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Natural proxy records of temperature- and hydroclimate variability with annual resolution from the Northern Balkan-Carpathian region for the past millennium - review & recalibration

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Abstract

A systematic compilation of temperature (n=10) and moisture sensitive (n=4) proxy records of the Northern Balkan-Carpathian (NBC) region with annual resolution for the past millennium is presented and evaluated. The proxy-climate relationship is re-evaluated using a uniform climatological dataset which, as an additional benefit, provides a longer calibration. The originally determined response seasons were in the most part verified. Spectral constraints were established by combining wavelet coherence analysis and band filtering, thus, the signal-to-noise ratio was successfully improved in certain cases, either by separating the temperature/moisture sensitive frequencies in complex signals, and/or by extracting "focus" bands. In the case of winter temperature, the earliest available dates in the natural proxy records were 1774AD, for spring and summer they were 1732AD and 1040AD respectively, while for hydroclimate this date was 1497AD. Although only one record was available for winter, it showed a pronounced similarity to winter temperature reconstructions from adjacent areas outside the NBC. Spring thermal proxies were comprised of grape-vine phenology data from the Western NBC margin, these being in quite good agreement with each other, for instance, in the case of the characteristic mutual decadal pattern the mild springs of the 1750s. In addition, a common long-term cooling trend was observed, starting in the mid-18th century and ending at the turn of the 20th century. The comparison of summer temperature records indicated that proxies of the same origin/source tend to show a stronger mutual variation than those located close to each other, but of different types. This serves as a warning in the interpretation of climate field reconstructions from multiproxy networks.

The studied summer proxies also show a remarkably strong linear relationship with nearby records outside the NBC, weakening as their distance increases. The two most persistent multi-decadal cold summer periods (~1780~1840 & 1430~1500AD) were decisively mirrored in the proxies. The longest and most recent reconstruction from the North Slovakian Tatras shows a unique warming (after ~1900AD) reflected neither within, nor outside the NBC, casting doubt on its reliability. In general, weaker coherence was observed between the hydroclimate proxies, drawing attention to a general phenomenon: the range of the degree to which hydroclimate proxies are spatially representative is usually smaller. Therefore, their network should be further developed. One of a few shared regional summer drought periods occurred in the 1750s, being most pronounced in the Central and Southeastern NBC. Moreover, this was reflected in the neighboring South Moravian drought history, too. These results will hopefully serve as a stepping-stone for future research on spatiotemporal patterns of climate changes and their causes in the NBC region.

Keywords: climate proxy; moisture & temperature records; spectral signal enhancement; spring; summer; winter

1. Introduction

In climate research, the regional approach to climate variability and change is becoming an increasingly important topic. An accurate understanding of the past one or two thousand years of Earth's climate history is critical in placing recent changes in the context of natural climate variability (PAGES_2k_Consortium, 2013).

The need for a better understanding of these phenomena is driven by the fact that local and regional climate variability (amplitudes and rates) (i) is much higher than variability on the global scale, and (ii) affects natural/managed environments and ecosystems services rather than global climate variability.

Besides large-scale climate reconstruction efforts focused on the last one to two thousand years (Moberg et al., 2005; Ljungqvist, 2010; Christiansen and Ljungqvist, 2012; PAGES_2k_Consortium, 2013), regional multiproxy compilations have also been prepared (Neukom et al., 2009; Klimenko and Solomina, 2010; Przybylak et al., 2010; Neukom et al., 2011; Trachsel et al., 2012; Tingley and Huybers, 2013; Trouet et al., 2013; Klimenko et al., 2014; McKay and Kaufman, 2014; Shi et al., 2015). Although Europe, on a global scale, has the greatest wealth of high-quality information for paleoclimate variability, the Northern Balkan-Carpathian (NBC) area is a region relatively poor in data in comparison to the rest of the continent. By gathering related studies of non-documentary climate evidence, the contours of a new database could be outlined, filling the niche in paleoclimate research of the NBC.

On an international level this work corresponds to the goals of the PAGES 2k initiative (Newman et al., 2009;Kaufman, 2014) in that it provides for the first time an improved and quality-checked long, high-resolution, sub-continental, temperature and hydroclimate proxy data collection for the studied region. This data can thus serve as a benchmark by which to measure the ability of regional climate models to reproduce past variability (Renssen and Osborn, 2003) and thereby evaluate the degree of uncertainty in future predictions. As an initial step, 10 temperature- and 4 moisture sensitive proxy reconstructions published for the NBC region during the past decade were assessed with the following aims:

(i) to provide a comprehensive literature collection of temperature- and moisture sensitive natural proxy records covering a significant part of the past 1000 years, with annual resolution guaranteed.

(ii) to recalibrate these records using the longest uniformly available climatological target variable at each site and proxy, and compare the results with the original calibrations.

In addition, an earlier European-scale climate field reconstruction (CFR) for the past 500 years covering all or part of the NBC area (Luterbacher et al., 2004; Pauling et al., 2006), included a single documentary derived historical climatological index series (Rácz, 1999) integrating documentary evidence for a very large area. Hence, representing the whole NBC region solely with this 'bulk' series may render it impossible for us to see the potential sub-regional differences. Furthermore, the reconstructions are biased towards the regional mean climate, as illustrated for instance, by the comparison-maps of a very recent European drought reconstruction (Cook et al.,2015). Besides the updated dataset, an exigent selection criterion, the re-evaluation/re-calibration attempt, and the special attention paid to the potential proxy-specific and sub-regional differences make this work different from previous review papers, e.g. Bartholy et al. (2004); Vadas and Rácz (2010, 2013). It should be noted here that the derivation of any new numerical reconstruction or CFR is still beyond the scope of the study, mostly because the currently available proxy network is very sparse.

Nevertheless, the major goals of the study are (i) to obtain a comprehensive picture of the proxies already at hand from the NBC before utilizing them in large scale CFRs, (ii) to evaluate the potential (dis)agreement of the climate histories represented by the proxy records in different parts of the NBC, and (iii) to indicate the most critical areas where there is a strong need to develop new reliable proxy data.

2. Materials and Methods

The climate of most of the NBC can be categorized as continental with warm summers (Köppen code: Cfb). The continentality increases eastwards, while Mediterranean characteristics appear in the southern/southwestern sector. A boreal climate with warm summers (Dfb) prevails over the larger part of the Carpathian mountain belt and its cool summer variant (Dfc) characterizes smaller parts of the northern and eastern ranges (Fig 1. Kottek et al., 2006), while a tundra climate (Köppen code: ET) is also found, though restricted to the regions of the highest peaks.

The frost period (T_{month}<0°C) is in general one to three months long. It would appear that the SE areas are the only ones where the average temperatures do not, or only slightly fall below zero (Fig. 1 G).

The rainiest period is May-June over most of the studied region (Fig. 1. A-F), while a slightly earlier rainfall peak is observed the SE sector (Fig.1. G, H). A second, minor, rainfall peak occurs around November.

Arid conditions usually prevail in late summer over the lowlands (Fig.1. B, G), especially where hot summers (Cfa) are accompanied by a relatively lower total precipitation.

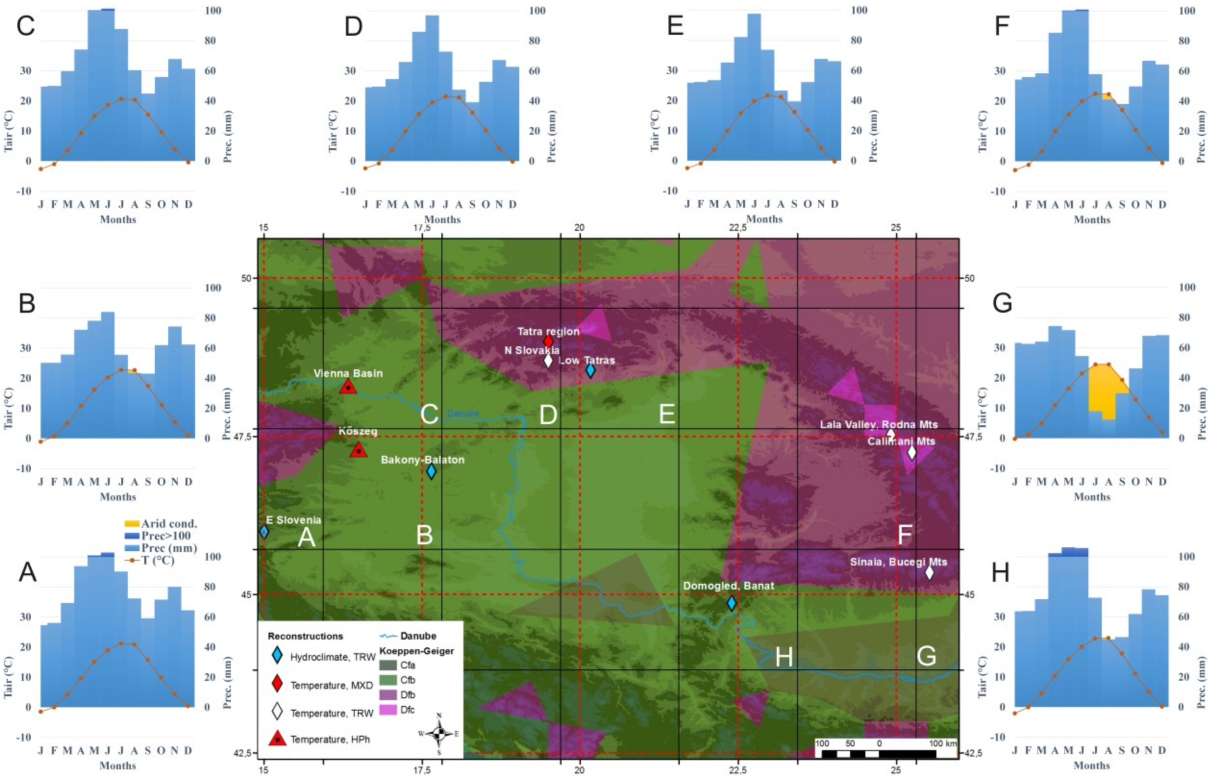


Fig. 1. Spatial distribution of the annual proxy paleoclimate records from the NBC covering significant part of the past millennium and the climate of the region. MXD: maximum latewood density, TRW: tree ring width, HPh: historical phenology. Grids of the CR20 reanalysis field (temperature, precipitation; 1851-2010; 2°x2° grid) marked with a black line and the self-calibrated Palmer Drought Severity Index (1850-2010; 2.5°x2.5° grid) a dashed red line. The Köppen-Geiger climate zones (based on Kottek et al., 2006) are shaded on the map. Diagrams around the map show the monthly mean temperature (orange curve) and precipitation totals (blue bars) of the CR20 grids with the proxy sites. Capital letters at the bottom left corner of the CR20 grid overlaying the map indicate the correspondence.

