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Potential to explain climate from tree rings in the south of the Iberian Peninsula

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ABSTRACT: Detecting and extracting the dominant climatic signal from tree-ring records derived from Mediterranean areas remains challenging because the relation between climate and tree-growth are usually characterized by a complex interplay of temperature and precipitation signals, with high spatial and temporal variability. Although several studies have established climate–growth relationships in old forests on the Iberian Peninsula (IP), a reliable calibration level between tree-ring data and the instrumental records making possible the inference of past climate has not yet been established, mainly due to low correlation coefficients (i.e. $r \leq 0.4$) and/or instability over time of the climate–growth relationships. We tested for spatial significance and temporal stability of climatic signals in a collection of tree-ring proxies at the Cazorla Range (NCZ), located in the southeast of the IP. The aim was to identify suitable proxies for further use in climate reconstructions. The tree-ring variables under investigation included tree-ring width (TRW), latewood width (LWw), maximum latewood density (MXD) and stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes. Our results show how the strength and temporal stability of the relationship between tree-ring proxies and selected seasonal climate variables largely depend on the climate data used. Moreover, imprecise identification of the climate signal may lead to erroneous evaluations of temporal stability. Overall, from the set of proxies measured at NCZ, TRW is suitable to reconstruct summer to autumn temperature while $\delta^{13}C$ can potentially be used as a proxy for summer precipitation reconstructions. The calibration–verification trials using both regression and scaling techniques revealed how scaling retains more inter-annual variability but decreases the values of the reduction of error (RE).

KEY WORDS: Tree-rings · Dendroclimatology · Climate signal · Temporal stability · *Pinus nigra* · Stable isotopes

1. INTRODUCTION

The Iberian Peninsula (IP) is characterized by a high climatic vulnerability caused by its location in the transition area between temperate and subtropical climates. A predominantly Mediterranean climate determines cool winters, dry and hot summers and a high spatial and temporal variability in precipitation (Rodriguez-Puebla et al. 1998). Under climate change conditions, this pattern can potentially be altered. Climate projections suggest increases in temperature and decreases in projected precipitation (Gao & Giorgi 2008), and there is already evidence of this in observations (i.e. Zorita et al. 2008). As a consequence, an enhancement of drought conditions is expected (IPCC 2007), which would severely affect vegetation dynamics since they are basically controlled by moisture availability (Piñol et al. 1998).

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In the current climate context, a better understanding of past changes would be valuable to determine to what extent current global changes are unusual, as well as to improve long-term predictive models (Briffa 2000, IPCC 2001). In this regard, proxy-based climate reconstructions are essential for the study of past climate dynamics since the length of instrumental series is very limited, mainly restricted to the 20th century. Up to now, climate reconstructions based on natural proxies are scarcely represented over the IP, especially in terms of tree-ring information (for a review of existing tree-ring based reconstruction in Europe, see Luterbacher et al. 2012). Climate reconstructions of the IP have been carried out based on documentary data (e.g. Barriendos 1997, Rodrigo et al. 2000), lake sediments (e.g. Moreno et al. 2008, Benito et al. 2010) and speleothems (Jiménez de Cisneros et al. 2003, Muñoz et al. 2009), whereas the few existing climate reconstructions based on tree-rings are not well-known in the dendroclimatological community since they were not published in international journals (e.g. Creus Novau et al. 1994, 1995, 2000, Creus Novau 1998, Creus Novau & Saz Sánchez 1999, Candela Jurado et al. 2001). Moreover, the existing tree-ring-based climate reconstructions at the IP are restricted to the Pyrenees (Planells et al. 2006, Büntgen et al. 2008, 2011).

Attempts in reconstructing past climate from tree-ring records in the IP are needed since they might be useful to bridge the gap between existing reconstructions of summer temperature (Büntgen et al. 2008, 2010) and aridity (Planells et al. 2006) in the Pyrenees, on the one hand, and drought reconstructions in Morocco (Esper et al. 2007, Touchan et al. 2010), on the other. To our knowledge, the only existing link is a 216 yr long autumn precipitation reconstruction and a 306 yr long summer temperature reconstruction based on tree-ring widths (TRWs) in the central system of the IP (Fernández-Cancio et al. 1996).

Three general requirements need to be met to develop an optimal tree-ring proxy-based climate reconstruction: (1) data from old trees growing at their limit of natural distribution where climate will have the greatest effects on their development (Fritts 1976); (2) significant relationships with climate parameters; and (3) stability over time of these relationships, since reconstruction are built under the assumption of a linear response of tree growth to climate (uniformitarian principle), and thus, reconstructions are made using simple linear models (Fritts 1976, Cook & Kairiukstis 1990).

Evidence exists of old forests in the Central (Génova Fuster & Fernández-Cancio 1999, Génova Fuster 2000) and Southern (Creus Novau 1998) IP. Among these forests, the Cazorla Range is where the oldest living trees south of the Pyrenees have been found (Creus Novau 1998). The length of the tree-ring chronology that is still reliable is approximately 1000 yr, underlining the crucial importance of these forests. Previous studies conducted at the Cazorla Range have described local stress factors that are growth-limiting enough to potentially reconstruct regional climate variability (Andreu et al. 2007, 2008, Martín-Benito et al. 2008, Dorado Liñán et al. 2011b) and have tested the stability over time of the significant correlations (Andreu et al. 2007, Martín-Benito et al. 2010, Andreu-Hayles et al. 2011). However, due to low correlation coefficients and/or instability over time of the climate–growth relationships, reliable calibrations of the tree-ring data against the corresponding instrumental records have not yet been established. Thus, no tree-ring proxy-based climate reconstructions have been performed.

For the calibration of tree-rings against instrumental records, the changing sensitivity of trees to climate is a fundamental problem in dendroclimatology, since this would imply the truncation of the pre-assumed linear climate–tree growth relationships (Briffa et al. 1998). Several studies have reported a misfit between tree-ring variables (such as TRW and maximum latewood density [MXD]) and temperature measurements in the most recent decades (Jacoby & D'Arrigo 1995, Wilmking et al. 2004, Driscoll et al. 2005, Büntgen et al. 2008, D'Arrigo et al. 2008, Zhang et al. 2008). Such a temporal instability is known as 'divergence' and the real cause is still unclear. There are several hypotheses: anthropogenic causes (Cook et al. 2004), 'end effect' caused by detrending of the series (Cook & Peters 1997, D'Arrigo et al. 2008), age-related effects (Szeicz & MacDonald 1994, Carrer & Urbinati 2004) and uncertainties related to both proxy and instrumental data (Esper et al. 2010a).

In this context, the inclusion of other tree-ring proxies such as stable carbon and oxygen isotopes ($\delta^{13}C$ and $\delta^{18}O$, respectively) will most likely help to shed more light on the possible causes of the 'divergence'. The stable isotope series do not undergo time-series treatments that might be responsible for the misfit with the instrumental records as usually done with TRW and MXD series (e.g. dentrending or standardization procedures; Cook & Kairiukstis 1990, Dorado Liñán et al. 2012b).

In order to make a significant step towards a potential tree-ring based climate reconstruction, we present a first critical evaluation of the potential of several tree-ring records from the Cazorla Range to be used as proxies for climate reconstructions in the South of the IP. The analysis includes (1) the assessment of the spatial significance of the climatic signals encoded in the different tree-ring parameters, (2) the evaluation of the temporal stability of the tree-ring record–climate relationships, and (3) a calibration–verification test against the target climate variable for the tree-ring proxies found suitable for climate reconstructions.

