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# Long term January–March and May–August temperature reconstructions from tree-ring records from Bosnia and Herzegovina

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## Abstract

We present the first spring and summer temperature reconstruction for the north-western part of the Balkan Peninsula. The reconstruction is based on tree-ring width measurements from 7 representative black pine (*Pinus nigra* Arnold) sites in Bosnia and Herzegovina (BiH). We found a significant, positive influence of above-average January–March temperatures on 4 sites (Blace, Peručica, Šator, Konjuh) and a negative influence of above-average May–August temperatures and a positive relationship with an above-average sum of May–August precipitation on tree-ring width formation from 3 sites (Krivaja, Prusac, Šipovo). A 31-yr running correlation between temperature and precipitation of the May–August period and tree-ring indices gave a stable relationship between 1901 and the 1960s, after which values of correlation coefficients decrease to the level of significance. A change in summer cyclones in the central part of the Adriatic Sea is presented as a possible cause of the divergence with the climate signal. In the period of calibration and verification of the linear model for the group of 3 sites (Krivaja, Prusac, Šipovo), the best relationship was found between tree-ring indices and mean May–August temperatures of the current year. For the group of 4 sites (Blace, Peručica, Šator, Konjuh), the relationship between tree-ring indices and mean January–March temperatures of the current year is the strongest. The developed models were used for reconstruction of May–August temperatures for BiH for the period 1701–1901 and January–March temperatures for the period 1685–1901. Using the method of percentiles (85th and 15th) we identified extreme hot/cool summers and warm/cold springs and compared them to available documentary historical sources and other reconstructions from the broader region.

## 1 Introduction

Documentary proxies of climate data from the 15th to the 19th centuries are well distributed over the Mediterranean region and are particularly abundant in Italy, France

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and the Iberian Peninsula. Proxies are less frequently found for the Balkan Peninsula area, i.e. Greece, former Yugoslavian countries, Albania, Bulgaria and Romania (Camuffo et al., 2010). Investigating climate-tree growth relationships, dendrochronological studies and reconstruction of climate variables, such as the investigation of the meridional Balkans (Xoplaki et al., 2001), can help validate historical explanations of climate variability and its impact on human life. One of the first dendrochronological investigations on the Balkan Peninsula was a study covering the area of Greece, Western Turkey, Cyprus and one location from Bosnia and Herzegovina (BiH), by which an Aegean master tree ring chronology was constructed (Kuniholm and Striker, 1983). With additional sampling of old houses and mosques, the chronology was extended back to 7000 BC and one location each from Italy and BiH were added (Hughes et al., 2001). In the eastern part of the Balkan Peninsula, in South-Western Bulgaria, 655-yr Bosnian pine (*Pinus heldreichii* Christ.) and 305-yr Macedonian pine (*Pinus peuce* Griseb.) chronologies were developed (Panayotov et al., 2010). In Romania, the first 1000-yr Carpathian tree-ring width (TRW) stone pine (*Pinus cembra* L.) chronology has been established and summer mean temperatures reconstructed for the period 1163–2005 (Popa and Kern, 2009). In Albania, a 1391-yr TRW chronology (617–2008) was developed and maximum density measurements were acquired on living and dead Bosnian pine trees (Seim et al., 2010). A high positive correlation with summer, particularly August temperatures was found, but no significant correlation with precipitation. A similar study was done on black pine (*Pinus nigra* Arnold) in Albania, whereby Levanič and Toromani (2010) developed a 238-yr TRW chronology. Tree-ring indices show a significantly negative response to summer temperatures and positive response to June precipitation. In sub-Mediterranean Slovenia, the formation of radial increments of *P. nigra* is stimulated by above-average winter and spring temperatures, while a negative impact of above-average temperatures in summer and during the entire vegetation period, from April through September, are clear (Ogrin, 2005). However, despite the numerous dendrochronological investigations across the Balkan Peninsula, climate reconstructions in the north-western part of the Balkan Peninsula are still not available.

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A 435-yr *P. nigra* regional chronology for BiH was therefore developed (Poljanšek et al., 2012) and compared with climate data from various sources.

## 1.1 Climate of the studied area

Geographically, the Balkan Peninsula represents the border between Mediterranean and Central European climates. The combined impact determines the climate in the western part of the Balkan Peninsula as a mixture of continental climatic influence from the interior of the peninsula, mountain climatic influence from the Dinaric Alps and Mediterranean influence from the Adriatic Sea. Annual precipitation and temperature regimes are characterized by seasonally diverse circulation patterns. In spring, an Atlantic High extending eastwards and over the Balkan Peninsula joins a low centre approaching from the southeast, causing a north–northeasterly flow over the Eastern Mediterranean area. The extension of the summer Asian thermal low is evident throughout the Eastern Mediterranean in all summer circulation patterns; however, it controls the weather in the region jointly with other principal pressure features (Kostopoulou and Jones, 2007).

In the light of expected climate change, heat waves in the Mediterranean region and on the Balkan Peninsula will intensify in the second half of the 21st century – they will be more frequent and will last longer. According to predictions, the minimum daily temperature during the worst heat events is expected to rise by around 3°C (Meehl and Tebaldi, 2004). In the Eastern Mediterranean and the Middle East, there will be a gradual and relatively strong warming of about 3.5–7°C between the 1961–1990 reference period and the period 2070–2099 (Lelieveld et al., 2012). The observed daytime maximum temperatures appear to be increasing most rapidly in the northern part of the region, i.e. the Balkan Peninsula and Turkey. Hot summer conditions that rarely occurred in the reference period may become the norm by the middle or end of the 21st century (Lelieveld et al., 2012). Moreover, a decrease in annual mean precipitation from –10% to more than –20% over some regions of the Mediterranean basin is expected by the end of the 21st century (IPCC, 2001). In the eastern part of the Mediterranean

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basin the observed strong drought period of the end of the twentieth century seems to be the strongest of the last 500 yr (Nicault et al., 2008). It is therefore important to investigate whether extreme events have already occurred in the past and how trees responded to them.

## 5 1.2 Species selection and response to climate

Selecting tree species growing on sites with limited between-tree competition and climate as the prevailing growth-limiting factor maximises the climate signal in tree-rings. *P. nigra* was chosen for this study, since it grows on extreme sites, has a good response to climate and reaches ages up to 500 years (Brus, 2004). The area of distribution of *P. nigra* covers the majority of the Mediterranean region (Vidaković, 1991), so the results of the climate-growth relationship from BiH can be compared to results from other regions. Its growth response to climate has been used in many climate-growth studies in the western (Martín-Benito et al., 2011, 2010b) and Eastern Mediterranean (Sevgi and Akkemik, 2007; Touchan et al., 2003), in the northern limit of its natural area – in Austria (Leal et al., 2008) and North-Eastern Romania (Levanič, 2012). Since the species is well-adapted to the Mediterranean and Southern European climate, *P. nigra* tolerates summer droughts and high temperatures (Penuelas and Pilella, 2003), but poorly tolerates drought during early spring (Wimmer et al., 2000).

In this paper, we present a climate reconstruction based on a *P. nigra* tree-ring width chronology from the north-western part of the Balkan Peninsula. The main goal is a climate reconstruction from Bosnia and Herzegovina (BiH), so the following aims were set:

- Identification of the climate signal in the tree-ring widths of *P. nigra* in BiH.
- Examination of the temporal stability of the climate signal.
- Reconstruction of the most limiting growth factor(s) for *P. nigra* in the north-western part of the Balkan Peninsula.

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- Identification of extreme climatic events in the past.
- Comparison of reconstructed extreme events with published historical sources.