2.1. Proxy dataset acquired

In every case, the chosen records had to meet the following criteria:

(i) they had to be from the region encompassed by 44.5-50°N and 15-26.5°E;

(ii) evidence had to be present that the record is sensitive to a climate parameter. This evidence may be statistical (e.g., correlation with a nearby instrumental record), or mechanistic (e.g., description by the authors of mechanisms by which the archive senses temperature change);

(iii) they had to reach back in time to before the beginning of continuous instrumental meteorological observations in the region, as benchmarked by 1775 AD for temperature (Vienna) and 1841 AD for precipitation (Budapest and Vienna); and

(iv) they had to have an annual resolution.

Original proxy data were acquired from public data repositories or from the authors of the original studies. For the detailed basic information see Table 1 and Fig. 1, while a brief description of each kind of proxy data, with special emphasis on the climate sensitivity (parameter and season) is provided in the Supplementary Content.

2.2. Climate data

According to the aims determined, the second step was to acquire the monthly climate data: air temperature at 2 m (°K); precipitation rate at surface ($\mathrm{kg\,m^{-2}\,s^{-1}}$) for the corresponding grid cells from the NOAA-CIRES 20th Century Reanalysis V2c project (CR20), covering 1851-2010 (Compo et al., 2011) and self-calibrated Palmer Drought Severity Index (scPDSI) with potential evaporation estimated by the Penman-Monteith method, dating back to 1850/51 (Dai, 2011a, b). In special cases where a significant part of the late 20th century was missing from the proxy record, thus biasing the recalibration exercise (Table 1), the nearest continuous and homogenized monthly air temperature series reaching back to the late 18th century (Vienna/ Hohe Warte or Budapest) (Böhm et al., 2010) was used to increase the performance of the recalibration in time.

2.3. Proxy climate correlation

After acquiring the necessary data, the proxy time series were correlated with the monthly climate data of the corresponding grid cells (Fig. 1) using product-moment correlation (Pearson, 1896). In special cases, additional comparisons were made with the nearest continuous and longest-available temperature records from Vienna or Budapest. As a next step, the months were chosen for which the climate data should be aggregated and correlated again, if necessary, with the proxy time series. The consecutive multi-monthly averages were computed in different combinations to find the season with maximum response.

2.4. Spectro-temporal coherence screening

As an additional tool, *wavelet transform coherence analysis* (WTC; Torrence and Compo, 1998; Liu et al., 2007; Veleda et al., 2012) was performed to find possible (un)even distributions of climate response in the time-frequency domain. WTC can reveal intermittent correlations, especially where coherence is high, but the power is minimal (Ng and Chan, 2012) and further enhance proxy / climate relationship investigations with the hope of being able to separate the climatic signals based on the frequency scale.

Wavelet transformation (WT) - providing the basis for WTC - could be defined as the convolution of the data and the wavelet function (Kovács et al., 2010). It is a function with a zero mean and which is localized in both frequency and time (Grinsted et al., 2004), with its adaptability based on the scaling method. The Morlet mother wavelet (Morlet et al., 1982) provided the source function to generate daughter wavelets, by scaling and transforming it (Kovács et al., 2010). The purpose of the wavelet transformation is multiple dissociation by decomposing the data in the scaling space. In this way, it is possible to reveal its self-similarity structure (Hatvani, 2014).

Table 1. Compilation of temperature and hydroclimate sensitive natural proxies with annual resolution from the Northern Balkan-Carpathian region (status as of July 1, 2015) and the recalibration results. MXD stands for maximum latewood density, TRW for tree ring width, HPh for historical phenology. Asterisk(*) indicates the recalibration test being not independent from the original study.

					Original study		**Recalibration**	
	Site	**Lat-Lon**	**Proxy**	**Period**	**Season**	**Reference**		**Season**
Temperature	Calimani Mts	47.25-25.25	TRW	1160-1964	(Jun)Jul-Aug	Popa and Kern, 2009	Temperature	(Jun)-Jul
	Kőszeg	47.3-16.5	Documentary phenology	1618-1874	May-Jul	Kiss et al., 2011		May-Jul
			HPh sprout length	1740-1998	½×Mar+Apr	Střeštikand Verő, 2000		Mar-Apr
	Lala Valley, Rodna Mts	47.53-24.92	TRW	1460-2005	Jun-Aug	Popa and Bouriaud, 2014		(Jun)-Jul
	Sinaia, Bucegi Mts	45.35-25.53	TRW	1774-2001	Nov-Jan	Popa and Cheval, 2007		Nov-Mar
	N Slovakia	48.7-19.5	TRW	1040-2011	May-Jun	Büntgen et al., 2013		May-Jun
	Tatra region	49-19.5	MXD	1709-2004	Apr-Sep	Büntgen et al., 2007		Apr-Oct
			TRW	1661-2004	Jun-Jul			Jun-Jul
	Vienna Basin	48.3-16.33	HPh vine flowering date	1732-1878	Apr-May	Maurer et al., 2009		Apr-May
			HPh grape harvest date	1523-1879	May-July			May-Jul*
Hydro-climate	Bakony-Balaton	46.95-17.65	TRW	1746-2003	Aug-Jul	Kern et al., 2009	PDSI	May-Aug
	Domogled, Banat	44.87-22.4	TRW	1688-2010	Jun-Aug	Levanič et al., 2013		Jul-Aug
	E Slovenia	46-15	TRW	1497-2003	Jun	Čufar et al., 2008		Jun
	Low Tatras	48.55-20.17	TRW	1744-2006	May-Sep	Büntgen et al., 2010		Apr-Jul

From the WT the WTC can be determined. This latter provides a clear picture of how coherent the cross wavelet transform (the areas with common power of the two variables) is in the time-frequency space (Torrence and Webster, 1999).

A close resemblance can be observed between the WTC and the traditional correlation coefficient. Thus, the WTC can be interpreted as the localized squared correlation coefficient in the time-scale plane (Grinsted et al., 2004). Therefore it is to be expected that the WTC power spectral density (PSD) graphs (e.g. Fig. 2) will indicate a mature period mostly in the lower period domains in the case of highly correlating time series (Galiana-Merino et al., 2014; Ng and Chan, 2012). However, this is not always true the other way around. If the WTC indicates a strong common periodic behavior, it does not mean that those two particular time series should correlate as well to the same degree, meaning that not only linear relationships lie behind the common periodic behavior.

The statistical significance of the wavelet coherence against a red noise background was estimated using Monte Carlo methods (Grinsted et al., 2004). It should be noted here that WTC produces edge artifacts, since the wavelet is not completely localized in time, thus the introduction of a cone of influence (COI) is suggested in which edge effects cannot be ignored (Torrence and Compo, 1998).

During the evaluation only those positive signals were considered which were significant (α=0.95), and where the "phase information" was in harmony with the sign of the correlation. Moreover, if the PSD graphs indicated a clear lack of coherence over the whole time-period both the proxy- and the climate data were frequency filtered to enhance their relationship. Finally, it should be noted that the WTC graphs were also applicable in evaluating how stable the climate signal over time in a certain frequency domain is.

2.5. Software used

`R` statistical environment (R_Core_Team, 2008) was used to conduct the calculations. Specifically, the correlations were obtained with a script written by the authors, the WTCs were generated with the `wtc` function of the `biwavelet` package (Gouhier, 2015), the frequency filtering was done using the `astrochron` package (Meyers, 2014) and the running correlations with the `gtools` package (Warnes et al., 2015). Maps were drawn using ArcGIS 10.2 software.

3. Results

Tree ring derived reconstructions dominate the database (10 out of 14) completed by the four phenology records (Table 1and Fig. 1). Average (maximum) length of the temperature sensitive annually resolved proxy records from the NBC was avg.420 (max = 971) years, while hydroclimate records are available for a much shorter timescale: avg.337 years and max 506 years. These pure statistics indicate that hydroclimate proxy data with annual resolution is technically unavailable for the last full millennium in the NBC.

In six of the fourteen cases, the original calibrations were perfectly verified using the introduced homogeneous climatic dataset, while in all the other cases the response seasons mostly overlapped with the primary studies. In four of the cases, the difference between the response seasons of the original- and the re-calibrations was only one month.

In almost all recalibrations a longer temporal window was available than in the original calibrations. There were only two exceptions, the Kőszeg sprout length (Section 3.1.2.1) and the Vienna Basin grape phenology proxies (Section 3.1.5). However, in the case of the Kőszeg record, the original study's calibration accuracy is questionable due to certain data preparation steps (for details see Supplementary Content), while in the case of the Vienna Basin record, the CR20 data might help to fine-tune climate response. It should be noted that, thanks to the long span of the recalibration (for details see Section 2.2), all the correlations considered as a final result were significant at $p<0.01$.

Regarding temporal stability, the reader is referred to the Supplementary Content, where each WTC graph was evaluated in the focus frequency domain of the particular proxy.

3.1. Temperature proxies

3.1.1. Mts Calimani and Mts Rodna, Swiss stone pine tree-ring width

Because both proxies from Mts Calimani and the Mts Rodna (CM andLL respectively) are derived from the same tree species (Popa and Bouriaud, 2014; Popa and Kern, 2009), and located in the same grid cell, they were hence calibrated to the same meteorological reference parameters. Therefore, it was to be expected that both would give the same climatic sensitivity and response, so they were handled together. In addition, this would function as an extra and independent verification of the two proxies.

In the case of both the CM & LL proxies, the correlation analysis with the temperature series (1851-1964 - CM& 1851-2005 - LL) indicated a maximum response for July and gave weaker correlations ($r_{CM}=0.11$; $r_{LL}=0.25$) than reported in the original study using a closer climate reference ($r_{CM}=0.39$; $r_{LL}=0.43$). This response with July temperature was located in the middle of the original calibration period (Tab. 1), thus in the first round the present study partially verifies the original one. However, by assessing the linear relationship between the proxy time series and a more than 100 years longer climate series, the Budapest temperature record, the maximum response was found to be in June-July with higher correlations – especially in the case of the CM ($r_{CM}=0.25$; $r_{LL}=0.26$), which is in good part overlaps the original calibrations, thereby confirming them. Despite the relatively low correlation coefficients they are physiologically meaningful, since the Alpine timberline is a well-known habitat in which growth is temperature-limited (e.g. Tranquillini, 1979; Weiser and Tausz, 2007).

WTC maps indicated a very weak coherence in the high frequency domains for CM (Fig. 2a) and LL (Fig. 2b) as well.

Thus, by separating the frequency domains into those above and below a 3-year period, correlations for the domain >3year period further increased to $r=0.33$ and $r=0.3$ for CM and LL respectively, while for the discarded domain (<3years) obviously decreased ($r=-0.1$ & $r=0.08$ for CM & LL respectively). This observation is in accordance with the findings from the Alpine TRW network where *Pinus cembra* was found to preserve the climatic signal better in the lower frequency domains (Frank and Esper, 2005).

