysical applications. Rev. Geophys., 1997, 35, 385–412

[22] Torrence C, Compo GP., A practical guide to wavelet analysis. Bull. Amer. Meteorol. Soc., 1998, 79, 61–78

[23] Sen AK., Spectral-temporal characterization of riverflow variability in England and Wales for the period 1865–2002. Hydrol. Proc., 2009, 23, 1147–1157

[24] Sen AK, Fang K., Multiscale variability and atmospheric teleconnections of the precipitation time series reconstructed from tree ring records in the Xiaolong Mountain, central China. J. Coupled Syst. Multiscale Dyn., 2014, 2, 9–14

[25] Sen AK, Ogrin D., Analysis of monthly, winter, and annual temperatures in Zagreb, Croatia, from 1864 to 2010: The 7.7-year cycle and the North Atlantic Oscillation. Theor. Appl. Clim., 2016, 123, 733-739, doi: 10.1007/s00704-015-1388-z

[26] Grinsted A, Moore JC, Jevrejeva S., Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlin. Proc. Geophys., 2004, 11, 561–566

[27] Torrence, C., Webster, P.J., Interdecadal changes in the ENSO–Monsoon System. Journal of Climate, 1999. 12, 2679–2690

[28] Higuchi, K., Huang, J., Shabbar, A., A wavelet characterization of the North Atlantic oscillation variation and its relationship to the North Atlantic sea surface temperature. Int. J. Climatol., 1999, 19(10), 1119–1129

[29] Brázdil R, Ŝamaj F, Valoviĉ Ŝ., Variation of spatial annual precipitation sums in Central Europe in the period 1881–1980. Int. J. Climatol., 1985, 5, 617–631

[30] Büntgen U, Brázdil R, Frank DC, Esper J., Three centuries of Slovakian drought dynamics. Clim. Dyn., 2010, 35, 315–329

[31] Manea A, Birsan MV, Tudorache G, Cărbunaru F. Changes in the type of precipitation and associated cloud types in Eastern Romania (1961–2008). Atmospheric Research. 2016, 169, 357–65

[32] Wibig J. Cloudiness variations in Łódź in the second half of the 20th century. Int. J. Climatol., 2008, 28, 479–491

[33] Matuszko D. Cloudiness changes in Cracow in the 20th century. Int. J. Climatol., 2003, 23, 975–984