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Abstract Since the end of the last glacial period, European Mediterranean mountains have provided shelter for numerous species of Eurosiberian and Boreal origin. Many of these species, surviving at the southern limit of their range in Europe and surrounded by Mediterranean ones, are relatively intolerant to summer drought and are in grave danger of loss, as a result of increasingly long and frequent droughts in this region. This is the case of the Scots pine (*Pinus sylvestris*) and the Austrian pine (*Pinus nigra* ssp. *salzmannii*) which are found on Central Iberian Peninsula at the edge of their natural range. We used a tree ring network of these two species to reconstruct past variations in summer rainfall. The reconstruction, based upon a tree ring composite chronology of the species, dates back to 1570 (adjusted R^2=0.49, P< 0.000001) and captures interannual to decadal scale variability in summer precipitation. We studied the spatial representativeness of the rainfall patterns and described the occurrence rate of extremes of this precipitation. To identify associations between macroclimatic factors and tree radial growth, we employed a principal component analysis to calculate the resultant of the relationship between the growth data of both species, using this resultant as a dependent variable of a multiple regression whose independent variables are monthly mean temperature and precipitation from the average records. Spatial correlation patterns between instrumental precipitation datasets for southern Europe and reconstructed values for the 1950–1992 period indicate that the reconstruction captures the regional signal of drought variability in the study region (the origin of this precipitation is convective: thermal low pressure zones induced in the inland northeastern areas of the Iberian Peninsula). There is a clear increase in the recurrence of extreme dry events as from the beginning of twentieth century and an abrupt change to drier conditions. There appears to be a tendency toward recurrent exceptionally dry summers, which could involve a significant change for the Eurosiberian refugee species.

Keywords Austrian pine · Climate change · Dendrochronology · Drought · Iberian Peninsula · Mediterranean forest · Scots pine

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Introduction

The Mediterranean mountains constitute the southern edge of the geographical area of numerous Eurosiberian species (Hampe and Petit 2005). They contain one of Europe's highest levels of flora diversity, likely resulting from the alternation between cold and warm periods during the Quaternary. Such an alternation caused the disappearance of many species from the temperate regions of the northern hemisphere, along with their temporary presence in more southerly latitudes, less affected by glaciations (Gómez-Campo 1985; Costa et al. 1998; Hewitt 2000; Sáinz and Moreno 2002; Väre et al. 2003; Vargas 2003; Martín-Bravo et al. 2010). Many species sought refuge in the Mediterranean mountains, where the

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topography resulted in a variety of microclimates providing suitable habitats during both warm and cold periods (Bennett et al. 1991; Taberlet and Cheddadi 2002). Increased diversity in the mountains of the Mediterranean Basin resulted from the arrival of Eurosiberian species and from the high degree of speciation which in turn was due to geographic isolation (Sáinz and Moreno 2002). At present, these mountains constitute cool wet islands of biodiversity in a warm dry area, with species of Eurosiberian and Boreal origin seeking refuge at the summits and in mid-mountain areas, and xerophyllous Mediterranean ones adapted to warm summers with high water deficit occupying lower altitudes (Pauli et al. 2012).

The Mediterranean region lies in a transition zone between the arid climate of North Africa and the temperate and rainy climate of Central Europe. Given this location, even minor changes in atmospheric dynamics have the potential to significantly affect climate in the Mediterranean Basin (Lionello et al. 2006). In projections of climate change, the Mediterranean Basin has been identified as one of the most vulnerable areas (Giorgi 2006) and is expected to undergo sharp increases in temperatures and aridity in comparison with other regions (Cubash et al. 1996; IPCC 2007). Aridification of southern Europe's climate enables us to predict that Mediterranean mountains will become warmer and drier than other European mountains, with an increase in interannual temperature and rainfall variability (Morales et al. 2005; Gritti et al. 2006; Nogués-Bravo et al. 2007, 2008; Giorgi and Lionello 2008). Current predictions of the effects of climate change indicate that the highly diverse genetic heritage of Mediterranean mountains will be significantly disturbed by the increased summer water deficit, and several authors have indicated a current readjustment of the biogeographic character of these mountains (Goodess and Jones 2002; Peñuelas and Boada 2003; Sanz-Elorza et al. 2003; Sanz et al. 2003; Mendoza et al. 2006; Jump et al. 2006; Wilson et al. 2007; Camarero and Gutiérrez 2007; López-Moreno et al. 2008; Linares and Carreira 2009; Pauli et al. 2012).