## 2 Materials and methods

### 2.1 Site description

Bosnia and Herzegovina (BiH) is located between 42° 26'–45° 15' latitude north and 15° 44'–19° 41' longitude east, in the north-western part of Balkan Peninsula. Seven sites, dispersed along the main mountain chain in BiH to cover the diverse climate of the studied region, were selected for this study. A moist meridional maritime airflow from the Adriatic Sea often intrudes into the Balkan Peninsula, where it collides with cooler air above the NW–SE oriented Dinaric Alps mountain chain, resulting in large amount of precipitation. Despite the large amount of precipitation, the studied sites are generally dry because of surface run-off, mostly southern exposition and steep slopes. The Krivaja and Konjuh sites are close to one another, but differ in altitude and aspect (Table 1).

### 2.2 Tree-ring data

Old, healthy and dominant or co-dominant trees were selected for sampling. From each tree, two cores from opposite sides were taken at breast height (1.3 m) and perpendicular to the slope to avoid compression wood. Cores were air-dried, glued onto wooden holders and sanded with progressively finer sandpaper until a highly polished surface was achieved (Stokes and Smiley, 1996). Samples were scanned using the ATRICS system (Levanič, 2007) and measured using WinDENDRO software (www.regentstruments.com). Cross-dating of TRW series was done with PAST-4™ software (www.sciem.com) using visual on-screen comparisons and statistical parameters, such as the  $t$ -value after Baillie and Pilcher ( $t_{BP}$ ) (1973) and Gleichläufigkeit

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coefficient (GLK%) (Eckstein and Bauch, 1969). Additional quality control was applied using the COFECHA program (Holmes, 1983). COFECHA assesses the quality of cross-dating and measurement accuracy of TRW series (Grissino-Mayer, 2001). If COFECHA highlighted any potential problems, the TRW were visually crosschecked and, if necessary, measurements repeated, re-checked or removed from further processing if recognized as unusable. The reasons for removing certain trees from the sample pool were growth anomalies connected with resin collection in the past, overgrown wounds or the occurrence of compression wood deep inside the trunk.

Individual TRW series were fitted with a cubic smoothing spline with a 50 % frequency response at 67 % of the series length to remove non-climatic trends due to the tree's age, size, and the effects of stand dynamics (Cook and Briffa, 1990). Standardisation was done using ARSTAN for Windows, version 4.1d, the program provided by Cook and Krusic, Lamonth-Doherty Earth Observatory, Columbia University (<http://www.ldeo.columbia.edu/trl>). Each year's ring width was divided by the year's value of the fitted curve to give a dimensionless index with a mean of one. Index values were then pre-whitened using an autoregressive model selected on the basis of the minimum Akaike criterion and combined across all series using a bi-weight robust estimation of the mean to exclude the influence of outliers. Two chronologies for each site were produced in this way; a standard chronology and a residual chronology containing only high-frequency variations with statistically removed autocorrelation (Cook, 1985; Cook et al., 1990). The signal strength in the residual chronology was tested using the Expressed Population Signal – EPS (Wigley et al., 1984). The calculation of EPS was based on a 50-yr running window, with a 49-yr overlap. The usable portion of a chronology was defined as the part in which a minimum number of trees maintained an EPS value above 0.85 (Briffa and Jones, 1990). The common signal strength through the chronology was also tested with a running Rbar. This is calculated by taking the average correlation between all series in a 50-yr window with a 49-yr overlap through the entire chronology. Year-to-yr variability in the TRW, was measured using

mean sensitivity (MS). An MS around 2.0 is generally accepted as indicating a series that is sensitive enough for climate reconstruction (Speer, 2010).

## 2.3 Climate data

We tested two different climate datasets for BiH. The first was the CRU TS3.1 dataset (Jones and Harris, 2008), acquired through the KNMI Climate Explorer web page (van Oldenborgh, 1999). This web page allows calculation of average climate data for a selected area or for a certain point on the CRU  $0.5^\circ \times 0.5^\circ$  grid. Available data covers from 1901 to 2009. The second climate dataset consisted of individual weather stations, provided by the Federal Hydro-meteorological Institute of BiH. The stations are Bjelašnica (2000 m a.s.l.), Čemerno (1305 m a.s.l.), Sarajevo-Bjelave (630 m a.s.l.), Šipovo (460 m a.s.l.) and Tjentište (580 m a.s.l.) (FHMZ, 2010). Bjelašnica and Čemerno weather stations are high mountain locations. Some datasets have gaps in the annual base because climate data collection was disturbed twice due to a state of war. Bjelašnica weather station has data for the time periods: 1895–1940, 1951–1992 and 2000–present. Sarajevo-Bjelave has a complete dataset from 1888 until the present. Other weather stations stopped collecting data due to disruption in 1992; Šipovo (1965–1992), Tjentište (1964–1992) and Čemerno (1958–1992).

We compared CRU TS3.1 to individual weather stations and found that they all show similar variations in temperature and precipitation data. In order to avoid problems with missing data in the local meteorological datasets, we decided to use a complete, homogenised, crosschecked and verified CRU TS3.1 dataset for further analysis. The KNMI Climate Explorer web page enables extraction of climate data for a certain point or an area, defined by its longitude and latitude. In our case, we set the limits for BiH to  $E16^\circ 33' - E18^\circ 45'$  and  $N43^\circ 20' - N44^\circ 20'$  and extracted one climate datum as the average for the studied region.

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## 2.4 Statistical analysis

Pearson's correlation coefficient was used to evaluate the relationship between climate and annual radial growth of *P. nigra*. Residual site chronologies were compared to mean monthly temperature and the monthly sum of precipitation, to detect potential differences in a tree's response to climate at different sites. In addition to simple monthly climate values for tree-ring indices comparison, we also generated a number of seasonal temperature and precipitation (not shown here) variables (e.g., May–August or January–March mean temperature), and correlated them with the tree-ring indices. The significance and confidence intervals of Pearson's correlation coefficient and the temporal stability of the relationship between climate and annual radial tree-growth were calculated using a bootstrap procedure (Guiot, 1991) in R libraries *dpIR* (Bunn, 2010) and *BootRes* (Zang, 2011).

A linear model was used to compute the relationship between tree-ring indices and climate data. To assess the quality of the model for climate reconstruction, the period of the measured meteorological data was split into two equal periods for calibration and verification (Fritts, 1976). The procedure was then repeated with the periods reversed. The reliability and prediction skill of the model was tested using mean squared error (MSE), reduction of error (RE) (Fritts, 1976), coefficient of efficiency (CE) (Cook et al., 1999) and Pearson's correlation coefficient ( $r$ ). Values were computed for both calibration and verification periods. If RE and CE coefficients are higher than zero, the relationship has a predictive value, and a transfer function can be calculated and applied on the regional chronology. Application of the transfer function on the chronology over a period of time for which there is no climate data results in reconstruction of the climate.

Years of extreme cold/warm springs and cool/hot summers were defined as years in which the reconstructed mean January–March or May–August temperatures were below or above the specified threshold. This approach was used by Touchan (2008) in the analysis of reconstructed precipitation in Tunisia. Thresholds can be specified

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by the final user of the reconstruction. In our case, we used 15th and 85th percentile thresholds.

### 3 Results

#### 3.1 Climate signal analysis

5 One local chronology was constructed for each sampled site in BiH. For more information about the chronologies, see Poljanšek et al. (2012). The temperature and precipitation (not shown here) signals in site chronologies were tested using Pearson's correlation coefficient between tree-ring indices and the CRU TS3.1 climate dataset for the period 1901–2009 from January to October (Jones and Harris, 2008). Two distinct and significant responses between site tree-ring indices and average monthly temperatures were found (Fig. 1).