2. MATERIALS AND METHODS

2.1. Tree-ring chronologies

Sampling was carried out in an area called Puertollano-Cabañas in the Cazorla Range (NCZ, hereafter) (37° 48′ N, 02° 57′ W) that is 1800 m above sea level (a.s.l.) (Fig. 1) dominated by an oromediterranean humid climate type (Rivas-Martínez 1983). In a forest dominated by *Pinus nigra* subsp. *salzmannii* (Dunal) Franco (*P. nigra*, hereafter), 89 samples were taken from 43 dominant living trees, with ages ranging from 250 to 902 yr. According to standard procedures, cores were cross-dated visually (Stokes & Smiley 1968), the widths of the tree rings were measured with an accuracy of 0.01 mm, using the linear table Lintab™ (Frank Rinn S.A.) and the TSAP-Win program (Rinn 2003), and finally the quality and correct

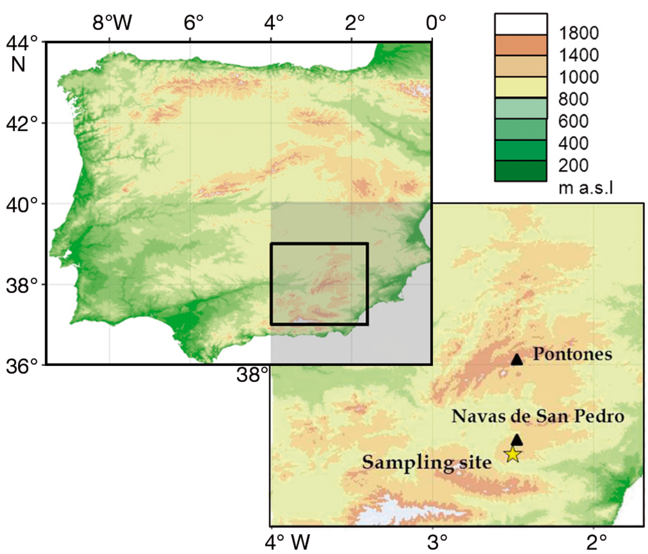

Fig. 1. Sampling area (Cazorla Range, NCZ) and (magnified portion) position of local weather stations (▲) relative to sampling site (☆). Shaded area limits the geographical box of gridded data used as regional climate data. m a.s.l.: meters above sea level

dating of the resulting series was checked with the software COFECHA (Holmes 1983). From the original set of samples, 32 cores were analyzed following X-ray microdensitometric techniques developed by Polge (1965) to obtain the latewood width (LWw) and the maximum density profile of every sample.

From the collection of cores measured for ring width and density, 11 samples were selected for isotopic analysis. Cores were analyzed individually and with annual resolution. For each sample, tree rings were split manually with a scalpel under a stereomicroscope and the α-cellulose was extracted chemically using the sodium chlorite and sodium hydroxide procedure as described in Loader et al. (1997). The extracted and purified α-cellulose was combusted to CO_2 in an elemental analyzer (Fisons NA 1500 NC) coupled via an open split to an isotope ratio mass spectrometer (IsoPrime, GV Instruments) operated in continuous flow mode, to obtain the carbon isotope measurements. Similarly, individual oxygen isotope samples were measured utilizing a TC/EA pyrolysis furnace and a mass spectrometer Delta V Advantage (Thermo Scientific) (more detailed information can be found at Dorado Liñán et al. 2011a). The isotope ratios are given in the conventional delta (δ) notation, relative to the standards Vienna Pee Dee Belemnite for $\delta^{13}C$ and Vienna Standard Mean Ocean Water for $\delta^{18}O$ (Coplen 1995).

Additionally, the $\delta^{13}C$ series were corrected for the decreasing trend introduced by the depletion in atmospheric $^{13}CO_2$ due to fossil fuel burning and deforestation since industrialization (ca. AD 1850). The correction comprised a subtraction of the annual changes in $\delta^{13}C$ of atmospheric CO_2, obtained from ice cores and direct measurements (Leuenberger et al. 1992, Elsig et al. 2009). The correction values were obtained from Leuenberger (2007) and McCarroll & Loader (2004).

Ring width and density series are known to display non-climatic trends due to the increase in trunk diameter associated with aging (Fritts 1976). Therefore, for the development of the TRW, LWw and MXD chronologies, each individual series underwent standard dendrochronological treatments, also called detrending, applied to remove these age-related trends while preserving inter-annual to multi-centennial climate signals (Cook & Kairiukstis 1990). The individual series were detrended fitting a negative exponential function using TurboArstan® (Cook 1999) and the chronologies of the different variables (TRW, LWw and MXD) were built by using a bi-weight robust mean to reduce bias caused by extreme values (Fritts 1976, Cook & Kairiukstis 1990).

Stable carbon and oxygen isotopes are usually not affected by age-related trends and thus, do not require detrending. For the samples used in the current study, the absence of age affects was confirmed in Dorado Liñán et al. (2012a), thus stable carbon and oxygen isotope chronologies ($\delta^{13}C$ and $\delta^{18}O$, respectively) were built by averaging the individual series without any prior detrending.

The signal strength of each master chronology was assessed using the Expressed Population Signal (EPS) (Wigley et al. 1984) to ensure reliability and representativeness of the final chronologies. The period used for the study (1901 to 2006) was found to be reliable for the parameters TRW, LWw, MXD and $\delta^{13}C$, indicated by their high EPS values above 0.85. For $\delta^{18}O$ the EPS was slightly below 0.85 but still reasonably acceptable for the present study (Table 1). The first autocorrelation coefficient (AC1) was obtained for each chronology to calculate the effective sample size (Box et al. 2008), following the formula:

$$N' = N \times \frac{(1 - AC1)}{(1 + AC1)} \qquad (1)$$

where N′ is the effective sample size, N is the sample size and AC1 is the first order autocorrelation.

2.2. Local and regional climate data sets

In order to assess the climate signals in the tree-rings along with their spatial significance, 2 types of climate data were employed for the analysis: climate data from nearby meteorological stations (local) and gridded climate data derived from 4 × 4° boxes (regional).

Local climate data was obtained from the Instituto Nacional de Meteorología (INM) network. Since meteorological stations are not available at the high altitudes where sampling was carried out, the longest records from the nearest stations were chosen. Mean monthly temperatures were derived from Pontones (38° 01′ N; 2° 52′ W) and precipitation data from Nava de San Pedro (37° 52′ N; 2° 53′ W) at 48.9 and 16 km from the sampling site, respectively.

The temperature data are available for the period 1904 to 1999 while the precipitation data cover the period 1912 to 1999.

The corresponding regional climate data were obtained from the CRU TS 3.0 database, which comprises various high resolution gridded monthly data derived from daily climate observations from meteorological stations (Mitchell & Jones 2005) covering the period 1901 to 2006. Temperature data are available in absolute values, precipitation data are anomalies from the reference period 1961 to 1990 (Mitchell & Jones 2005) and additionally, the Palmer Drought Severity Index (PDSI; Palmer 1965) was also used. The meteorological records were derived from a geographical box set to 36–40° N and 4–0° W (Fig. 1).