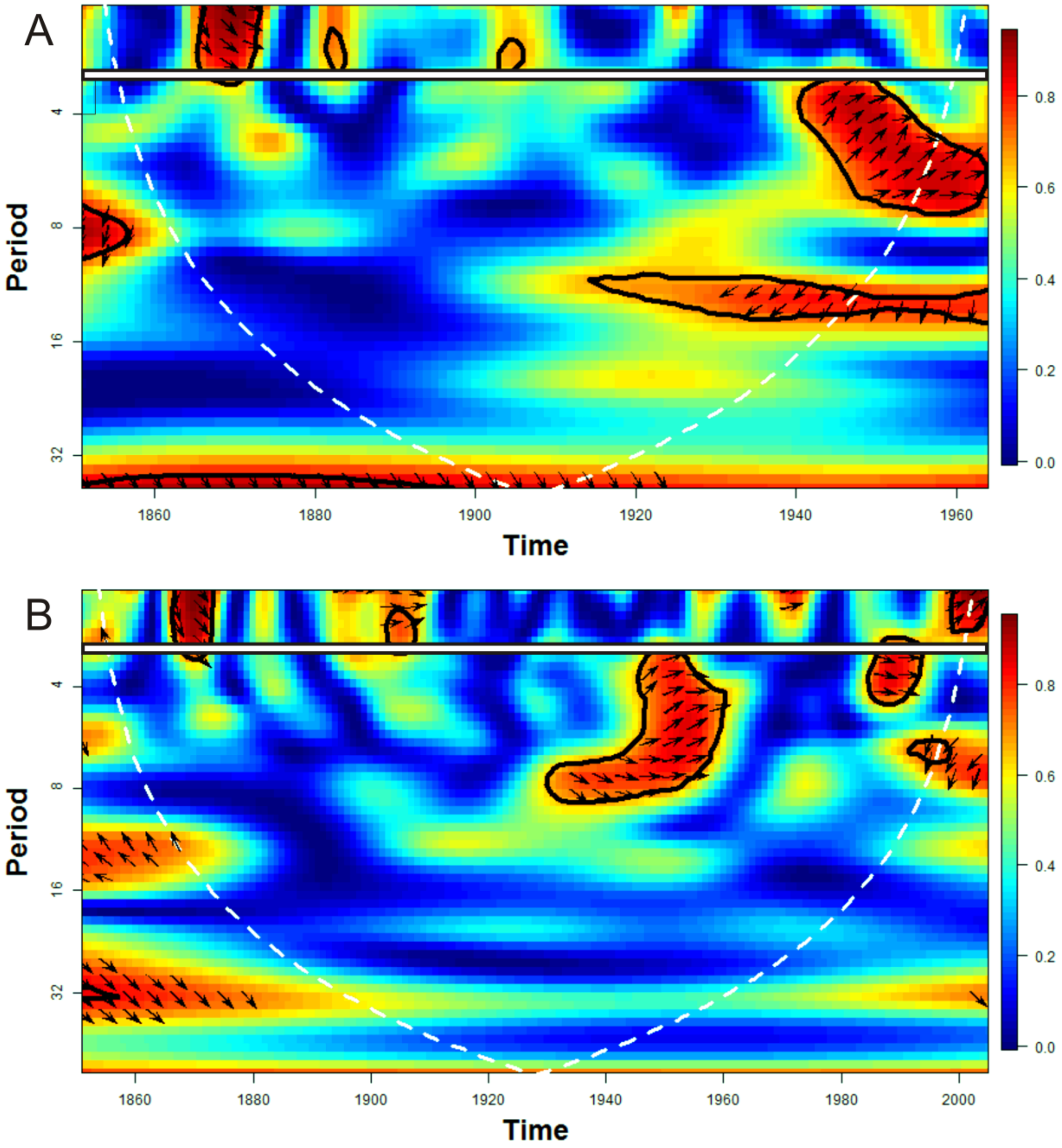


Fig. 2. WTC of the CM (1851-1964) A) & LL (1851-2005) B) and the gridded July temperatures. The 5% significance level against red noise is shown as a thick black contour. The relative phase relationships are shown as arrows (with 'in-phase' pointing right, 'anti-phase' pointing left, and where the arrow is pointing straight up, the climate led the proxy by a quarter of the corresponding period). The areas outside the white dashed line mark the COI. The white horizontal line indicates the approximated period of separation.

3.1.2. Kőszeg

3.1.2.1. Vinesprout length

With recalibration, using the March-April average Vienna temperature records (1775-1906), the original calibrations were verified(r=0.57). However numerous differences should be underlined between the present and the original study. It has been known that a breakpoint may exist in the data due to the change in grape species cultivated around the turn of the 20thcentury. The traditional species of that time died out quite fast because of a *Viteus vitifoliae* infection, so new grape species had to be planted. Thus, in the original study, the 20th century variance bias was arbitrarily corrected by multiplying the data by two and three. In the present study however, the anticipated change in the related proxy records was objectively determined at 1906/1907 by the application of a break-point analysis (for details see Supplementary Content), and the data after 1906 was discarded. For these reasons the interval was shorter than in the original study (Střeštik and Verő, 2000).

It should be noted that the recalibration with the gridded temperature series gave the same temperature response (March-April; r=0.39), despite the temporal coverage being much shorter (1851-1906), therefore the latter was chosen as the final result.

3.1.2.2. Historical vine-grain phenology

Vienna Hohe Warte temperature records (1775-1874) have been used in the current recalibration trial as the calibration target, offering a 5 year longer overlap at a closer location compared to the more distant Budapest station (1780-1873) used in the original study. May-July average temperature sensitivity, was in fine accordance with the original calibrations (Kiss et al. 2011), and was verified at r=0.67, with slightly weaker correlations though with a somewhat longer dataset.

It is important to state that the gridded temperature records in this case gave a different response season than the original study (July-September; r=0.63), but this was presumed to be the result of the extremely short temporal overlap between the climate and the proxy records (1851-1874). Thus, the Vienna temperature was chosen as the final result.

3.1.3. Sinaia, Silver fir tree-ring width

The recalibration using the November-March average temperature records (1852-2001; r=0.37) reaching 90 years further back in time than the original calibration, mostly verified those, although with a weaker response. The main difference between the two was that in the recalibration the response season was two months longer, reaching as far as March, instead of ending in January. However, both suggest that the main response registered in the proxy is winter-early spring temperature. The strongest correlation being with a dormant season climate parameter may be unusual for a tree-ring proxy, however, since (i) Popa and Cheval (2007) in the original study also found response to winter temperatures using a different instrumental target; (ii) a recent comprehensive dendroecological study of the species reported that growth of silver fir forests in non-Mediterranean areas is limited by cold conditions in late winter to early spring (Gazol et al., 2015), and (iii) additional recent independent local scale analyses of silver fir stands from the S Carpathians have also observed the same phenomena (Holobâcă et al., 2014; Holobâcă et al., 2015), the results were accepted.

WTC indicated a strong in-phase coherence between the proxy and the climatic variable only within the 16-year period. Outside of it, only anti-phase coherence exists (Fig. 3). This feature contradicts the positive sign of correlation (for details see Section 2.3).

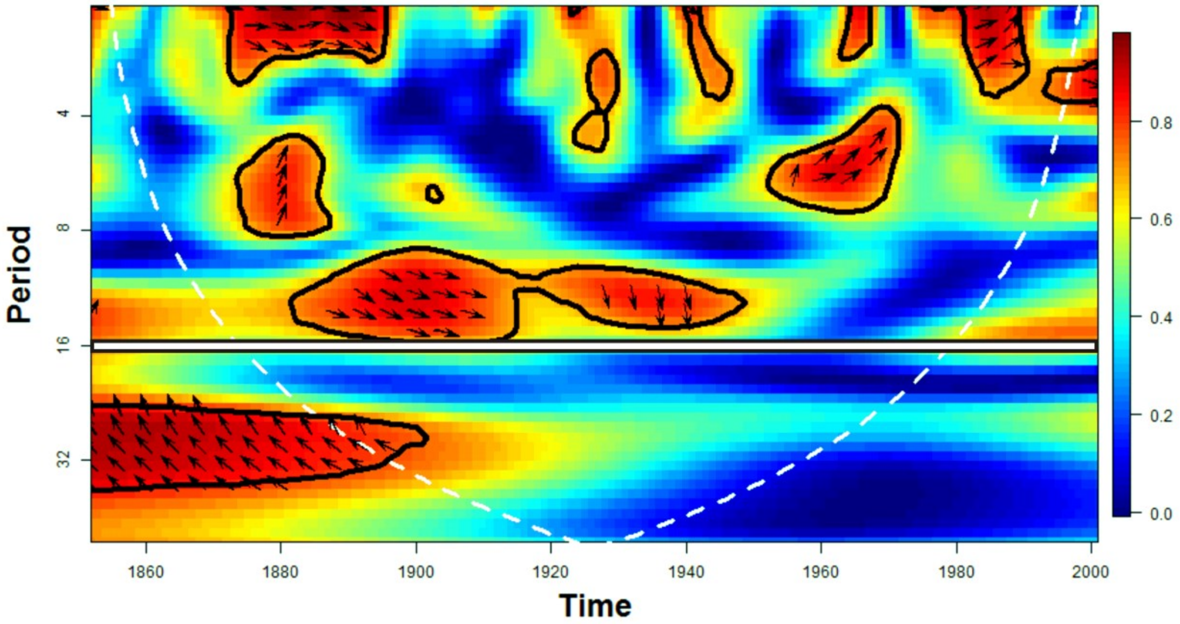


Fig. 3. WTC of the Sinaia silver fir TRW and the November-March average CR20 temperature time series (1851-2001). Further interpretation of graphical elements can be found in the caption to Fig. 2.

Thus, the frequency domain above the 16-year period was discarded, in which the proxy and the gridded temperature did not show any linear relationship (r=-0.07), while in the domain under the 16-year period it increased to r=0.4.

3.1.4. N Slovakia, larch tree-ring width

Reassessing the N-Slovakian TRW calibration it was found that the May-June average temperature indeed possesses the strongest response signal, even on a time scale reaching about 50years further back, to 1851 (Table 1), than the original calibration (1901-2009). This longer time coverage and broader spatial coverage from the climate data side may be the reason behind the weaker response in the target season (r=0.28) than in the original paper (Büntgen et al., 2014).

3.1.5. Tatras (Poland-Slovakia border region) Norway spruce-dwarf pine composite tree-ring width and larch latewood maximum density

The recalibration of the TRW and MXD proxies from the PL-SK border region mostly verified the original calibrations. For TRW, the response with June-July average temperature was confirmed with a ~50years longer dataset, however, with a weaker linear relationship (r=0.44) between the proxy and the climate variable. In the case of the MXD, however, the correlation (r=0.6) was of the same magnitude as that in the original study (Büntgen et al., 2007), but the response season was extended by one month, reaching into early fall (April-October average gridded temperature).