On the Iberian Peninsula, the few climate reconstructions existing to date show a gradual warming process as from the beginning of the twentieth century compared with the period of cooling and erratic rainfall that occurred between the fourteenth and nineteenth centuries (Sanz 2003; Font 1988; Rodrigo et al. 1999). The climate record of the last few decades shows a clear acceleration of this warming as from the 1980s (Raso 1997; Granados and Toro 2000; Agustí-Panareda and Thompson 2002; Macias et al. 2006) with an apparent decrease in rainfall from the 1990s (Rodrigo et al. 1999, 2000; De Luis et al. 2000; Sanz 2003; Lehner et al. 2006).

In the current context of change, Pilcher et al. (1984) and Grudd et al. (2002) have provided calendrical records of long tree ring chronologies which enable reconstruction of climate variability in the past. In the Mediterranean mountains, however, most studies of dendroclimatic reconstruction have as yet involved little in-depth analysis of trends in series or in the cyclical patterns of climate and its possible effects on species distribution (Munaut and Serre-Bachet 1982; Till and Guiot 1990; Gutiérrez 1992; Fernández et al. 1996; Génova and Fernandez 1999; Génova 2000; Macias et al. 2006; Andreu et al. 2007, among others).

The main objective of this study involved developing a multicentury low-frequency summer precipitation reconstruction in Mediterranean-type mountains, specifically for the central Iberian Peninsula, from tree ring chronologies of Scots pine (*Pinus sylvestris* L.) and Austrian pine (*Pinus nigra* Arnold ssp. *salzmannii*). Both species are located in this peninsula at the edge of their phytogeographical range (Fernández et al. 1996; Génova and Fernández 1999; Génova 2000). Here, the summer water deficit contrasts with the temperature limitation observed by other authors at higher latitudes in Europe, where summertime water availability does not constitute a limiting factor (Grace and Norton 1990; Rolland and Schueller 1994; Guerrero et al. 1998; Kirchhefer 2001; Tardif et al. 2003; Koprowski et al. 2012). The specific objectives involved (a) recognizing the most relevant modes of temporal variability in the summer precipitation reconstruction in order to better understand the main periodicity characterizing summer precipitation variability, (b) assessing changes in variability during the last century compared to the previous ones, (c) comparing this reconstruction with previous tree ring precipitation records on the Iberian Peninsula and (d) establishing the spatial representativeness of the reconstructed precipitation patterns on the Iberian Peninsula.

Materials and methods

Study area and species

We studied the Guadarrama Mountains (Guadarrama National Park, 40°50′ to 41°15′N; 3°30′ to 4°20′W), in the Central Range of the Iberian Peninsula (Fig. 1). Granitic and metamorphic materials predominate in this area (Muñoz and Sanz-Herráiz 1995), where average elevation is 2,000 masl and maximum altitude is 2,430 m. The regional climate is a Mediterranean mountainous one, with simultaneous rainfall minima and temperature maxima during summer, which gives rise to severe water stress. Rainfall occurs mainly during the cold period (spring, autumn and winter) and is caused by successive depressions from the Atlantic Ocean. During the summer, low rainfall is recorded. It is of convective origin and is conditioned orographically (Ruiz-Labourdette et al. 2011a).

The vegetation in the altitudinal belt (1,500–2,100 m) comprises forests of *P. sylvestris* and small marginal stands of *P. nigra* ssp. s*alzmannii*. The former is a typically Eurosiberian