On the sites Blace, Peručica, Šator and Konjuh, we found a significant response to mean monthly January, February and March temperatures. On the other three sites, Krivaja, Prusac and Šipovo, we identified a clear response of TRW to mean monthly 15 May, June, July and August temperatures and summed precipitation. Based on correlation analysis (Fig. 1), we combined the site chronologies into two parts, reflecting spring and summer responses to climate. The sampled trees from the sites Blace, Peručica, Šator and Konjuh aggregated into a “SPRING” group and trees from the sites Krivaja, Prusac and Šipovo aggregated into a “SUMMER” group. Two newly developed group chronologies were developed in this way (Fig. 2). The chronology for the 20 SUMMER group, constructed from a combination of trees from the associated sites, is longer than the SPRING chronology. According to EPS values, however, the time-span of the chronology available for reconstruction is longer for the SPRING group (Table 2, Fig. 2). While there are some differences between the groups in the mean values of raw 25 chronology (mean) and standard deviation (STD), the value of mean sensitivity (MS) is practically the same (Table 2).

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In the next step, group residual chronologies were compared to monthly climate data and created aggregates of January-February-March (JFM) and May-June-July-August (MJJA) climate variables (Fig. 3). While the SPRING group chronology has a significant January-February-March signal and weak summer signal, the SUMMER group chronology has a distinct summer (May-June-July-August) and weak early year (early spring) signal. Pearson's correlation coefficients between the TRW indices and temperature were 0.40 ( $p < 1\%$ ;  $n = 109$ ) for JFM in the SPRING group and  $-0.58$  ( $p < 1\%$ ;  $n = 109$ ) for MJJA in the SUMMER group. In the SPRING group, MJJA temperature and precipitation influence are also significant, but not stronger than in the SUMMER group.

The spatial strength of the SPRING and SUMMER chronologies, tested using spatial correlation in KNMI Climate Explorer (van Oldenborgh, 1999), showed that the SPRING residual chronology correlates best with the aggregated JFM average temperature ( $0.4 > r > 0.5$ ,  $p < 0.05$ ) in the area extending north to Hungary, east to the Black Sea, south to Greece and west to the Adriatic Sea (Fig. 4, left). The SUMMER residual chronology correlates best with the aggregated MJJA temperature ( $-0.6 < r < -0.5$ ,  $p < 0.05$ ), covering the complete western and major central part of the Balkan Peninsula, from Greece to Hungary (Fig. 4, right). This makes our chronologies valuable proxies for large-scale climate reconstruction.

### 3.2 Temporal stability of the climatic signal

The correlation between TRW indices and MJJA temperatures for the SUMMER group chronology was  $-0.58$  and with MJJA precipitation 0.55 (in both cases  $n = 108$ ,  $p < 0.001$ ). For the SPRING group chronology, the correlation between TRW indices and JFM temperatures was 0.40 ( $n = 108$ ,  $p < 0.001$ ). In addition to the statistical significance of the correlation coefficients for the whole period of available meteorological data (1901–2009), we also tested the temporal stability of the relationship between temperature and precipitation data and tree-ring indices using a 31-yr running correlation, lagged by 1 yr, as previously used by Brázdil et al. (2010). The MJJA temperature

and precipitation signals in the SUMMER group are stable between 1901 and 1965 (Fig. 5). After that period they start to approach a 95 % significance line and reach the level of significance between 1981 and 1982. The 31-yr running correlation revealed that the JFM temperature signal in the SPRING group is stable in the period between 1901 and 1941, when the latter repeatedly oscillates around the 95 % significance line (not shown here). This indicates that the late winter-early spring signal in the TRW is weaker than the summer signal.

### 3.3 Transfer function development

Based on correlation analysis, we developed three linear models between the newly developed TRW indices and mean JFM, MJJA temperatures and summed MJJA precipitation. The model for the first equation is:  $Y = 19.74 - 4.13X$  ( $F = 54.2$ ,  $p < 0.0001$ ), where  $Y$  is the mean MJJA temperature ( $^{\circ}\text{C}$ ) and  $X$  represents TRW indices of the SUMMER group. The predictor variable accounts for 34 % of the variability of the climate. The second regression model, between the SUMMER group TRW indices (predictor) and the sum of MJJA precipitation (prediction), is also significant ( $F = 43.7$ ,  $p < 0.0001$ ). The model equation is:  $Y = -12.76 + 347X$ , where  $Y$  is the sum of MJJA precipitation (mm) and  $X$  represents the TRW indices. The predictor variable accounts for 29 % of the variance. The third regression model is between the TRW indices (predictor) of the SPRING group and mean JFM temperature (prediction). The model equation is:  $Y = -4.74 + 4.58X$ , where  $Y$  is the mean JFM temperature ( $^{\circ}\text{C}$ ) and  $X$  represents the TRW indices. The model is significant ( $F = 17.8$ ,  $p < 0.0001$ ). The predictor variable accounts for only 14 % of the variance, which is less than with the first two models. The prediction skill and stability of all three models was verified using a split-sample procedure, by dividing the period into two subsets of equal length for calibration and verification; 1901–1955 and 1956–2009 (see Table 3 and Fig. 6).

Comparing the results of correlation analysis and the split-sample procedure between MJJA temperature and precipitation for the SUMMER group, we identified mean MJJA temperature as the most significant seasonal predictor for the reconstruction,

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with RE and CE values 0.35 and 0.32, respectively (Table 3). The split-sample calibration-validation exercise indicated stability of the relationship over the two halves of the available instrumental data period (Table 3 and Fig. 6). The similarity and strength of the derived calibration equations and verification tests of the two subset periods justify using the full period for developing the mean MJJA temperature reconstruction. For the SPRING group, the correlation analysis and split-sample calibration-validation exercise confirm JFM temperature as the significant seasonal predictor for the reconstruction (Table 3). Since all RE and CE values are greater than 0, the transfer functions can be used for the reconstruction of JFM and MJJA temperatures.

### 3.4 Identification of hot and cool summer periods

The 15th and 85th percentiles of observed mean MJJA temperature (15.7 °C), computed for the period 1901–2009, were used to delineate cool and hot summers. For the observed temperature, the 15th percentile corresponds to 14.75 °C and the 85th percentile to 16.58 °C. For the predicted temperature, the same percentiles (15th and 85th) for the selected period are 15.08 and 16.33 °C, respectively. The same percentiles correspond to different thresholds for observed and predicted MJJA temperatures, which is a consequence of compression of variance in the reconstruction process (Touchan et al., 2008). The correlation coefficient between the reconstructed and observed temperatures is 0.58 ( $n = 109$ ,  $p < 0.001$ ). With a threshold set at the 15th and 85th percentiles, we were able to reconstruct 6 out of 17 observed hottest summers and 6 out of 17 observed coolest summers in the available meteorological data set. The years 1945, 1947, 1950, 1988, 2000 and 2003 were identified as hot and 1913, 1926, 1959, 1960, 1978 and 1984 as cool summers (Fig. 7).

Reconstructed cool and hot summer periods were identified in a two-step procedure; first with a threshold for observed temperatures and then with threshold for predicted temperatures. The designations of hot and cool summers discussed in subsequent sections are based on the 14.75 °C and 16.58 °C thresholds defined from the percentiles of the measured temperature (Fig. 7). With 14.75 °C and 16.58 °C as thresholds, the

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reconstruction for the period 1701–2009 contains 15 cool (1710, 1711, 1729, 1735, 1831, 1833, 1870, 1871, 1885, 1896, 1898, 1913, 1959, 1966, 1984) and 16 hot summers (1715, 1725, 1782, 1802, 1823, 1835, 1872, 1880, 1907, 1945, 1947, 1950, 1958, 1968, 1971, 2000) (Fig. 8).