3.1.6. Vienna Basin

3.1.6.1. Vine flowering date (VFD)

With recalibration, using the April-May average Vienna Hohe Warte temperature records (1775-1878) the original calibrations were verified (r=-0.72), giving a slightly stronger correlation than the original study.

In the analysis the correlation with the gridded temperature records already positioned the maximum response season at April-May (r=-0.74), but the overlapping time period between the proxy and the climate data was only ~30years, thus the closest longest homogenized temperature records were used to obtain a more robust result.

3.1.6.2. Grape harvest date

In the present study independent verification of the GHD recalibration was limited, since the same proxy, same climate variables and the same time spans were used as in the original one (Table 1) (Maurer et al., 2009). Therefore, it was not surprising that the original calibration of May-July average air temperature was verified (r=-0.77).

It should be mentioned, however, with the CR20 time series, the May-September averages gave the strongest response (r=-0.47). Unfortunately, again, because of the short overlapping time interval (only ~30years) the correlations with the Vienna temperature had to be accepted as the final result. It should be noted here that a similar proxy from the region (Kiss et al., 2011) indicated the May-July average temperatures as the main response (Section 3.1.2.2) as well.

3.2. Hydroclimate proxies

3.2.1. Bakony-Balaton, oak tree-ring width

The recalibration of the Bakony-Balaton TRW proxy indicated May-August average scPDSI as the climate variable with the most significant response (r=0.45) for about a dataset about 50-years longer (1850-2003) than the original calibration, indicating the previous August-July average precipitation (r=0.65) (Kern et al., 2009) as the response season.

In the original study, stacked precipitation records of four local rain gauges gave a stronger response than found in the present study with the gridded scPDSI; probably indicating a strong local signal for the proxy. However, in the absence of ~150 year long local PDSI/drought indices, it is difficult to test whether it would give an even more pronounced local response or not.

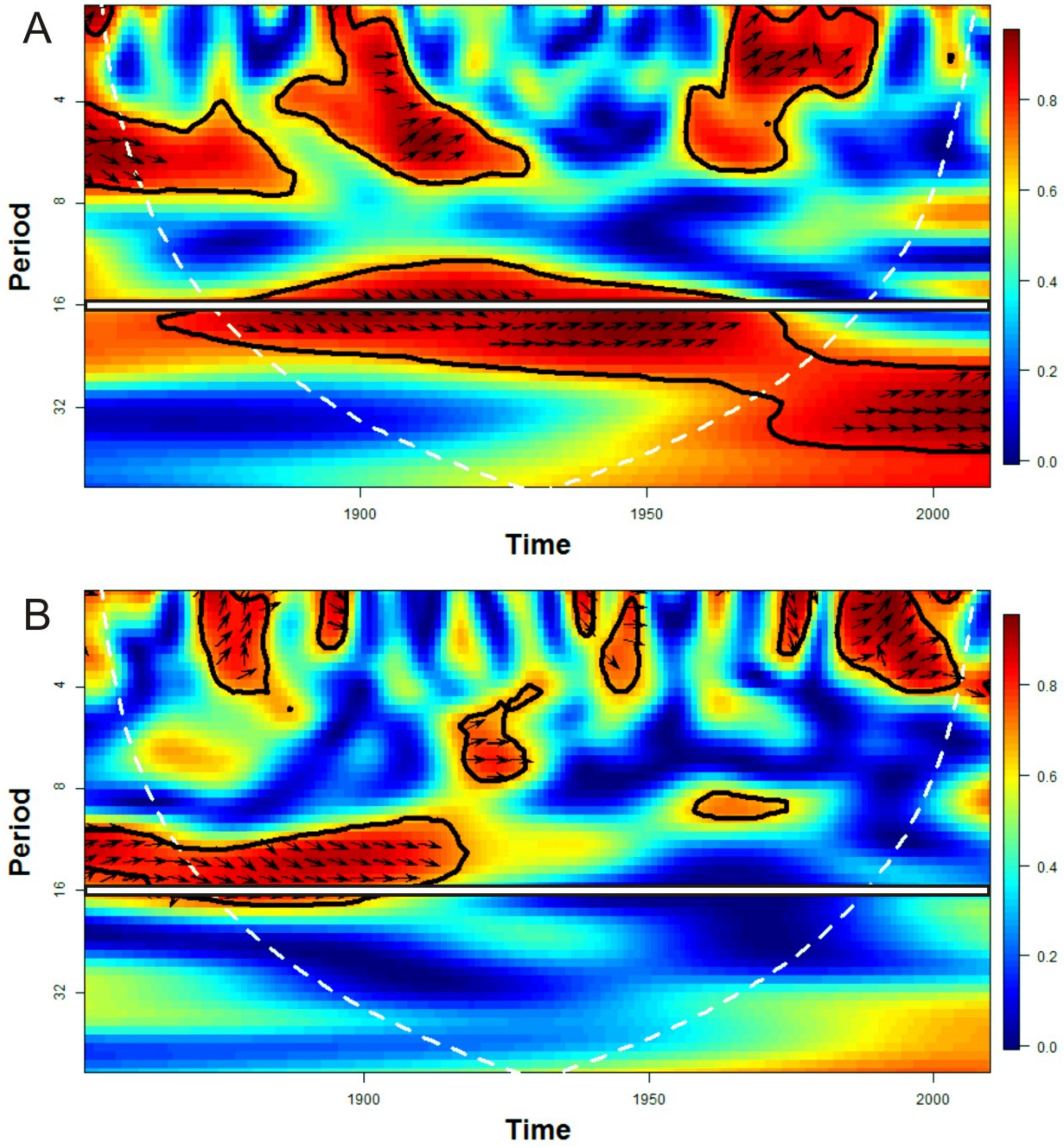


Fig. 4. WTC of the Domogled pine TRW and the July-August average scPDSI series (1852-2010) A) and the February-April average CR20 temperature time series (1851-2010) B). Further interpretation of graphical elements can be seen in the caption of Fig. 2.

3.2.2. Domogled, Black pine tree-ring width

Slight differences between the original- and the recalibrated growth-climate relation were observed. Here, instead of placing the maximum response signal in June-August (Levanič et al., 2013), the ~50 year longer recalibration found that the Domogled TRW is a drought proxy with a response to the average July-August scPDSI (1852-2010; r=0.51).

Based on the correlation analysis a complex climatic signal was outlined, with spring temperature having a positive (February-April; r=0.32), and summer drought having a negative (July-August; r=0.42) effect on pine growth. This growth-climate relationship in this southern location of the NBC fits fairly well with the key findings of the recent study on the climate sensitivity of the pines over the Mediterranean area (Seim et al., 2015). This study found summer drought to be the primary limiting, and warm early growing seasons as a secondary stimulating factor of pine growth in the eastern Mediterranean region.

Wavelet coherence analysis indicated significant coherence with both growth modulating climate factors at the inter-annual/sub-decadal scale (Fig. 4). However, it was presumed that by separating the frequency domains at the 16-year period an enhanced signal could be obtained for summer drought, because at frequencies above 16 years spring temperature may only have a weak effect (Fig. 4b).

Above the 16-year period, (i.e. on the inter-decadal scale), the strength of temperature signal in the proxy decreased to r=0.17, while the response for the PDSI increased to r=0.51.

3.2.3. E Slovenia, oak tree-ring width

With recalibration, the results of the original study were in the main verified. It was concluded that for 1850/51-2003 the maximum response of the proxy can be found with the June gridded temperature and scPDSI (r=-0.38 & 0.35 respectively). This response is lower than in the original study, but it should be noted again that this is very likely due to the much larger (2x2°) spatial coverage of the meteorological data used in the current recalibration.

At first, the TRW proxies gave a meaningful response with the CR20 precipitation, primarily for June (r=0.25). The signal was somewhat improved by averaging June and July precipitation (r=0.27). In addition, significant correlations were found with temperature and scPDSI for June (r=-0.38 & 0.33 respectively). These findings concurred with the message of the original calibration (Čufar et al., 2008), that this proxy reflects a mid-summer drought signal.

However, evaluating their WTC PSD graphs (Fig. 5) it became clear that there may be an opportunity to enhance the most meaningful climate signals (T & scPDSI) by separating the frequency domains to annual (<4-year period), inter-decadal (4-14-year period) and decadal (>14-year period) bands.

After separation of the bands, correlation between the proxy record and scPDSI increased to r=0.35 on the inter-decadal scale, while temperature was proven to have the weakest correlation in the 4-14 year spectral range (r=-0.29). Thus, the hydroclimate signal can be confirmed by keeping the signal within the 4-14 years spectral band and by choosing scPDSI as the main climate response parameter.

1.1.1. Low Tatras, Scots pine tree-ring width

With the approximately 50 years longer climate dataset (1851-2006), the recalibration verified the main response variable to be PDSI (r=0.47), but with a response season extending into spring (April-July), and with a weaker correlation than in the original calibration (Büntgen et al., 2011). Nevertheless, the drought-sensitivity of the proxy was verified.