Table 1. Different tree-ring chronologies from samples from the Cazorla Range including the no. of trees and no. of radii, the detrending technique applied, the expressed population signal (EPS) and the first autocorrelation coefficient (AC1). TRW: total ring width, LWw: latewood width, MXD: maximum latewood density, $\delta^{13}C$: stable carbon isotope ratio, $\delta^{18}O$: stable oxygen isotope ratio, na: not applied; *$p < 0.05$

Chronology	Trees	Radii	Detrending applied (function)	EPS	AC1
TRW	43	89	Negative exp.	0.95	0.35*
LWw	25	32	Negative exp.	0.92	0.22*
MXD	25	32	Negative exp.	0.88	0.06
$\delta^{13}C$	11	11	na	0.86	0.22*
$\delta^{18}O$	10	11	na	0.80	0.23*

2.3. Data analysis

Correlations between each tree-ring variable and monthly local and regional meteorological data were performed from July of the previous year (t − 1) to December of the current year (t). Significance levels for the Pearson's correlation (95 and 99%) coefficient were adjusted according to the effective degrees of freedom of each series. Correlations were also calculated between the most representative seasonal climate variable and the tree-ring variables. Combinations of climate and tree-ring variables displaying highly significant correlations ($p < 0.01$) were analyzed further.

The temporal stability of the highly significant relationships between the tree-ring series and the climate record was assessed in 2 ways. (1) By comparing the correlations between tree-ring series and the seasonal climate record in 2 periods: the first and second halves of the 20th century. When correlations were highly significant ($p < 0.01$) in both periods, the Fisher r-to-z transformation (z) was used to test for significant differences in the correlations of both segments. (2) Both the tree-ring record and the selected seasonal climate variable were correlated using a 50 yr running correlation window to test for the evolution of the relationship during the 20th century.

Tree-ring records that displayed highly significant correlations with climate variables ($p < 0.01$) during both the first and second half of the 20th century, and that exhibited no statistical differences between the sub-periods, were considered most suitable for further dendroclimatic investigations, and thus underwent calibration–verification trials using the split method (Snee 1977). The climate record is split in 2 parts; tree-ring chronologies are calibrated with the first half of the instrumental temperature record and the obtained model is validated on the second half, and vice versa. Calibration against the overlapping instrumental record was performed applying the 2 main methodological techniques: scaling and direct regression (Esper et al. 2005). The coefficient of determination (r^2), Pearson's correlation coefficient between observed and predicted values ($r_{obs–pred}$) and reduction of error (RE) (Cook et al. 1994) were calculated to test the validity of the models derived from both methodologies.

3. RESULTS

3.1. Local and regional climate signals

The magnitude and significance of the linear correlation between the tree-ring records and the local and regional climate data sets show the spatial significance of the climate signals encoded in the different tree-ring parameters (Fig. 2). Correlations of tree-ring parameters and local climate at the NCZ were described in detail in previous studies (cf. Dorado Liñán et al. 2011b). On a regional scale, July to October temperatures of the previous year exert a strong negative influence on TRW ($r = -0.40$, $p < 0.01$) but the influence on LWw is not significant ($r = -0.23$, $p > 0.05$). For both parameters (TRW and LWw), the June to July mean temperature of the current year shows a significant negative influence regardless of spatial scale. The influence of precipitation on the ring-width parameters (TRW and LWw) is generally less significant and spatially more variable. The only highly significant positive correlation is indicated for TRW and the regional June to September precipitation of the previous year ($r = 0.38$, $p < 0.01$).

MXD displays highly significant positive correlations with current winter to spring temperatures ($r = 0.31$ at local and $r = 0.42$ at regional scales, $p < 0.01$) and with July to December precipitation of the previous year ($r = 0.26$, $p < 0.05$ at local and $r = 0.36$, $p < 0.01$ at regional scales). When using regional climate data, both signals are enhanced and summer temperatures of the current year become more influential on MXD.

Stable isotopes show the most remarkable changes in terms of correlations with climate factors on increasing spatial scales. Locally, stable carbon isotopes display significant correlations only with November precipitation of the previous year ($r = 0.28$, $p < 0.05$) and July precipitation of the current year ($r = -0.28$, $p < 0.05$), whereas no significant correlations with monthly temperature data are found. Highly significant positive correlations with local temperatures are found for the season September to October ($r = 0.33$, $p < 0.01$). When applying regional climate variables, the negative correlation of $\delta^{13}C$ with summer precipitation is enhanced. The $\delta^{13}C$ then strongly correlates with monthly July and September precipitation data and the corresponding seasonal sum calculated for July to September ($r = -0.46$, $p < 0.01$). At the same time, $\delta^{13}C$ displays significant positive correlations with August temperatures of the previous year ($r = 0.34$, $p < 0.01$) and September temperatures of the current year ($r = 0.31$, $p < 0.05$). September to October temperatures exert a similar influence to that of the local temperatures.

Regardless of the spatial scale, stable oxygen isotopes do not display significant correlations with monthly temperature and precipitation variables, despite a general pattern of higher correlations with the regional climate data. Only monthly PDSI values display significant negative correlations with $\delta^{18}O$ during the entire growing period and with the seasonal PDSI means of June to July ($r = -0.41$, $p < 0.01$). Similarly, $\delta^{18}O$ significantly correlates with February to September precipitation at regional scales ($r = -0.38$, $p < 0.01$).

The summary of the most significant correlations ($p < 0.01$) with local and regional seasonal climate variables at NCZ (Fig. 3) reveals high correlation coefficients with local and regional temperature data whereas the precipitation signals are only highly significant when using regional climate data. July to October temperatures are the dominant seasonal climate signal influencing TRW on local ($r = -0.54$) and regional ($r = -0.40$) scales, but June to July temperatures of the current year only exert a highly significant influence on LWw at local scales ($r = -0.43$). The opposite results are illustrated for MXD and January to May, showing higher correlations at regional ($r = 0.42$) than local ($r = 0.31$) scales. For $\delta^{13}C$ and September to October temperatures, only small differences can be found between the correlations with local ($r = 0.33$) and regional ($r = 0.34$) climate data.

Precipitation signals are generally weaker and correlations with tree-ring parameters are most significant when applying regional climate data from the