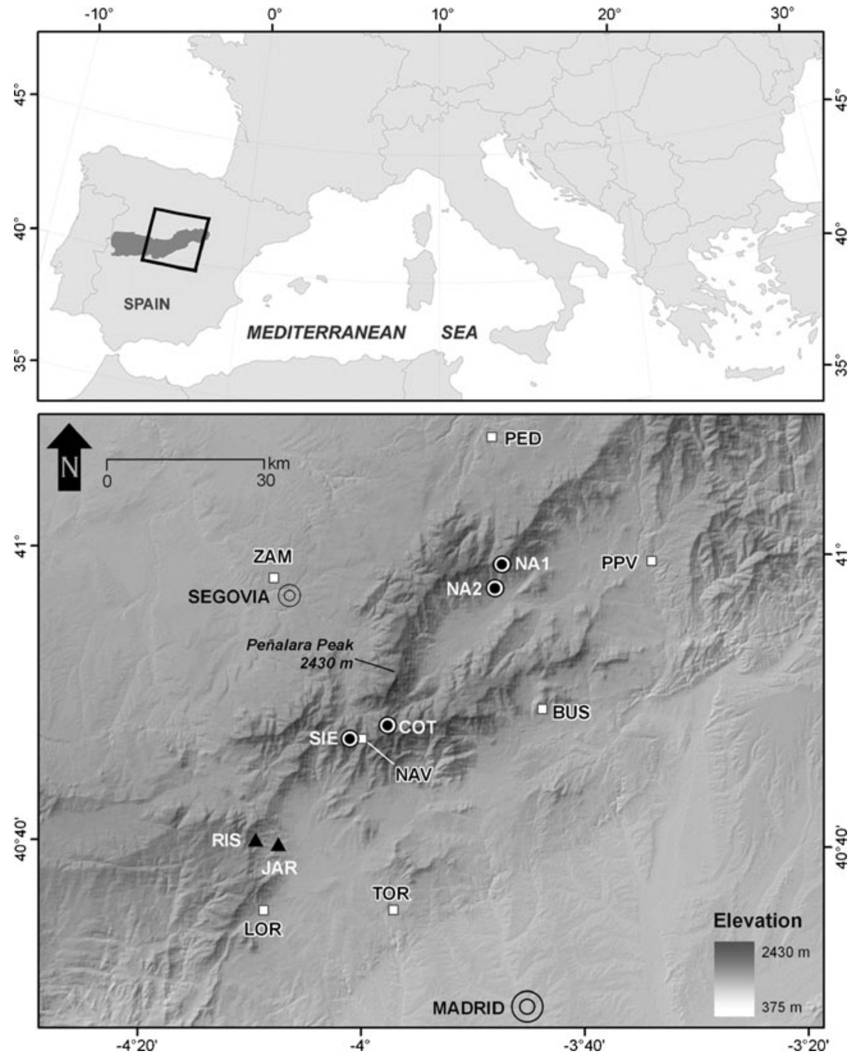


Fig. 1 Central Range of the Iberian Peninsula and below the study area. *Circles and triangles* indicate the location of the *P. sylvestris* and *P. nigra* ssp. *salzmannii* tree ring chronologies, respectively. *White squares* indicate the temperature and precipitation meteorological stations used in the reconstruction. The cities of Segovia and Madrid are shown. Site codes are given in Tables 1 and 2

conifer and one of the more cold-tolerant pines, but it is intolerant to summer drought (Critchfield and Little 1966; Gandullo and Sánchez-Palomares 1994). In the study area, it constitutes one of the southernmost relict populations of the cold ecological optimum pine forests of Eurasia, as well as an isolated genetic pool (Comps et al. 1991; Prus-Glowacki and Stephan 1994; Rubiales et al. 2010). The species *P. nigra* is somewhat more tolerant to summer drought, although it also grows better with summer rain events (Costa et al. 1998; Génova and Fernández 1999; Leal et al. 2008). Its population in the study area is the westernmost of this species in Europe. The subspecies s*alzmannii* is endemic to the Iberian Peninsula and presents better adaptation to climate continentality and summer drought than others (Costa et al. 1998). Below the pine forest lies a belt of Eurosiberian broadleaved forests, with *Fagus sylvatica* L., *Quercus petraea* (Matts.) Liebl. and *Fraxinus excelsior* L. in the zones remaining wet in summer. Sub-Mediterranean broadleaved forests comprising oak (*Quercus pyrenaica* Willd.) are present in the intermediate rainfall areas, and Mediterranean forests comprising Holm oak (*Quercus ilex* L. subsp. *ballota* (Desf.) Samp.) are characteristic in the piedmont areas presenting a higher summer water deficit. Above the pine forests, there is a belt of high-altitude Mediterranean scrub (*Juniperus communis* L. ssp. *alpina* (Suter) Celak, *Cytisus oromediterraneus* Riv. Mart.), and on the mountaintops, one can find high-altitude psycroxerophilous herbaceous communities with *Festuca ovina* L. subsp. *indigesta* (Bss.) Hach. Synopses of flora and vegetation are given in Rivas-Martínez (1987), Luceño and Vargas (1991), Martínez (1999), Martínez and Costa (2001) and Ruiz-Labourdette et al. (2011a).