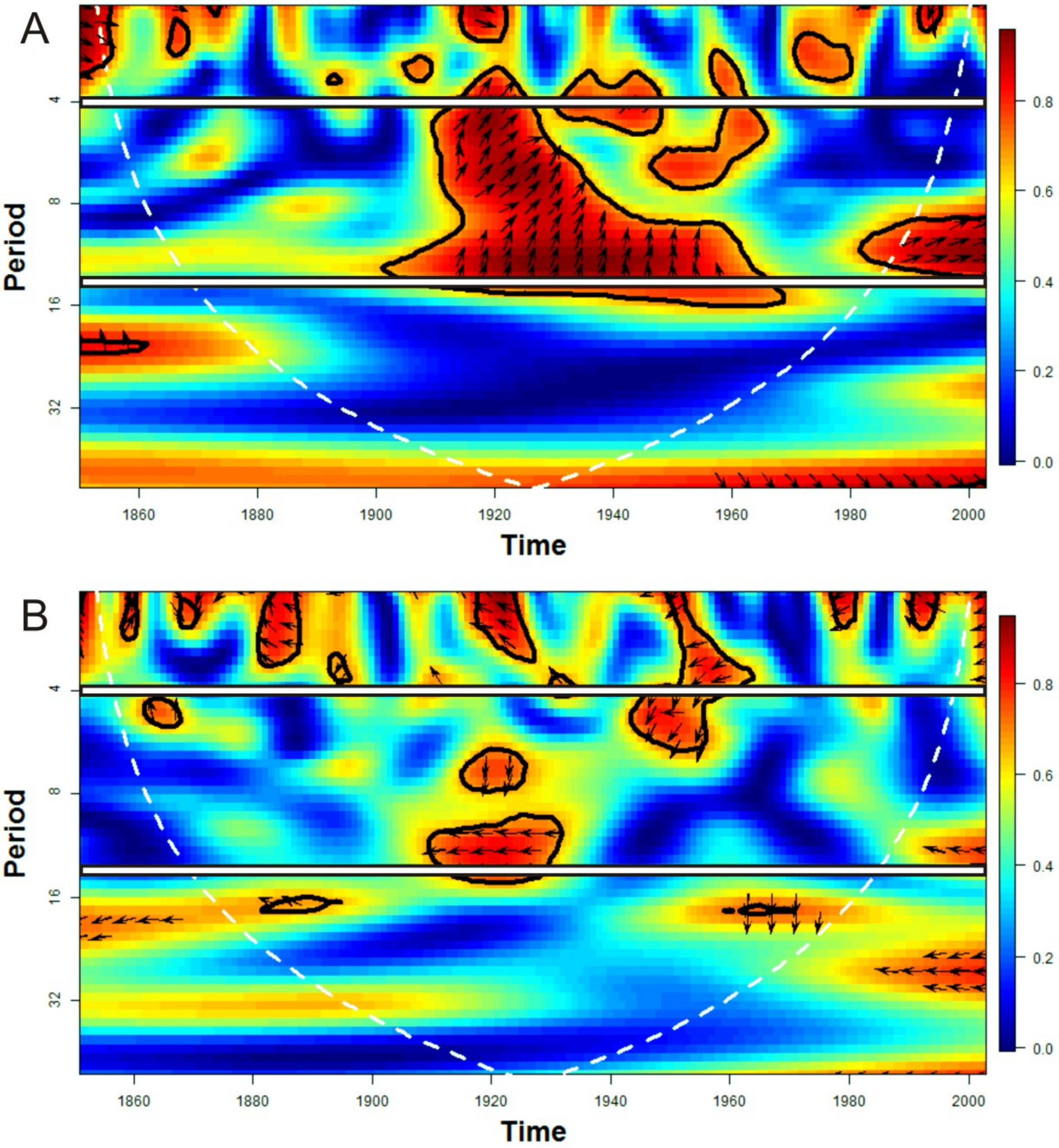


Fig. 5. WTC of the E Slovenian oak TRW and the June scPDSI series (1850-2003) A), June temperature (1851-2003) B). Further interpretation of graphical elements is found in the caption of Fig. 2.

2. Discussion

Millennial climate variability in the Northern Balkan-Carpathian realm can be assessed based on dendroclimatological and phenological evidence. The proxy information will be discussed on a seasonal basis for temperature; however, where the recalibration results pointed to summer-drought sensitivity, all the available hydroclimate proxy records will be discussed together in one section. A prompt observation identified the fact that no natural proxy providing information for the fall season prior to the instrumental era is yet available from the NBC.

The proxy information on seasonal temperatures from NBC will be compared to the same seasonal means derived from monthly temperature reconstructions dating back to1500AD for Central Europe (CEU; (Dobrovolny et al., 2010)) and discussed for each season (winter, spring, summer). Moreover, additional relevant reconstructions from neighboring regions will be used to broaden the spatial comparison of the patterns found. A recently published European drought reconstruction (Old world drought atlas OWDA; Cook et al., 2015) provides excellent opportunities for independent comparisons regarding hydroclimate proxy records, especially since the chosen sensitivity parameter (scPDSI) is the same as ours. It should be noted, however, that the present analysis is not fully independent of the OWDA, because the E Slovakian record is included in both. However, on the one hand, the other three hydroclimate proxies presented here were not part of the OWDA, on the other hand, they use such proxies which were not at our disposal at the time of the study. Thus, the comparison is meaningful. As a temporal constraint the discussion (comparisons) is focused on the pre-instrumental period (*c.* 1850 AD).

2.1. Temperature variability

2.1.1. Winter

In the NBC, only a single natural proxy record exists, representing the winter regime prior to the instrumental era, providing information only about medium frequencies.

The running correlation analysis using the Sinaia proxy-and the CEUwtr record indicated a generally positive linear relationship with temperature (r=0.31), which even increased to r=0.47 if a 14 year period (1824-1837) with a sharply reversed relationship (r=-0.29) is excluded (Fig. 6). Another interesting fact is that correlations were not only found in the years directly followed by the calibration period (mid-19th century), where the Sinaia chronology contains the maximum number of samples, but similarly strong relationships were found at the beginning of the 18th century as well, at which point replication of the chronology decreased. Because of the long distance (>~1,000 km) between the proxy and the core region of the CEU reconstruction, this similarity is somewhat surprising; nevertheless, it suggests a dominant and homogeneous pattern of winter temperatures over vast areas of Europe. Findings suggest that in the particular period (1823-1837) represented by negative correlations, the Sinaia region detached from the Central European winter climate regime.

The reconstruction emphasizes alternative sequences of years or decades with warm/cold winters: the intervals 1790-1802 and 1874-1888 had cold winters, while the winter beginning with warm temperatures were 1836-1846, and 1860-1873, thus lying mostly in the pre-instrumental era.

It was also found that most of the negative pointer years (negative peaks) (e.g. 1805; 1808; 1867; 1874; Fig. 6a) in the Sinaia winter proxy were in accordance with reconstructed winter-early spring temperatures from Poland (Przybylak et al., 2005). The most pronounced exception is the coldest winter of 1846/47, which is also reflected in the CEUwtr, but with a smaller magnitude. As a final comment, the study of Schichler et al. (1997) from the southern bordering zone of the NBC also indicated that winter temperature is the primary growth regulating factor for silver fir in that region. This should encourage scientist to look for old-grown silver fir stands, develop long chronologies along the southern borders of the NBC and test the chronological signal for winter temperature to improve the spatial coverage of winter thermal proxies over the NBC.

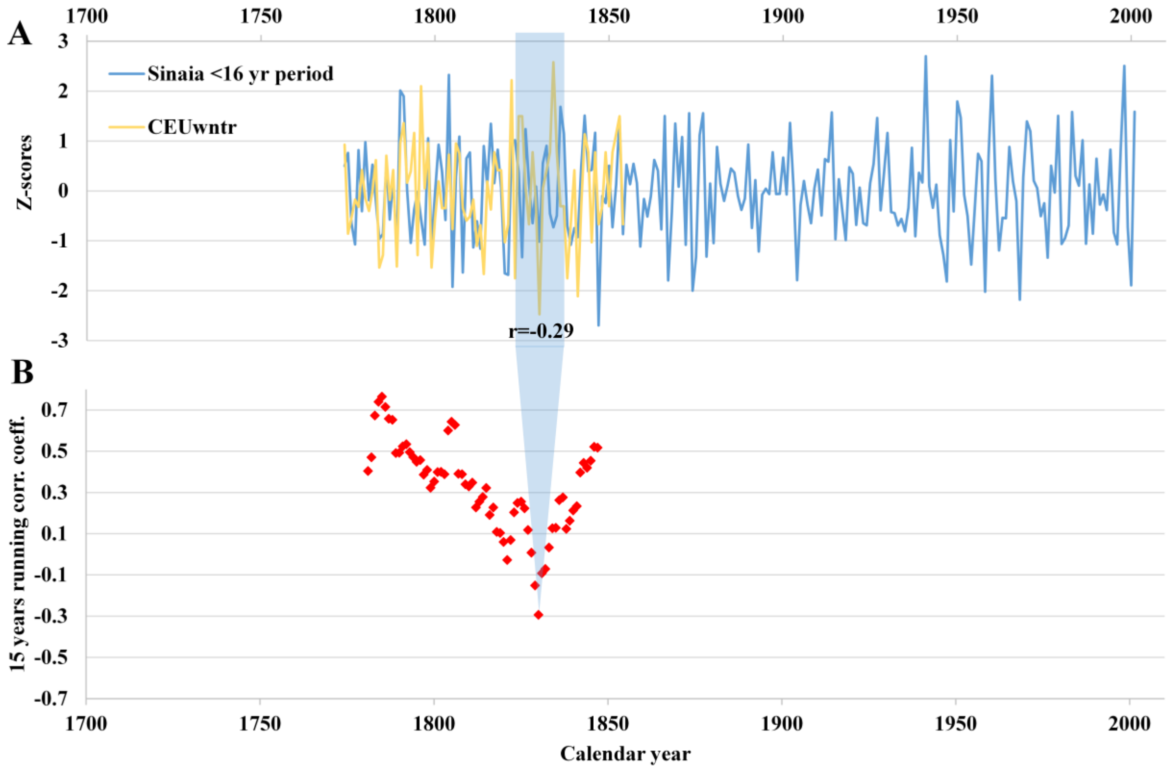


Fig. 6. The winter temperature proxy from the South-East NBC and the CEUwinter reconstruction z-score transformed for their common period (1774-1854) A) and their 15 year running correlations (1774-1854) B)

2.1.2. Spring

In the western part of the NBC domain, VFD from Klosterneuburg and grape sprout length of Kőszeg presented a sensitivity period confined to the spring season with opposite correlations - if spring is warm, then vine flowering occurs earlier, while the sprout length becomes longer. Although both proxies indicated a spring sensitivity window with an only one month overlap, a moderate linear relationship was detected (r=0.42) (Fig. 7a).

Clear periods can be observed, however, where the two proxies responded in a strikingly similar way to spring temperatures e.g. from the 1850s to the beginning of the 1870s. A similar pattern is seen in the mid- to late-18th century. It should be noted, that sprout length has a positively biased characteristic (Fig. 7a): it cannot grow negatively and, as such, it is unable to respond to temperature below certain threshold. Therefore, the two records can complement each other in case of gaps, and the joint record permits a more or less continuous estimate back to 1740 and a short glimpse back into the 1730s.