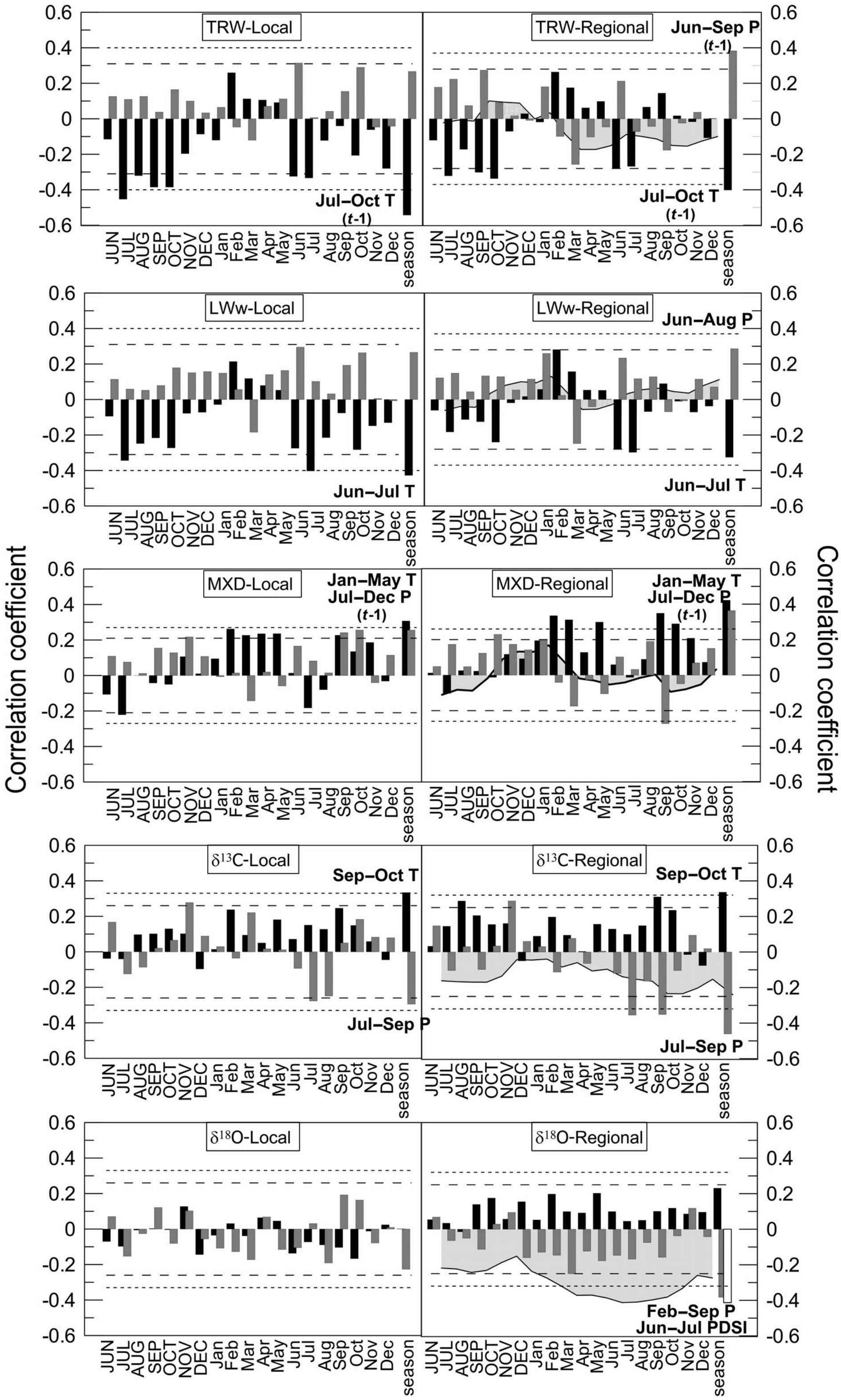

Fig. 2. Monthly correlation coefficients between climate and tree-ring proxies from the Cazorla Range for the period June of the previous year (t – 1; in capital letters) to December of the current year (t; in lower-case letters) at 2 scales: local and regional. Significant seasonal correlations are also shown and labelled with month ranges when significant. Grey bars are correlation with precipitation (P) and black bars with temperature (T). Grey-shaded areas (only shown when significant) and white bar (bottom right panel) indicate correlation with the Palmer Drought Severity Index (PDSI). Dashed and dotted lines: 95 and 99% significance level, respectively. See Table 1 legend for proxy abbreviations

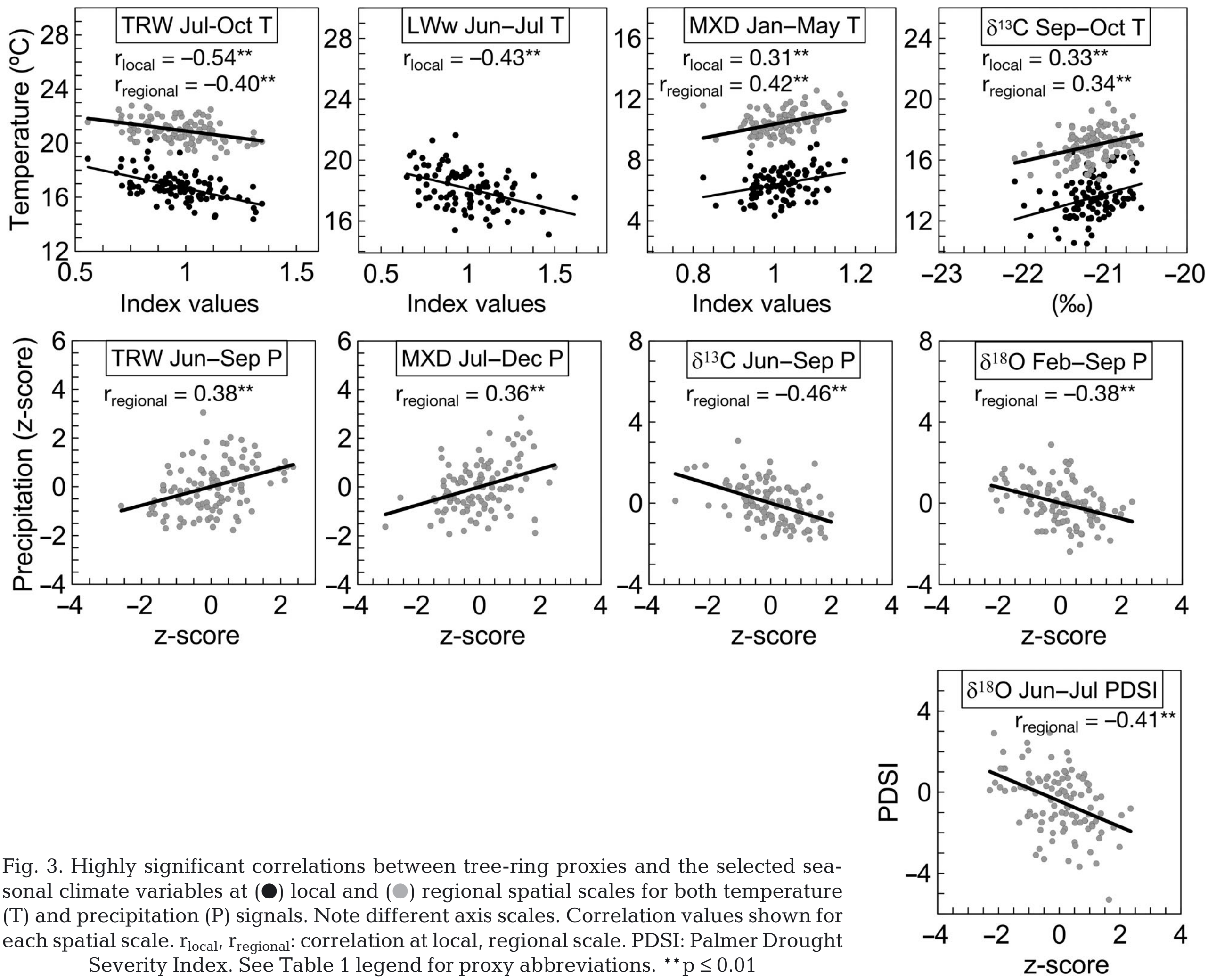

Fig. 3. Highly significant correlations between tree-ring proxies and the selected seasonal climate variables at (●) local and (●) regional spatial scales for both temperature (T) and precipitation (P) signals. Note different axis scales. Correlation values shown for each spatial scale. r_{local}, $r_{regional}$: correlation at local, regional scale. PDSI: Palmer Drought Severity Index. See Table 1 legend for proxy abbreviations. $^{**}p \leq 0.01$

summer season. TRW data display significant correlations with June to September precipitation of the previous year (r = 0.36). Similarly, $\delta^{13}C$ correlates well with June to September precipitation (r = −0.46) of the current year. MXD and $\delta^{18}O$ seem to be influenced by moisture conditions towards the end of the growing seasons. MXD is influenced by July to December precipitation (r = 0.36) and $\delta^{18}O$ correlates significantly with regional February to September precipitation of the current year (r = −0.38). $\delta^{18}O$ is the only tree-ring parameter that displays a significant drought signal, indicated, in particular, by the correlation with the regional June to July PDSI (r = −0.41).