Tree ring network

Six annual ring width chronologies of *P. sylvestris* and *P. nigra* were compiled and revised for this study from the collections of Génova (1994), Génova and Fernández (1999) and Génova (2000) (Table 1). Tree ring sampling sites are shown in Fig. 1. Two radii from at least ten individuals were collected in each of these sites. Tree rings were measured to

Table 1 Characteristics of tree ring chronologies from the Central Iberian Peninsula (site codes are used in Fig. 1). Calculations are performed for each of the species. The correlation was calculated for the 1513–1992 (*P. sylvestris*) and 1462–1992 (*P. nigra* ssp. *salzmannii*) periods

Species	Site name	Code	Lat N, long W	Period	Elevation (m)	Corr.[a]
Pinus sylvestris	Navafría 1	NA1	40°59′, 03°48′	1685–1992	1,900	0.64
	Navafría 2	NA2	40°58′, 03°48′	1787–1992	1,630	0.49
	Cotos	COT	40°48′, 03°58′	1513–1994	1,900	0.60
	SietePicos	SIE	40°47′, 04°01′	1527–1995	1,950	0.65
Pinus nigra ssp. *salzmannii*	Riscopol	RIS	40°40′, 04°10′	1523–1988	1,600	0.69
	Jarosa	JAR	40°40′, 04°09′	1462–1992	1,400	0.69

[a] Mean of the correlations is indicated for each tree ring chronology with all the others ($P<0.001$)

the nearest 0.001 mm, cross-dated and standardised with the use of standard dendrochronological techniques (Holmes 1983; Stokes and Smiley 1996; Fritts 2001). Cross-dating verifies the assignment of a calendar year to each ring in each sample by comparison of the growth patterns among the different cores and sections. We examined the quality of the cross-dating using the software COFECHA (Holmes 1983) and CrossdateR (Bigler 2006) to detect measurement and cross-dating errors. We detrended ring widths into dimensionless indices to remove the effects of changes in tree growth that resulted from aging, to homogenise the mean and variance and to produce a standard chronology for the site. To this end, we employed the negative exponential, the best fit among various equations tested, to eliminate the tendencies resulting from the increase in age (we subsequently smoothed the residuals obtained by means of a function spline). Prior to the use of the negative exponential for all their time series detrending, we visually inspected the curve fitting by means of individual time series. This standardisation process eliminates variability in the tree ring series unrelated to climate (e.g., tree aging or forest disturbances, Fritts 2001).

In order to preserve a high percentage of the low-frequency variance, we accomplished standardisation by fitting each ring width series to a negative exponential or linear regression curves, with ARS41win (Cook and Krusic 2006).

The highly significant correlations between chronologies of the same species enabled them to be grouped into two composite chronologies. These chronologies were obtained by analysing, with the above-mentioned software, all the radii of the individual sites included in each composite. The quality of the tree ring chronologies was assessed by means of running series of Rbar, the mean correlation coefficient of all possible pairings among tree ring series from individual cores, computed for a specific common time interval. We used a 50-year window with a 25-year overlap. The expressed population signal (EPS) statistics, which quantify the degree to which a particular sample chronology portrays a hypothetical chronology that would have been infinitely replicated (Briffa 1995), was used to assess the quality of the composite chronologies. To denote a good level of common signal fidelity between trees in the reconstruction (Wigley et al. 1984), we calculated the EPS before and after combining the chronologies. For the reconstruction, we only used the portion of the chronologies falling above the threshold (0.85). We determined the EPS for the final chronology using the tree means from all sites included in each composite chronology. Thus, we obtained two EPS values, one for each species (Cook and Kariukstis 1990).