### 5 3.5 Identification of cold and warm spring periods

The 15th and 85th percentiles of observed mean JFM temperature ( $-0.2^{\circ}\text{C}$ ) computed for the period 1901–2009 were used to delineate cold and warm springs. For the observed temperature, the 15th percentile corresponds to  $-1.97^{\circ}\text{C}$ , and the 85th percentile to  $1.34^{\circ}\text{C}$ . For the predicted temperature, the same percentiles (15th and 85th) for the selected period are  $-0.84$  and  $0.47^{\circ}\text{C}$ , respectively. The correlation coefficient between the reconstructed and observed temperatures is 0.40 ( $n = 109$ ,  $p < 0.001$ ). According to the chosen percentiles, the springs of 1902 and 1989 were identified as warm and 1905, 1917, 1929, 1940 and 1963 as years with a cold spring (not shown here). With a threshold set at the 15th and 85th percentiles, we were able to reconstruct 2 out of 17 observed warm springs and 5 out of 16 observed cold springs in the chosen meteorological data set. With  $1.34^{\circ}\text{C}$  and  $-1.97^{\circ}\text{C}$  as thresholds, the reconstruction from the SPRING group for the period 1685–2009 contains three cold (1725, 1763, 1782) and three warm springs (1772, 1843, 1876) (Fig. 9).

## 4 Discussion

### 20 4.1 General response to climate

Temperature reconstruction for the north-western part of the Balkan Peninsula is based on the *P. nigra* TRW chronologies for the BiH area (Poljanšek et al., 2012). Each site chronology was compared to CRU TS3.1 climate data for the BiH area. Correlation analysis (Fig. 1) confirmed that the mountain ridges in BiH represent a climatic barrier

between Mediterranean and continental climate, similar as Pirin Mountains in south-west Bulgaria spatially mark a transition between the Mediterranean and temperate climate zones (Grunewald et al., 2009). Four out of seven site chronologies showed a significant response to spring temperatures, while the remainder showed summer temperature and precipitation signals. Based on a correlation matrix (Fig. 1), we divided the studied sites into two groups – SUMMER (Krivaja, Prusac, Šipovo) and SPRING (Blace, Peručica, Šator and Konjuh) group. The SPRING sites are located on the Mediterranean exposed wet side of the Dinaric massif and are more influenced by spring temperature, while the SUMMER sites are located in the eastern, drier side of the Dinaric massif (or in the precipitation shadow) and are more under the influence of summer temperatures (Fig. 4). The exception is the Konjuh site (in the SPRING group), since it is located in the interior of BiH but contains a significant spring temperature signal. This may be connected to the serpentine bedrock of the site, since serpentine is a water bearing rock. Krivaja is also on serpentine but its elevation is only 500 m, which may be why it has a summer climate signal.

In general, the annual radial growth of *P. nigra* in BiH is influenced positively by January to March temperatures of the current year and negatively by mean May to August temperatures, while precipitation in the period May–August has a positive affect (Fig. 3). This result is similar to that from sub-Mediterranean Slovenia, where a positive influence of winter-spring temperatures and negative influence of summer temperatures has been reported (Ogrin, 2005). January and March temperatures of the current year have no direct influence on cambium activity, but their positive influence on radial growth can be explained through water availability at the beginning of the growing period, caused by mild and wet winters.

Mild and wet winters over the western part of the Balkan Peninsula are connected to negative NAO phases (López-Moreno et al., 2011). During the negative NAO phases, the meridional sea level pressure is weakened, favouring the advection of warm Atlantic influences. In addition, strong meridional flows advect cold air into Northern Europe. For negative NAO winters, the Western Balkans experience anomalously cyclonic

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circulation and enhanced precipitation and therefore sufficient soil recharge. This has a positive influence on a wider radial increment of *P. nigra*. During cold winters, storm tracks from the Atlantic move towards Northern Europe, leading to dry winters in the Mediterranean, including the Western Balkans. Lopez Moreno and Vicente Serrano (2008) report that, during negative phases, the standardized precipitation index is dominantly positive in Southern Europe, including the Balkans, indicating wet conditions.

Radial growth of *P. nigra* in the mountains of the western part of the Balkan Peninsula is negatively affected by above-average May–August temperatures and positively by precipitation in the same period. This contradicts findings from the Alps, where tree growth is mainly influenced by temperature and the influence of above-average temperatures on tree-ring formation is positive (Frank and Esper, 2005; Rossi et al., 2007; Levanič et al., 2009; Carrer et al., 2007) or in the drier Mediterranean region, where precipitation governs tree-growth (Touchan et al., 2005b, 2008). The reason why our findings are not identical to observations in other parts of the Mediterranean region, where precipitation plays an important role in tree growth and the dynamics of TRW formation (Touchan et al., 2005a, 2007), may be orographic precipitation. The weaker precipitation signal in BiH comparing to those from the Mediterranean region (Martín-Benito et al., 2010b; Touchan et al., 2005b) may be a consequence of high amounts of precipitation along the Adriatic coast. Although significant, the precipitation signal in the TRW is not as strong as the temperature signal, because the Dinaric Mountains, stretching along the Adriatic coast, are well supplied with water. Towards the interior of the Balkan Peninsula and in Central Europe, an increasing influence of precipitation on growth has been observed in the Vienna basin region (Strumia et al., 1997) and Romania (Levanič, 2012), where *P. nigra* reacts more strongly to July rainfall than to temperatures. Similar results have been reported from Turkey, where *P. nigra* responds positively to summer precipitation, but not to temperature (Sevgi and Akkemik, 2007).

In contrast to the relatively uniform response to a single climatic factor, a combined response of *P. nigra* to precipitation and temperature has been reported from Albania and Spain, which is similar to our finding in BiH. In Albania, a significant negative

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response to June, July and August temperatures and positive response to June precipitation on tree radial growth has been observed, while the influence of May temperatures was just on the limit of significance (Levanič and Toromani, 2010). In Spain, July and August temperature and precipitation have a significant effect on tree-ring formation (Martín-Benito et al., 2010a). Our findings are therefore more in accordance with results from Albania and Spain than those from other countries.

The SUMMER group contains stable and significant temperature ( $r = -0.58$ ) and precipitation ( $r = 0.40$ ) signals (Fig. 3). Signals are stable from the beginning of the climate CRU dataset, until the end of the 1960s (Fig. 5). Weakening of the signal occurs simultaneously with changes in summer precipitation and temperature decadal variations. The period of decreased sensitivity of trees to summer temperature and precipitation starts at the end of the 1960s and lasts to the beginning of the 1990s. According to Mariotti and Dell'Aquila (2012), this period was characterized by outstanding decadal variations of summer temperature over the entire Mediterranean region. The coolest periods in the Mediterranean region after 1950 were during the 1960s and 1970s, with the coolest summer in 1976 and the warmest summers in the 1990s. Mediterranean summer temperature anomalies were also very well reflected in BiH, where the coolest summer was recorded in 1974 and the warmest summers in 1994, 1998 and 2000. The cooling trend for the period 1950 to 1960 is  $-1.15^{\circ}\text{C decade}^{-1}$ , whereas a trend of  $0.5^{\circ}\text{C decade}^{-1}$  was recorded for the period between 1980 and 1999 (Xoplaki et al., 2003). There is also a clear tendency for wetter summers between 1967 and 1985 over the Balkan region, when compared to previous decades (Blade et al., 2011), while the period after 1985 was characterized by drier summers. It should be emphasized, though, that the drying trend after 1970 was less pronounced than the wetting trend two decades earlier.