In accordance with Fig. 3, the pattern of field correlations of the seasonal signals (Fig. 4) shows that temperature signals correlate more strongly and with a larger area than precipitation signals. The precipitation signals tend to be weaker and display a more irregular pattern of spatial correlations compared to temperature, while PDSI shows the most localized spatial correlation, concentrated in the Mediterranean margins.

3.2. Stability test of the climate signals

The comparison of the correlations between tree-ring series and the seasonal climate record in the 2 periods reveals that temperature signals are stronger in the first half of the 20th century than in the second half for TRW, LWw and MXD (Table 2). In contrast, $\delta^{13}C$ displays a stronger summer temperature signal in the second half of the 20th century than in the first half for both the local and the regional climate data.

The strengths of correlations between the proxy records TRW and $\delta^{13}C$ and the corresponding target seasonal precipitation data decrease in time, display-

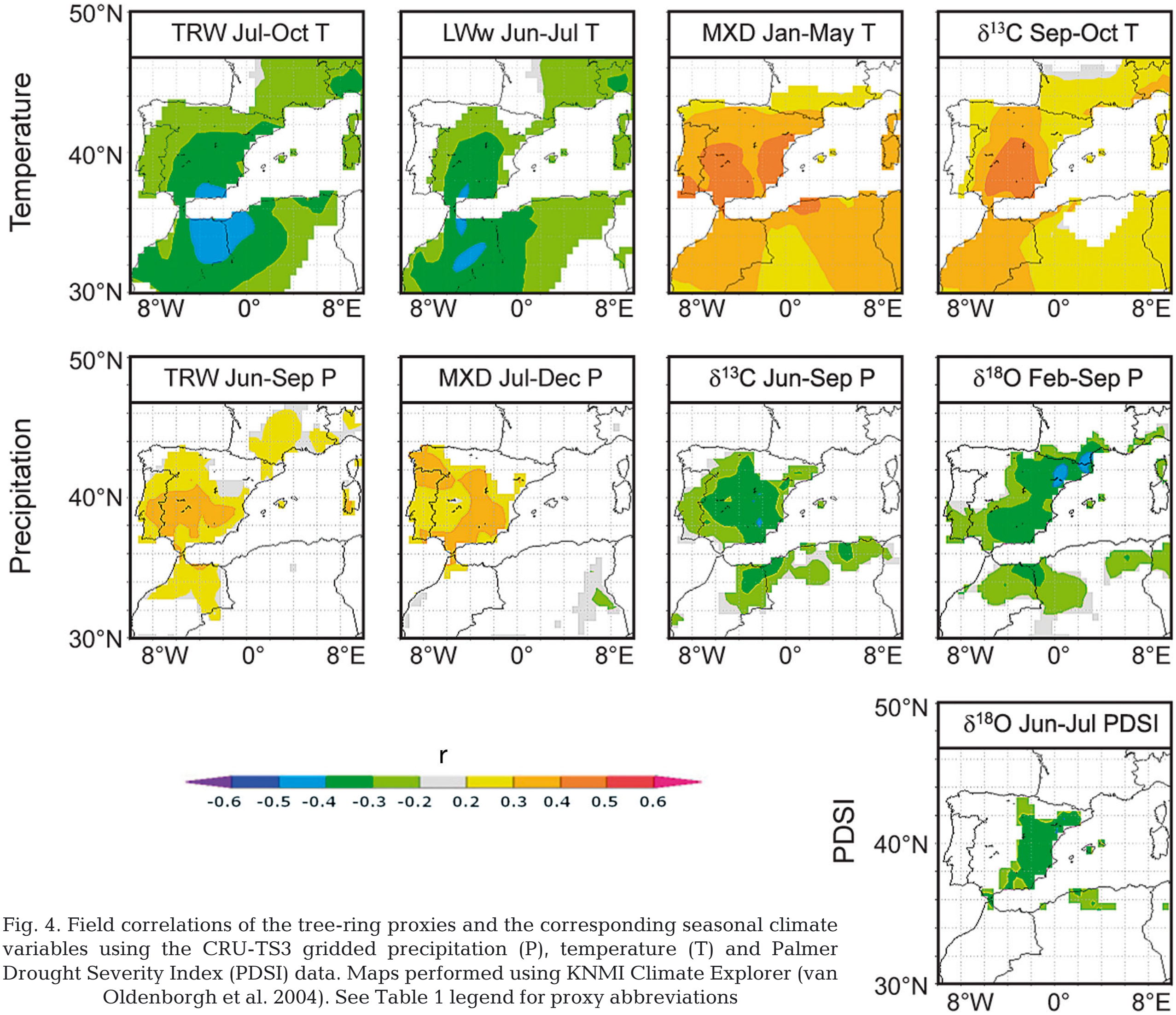

Fig. 4. Field correlations of the tree-ring proxies and the corresponding seasonal climate variables using the CRU-TS3 gridded precipitation (P), temperature (T) and Palmer Drought Severity Index (PDSI) data. Maps performed using KNMI Climate Explorer (van Oldenborgh et al. 2004). See Table 1 legend for proxy abbreviations

ing higher correlation coefficients in the first half of the 20th century (1901 to 1953) (Table 2). In contrast, MXD and especially δ^{18}O display an increase in signal strength in the second half of the 20th century (1954 to 2006). The correlations between δ^{18}O and the regional PDSI display values of r = –0.15 for the period 1901 to 1953 and r = 0.59 for the period 1954 to 2006. Only 5 combinations of tree-ring parameters and climate data are suitable for further analysis since they display highly significant correlations ($p < 0.01$) in both first and second half of the 20th century: (1) TRW and local July to October temperature, (2) LWw and local June to July temperature, (3) δ^{13}C and regional September to October temperature, (4) MXD and July to December regional precipitation and (5) δ^{13}C and June to September regional precipitation. The Fisher r-to-z transformation (z) did not reveal significant differences for any of the studied variables (Table 2). Thus, all the correlations of tree-ring records with climate variables were statistically stable over time.

Running correlations between the tree-ring records and the corresponding climate seasons (Fig. 5) show remarkably stable relationships along the whole calibration period. Especially, for TRW and local July to October temperature and δ^{13}C and regional June to September precipitation, the relationships are stable and the correlation values always stay above the 99% significance levels. The remaining combinations (LWw and local June to July temperature, δ^{13}C and September to October temperature and MXD and July to December regional precipitation) display values that always stay above the 95% significance level, but not always above the 99%.