For climate data, we analysed monthly temperature and precipitation records from 64 rain and 41 temperature stations providing data for the twentieth century in the study area. Climatic records were provided by the Spanish State Meteorology Agency (AEMET). We selected these stations, considering (a) temporal stability (only stations with complete or almost complete records were used, and a minimum of 70 % of monthly data was required); (b) density (spatial coverage of the stations); and (c) homogeneity of time series. We applied a Mann–Kendall to the stations and detected no inhomogeneities in the stations chosen. We discarded stations with a significance level ≥0.05. Following these criteria, we selected seven meteorological stations (Fig. 1 and Table 2).

We filled gaps in monthly data by considering data from other stations in the study area by means of AnClim software (Stepanek 2007). The stations selected to complete the monthly data did not present anomalous patterns in monthly plots (unexplained outliers) and showed significant correlations among each other ($P<0.05$). Thus, we obtained the most reliable instrumental records to maximise the regional climatic signal. We used the completed series to compile the regional averages of total precipitation and temperature for the Guadarrama Mountains. To obtain suitable climatic data for the reconstruction, monthly precipitation and temperature values of the stations were divided by the means of the 1942–1992 period; hence, a percentage (%/100) was calculated for every month and for each station. The procedure made all the stations comparable regardless of the absolute climatic values.

Climate reconstruction

To identify associations between macroclimatic factors and tree radial growth, we first performed a principal component

Table 2 Instrumental meteorological stations from Central Spain used in the analysis. Their locations in the study area are shown in Fig. 1

Weather stations	Code	Lat N, long W	Type	Elevation (m)	Available data (1942–1992)	
					P (%)	*T* (%)
Pedraza	PED	41°07′, 03°48′	P	1,060	94	–
Zamarramala	ZAM	40°58′, 04°08′	P, T	1,000	98	84
Bustarviejo	BUS	40°49′, 03°44′	P	1,248	70	–
Navacerrada Puerto	NAV	40°46′, 04°00′	P, T	1,890	100	100
San Lorenzo de El Escorial	LOR	40°35′, 04°08′	P	1,028	74	–
Torrelodones	TOR	40°35′, 03°57′	P	900	84	–
Presa de Puentes Viejas	PPV	40°59′, 03°34′	P, T	960	92	82

P pluviometric, *T* thermometric

analysis (PCA) of the tree rings with indices from the two composite chronologies (*P. sylvestris* 483 annual records, *P. nigra* 531 annual records, 423 observations in common). We attempt to obtain the resultant of the relationship between the growth data of both species. Given that the covariance between both series of data, previously standardised, provides the value of the correlation coefficient, the PCA can be used as a tool for obtaining the corresponding equation of this resultant (dependent variable) (Lara et al. 2008). We subsequently used this resultant as a dependent variable of a multiple regression whose independent variables are monthly mean temperature and precipitation from the average records (Lara et al. 2001). The statistical association between the PCA axis and each climate variable was examined over the common period for the chronologies and the instrumental climatic record (1942–1992). As tree radial growth is influenced by climatic conditions several months prior to ring formation (Fritts 2001; Lara et al. 2005), we included both the previous and current growing seasons in this analysis. Consequently, correlations between ring width and climate data were calculated for 18 months, starting in May of the previous growing season and ending in October of the current one. We also calculated correlations for various monthly combinations, following the methods described by Blasing et al. (1984).

The reconstruction equation for summer precipitation was estimated by regressing the precipitation record on the PC1 obtained from the two composite tree ring chronologies that significantly correlated with precipitation. The complete observation period (1942–1992), common both to the tree ring and the precipitation data, was used for calibration, and the 'leave-one-out cross-validation' method was used to validate the regression model (Michaelsen 1987). In this method, a model is calibrated on all values but one; this value is then estimated and the process repeated until each value in the calibration period has been subjected to this process (Woodhouse and Lukas 2006). The strength of the regression model was characterised by the adjusted R^2 and the F level was estimated as a goodness-of-fit test. We assessed the capacity of the regression model to reconstruct summer precipitation using the reduction of error statistic (RE), the root mean squared error (RMSE) and the coefficient of efficiency (CE) (Fritts 1976; Cook et al. 1999).

We tested autocorrelation of the residuals from regression with the Durbin–Watson statistic (Draper and Smith 1981).

Results

The chronology of *P. sylvestris* surpasses the upper EPS value of 0.85 in the 1545–1995 period and that of *P. nigra* in the 1570–1992 period. We therefore chose the common period (1570–1992) in both chronologies to perform the reconstruction (Table 3).