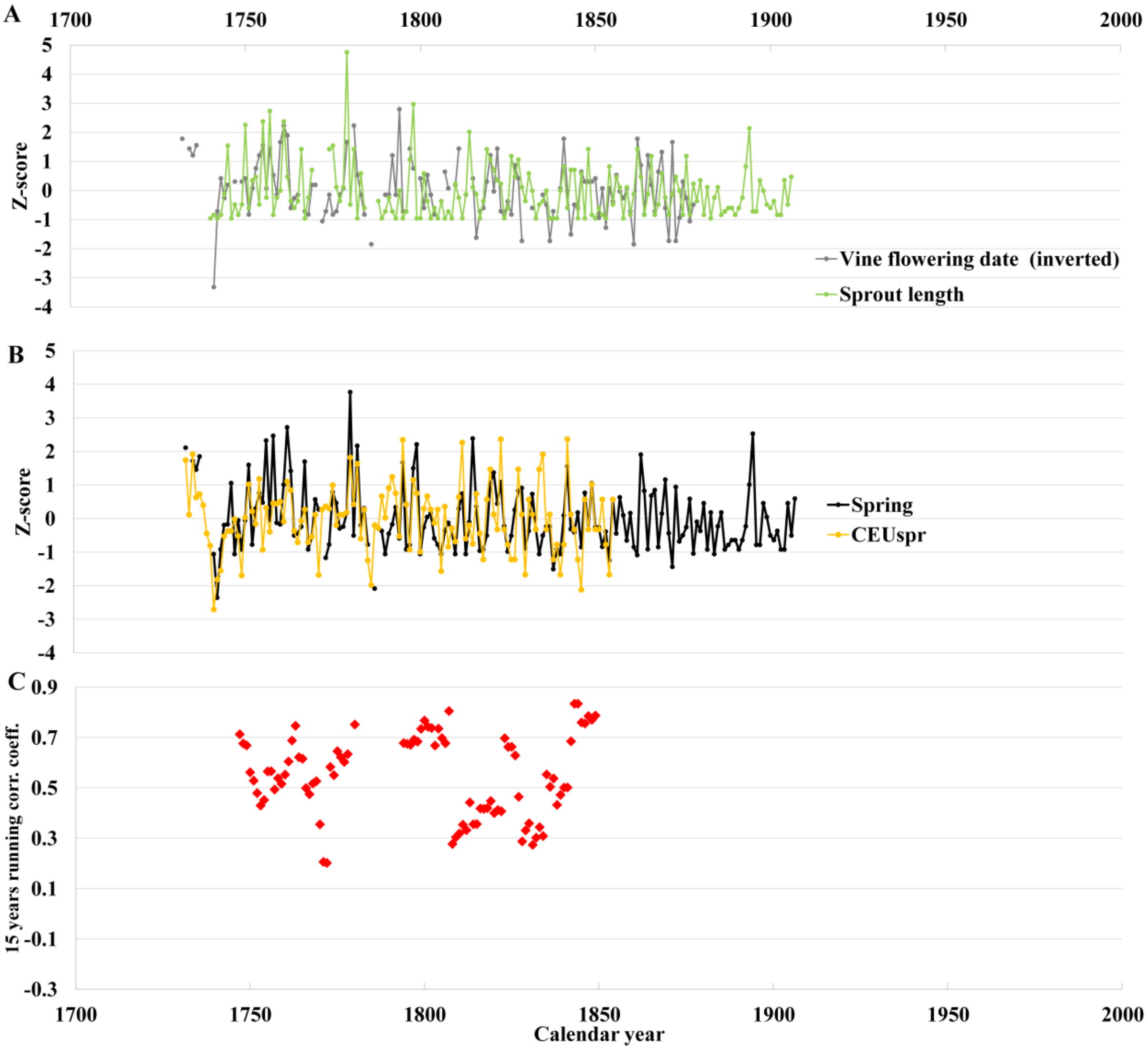


Fig. 7. The spring temperature proxies from the West NBC. Z-score standardized time series of vine flowering date and sprout length (the common period for Z-transformation was 1741-1878) A), CEUspr reconstruction and the stacked record for the spring temperature (Z-transformed for the entire overlap) B), and their 15 year running correlations C)

When compared to the CEU spring reconstruction, both visual (Fig.7b) and statistical (Fig.7c) evidence pointed out two pentennial periods centered on 1802 & 1846 had the best common variability (r > 0.7) (Fig. 7bc). In addition, the full period correlation (r= 0.58) is (i) in general stronger than between the spring proxies against each other, (ii) on the same scale as that found between the individual proxies and the Vienna instrumental temperatures (Section 3.1.6.1 & 3.1.2.1), and (iii) in general it shows a much more modest linear relationship than in the winter situation with corresponding CEU reconstruction. Out of the three periods with the most reduced common variance (r < 0.3), in the first two (around- 1770 & 1805) the west NBC proxies are not in line, while in the last one (around 1830) the sprout length- and the VFD records are in agreement with each other, but not with the CEUspr reconstruction.

Cold spring temperatures (negative extremities) are more poorly captured than the warm ones in the stacked spring temperature proxy; this is most likely the consequence of the mentioned bias in the sprout record. However, paradoxically, the frosty temperatures of the early 1740s springs and the mid-1780s were mirrored in the CEUspr reconstruction (Fig.7b). It should be noted that in the case of both occurrences there was a one year shift between the cold peaks. In the CEUspr, the coldest spring occurred in 1740, while in the stacked record in 1741. This 'misfit' might be caused by the lack of the VFD record from 1740 (Fig. 7a), and the earlier mentioned positive bias related to zero sprout length. As for the latter event, the CEUspr cold peak was 1785, while there was no data for spring temperatures from the west NBC in that particular year, only for 1786. Therefore, this is not a real misfit, because proxy information is simply missing from this particular year.

Nevertheless, the stacked western NBC spring record follows the interannual variability of the Central European spring temperatures quite well, including the chilly springs of the early 1740s.

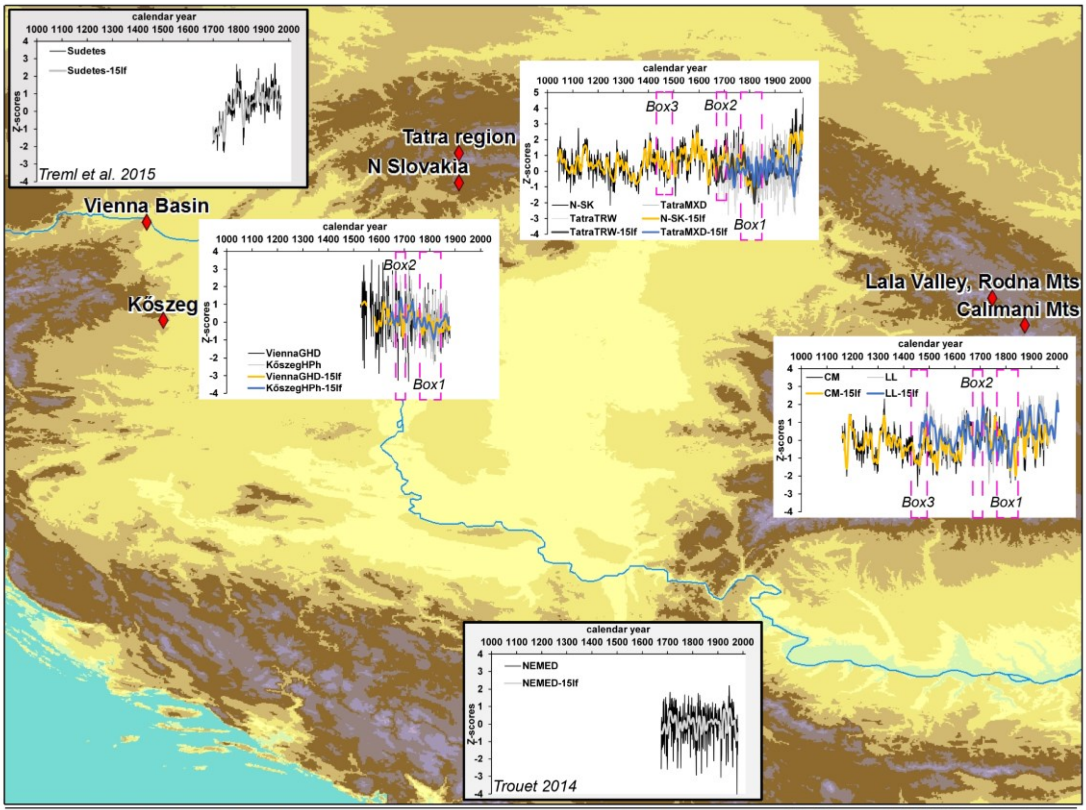
2.1.3. Summer

The richest data source from the NBC is available for the summer season. Seven proxy records show an interesting spatial alignment. Records relying dominantly on historical phenology group at the western part of the NBC region, while in eastern margin of the NBC Stone pine TRWs can be found. The pattern is strikingly similar within these sub-regions.

The relationship between the proxies will be mainly discussed referring to their full temporal coverage, and only in certain cases will the longest common overlapping period (1709-1854) be referred to.

At first glance, it becomes apparent that the strongest linear relationships were obtained between the closest proxies (Vienna GHD & Kőszeg HPh r=0.62; CM & LL r=0.59), which, as mentioned above, are of similar origin (Fig. 8 inset table). Three tree-ring derived temperature sensitive proxies are available from the third region, the Tatras, but they are diverse regarding the parameters and species (see Section 3.1. and Supplementary Content for details). The MXD record has a generally high temperature sensitivity, accompanied by a relatively long sensitivity window (Schweingruber et al., 1978). It has a reasonably good correlation with the TRW from the same site (r=0.33).

Although the most recent record based on larch TRW (N-SK) (Büntgen et al., 2013) only poorly correlates with (i) the former reconstructions from the Tatras (r<0.19) and (ii) with other records of the NBC for full time interval, it shows a somewhat stronger linear relationship in the common interval (1709-1854) with the CM from the E NBC, the Kőszeg HPh from the W NBC and the Tatra TRW from its own domain (Fig. 8 inset table). This improvement is very likely caused by the exclusion of the 20th century part from the "common period". When the N-SK shows a pronounced positive shift reflected neither in the proximal, nor in the distal summer temperature proxies of the broader region. The applied detrending method is declared to preserve the decadal fluctuations (see Supplementary), so the extraordinary low-frequency pattern seen in the last ~150 years in N-SK remains questionable. Note that the original study (Büntgen et al., 2013) also underlined the risk that this record cannot be an undisturbed record of past temperature history. Presented comparisons with surrounding temperature sensitive proxies, interestingly, tend to confirm the temperature signal (both for high and medium frequencies) for the pre-instrumental era while querying the interpretation of the increasing proxy values as evidence of rising temperature after the 1890s.



	N-SK	CM	LL	TatraMXD	TatraTRW	ViennaGHD	KőszegHPh	*CEUsmr*	*NEMED*	*Sudetes*
N-SK	-	0.58	0.26	0.16	0.46	0.20	0.32	*0.24*	*0.12*	*-0.19*
CM	0.07	-	0.62	0.21	0.57	0.28	0.31	*0.24*	*0.18*	*0.01*
LL	0.20	0.59	-	0.14	0.34	0.16	0.16	*0.19*	*0.12*	*0.10*
TatraMXD	0.11	0.17	0.17	-	0.36	0.43	0.40	*0.41*	*0.34*	*0.31*
TatraTRW	0.19	0.45	0.29	0.33	-	0.32	0.42	*0.37*	*0.15*	*0.32*
ViennaGHD	0.13	0.12	0.08	0.40	0.26	-	0.67	*0.49*	*0.32*	*0.06*
KőszegHPh	0.29	0.26	0.16	0.41	0.31	0.62	-	*0.45*	*0.41*	*0.01*
CEUsmr	*0.00*	*0.18*	*0.14*	*0.41*	*0.30*	*0.51*	*0.38*	-	*-0.01*	*0.12*
NEMED	*0.02*	*0.13*	*0.10*	*0.49*	*0.14*	*0.30*	*0.33*	*0.02*	-	*-0.05*
Sudetes	*0.01*	*0.07*	*0.34*	*0.24*	*0.35*	*0.00*	*0.01*	*0.08*	*0.00*	-

Fig. 8. The summer temperature proxy records from the NBC (white background) and its surroundings (grey background). The time series were Z-score standardized (for the longest common interval: 1709-1854) and provided in separate graphs for the western, northern and eastern clusters. Boxes (1, 2 & 3) frame the mutually present temperature fluctuations as discussed in the text. The correlation matrix is displayed below the map. The correlation coefficients computed for the common period are above the diagonal (white), while for the full period these are below it (grey). The black line in the table delimits "within-NBC" proxies.