Table 2. Correlations of all tree-ring proxies with the corresponding climate factor for the 2 split periods of the local and regional instrumental records and the Fisher r-to-z test performed. Highly significant correlations (p ≤ 0.01) in both periods in **bold.** See Table 1 legend for proxy abbreviations. ns: not significant, *p ≤ 0.05, **p ≤ 0.01

Proxy	Temperature					Precipitation					PDSI		
Scale	Season	r_1 Loc: 1904–51 Reg: 1901–53	r_2 Loc: 1952–99 Reg: 1954–2006	Fisher test z	Fisher test p	Season	r_1 Loc: 1912–55 Reg: 1901–53	r_2 Loc: 1956–99 Reg: 1954–2006	Fisher test z	Fisher test p	Season	r_1 Reg: 1901–53	r_2 Reg: 1954–2006
TRW													
Local	Jul to	$\mathbf{-0.57^{**}}$	$\mathbf{-0.52^{**}}$	−0.22	>0.05	Jun to	ns	ns				ns	ns
Regional	Oct	−0.53**	−0.33*			Sep	0.47**	0.29*				ns	ns
LWw													
Local	Jun to	$\mathbf{-0.47^{**}}$	$\mathbf{-0.36^{**}}$	−0.66	>0.05	Jun to	ns	ns				ns	ns
Regional	Jul	ns	ns			Aug	ns	ns				ns	ns
MXD													
Local	Jan to	0.54**	0.24			Jul to	ns	ns				ns	ns
Regional	May	0.37**	0.28*			Dec	$\mathbf{0.34^{**}}$	$\mathbf{0.38^{**}}$	−0.23	>0.05		ns	ns
δ^{13}C													
Local	Sep to	0.26*	0.41**			Jun to	ns	ns				ns	ns
Regional	Oct	$\mathbf{0.38^{**}}$	$\mathbf{0.42^{**}}$	−0.12	>0.05	Sep	$\mathbf{-0.50^{**}}$	$\mathbf{-0.45^{**}}$	−0.25	>0.05		ns	ns
δ^{18}O													
Local		ns	ns			Feb to	ns	ns			Jun to	ns	ns
Regional		ns	ns			Sep	−0.24*	−0.48**			Jul	−0.15	−0.59**

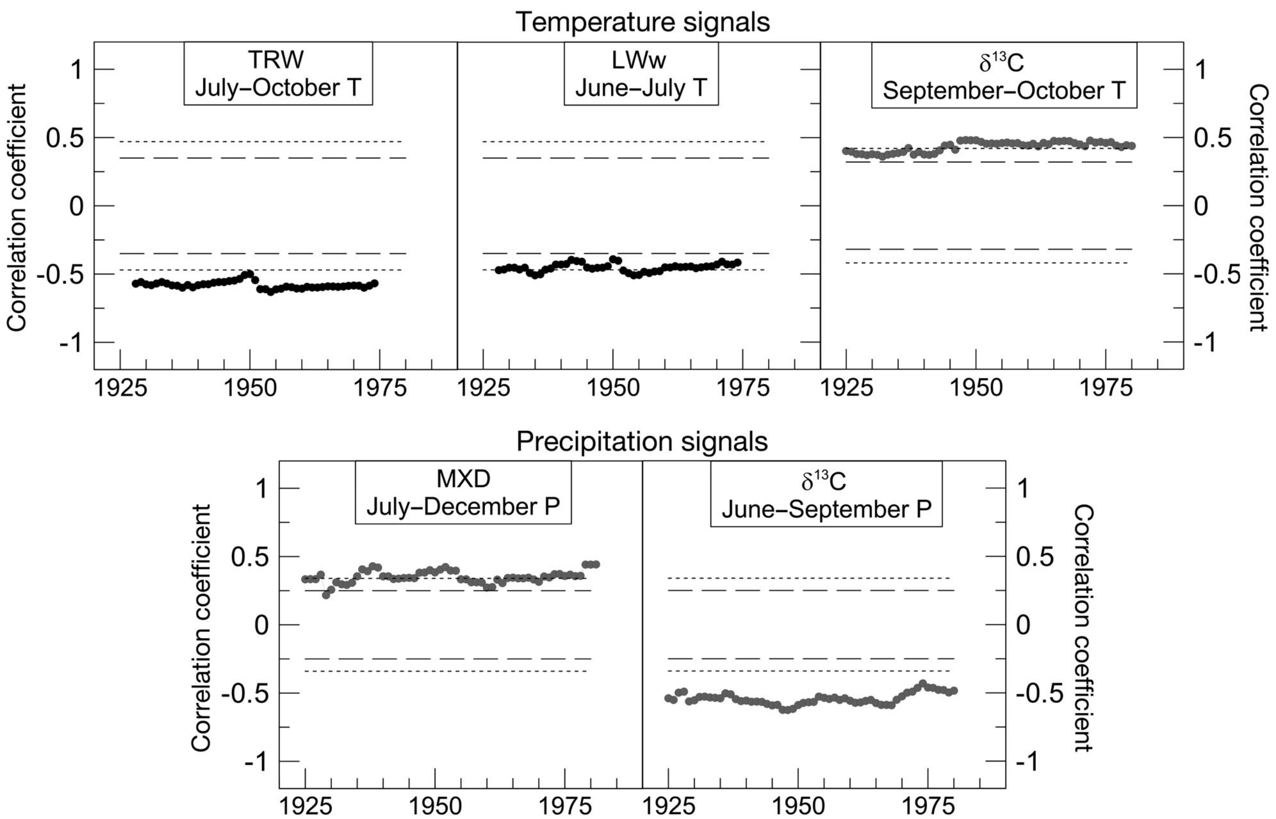

Fig. 5. Running correlations over 50 yr periods for (●) local and (●) regional climate data, showing the temporal evolution of the relationship between the tree-ring proxies and the corresponding seasonal climate variables for temperature (T) and precipitation (P) signals. Dashed and dotted lines: 95 and 99% significance levels, respectively. See Table 1 legend for proxy abbreviations

3.3. Calibration of selected tree-ring records

Calibration and verification trials were carried out for TRW, LWw, MXD, $\delta^{13}C$ and the respective temperature and precipitation variables (Table 3). TRW displays the highest coefficient of determination in both parts of the split period (r^2_1 = 32%, r^2_2 = 27%) followed by $\delta^{13}C$ as a proxy for precipitation (r^2_1 = 25%, r^2_2 = 20%).The percentage of explained variance is consistently lower for LWw, $\delta^{13}C$ and MXD as temperature proxies, especially in the second half of the split period, and the lowest for MXD.

With respect to the methods used for estimating the temperature and precipitation values based on tree-ring proxies, the RE statistic displays lower values when using scaling than when applying regression. This may be due to larger offsets between the instrumental and reconstructed values. The difference in the variance captured by every reconstruction technique becomes obvious in Fig. 6. In general, simulated temperatures using scaling display variabilities close to those of the instrumental record, while estimation using regression generates a 'smoothed' series, indicating that less variability is preserved. However, the difference in the amount of variability retained by scaling and regression is reduced as the explained variance increases; thus, for TRW the differences are smaller and for MXD are large.

4. DISCUSSION

4.1. Spatial significance of the climate signals

Generally, climate signals in tree-ring records described for Mediterranean climates tend to be much weaker than those in more temperate climates. Furthermore, the climate–growth relationship is not yet fully understood. In addition, tree growth at the IP comprises an important local component due to the uneven topography which causes distinct regional climate conditions in this part of the Mediterranean basin (Barbéro et al. 1998). In this context, the selection of suitable climate data as well as the detection of the climate signal encoded in each tree-ring variable is more challenging than elsewhere.

At NCZ, the more traditional tree-ring proxies (TRW, LWw) encode temperature signals for the previous and current year of growth that decrease in strength on a regional scale. In contrast, MXD and stable carbon and oxygen isotopes (especially $\delta^{18}O$) display poor correlations with local temperature and moisture data. However, the strength of their relations with climatic variables is considerably enhanced on regional scales. Similar results were reported by Andreu et al. (2008) and Planells et al. (2009).