Figure 2 shows correlation functions between radial growth (PC_1 ordination axis of regional residual chronologies) and monthly temperature and precipitation data. Only summer rainfall in the current growing season presented a statistically significant correlation, having a positive effect on tree ring width ($P>0.95$, $r>0.36$). We selected the summer season for the reconstruction, as this is the combination of monthly rainfall showing the highest correlation with tree growth ($P>0.95$, $r=0.64$). In contrast, temperature has a negative effect on tree ring width in the same period and a positive effect in spring, but correlations were not strong enough to permit suitable reconstruction of past temperature variations.

The regression model used to reconstruct summer rainfall as a function of tree rings was

$$SR_t = -0.0168 + 0.1239PC_1$$

where SR_t is estimated summer rainfall (May to August) in the Guadarrama Mountains of year t, and PC_1 is the principal component amplitude from the two composite tree ring chronologies for year t. The model explained 49 % of the total variance in summer precipitation (F value=47.43, verification RE=0.45, RMSE=0.138, CE=0.148). The residuals of this regression were distributed normally (Shapiro–Wilk's W test;

Table 3 Characteristics of the composite tree ring chronologies. The values of the correlation with summer rainfall (May–August) for the 1942–1992 period are indicated

Species	Number of series	Number of trees	Max. age (years)	Period	Period (EPS>0.85)	Corr. (1942–1992)
Pinus sylvestris	112	59	482	1513–1995	1545–1995	0.56
Pinus nigra ssp. *salzmannii*	49	26	506	1462–1992	1570–1992	0.67

EPS expressed population signal

P=0.321) and not significantly autocorrelated (Durbin–Watson statistic=2.04).

The predicted series capture both high- and low-frequency variations in the instrumental record observed (Fig. 3a). Examination of the summer rainfall reconstruction (Fig. 3b) and data records observed indicates (a) moderate to severe multi-decadal drought events centred in the first half of the seventeenth century (1600–1630); (b) moderate wetter conditions for the 1650–1680 period; (c) moderate drought conditions for the 1750–1770 period; (d) severe wet conditions centred in 1780; (e) decadal severe droughts around 1940 and 1965; and (f) multi-decadal moderate wet conditions from 1970 to 1990, with an abrupt change to drier conditions as from 1990s, the largest change being within the 1570–2005 series.

Figures 4 and 5 show the analysis of the variability in the reconstructed summer precipitation series (1570–1992). The significant periodicity of the summer rainfall reconstruction across the time–frequency domain, detected with the use of wavelet power spectrum and periodogram (Urrutia et al. 2011), shows that there is a dominant interdecadal mode close to 25 years, of the intermittent type. This periodicity, which can be seen in the spline of Fig. 3b, is nearly constant for the analysed series, with breaks in the second half of 1600 and in the middle of the 1800s. In addition, throughout most of the series, a short period (2–4 years), also intermittent and less marked than the previous one can be observed.

Figure 5 shows the evolution of summer rain extremes for the 1570–1990 period, based both on reconstructed (1570–1941) and on observed (1942–2005) data and for four types of extreme events, identified by the use of percentiles in the distribution (Jones et al. 1999): extreme wet events (summer rainfall >90 percentile of the summer rainfall series) and extreme dry events (<10 percentile of the summer rainfall series). We used a randomisation test to test for the existence of significant trends in the temporal series of extreme events. We employed a Monte Carlo approach in which the permutations are found by random selection. The total number of permutations was 10,000 for each series. In both cases, the tendency of the series was significantly different from random (P observed ≥ expected=0.000001).