Precipitation variations on decadal and multi-decadal scales are significantly affected by the variability of the North Atlantic Oscillation (NAO), which modifies sea level pressure and associated circulation anomalies (Mariotti and Dell'Aquila, 2012). Summer temperature, on the other hand, is significantly influenced by the Atlantic multi-decadal

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Oscillation (a mode of variability occurring in the North Atlantic Ocean and which has its principal expression in the sea surface temperature field). Summer NAO (SNAO) explains around 30 % of decadal precipitation variability over the Balkans (Folland et al., 2009). It has been shown that the existence of upper level troughs over the Balkans, Italy and Spain can explain the SNAO influence on summer precipitation (Blade et al., 2011). Associated mid-level cooling of the troposphere increases the potential instability of the atmosphere, which leads to favourable conditions for the development of summer convection. The correlation between SNAO and the Lifted Index (a measure of potential instability of an air parcel) is negative over the Mediterranean region, which indicates unstable conditions during positive SNAO (Blade et al., 2011). High SNAO values can be observed during the wetter and cooler period between 1968 and 1985. More local patterns indicate that the number of summer cyclones in the central part of the Adriatic Sea increased significantly after 1970, affecting precipitation in the Western Balkans (Bartholy et al., 2009). This concept is important, since large scale patterns are important in triggering local summer convection. Regional processes and feedbacks modulate the influence of large scale anomalies over the Mediterranean during summer. Mariotti and Dell'Aquila (2012) have shown that these processes may involve cloud cover, land surface modifications and include positive soil moisture-precipitation and soil moisture-temperature feedback.

Many regional processes that were modified due to increased SNAO could mask the significant relationship among precipitation, temperature and tree growth. These processes can have a profound impact on tree growth, since incoming solar radiation and moderate heat flux are supporting factors for growth (Weitzenkamp et al., 2007). The weakening of the correlation between radial tree growth and climatic variables after 1970s (Fig. 5) may therefore be a consequence of changes in large-scale circulation patterns, which affect local stability conditions and therefore many regional processes. Changes in incoming solar radiation due to increased cloud cover could weaken the temperature and precipitation growth relationships of *P. nigra* by having a direct effect on gross primary production. Identification of significant processes is beyond the

scope of this article but should be addressed in future studies. Such variation or weakening of the summer temperature/precipitation signal in SUMMER group is not seen in the SPRING group. Analysis of cyclone activity over the Adriatic Sea has revealed that more pronounced changes in cyclone frequency occur during the summer than in spring (Bartholy et al., 2009), which is thus in accordance with the observed signal in the SPRING group.

Evidence of change in the climate-growth relationships for *P. nigra* is reported for almost the same time period for Austria (Leal et al., 2008) and the Eastern and Northern Iberian Peninsula for *P. nigra*, *Pinus sylvestris* (L.) and *Pinus uncinata* (Ramond ex. DC) (Andreu et al., 2007). The decrease in sensitivity of *P. nigra* trees in Austria is ascribed to an improvement in water-use efficiency arising from a stimulation of photosynthesis and declining stomatal conductance as a consequence of the increasing CO<sub>2</sub> concentration in the atmosphere (Leal et al., 2008). On the other hand, Andreu et al. (2007) report that, at the end of the first half of the 20th century, the relationship between tree growth and late summer/autumn temperatures of the year before growth changed and became stronger. Higher correlations between larch tree growth and summer temperature after the 1970s are also reported from the Maritime French Alps (Büntgen et al., 2012). Sarris et al. (2007), meanwhile, present evidence for the Eastern Mediterranean area of rapid mortality of trees due to lack of precipitation after the late 1970s.

## 4.2 Identification of extreme periods

Based on two *P. nigra* chronologies (from two groups), we reconstructed the two most significant climate factors – MJJA temperature for the period 1701–1901 (200 yr) and JFM temperature for the period 1685–1901 (216 yr). The strength of the model for reconstructing extreme cool or hot summer temperatures depends on the percentage of explained variability and user-defined thresholds for percentiles. Again, thresholds are specified by the final user of the reconstruction and the higher percentile values that are chosen, the fewer (but more extreme) events will be discovered. Touchan et al. (2008) used the 12th and 88th percentiles as a threshold for dry and wet extreme events. Their

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correlation between reconstructed and observed precipitation was  $r = 0.79$ , which is stronger than ours ( $r = 0.58$ ). Using the published threshold, we identified only 4 predicted out of 17 observed hottest summers and 4 out of 17 observed coolest summers. We therefore adjusted the threshold to the 15th and 85th percentiles and re-applied the model to the reconstructed series and discovered additional extreme years. With the new threshold, we could predict 6 out of 17 observed hottest summers and 6 out of 17 coolest summers (Fig. 7). When using the threshold of the 15th and 85th percentiles on reconstructed MJJA temperature in the period 1701–1901, we discovered 15 cool and 16 hot summers (Fig. 8). Reconstructed extreme hot and cool summers in BiH were compared to those published in the literature for other regions (Table 4). We also tested the 12th and 88th percentiles (Touchan et al., 2008) for identification of extreme spring events. Using the 12th and 88th percentiles, we discovered 4 cold and 1 warm spring, while with our threshold, set at the 15th and 85th percentiles, we were able to reconstruct 2 out of 17 observed warm and 5 out of 16 observed cold springs in the chosen meteorological data set. Years 1917, 1940, 1963 were recognized as years with cold JFM period in BiH; this years had also anomalously cold January-April seasons over much of Europe and the Mediterranean area (Luterbacher et al., 2010). Due to the poorer strength of the relationship between temperature and TRW indices in the SPRING group, the number of extreme JFM events is lower than with MJJA.

Comparing the identified hot and cool summers to reported extreme events from the surrounding regions, some common events between the Eastern Mediterranean and Continental Europe were observable. For example, the summer of 1725 was the hottest in our reconstruction and it was part of a two-yr major drought in Anatolia and Syria (Touchan et al., 2007). Similarly, there is a connection with Slovakia and the Czech Republic, since our predicted cool summer in 1871 coincides with a climatic event in Slovakia (Büntgen et al., 2010b). In general, cool summers (1984, 1896, 1871, 1831, 1735) are related to oscillation patterns from Continental Europe and regions north of BiH, while warm events (1802, 1782, 1725, 1715) are more related to oscillation from the South-Eastern/Eastern Mediterranean (Table 4). Our results are supported

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by the strong and consistent anti-phase relationship between a summer temperature reconstruction from Bulgaria and a reconstruction of the sNAO, which suggests that the sNAO pattern is the main driving force of the teleconnection between summer temperatures in South-Eastern versus North-Western Europe (Trouet et al., 2012).

5 Comparing years with extreme hot summers to years with extreme cold springs (since both hot summers and cold springs have a negative effect on radial growth), we found that 1725 and 1782 were extreme in both groups. Cool and wet conditions in the spring of 1725 prevailed over BiH and Slovakia (Brázdil et al., 2008). Later, during the summer of the same year, extensive anomalous low-pressure conditions, extending from Northern to Central Europe, may have been connected with the wet and cool conditions over Slovakia (Brázdil et al., 2008), while BiH was influenced by the hot summer weather from the Eastern Mediterranean, similar to Anatolia and Syria (Touchan et al., 2007). The winter of 1782, also found in BiH, is reported for Greece as harsh and cold, with Lake Karla freezing and the destruction of olive and fruit trees, as well as the death of animals, while plague and the deaths of people are mentioned for BiH (Xoplaki et al., 2001). Later in the year, drought events during the summer season extended north to Slovakia (Büntgen et al., 2010a), east to the Western Black Sea region of Turkey (Akkemik et al., 2005) and south-west to BiH.