The studied summer proxies show a remarkably strong linear relationship also with nearby records from outside the NBC. The correlation coefficients computed between the CEUsum and the W NBC records closest to it ranged from r=0.38 to r=0.51, and were just slightly lower for two of the more distantly situated Tatra triplet (Fig. 8 inset table). The outlier is again the N-SK (r=0.00). The summer temperature proxies from the E NBC show a mutually weakened coherence. Attention should be paid to this observation, since for winter good correlations were found between the CEU and the available NBC proxy located at the distant SE corner of the NBC (see Section 4.1.1.). In summer meaningful coherence was sustained only in the western parts (Fig. 8), while falling below r=0.18 for the E NBC.

Summer temperature sensitive tree-ring proxies from the neighborhood of the NBC came from a North-eastern Mediterranean- (NEMED; Trouet (2014)) and a N Bohemian (Sudetes; Treml et al., 2015) reconstructions. The NEMED is a multi-site composite MXD record from the 15°-25° E & 38°-45° N domain (covering 1675-1980 AD). The Sudeten record is an almost 300 years long multi-site spruce TRW reconstruction, where two chronology variants were available for comparison. From a methodological point of view only the RCS technique is capable of retaining low-frequency signals (Peters et al., 2015). In addition, Treml et al. (2015) declared concerning the Sudeten reconstruction that in this particular case, high-frequency variability was similar irrespective of which detrending (RCS or individual detrending) approach is used; therefore, the RCS was chosen.

The N Bohemian tree-ring derived summer proxy gave a positive linear relationship with the Tatra cohort regardless of the length of the overlap (Fig. 8). Although the western NBC reconstructions built on historical records are not further away from the Sudetes reconstruction than the Tatras, still no results worth discussing were obtained.

The NEMED reconstruction was most similar to the Tatra MXD and the W NBC historical phenology based records regardless of the time window (Fig. 8 inset table). The highest correlation (r=0.49) was found with the Tatra MXD, despite the fact that they are the furthest apart. This is an additional instance that might lead us to suspect that the proxies of the same origin tend to carry a better common signal, as seen from within the NBC.

The low frequency (15 year low-pass filtered) signal, with pronounced inter-decadal fluctuations, indicated a highly similar pattern within their own cohort in the western and eastern regions of the NBC. Despite this, temporary differences may be observed. Prior to 1500 AD, there is a misfit between the CM & LL proxies, whereas the CM oscillates around a lower mean, but still following LL. In addition, after the 19th century the magnitude of the negative anomalies in the CM are larger than those in the LL record.

In the Tatra Mts, representing the northern cohort, the low-frequency signal was not homogeneous. In the longest larch TRW record (N-SK), a positive shift can be observed in the 20th century, not reflected in either the neighboring proxies within the NBC, nor the summer temperature reconstructions from the surrounding areas. As for the phenology proxies of the western NBC domain, a common decreasing trend can be observed, in which the two proxies are aligned up to the mid-19th century, when Kőszeg HPh starts to increase earlier.

Similar patterns were found between the different proxies. In the low frequency records, cold summer conditions prevailed over the entire NBC from ~1780 to ~1840, starting a couple of years earlier and lasting longer in the eastern- and the western NBC respectively (Fig. 8:box1). The cold peak of this period (1810s), also well known in large scale temperature histories (Masson-Delmotte et al., 2013), was reflected in the CM & LL, the vine phenology, the Tatra proxies (with slight misalignment), and both the Sudeten and NEMED reconstructions outside of the NBC.

The pre-instrumental warm peak (1720s) is in agreement with the LL & CM proxies as well as the vine phenology records within the NBC (Fig. 8), but not outside it. Moreover, the Tatra records, although inside the NBC, did not show this peak.

Another characteristic pattern of cold summers with intermittent warm spells was seen in the late-17th century in the vine phenology (W NBC), the pine TRWs (E NBC) and, imperfectly, in the Tatra spruce TRW, but not in the larch TRW record (N-SK; Fig. 8: box2). Another shared wave moving forward back in time is a cooling trend starting from 1430 and reaching its minimum around 1470, followed by an abrupt warming reaching its maximum shortly before the turn of the 16th century (Fig. 8:box3). As an ultimate observation, no shared and meaningful pattern can be mentioned in the two proxy records reaching further than the mid-15th century (CM & N-SK). Whether this should be attributed to the quality of the data, or may reflect real divergence in climate histories remains an open question. However, the observed quality coherence over the last 450 years does not support the idea that such a strong spatial difference may have a duration of centuries in the NBC. Thus, it is most likely to be related to a proxy-quality problem.

Although all proxies were proven to be sensitive to summer temperatures, still the same type of records – even over large distances - correlated more strongly with each other than proximal but differing types of proxies. For example, the Sudeten spruce TRW showed a stronger linear relationship with the Tatra spruce TRW than with the reconstructions built on historical phenological records from even shorter distances. Thus, it may not be enough simply to assess the proxy records at hand, but their physiological origin should be also taken into account for climate field reconstructions employed on multi-proxy networks. This is a kind of warning message relevant well beyond the NBC. If different proxies with different sensitivity are at hand, then the spatial patterns in the proxy network may be biased purely by the difference in the type of the record.

2.2. Hydroclimatological variability

Tree-ring based reconstructions provide information for the hydroclimatological variability over the past 300-500 years within the NBC: from East Slovenia (E Slov) the Low Tatra Mts (LT), Bakony Mts (BB) and the Banat region (Dom). As discussed before, the spatio-temporal extension of the available hydroclimatological proxies is more limited. Since an improved hydroclimate signal was found for below and above the 14-year period for E Slov and Dom, the other hydroclimate proxy signals (BB and LT) were also treated with the same spectral filtering to better guide specific discussions.

Regarding inter-decadal variability, all the three proxies (BB, LT & Dom) increased in parallel, but only at the beginning of the 19th century for the pre-instrumental era. Meanwhile, parallel fluctuations were observed for various pairs of proxies throughout the investigated time interval. In the overlapping period of the three proxy records where the data above the 14-year period were assessed (E Slov, BB, LT), the number of extremes (outside 2σ) was close to identical for each (~10 events). No extreme event was found common to all three proxies. A tendency of more frequently occurring large amplitude extreme events can be seen in the E Slov record prior to 1600. Although this might even be an actual change in short-term drought variability, it may also be partially the result of a methodological bias, because the possible variance artefact created by decreasing sample size was not corrected (Čufar et al., 2008).

Annually resolved multi-centennial hydroclimate reconstructions (Brázdil et al., 2013; Büntgen et al., 2011; Cook et al. 2015) offer a particularly good opportunity for an extended spatial comparison. In the following, the results will be discussed separately for the sub-decadal and inter-decadal scales.

2.2.1. Inter-decadal variability (Dom, LT, BB)

Besides their comparison with each other, meaningful correspondences were obtained by comparing the Dom, LT, BB proxies with other hydroclimate evidence (Fig. 9).

For example, graphical comparisons with hydroclimate histories from the western margin of the NBC revealed a couple of similarities. In temporal order, a single drought proxy from the SE NBC region (Dom) interestingly shows a good parallel fluctuation with the Moravian reconstructions (Büntgen et al., 2011) in the 17th century and with the summer drought periods around 1750s. This event was mirrored in the Central NBC as well (BB).

This period of explicit drought coincided with the warmest spring on record (Section 4.1.2). Above-average spring temperatures were found to be accompanied by below average precipitation over inland Europe (Madden and Williams, 1978), where dry conditions favor more sunshine and less evaporative cooling, while wet periods tend to be cool (Trenberth and Shea, 2005). Thus, warm spring climatic conditions could induce summer droughts in this specific period.

Moving forward, in the period from 1795 to the mid-1830s, a similar drought-history unfolded over the entire NBC, and was reasonably well reflected in the S Moravian May-June drought history (Büntgen et al., 2011). Another shared pattern is the drought period of the late 18th century. The peak-drought first manifested itself in the SE, then the N part of the NBC and ultimately in the Central NBC, but here it was of a smaller magnitude. The latter precisely fitted a similar drought event occurring in Moravia.

A documentary-based qualitative record of hydroclimate changes of the W NBC (water level changes of Neusiedler See) dated back to the 1600 (Kopf, 1963;Kiss, 2009) with the exception of a single short period (the 1864-70 low, in alignment with Dom), surprisingly, did not match with the drought proxies of the NBC.

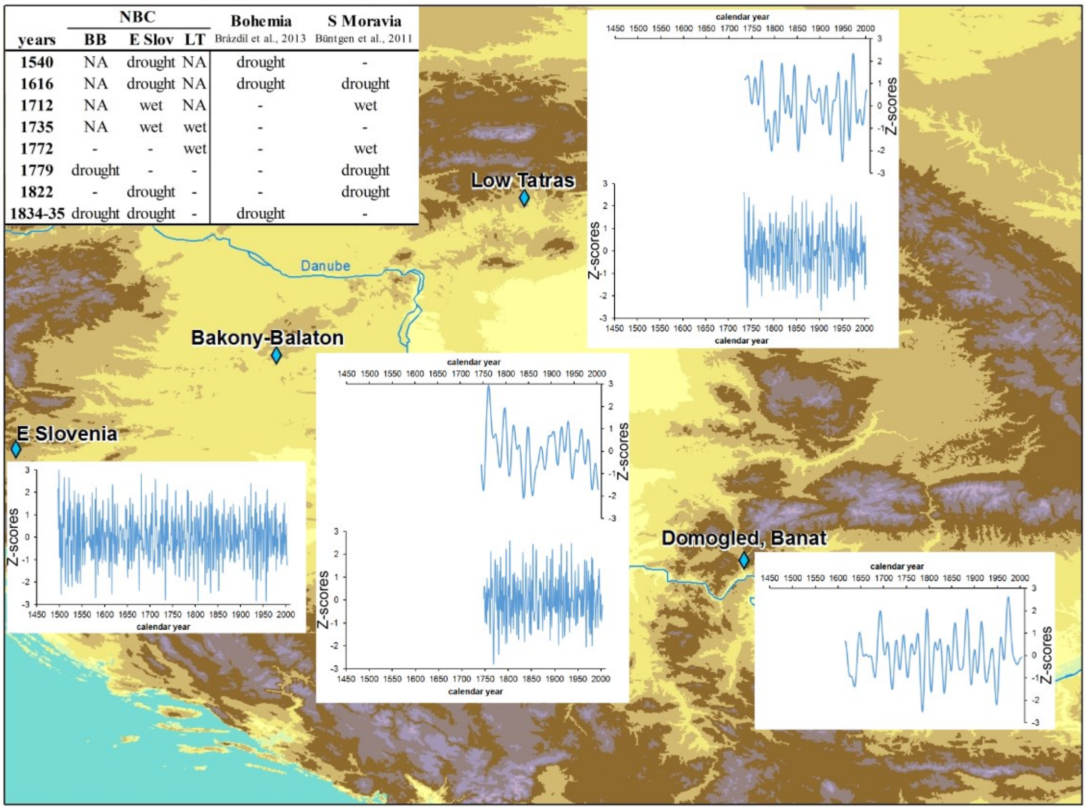
Continental scale patterns (Cook et al., 2015) in relation to drought peaks (specifically 1718/19; Brázdil et al., 2013) in the Czech lands were reflected in the Dom proxy. While the

OWDA did not indicate a prolonged, two-year drought in the S Carpathians, still the Dom proxy gave the same two-year response as the Czech reconstruction.