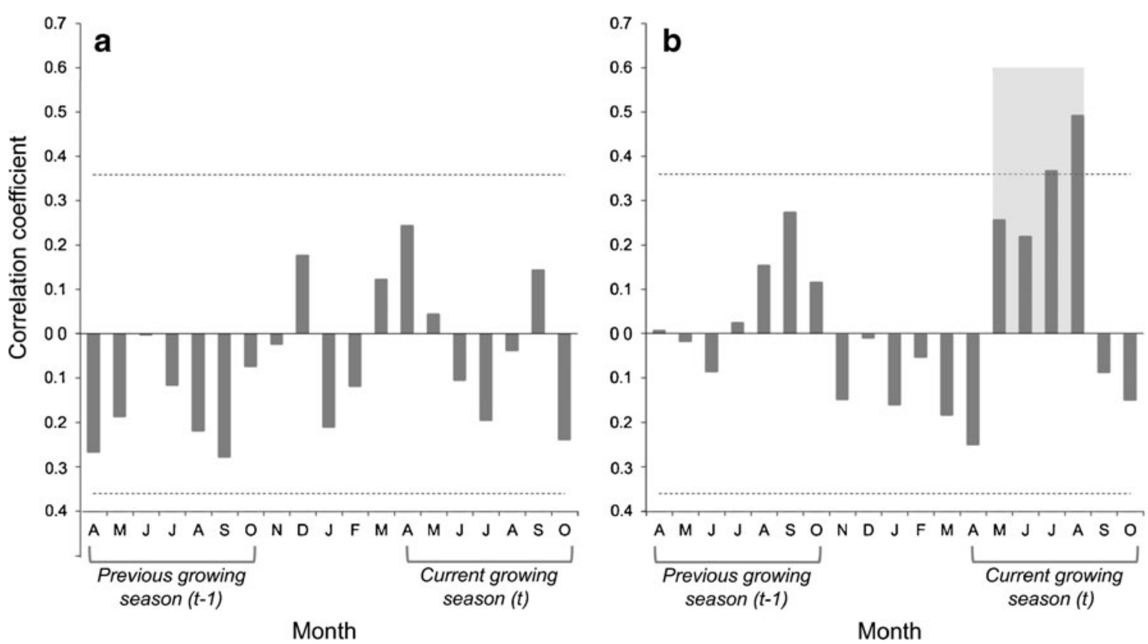


Fig. 2 Correlation functions for *P. sylvestris* and *P. nigra* ssp. *salzmannii* in the Guadarrama Mountains. The correlation coefficients compare the first PCA ordination axis of regional residual chronologies of both species with regional mean monthly temperatures (**a**) and regional total monthly precipitation (**b**) over the 1942–1992 period. The *light grey bar* shows the value of the correlation coefficient considering total precipitation in May, June, July and August. Positive correlation indicates that above-average radial growth is associated with above-average values of precipitation or temperature. *Dashed lines* indicate significant correlations (P< 0.05; r>0.36 or <0.36)