20 The winter of 1929 is also interesting, characterized as an extremely cold winter in Slovakia (Büntgen et al., 2011). In this year, the sea froze in the Venice lagoon (Camuffo and Enzi, 1992). The average monthly January–March temperature in 1929 for BiH was  $-3.9^{\circ}\text{C}$ , while the long term average (1901–2009) was  $-0.2^{\circ}\text{C}$  (Jones and Harris, 2008). Although the influence of the severe cold winter of 1929 in BiH was identified by the 15th percentile of measured and predicted spring JFM temperatures, it did not exceed the adapted threshold values for reconstruction (with a predicted value of  $-1.63$  it does not pass the threshold of  $-1.97$ ). It was not therefore recognized as extreme in the spring temperature reconstruction. This suggests that the springs of 1763 and 1782 were even more extreme from the point of view of tree growth. Events not confirmed in various literatures may be limited to the BiH area only, such as the spring of 1763. For

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closer examination of the discovered climatic events from BiH, further investigation of the documentary archives with an emphasis on the region of the Western Balkans is needed.

## 5 Conclusions

5 The mixed climate response divided 7 site chronologies into two groups. Tree-ring widths of *P. nigra* from the sites Blace, Peručica, Šator and Konjuh (SPRING group) contain a valuable and significant January–March temperature signal, while tree-ring widths from the sites Krivaja, Prusac, Šipovo (SUMMER group) contain May–August temperature and precipitation signals. Both signals from the SUMMER group are stable  
10 from the beginning of the available CRU TS3.1 climate data until the late 1960s. In the period 1970–1990, trees had a weaker response to summer climate. We associate this with circulation patterns in the Adriatic Sea, where, according to the literature, the number of summer cyclones in the central part of the Adriatic Sea increased significantly after 1970, affecting precipitation distribution and abundance in the Western Balkans and, consequently, also the *P. nigra* response to climate. We proved that mean May–  
15 August temperature is the main factor affecting the growth of the trees of the SUMMER group and January–March temperature from the SPRING group. By means of spring and summer temperature reconstruction and the application of the percentile method for identifying extreme climatic events, we discovered 15 cool and 16 hot summers and 3 cold and 3 warm springs. The identified cool summer events from the BiH area are related to oscillation patterns in Northern and Continental Europe, while hot summer events are more related to oscillation in the South-Eastern/Eastern Mediterranean. More thorough identification of these relationships should be a part of future studies.

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**Table 1.** Characteristics of sampled sites, after Poljanšek et al. (2012).

Site	Latitude/Longitude	Elevation	Slope	Aspect	Bedrock	Sampled trees	Time span
Blace	43° 31' N/18° 07' E	950 m	50°	SE	Dolomite	21	1625–2010
Konjuh	44° 17' N/18° 32' E	1100 m	45°	S	Serpentine	24	1626–2010
Krivaja	44° 13' N/18° 29' E	500 m	60°	NE	Serpentine	18	1667–2010
Peručica	43° 19' N/18° 42' E	1450 m	55°	S	Limestone	33	1603–2010
Prusac	44° 04' N/17° 21' E	1100 m	65°	S	Limestone	15	1694–2010
Šator	44° 11' N/16° 36' E	1300 m	55°	S	Dolomite	20	1813–2010
Šipovo	44° 17' N/17° 12' E	1100 m	60°	S and N	Limestone	35	1576–2005

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**Table 2.** Basic information on the SUMMER chronology, based on trees from the sites Blace, Peručica, Šator and Konjuh, and the SPRING chronology with trees from the sites Krivaja, Prusac and Šipovo (for abbreviations, see text).

Group	Time span	Length	Trees	Cores	Avg. $t_{BP}$	Avg. GLK %	EPS > 0.85	Raw chronology		
								Mean	STD	MS
SUMMER	1576–2010	434	68	109	9.4	66.3	1701	0.79	0.41	0.238
SPRING	1603–2010	407	98	176	10.6	68.3	1685	1.01	0.59	0.239

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**Table 3.** Results of calibration and verification procedure for all three models (see text); MSE – mean squared error; RE – reduction of error; CE – coefficient of efficiency;  $r$  – simple Pearson's correlation coefficient;  $r^2$  – regression coefficient or explained variance. Stars denote significance of the linear model.

	Mean MJJA Temperature		Sum MJJA Precipitation		Mean JFM temperature	
Calibration	1956–2009	1901–1955	1956–2009	1901–1955	1956–2009	1901–1955
Verification	1901–1955	1956–2009	1901–1955	1956–2009	1901–1955	1956–2009
MSE	0.64	0.73	389	363	2.42	1.78
RE	0.35	0.28	0.33	0.22	0.19	0.08
CE	0.32	0.31	0.25	0.31	0.06	0.25
$r$	–0.53**	–0.67***	0.47***	0.59***	0.28*	0.48***
whole $r$	–0.58***		0.54***		0.40***	
$r^2$ -cal	0.28***	0.45***	0.22***	0.35***	0.08*	0.23***
$r^2$ -ver	0.45***	0.28***	0.35***	0.22***	0.23***	0.08*

\* =  $p < 0.05$ , \*\* =  $p < 0.01$ , \*\*\* =  $p < 0.001$ .

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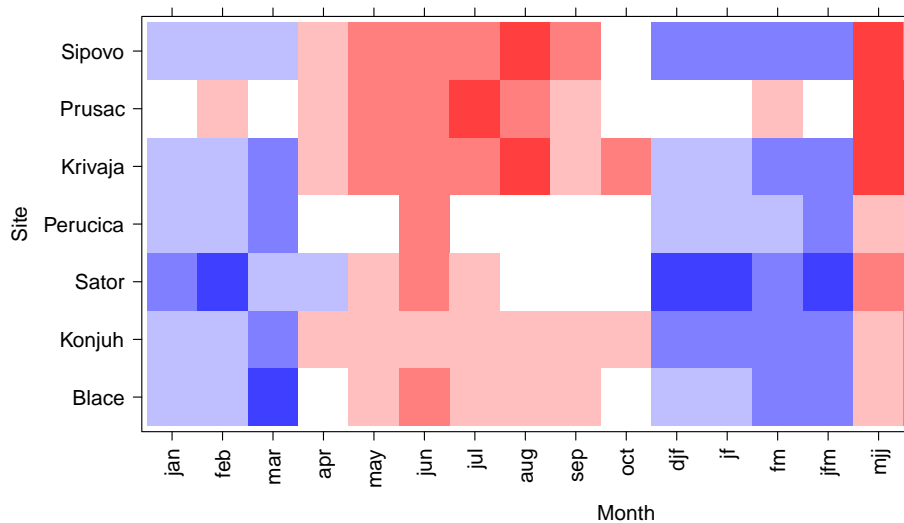
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**Table 4.** List of cool/hot summers and cold/warm springs, compiled from various climate reconstructions and documentary sources. Those that are presented are common to the temperature reconstruction in BiH.