2.2.2. Sub-decadal investigations (BB,E Slov, LT)

As previously discussed, perfect coincidences of extreme moisture conditions are rarely found between the NBC hydroclimate proxies and the surrounding reconstructions (Fig 9 inset table).

Given that the number of matches decreased (6E-Slov;2 BB;1 LT) moving away from the S Moravian & Bohemian regions, this suggests a spatial trend. In other words, there is still a visible connection between the W margin of the NBC and the Central European drought zone, which decays towards the East. We should note here that the 1616 peak drought in the Czech lands was found to be a drought event in the SWNBC as well.



	NBC			Bohemia	S Moravia
years	BB	E Slov	LT	Brázdil et al., 2013	Büntgen et al., 2011
1540	NA	drought	NA	drought	-
1616	NA	drought	NA	drought	drought
1712	NA	wet	NA	-	wet
1735	NA	wet	wet	-	-
1772	-	-	wet	-	wet
1779	drought	-	-	-	drought
1822	-	drought	-	-	drought
1834-35	drought	drought	-	drought	-

Fig. 9. The hydroclimate proxy records from the NBC. The time series were Z-score standardized (for the longest common interval: 1746-2003) and are provided in separate graphs. The low frequency signals were obtained with a 14-year spectral filtering (details in the text). The inset table displays the coinciding extremes occurring in at least two of the records in pre-instrumental times.

The weak harmony of the NBC hydroclimate proxies with each other, taken with the surrounding reconstructions reassures us that the hydroclimatological signal over the broader region is spatially heterogeneous (Büntgen et al., 2010; Kern et al., 2013). A spatial analysis of drought history documented on the basis of 50 years of instrumental observations over the region also points out that even the severest drought episodes have not affected the NBC in a uniform way (Spinoni et al., 2013).

The fact that the 1741 extreme drought extended from the British Isles to the W continent (Cook et al., 2015) is reflected in neither of the studied NBC proxies being in harmony with the OWDA maps. In that particular year, only the areas N of the main orographic climate divide (the Alpine-Carpathian Chain) were affected by severe droughts on the continent. Nevertheless, it should be noted that a severe drought event was recorded in the LT proxy, but presenting itself one year later in 1742

A more precise knowledge of hydroclimate variation in the Pannonian Basin is not only important for rain-fed agriculture in this environmentally sensitive region, but also critical for the water- and life securities of those in and beyond the Carpathian-Balkan Region.

2.3. Further potentials& recommendations

Historical phenology records also have a great potential for further numerical climate reconstructions. Additional historical vine and grape phenology data are available from Kecskemét (Central Hungary) from the late 17th to the early 19th centuries (Szabó, 1934), and from Kőszeg for the period of 1649 –1820 (Szövényi, 1965). However, neither data set has been analyzed from a climatological point of view (Kiss, 2009). Because of the exceptionally strong temperature signal of this proxy type (see Sections3.1.2. and 3.1.6.), they definitely have great potential. Similarly, other historical phenological records are available from the region. Nejedlik and Szalai (2009) presented 53 phytophenological stations available from the 19th century extending over the entire currently studied region over a wide spatial and elevation range from the Adriatic coast up to the Carpathian mountain belt. However, only isolated records have been evaluated thus far, for instance from Croatia (Vucetic and Vucetić, 2006) or Romania (Lehoczky et al., 2016). To fill in the many gaps in the presently available records is a major task for the future.

Significant stone pine populations are known from other ranges of the Carpathian Arc. An old Tatra chronology (Bednarz 1984) craves for fusion with recent collections (Janecka and Kaczka, 2014, 2015) and a multi-centennial Southern Carpathian data collection is also under development (Popa and Nechita, 2011). The comprehensive evaluation of these datasets is highly encouraging, since the established stone pine TRW network has probably the greatest potential to provide a homogenous millennium-long proxy network for summer temperature variability for the NBC.

With regard to the strong temperature signal (without any sign of spectral distortion) of the MXD chronologies, the development of additional density-related records (MXD or blue intensity (BI)) are also to be encouraged. The first results from pilot studies on BI signals in Tatra conifers are very promising (Janecka and Kaczka, 2015). Since (late-) growing season temperature forces strongly and homogenously the density (i.e. cell wall lignification) fluctuations of conifers, even beyond the timberline, the collection of different species into composite MXD (or BI) chronologies could be a potential solution to the extension of density-based temperature reconstructions back to the 1st Millennium. The successful cross-dating between the floating spruce chronologies developed from subfossil material found in the NE Carpathians and the early section of the Calimani stone pine chronology (Árvai et al., 2016) is a very promising step towards the development of such a composite conifer chronology, at least for the Eastern NBC. As for the hydroclimate proxies, historical timber disposes of probably the greatest potential for the extension of the presented (and other, shorter) records back in time to improve both the spatial- and temporal coverage of hydroclimate proxies in the NBC.

Last but not least, there is – in the NBC – a virtually unexploited natural proxy type which has great potential for the provision of high-quality temperature information exactly for the poorly represented winter- and the unrepresented fall season, namely freshwater ice conditions (so-called ice phenology). In the NBC historical records of river- and lake ice phenology are available for a period extending back a couple of centuries (Kiss, 2012; Vadas, 2013). The physical basis upon which certain ice phenomena may be linked to ambient temperature changes (e.g. ice occurrence to accumulated negative heat; ice break-up or ice disappearance to accumulated positive heat) is obvious and well substantiated (Carlson, 1981; Beltaos and Prowse, 2009; Kirillin et al., 2012). Nevertheless, it is highly recommended that special attention be paid to anthropogenic impacts, which may have modified the river-ice regime in densely populated regions with long history of river regulation, such as the NBC (Takács et al., 2013; Takács and Kern, 2015). A recent study on the lower course of the river Drava, located in the southwestern corner of the NBC (Takács and Kern, 2015), presented an exceptionally strong correlation between certain ice parameters and monthly or seasonal mean temperature (e.g. ice-off date vs Jan- Feb mean temperatures ($r=0.81$, $p<0.05$), total number of icy days and the mean winter temperature ($r=0.88$, $p<0.05$)). In the case of other rivers of the NBC, the first occurrence of river ice was found partially to reflect the late-fall thermal conditions: the Danube at Budapest vs Nov-Dec mean temperature ($r=0.56$), the Rába at Ragyogóhíd vs. Nov-Dec mean temperature ($r=0.48$) (Takács et al., 2013). This is possibly due to the difference in the relationship of the climate and the hydrological conditions from catchment to catchment.

These data not only represent a parameter group which co-varies in quite close accord with winter temperature but there is also a very solid physical (i.e. non-biological) basis to the linking of ice phenomena to particular ambient thermal conditions; hence, this could provide an independent record against which to check the temporal stability of the winter temperature signal of the silver fir TRWs. These various courses of action might hold the greatest potential for bringing about a significant advance in the near future in high-resolution paleoclimatology in the NBC.

3. Conclusions and outlook

By compiling and re-evaluating the temperature and hydroclimate proxy records derived from natural archives from the NBC a complex overview and valuable new dataset was obtained. The uniform climate targets with extended temporal coverage were achieved and the originally reported climate sensitivities were verified. The results are encouraging, since the original studies employed rather diverse climate data.

By comparing the South-Eastern NBC winter temperature proxy with nearby (Central European and Polish) records, surprisingly good similarities were found. This suggests a dominant and homogeneous large-scale inter-annual variability of winter temperatures over vast areas of Europe. Closer scrutiny of the climate signal in the long silver fir chronologies along the Mediterranean margin of the NBC and the appending of the documentary records on historical lake- and river ice phenology to the long instrumental series will probably have the effect of improving our knowledge of winter temperature reconstructions in the region.

The currently available spring proxies from the Western NBC were in quite good agreement. The most characteristic multiannual pattern, at the beginning of the 1740s, for instance, provided evidence that the Central European spring cold conditions were extended to the western NBC as well as being the coldest springs of the last ~300yrs in this sub-region. Assessment of further phyto-phenological data seems the most promising course to complete the spring temperature network for the NBC.

On a sub-regional level the summer proxies showed a quite strong similarity to three characteristic periods: ~1780-1840 (cold peak: 1810s); late-17th century; ~1430-1500 (cold peak: 1470). While certain different origin proximal records were weakly correlated, the same type of proxies were in harmony for even larger distances. This is a bad omen for multiproxy networks, due to the risk that an excessive portion of spatial variance seems not to be attributed to the climatic signal stored in the proxy.

The hydroclimatological signal in the NBC was found to be rather heterogeneous in space. The seasonal structuring of the proxy evaluation permitted the recognition of an interesting correspondence: summer droughts were preceded by warm springs in the 1750s, suggesting that warm spring climatic conditions induced summer droughts in the specific period. To decide whether this is an exceptional case, or can generalized as a conclusion, is still an open question; further evidence is needed.

Proxy records reaching back more than 2000 years are also available from the NBC, mainly from lake- and cave deposits, but with coarse resolution (Németh et al., 2014). However, combining annual- and coarse resolution proxy records is one of the greatest challenges in paleoclimate research (Moberg et al., 2005; Tingley and Huybers, 2013; Werner and Tingley, 2015), and lies beyond the scope of the present paper.

It is to be hoped that this critically revised comprehensive dataset serves as a valuable and solid basis for (i) integration into the Pages 2ka initiative, and (ii) the investigation of the spatial-temporal pattern of climate changes and their causes in the NBC region.

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