While significant temperature signals were found using both local and regional climate data sets, significant precipitation signals were found only when using regional climate data. For instance, significant $\delta^{18}O$–climate relationships could hardly be found when using local climate data while the relationships found with the regional grid data set were stronger and in agreement with recent reports from the Swiss Alps (Saurer et al. 2008, Battipaglia et al. 2009), as well as with regional patterns described by Treydte et al. (2007). Similarly, when using local climate data, $\delta^{13}C$ and MXD showed a significant negative correlation with summer and July to December precipitation, respectively. The significance of these moisture signals increased when using regional climate data. The negative correlation between $\delta^{13}C$ and summer

Table 3. Calibration and verification statistics for the variables tree-ring width (TRW), latewood width (LWw), maximum latewood density (MXD) and stable carbon isotopes ($\delta^{13}C$) using the 2 meteorological records: a local station and a regional grid. r^2: coefficient of determination, $r_{obs\text{-}pred}$: correlation between the real and the predicted values; RE: reduction of error; parentheses: RE of scaling technique

Tree-ring proxy	Climate record	Seasonal variable	Calibration1 Loc: 1904–1951 Grid: 1901–1953 r^2_1 (%)	Verification1 Loc: 1952–1999 Grid: 1954–2006 $r_{obs\text{-}pred1}$	RE_1	Calibration2 Loc: 1952–1999 Grid: 1954–2006 r^2_2 (%)	Verification2 Loc: 1904–1951 Grid: 1901–1953 $r_{obs\text{-}pred2}$	RE_2
Temperature signal								
TRW	Local	Jul–Oct	32	0.57	0.31 (0.16)	27	0.52	0.21 (–0.11)
LWw	Local	Jun–Jul	24	0.47	0.26 (0.1)	13	0.36	0.22 (–0.38)
$\delta^{13}C$	Regional	Sep–Oct	14	0.38	0.06 (–1.99)	18	0.42	0.15 (–0.3)
Precipitation signal								
MXD	Regional	Jul–Dec	11	0.34	0.11 (–12.73)	14	0.38	0.14 (–4.5)
$\delta^{13}C$	Regional	Jun–Sep	25	0.50	0.23 (0.00)	20	0.45	0.19 (–0.16)

precipitation has been reported for different pine species across the Iberian Peninsula (Andreu et al. 2008, Voltas et al. 2008), the Alps (Treydte et al. 2001, Gagen et al. 2004, 2006) and in Finish Lapland (Gagen et al. 2007). This common summer precipitation signal seems to override individual signals, such as the species-specific physiology, the micro-site conditions and even the local climate peculiarities, and need to be explored further, as done initially by Treydte et al. (2007).

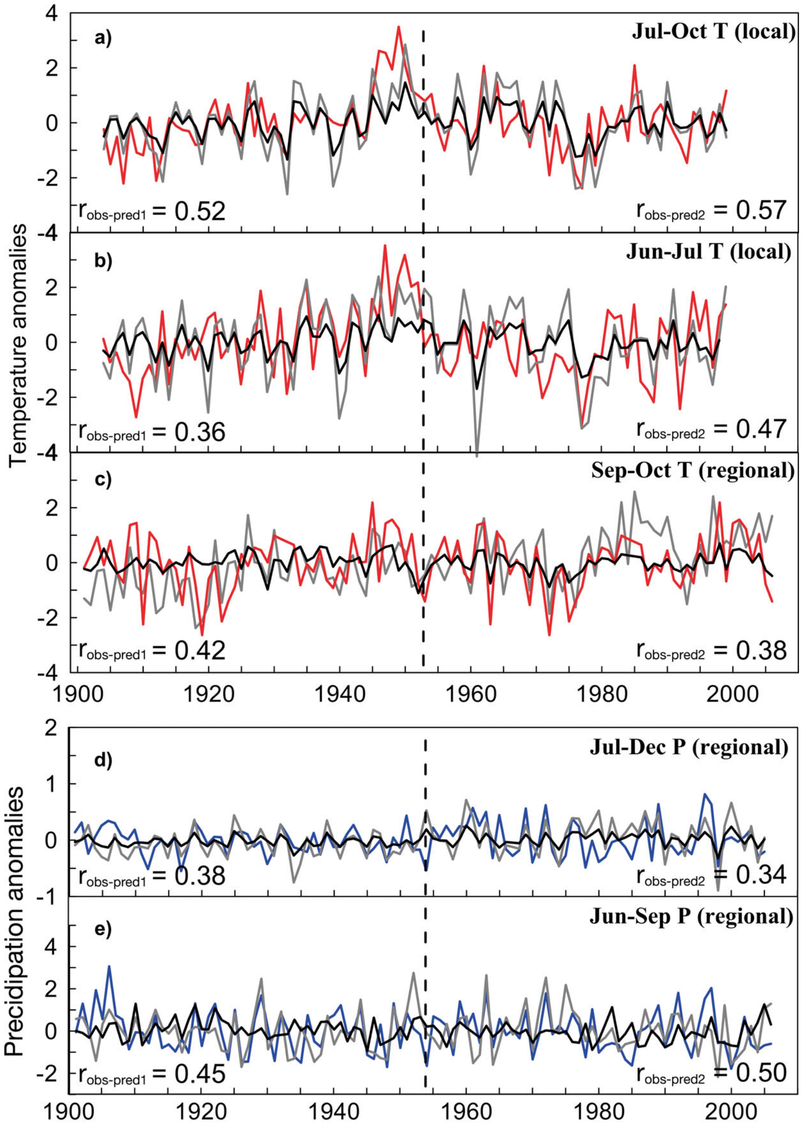

Fig. 6. Calibration–verification trials using the split-period method and applying both scaling and regression techniques. (a–e) Values estimated by (black) regression and (grey) scaling. (a,b,c) Tree-ring records and seasonal temperature (T; red line): (a) tree-ring width (TRW) and local July to October temperature, (b) latewood width (LWw) and local June to July temperature, and (c) stable carbon isotope ratio ($\delta^{13}C$) and regional September to October temperature. (d,e) Tree-ring records and seasonal precipitation (P; blue line): (d) maximum latewood density (MXD) and regional July to December precipitation, and (e) stable carbon isotope ratio ($\delta^{13}C$) and regional June to September precipitation

In Dorado Liñán et al. (2011b) no significant correlation between tree-ring parameters and the PDSI was found on a local scale at NCZ. The correlations between tree-ring stable isotopes and the PDSI were found to be significant only at regional scales and were especially strong between the annual mean PDSI and $\delta^{18}O$. Stable isotope variations in tree rings seem not to be as strongly dependent on local site conditions as growth or wood density are (McCarroll & Loader 2004, Saurer et al. 2008). Indeed, tree-ring proxies sensitive to precipitation or moisture, such as stable isotopes, tend to correlate better with the regional climate signals, representing a more homogenized form of climatic circulation patterns than local patterns.

Precipitation at the Iberian Peninsula is characterized by a high spatial heterogeneity (Rodriguez-Puebla et al. 1998) and precipitation in NCZ is particularly high in comparison to southern Spanish regions (Heywood 1961) due to the influence of both the Atlantic Ocean and the Mediterranean Sea. The existence of different sources of rain in combination with the rugged topography of the region leads to a high spatial variability in rainfall. Therefore, the distance between the sampling site and the local station may be responsible for the low correlations between the tree-ring variables and the precipitation data from the local station. The general lack of correlation between the tree-ring variables and PDSI at local scales is unsurprising given the relatively high rainfall in the NCZ.