Cool	Hot	Historical summer events	Reference
1984		Italy, north-central: spring killing frost	Camuffo et al. (2010)
	1950	Italy, south area: one of the hottest summers	Camuffo et al. (2010)
	1947	Slovakia: dry spell from March–August	Büntgen et al. (2010b)
1896		Wet year in Western Black Sea region of Turkey	Akkemik et al. (2005)
		Northern-Central Italy: humid summer	Camuffo et al. (2010)
1871		Slovakia: wet from April to June (very wet in May)	Büntgen et al. (2010b)
		Czech Lands: 3 weeks of rain in July–August	Büntgen et al. (2010b)
		Wet year in Western Black Sea region of Turkey	Akkemik et al. (2005)
1870		Hungary: Autumn rains	Kiss et al. (2011)
	1835	Slovenia: June–August drought	Ogrin (2002)
1831		Western Europe experiencing cool conditions	Briffa et al. (1988)
		Etna eruption in March, April	Bonaccorso et al. (2004)
	1802	Drought in Cyprus	Fikret and Suraiya (2002)
		Serbia: Lack of rain from May until October	Xoplaki et al. (2001)
		One of the hottest summers in Italy	Camuffo et al. (2010)
	1782	Drought in Western Black Sea region of Turkey	Akkemik et al. (2005)
		Reported low water in Danube due to long-term drought	Büntgen et al. (2010b)
1735		Wet year in Western Black Sea region of Turkey	Akkemik et al. (2005)
1729		Italy, south: coldest winter	Camuffo et al. (2010)
	1725	Major drought in Anatolia and Syria	Touchan et al. (2007)
	1715	Dry year in Western Black Sea region of Turkey	Akkemik et al. (2005)
		Greece: very long dry periods	Xoplaki et al. (2001)
1711		Slovenia: period of above-average wetness	Ogrin (2002)
1710		Former Yugoslavia: bad harvest, famine	Xoplaki et al. (2001)
Cold	Warm	Historical spring events	Reference
1782		Greece: harsh cold, freezing of Lake Karla, destruction of olive-trees	Xoplaki et al. (2001)
		France: spring killing frost	Camuffo et al. (2010)
	1772	Czech: mild winter 1771–1772	Büntgen et al. (2010a)
1725		Slovakia: cool and wet conditions in spring	Brázdil et al. (2008)

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**Fig. 1.** Response of tree-ring width residual site chronologies to different monthly temperature variables for the period 1901–2009. White squares indicate no correlation.

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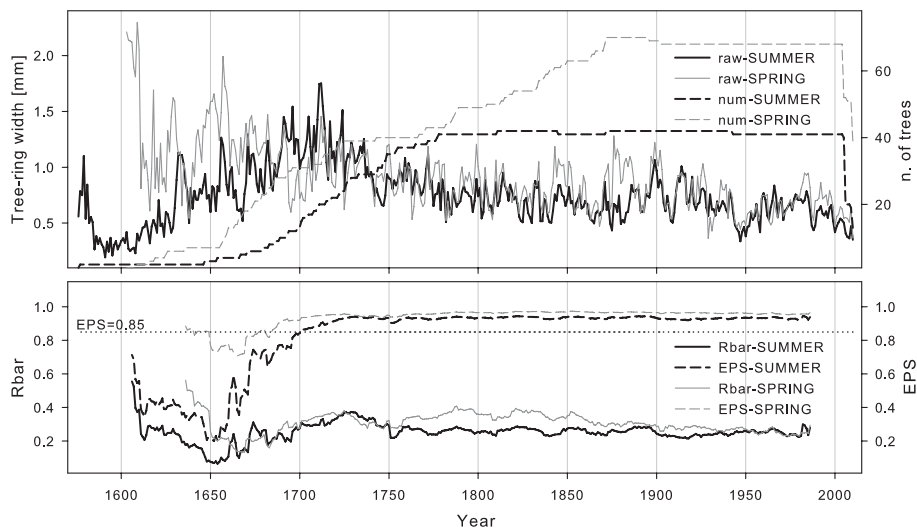
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**Fig. 2.** Raw chronologies (raw) of SUMMER and SPRING group with information on their sample depth (num), with Rbar and EPS of residual chronologies.

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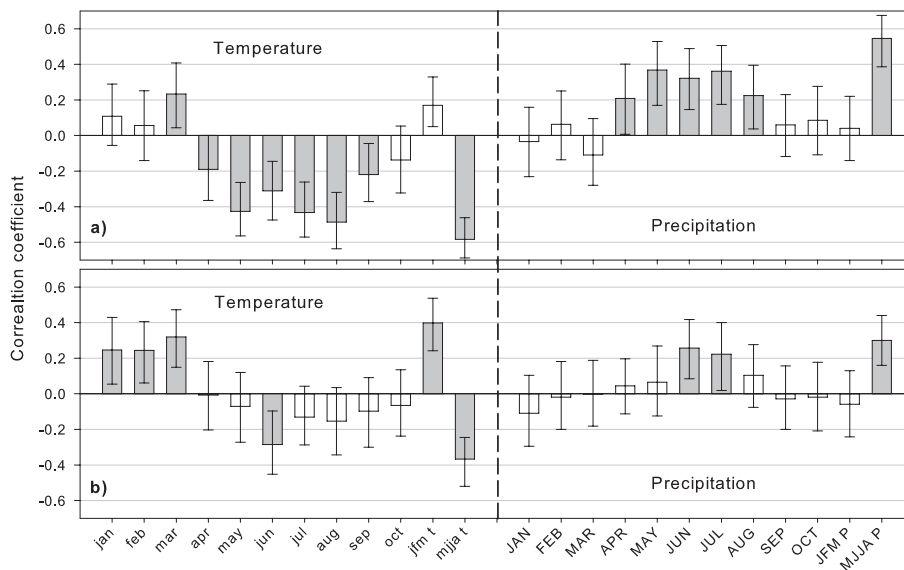
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**Fig. 3.** Bootstrapped correlation coefficients between residual chronology and climate data for the period 1901–2009; **(a)** SUMMER group, **(b)** SPRING group (for abbreviations, see text). Grey bars mark a significant correlation ( $p < 0.05$ ), 95% confidence intervals are displayed with error bars. The left column marks temperature, the right precipitation coefficients.

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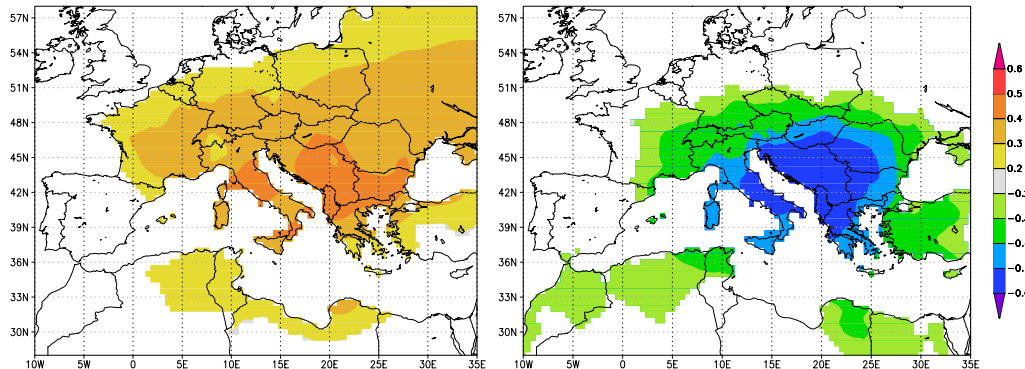
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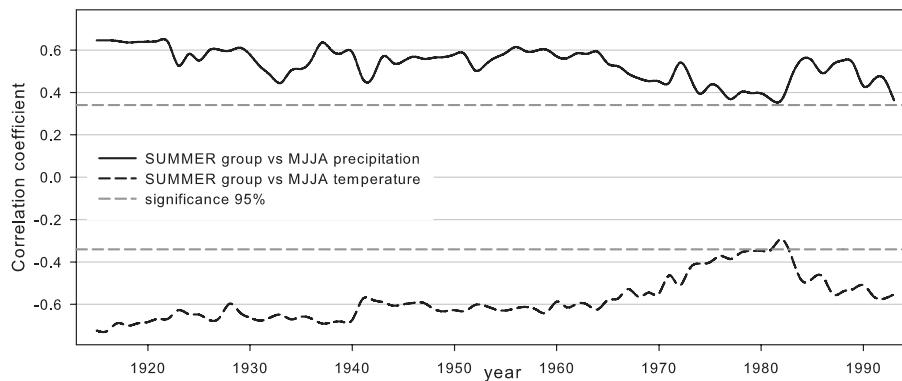


**Fig. 4.** Spatial correlation with 95 % significance for the period 1901–2009 between CRU TS3.1 and mean January–March temperature and aggregated tree-ring width chronology for the sites Blace, Peručica, Šator and Konjuh (left) and mean May–August temperature and aggregated tree-ring width chronology for the sites Šipovo, Prusac and Krivaja (right).