4.2. Temporal stability of the climate signals

Several recent studies reported a decrease in the ability of TRW and MXD series to track the increase in temperatures over recent decades (e.g. Cook et al. 2004, D'Arrigo et al. 2008). In the case of NCZ, an increase in TRW and LWw sensitivity to temperatures for the second half of the 20th century leading to a temporal instability of the climate signal has been previously described locally (Martín-Benito et al. 2010) and on a regional scale (Andreu et al. 2007). However, such instability could not be confirmed by our study. While we usually found a decrease in sensitivity to temperature for TRW, LWw and MXD towards the second half of the 20th century, the highest significant correlations ($p < 0.01$) between tree-ring parameters and temperature variables were found to be statistically and visually stable. Therefore, in contrast to previous reports at the same site, we were able to find stable relationships. Those that were less stable were usually due to a decrease in the correlation between tree-ring parameters and climate.

The differences may be due to 2 reasons. (1) Previous studies (Andreu et al. 2007, Martín-Benito et al. 2010) analysed monthly temperatures and tested the stability using individual months that displayed the highest correlations. However, individual months may not correspond with the most limiting climatic period for tree growth, which often comprises a combination of successive months. As previously reported, a 'suboptimal' selection of the target climate variables may lead to imprecise evaluations and thus approaches considering individual months are more likely to behave unstably (Frank et al. 2007).

(2) The lack of comparability of these 3 studies needs to be taken into account. For instance, the samples used by Martín-Benito et al. (2010) were not derived from the altitudinal limit of distribution of *Pinus nigra*, where climate exerts a predominant influence on tree growth (Fritts 1976, Körner 1998). Therefore, the climate–growth relationships as well as their temporal stability may vary with regard to the distance of sampling sites from the altitudinal tree line. The present study also shows how the sensitivity of TRW and LWw to temperature decreases with increasing spatial scales, and thus the differences in the climate data used for each study should not be neglected as a possible source of discrepancies.

The only tree-ring record that displays an increased sensitivity to summer temperature during the 20th century is $\delta^{13}C$. Increasingly warmer conditions and extremes described for the Mediterranean areas (IPCC 2001, Giorgi et al. 2004, Zorita et al. 2008) may be enhancing the stomata closure to cope with the water stress and thus, increasing the $\delta^{13}C$ values, as previously pointed out by Andreu et al. (2008). Studies concerned with the stability of summer temperature signals encoded in $\delta^{13}C$ also report an increased sensitivity in the most recent decades (e.g. Andreu-Hayles et al. 2011, Seftigen et al. 2011) or shifts in the dominant monthly temperatures (e.g. Reynolds-Henne et al. 2007, Hilasvuori et al. 2009). However, the temperature signal in $\delta^{13}C$ at NCZ is stable at regional scales, while changing relationships for the 2 subdivided periods were only found when using local climate data. As exposed by Esper et al. (2010a), uncertainties related to the target climate data such as homogenization processes and statistical techniques applied (e.g. to build the grid data) could also be sources of misfits when calibrating against tree-ring records, underlining the importance of selecting the right climate data.

Stable signals in $\delta^{13}C$ and MXD were displayed with regional June to September precipitation data and regional July to December precipitation, respectively. The differences between the correlations in the 2 subperiods are non-significant and both climates signals are stable. In contrast, $\delta^{18}O$ displays increasingly negative correlations with February to September precipitation as well as with June to July PDSI. The change in the correlation for the subdivided periods points to an unstable relationship, caused by an enhanced dependency on moisture. This increased sensitivity of $\delta^{18}O$ to moisture during the most recent decades has recently been described for other study sites (e.g. Finland, Hilasvuori et al. 2009; Sweden, Seftigen et al. 2011) and has been associated with isotope enrichment in leaves due to lower humidity conditions. At NCZ, the warmer conditions described for the last decades have occurred in combination with an increase in precipitation variability and frequency of climatic anomalies at the Iberian Peninsula (Rodriguez-Puebla et al. 1998, Romero et al. 1998, Manrique Menéndez & Fernández-Cancio 2000). Thus, an increase in $\delta^{18}O$ enrichment in tree rings due to increased moisture deficit seems likely. Such a moisture deficit would be expected to affect stomatal apertures, and to trigger the influence of precipitation on $\delta^{13}C$ (McCarroll & Loader 2004). However, as mentioned before, $\delta^{13}C$ at NCZ and summer precipitation display a strong and stable relationship.

Usually $\delta^{18}O$, as well as $\delta^{13}C$, are used in their raw form, but recent publications have pointed out the existence of low-frequency signals in the $\delta^{18}O$ series that might not be related to climate (Esper et al. 2010b, Dorado Liñán et al. 2011b). Thus, the temporal instability found for the significant climate signals of $\delta^{18}O$ at NCZ may not be due to increased constraints resulting from water stress, but to low-frequency noise in the $\delta^{18}O$ series or a combination of both. In any case, this proxy seems unsuitable for reconstructions before further investigations are performed.

4.3. Suitable proxies for climate reconstructions at NCZ

Among the 5 highly significant and stable climate signals found in NCZ tree-ring variables, TRW and the local mean July to October temperature and $\delta^{13}C$ and June to September precipitation were the most suitable. The relationships were highly significant and stable, statistically and visually. Additionally, the calibration–verification trials comprising both regression and scaling techniques show satisfactory skill in reconstructing climate, since both proxies explain >20% of the variance. From the 2 methods applied for estimating temperature and precipitation values based on tree-ring proxies, regression keeps the variability of the reconstruction below that of the instrumental record, while scaling retains more inter-annual variability. However, scaling also displays increased noise and, as a consequence, the value of RE tends to be negative thereby confirming results recently reported by other authors (Esper et al. 2005, McCarroll et al. 2011). Overall, the quality of a proxy-based climate reconstruction seems to depend more on the selection of the proper target climate record rather than on the technique used for the reconstruction (Esper et al. 2005).

5. CONCLUSIONS

Detecting and extracting the key climatic signals in tree-ring records of the Mediterranean area remains challenging because the relationship between tree growth and climate involves a complex interplay between temperature and precipitation signals, with high spatial and temporal variability.

In general, the strength and temporal stability of the relationship between tree-ring proxies and selected seasonal climate variables largely depend on the climate data used. In the present study, correlations with temperature were found to be more significant and stable when using local climate data, while correlations with precipitation were only highly significant when using regional climate data.

In addition to the selection of the suitable climate data, precise evaluation of the potential of a tree-ring variable for further use in climate reconstructions is critical in order to unequivocally identify the climate signal encoded in each tree-ring parameter. Imprecise identifications, such as monthly instead of seasonal climate variables, may lead to the erroneous removal of a suitable tree-ring proxy.

Instabilities revealing the non-stationary nature of the climate signals, such as the correlations between $\delta^{18}O$ and climate, need further investigation in order to clarify whether the instabilities are due to a shift in the response to climate or due to uncertainties related to both proxy and instrumental records.

At NCZ, several climate signals could be potentially used in climate reconstructions. Among this group, TRW seems to be the most suitable parameter to reconstruct summer to autumn temperatures, while $\delta^{13}C$ is a suitable proxy for the reconstruction of summer precipitation at the Cazorla Range.

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