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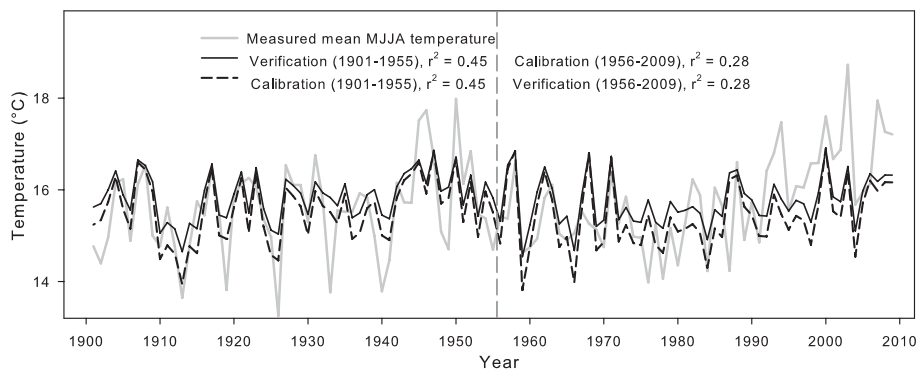


**Fig. 5.** 31-yr symmetrical, non-weighted running correlation between SUMMER group residual tree-ring width series and mean May–August temperature and summed May–August precipitation. Source of climate data: CRU TS3.1 (for abbreviations, see text).

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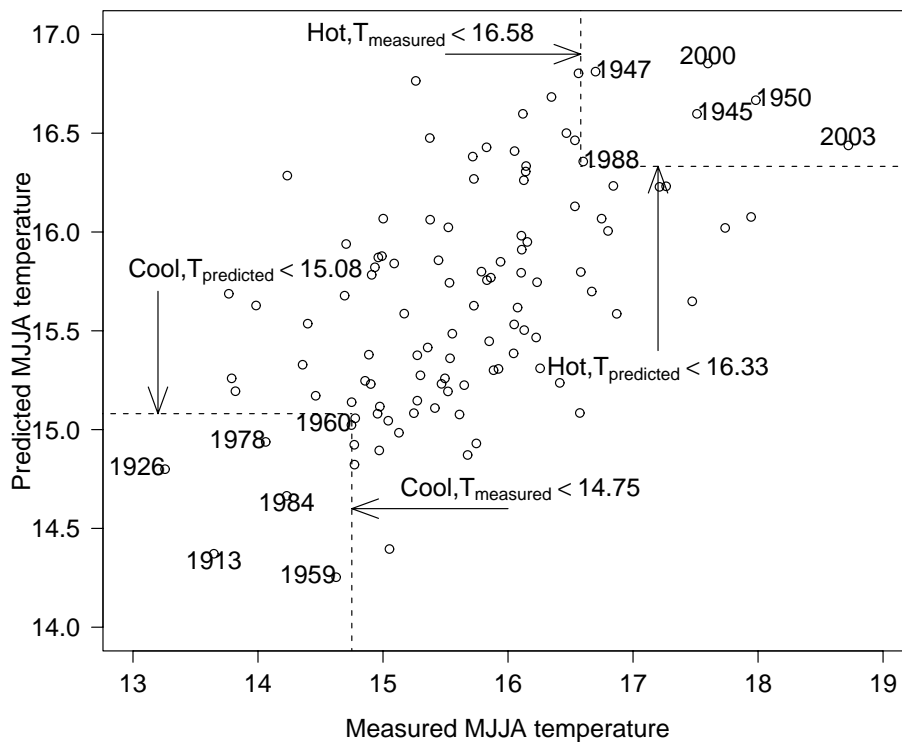


**Fig. 6.** Time series plots of measured (grey line) and reconstructed mean May–August temperature for the calibration and verification periods of the split sample procedure (black and dashed black line).

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**Fig. 7.** Identification of hot and cool summer periods. Dashed lines mark thresholds used to define years with cool or hot summer periods with the 15th and 85th percentiles (see text).

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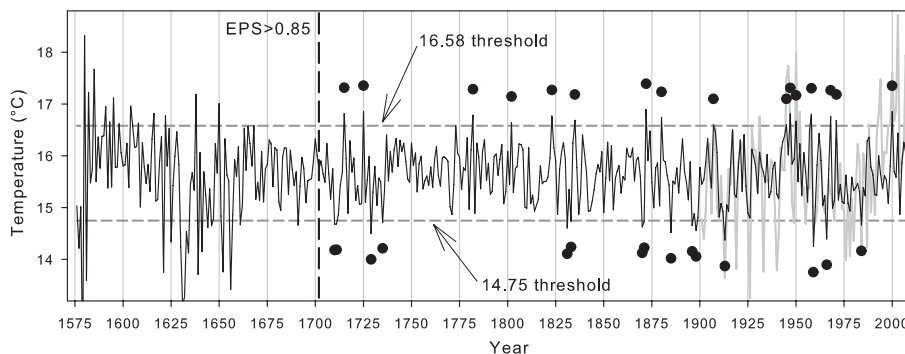
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**Fig. 8.** Comparison of predicted (black line) and observed May–August mean temperatures (grey line) with black circles marking hot and cool summers as defined by 15th and 85th percentile thresholds of the measured data (dashed horizontal lines). EPS marks the end of the usable length of the reconstruction.

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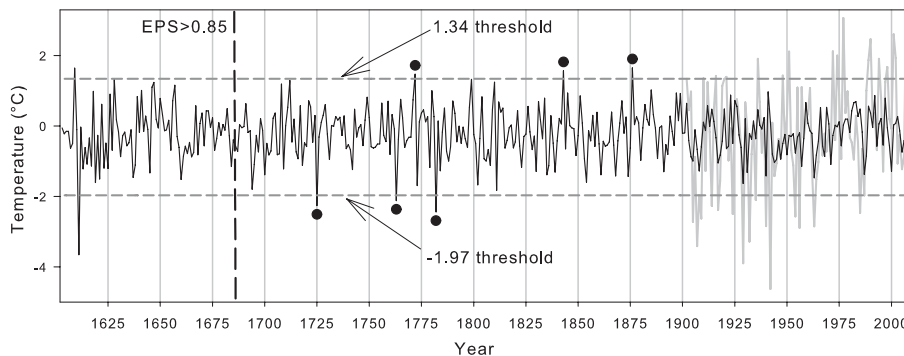
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**Fig. 9.** Comparison of predicted (black line) and observed January–March mean temperature (grey line) with black circles marking warm and cold springs as defined by 15th and 85th percentile thresholds of the measured data (dashed horizontal lines). EPS marks the end of usable length of reconstruction.

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