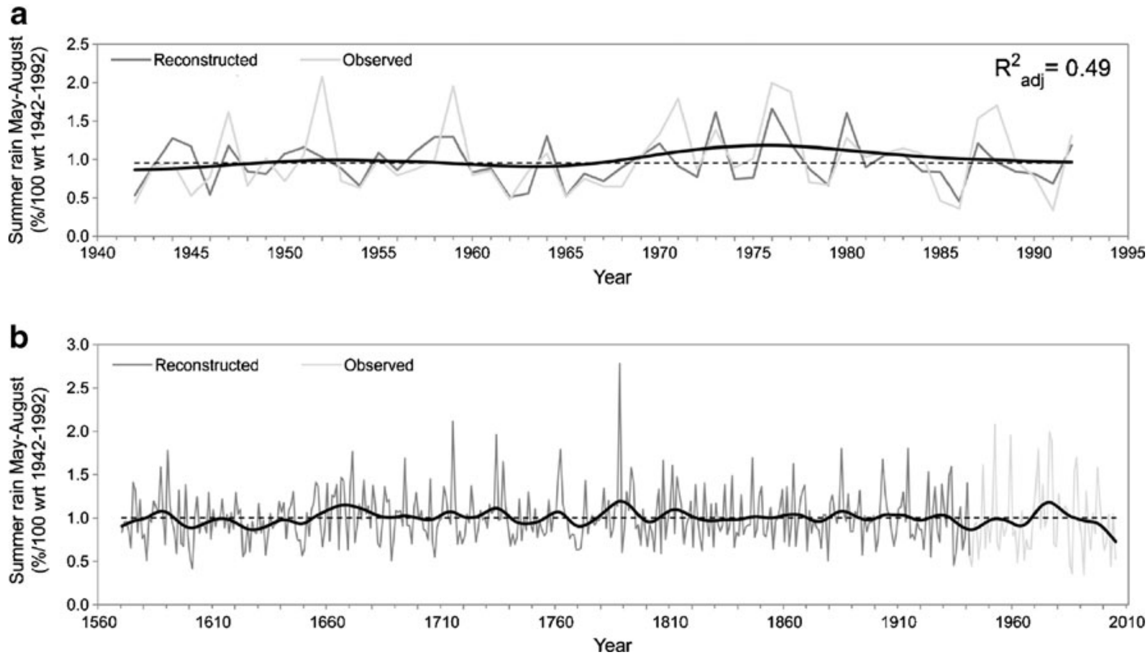


Fig. 3 Tree ring reconstruction of summer rainfall for the Central Range of the Iberian Peninsula. **a** Summer precipitation observed and reconstructed from tree rings (May–August) during the 1942–1992 calibration period with spline of observed data (*continuous black line*). **b** Reconstructed and observed summer precipitation plotted annually from 1570 to 2005 with spline of reconstructed data (*continuous black line*). The spline used to emphasise the long-term variations is a cubic spline version designed to reduce 50 % of the variance in a sine wave with a periodicity of 25 years (Cook and Peters 1981)

These results indicate that in the Central Mountains of the Iberian Peninsula, the recurrence intervals of extreme droughts are 4.5 and 9 years, respectively. During the first half of the 1600s, the wet and extreme events were scarce. The dry ones, however, were relatively abundant. This behaviour coincided with the precipitation minimum observed in this period. There was a predominance of wet extremes during the second half of the seventeenth century, coinciding with the absolute maximum of the series, two phases of stability (absence of extremes) during the 1720–1770 and 1840–1900 periods and a sharp rise in the occurrence of extreme dry events starting in the twentieth century.

To determine the spatial representation of the climatic signal of this reconstruction, we calculated correlation maps comparing (a) the reconstructed May–August precipitation with the 0.25°×0.25° gridded May–August precipitation from the E-OBS 3.0 dataset for their 1950–1992 common period (Haylock et al. 2008) and (b) the reconstructed summer precipitation for the 1942–1992 period with the HadSLP2 2°×2° gridded May–August sea level pressure (Allan and Ansell

Fig. 4 Periodicity analysis of reconstructed summer rainfall series. **a** Wavelet power spectra. The *white line* indicates the cone of influence; points outside have been influenced by the boundaries of the time series. **b** Global wavelet power spectrum (95 % confidence interval shown as a *red line*). In the spectra, one can observe peaks with $P<0.05$ between 25 years (low frequency) and 2–4 years (high frequency)

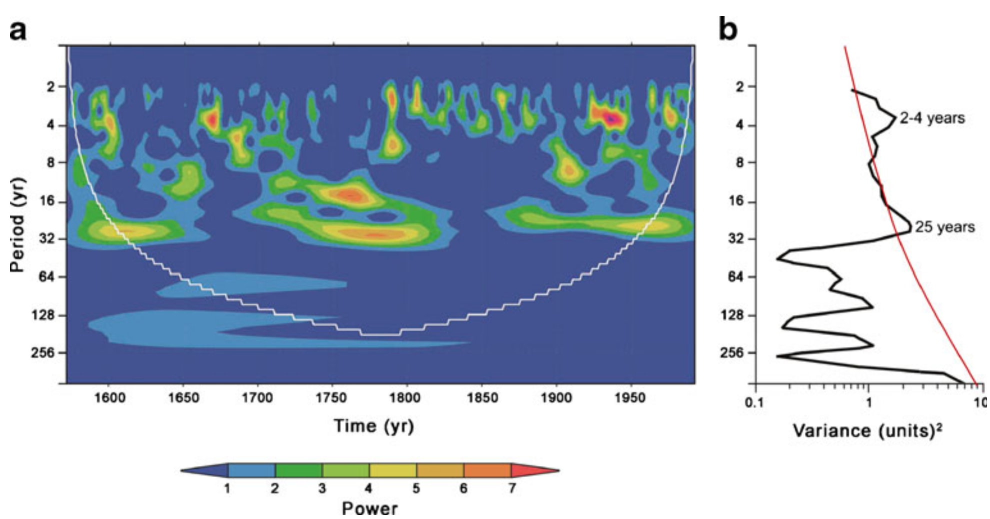
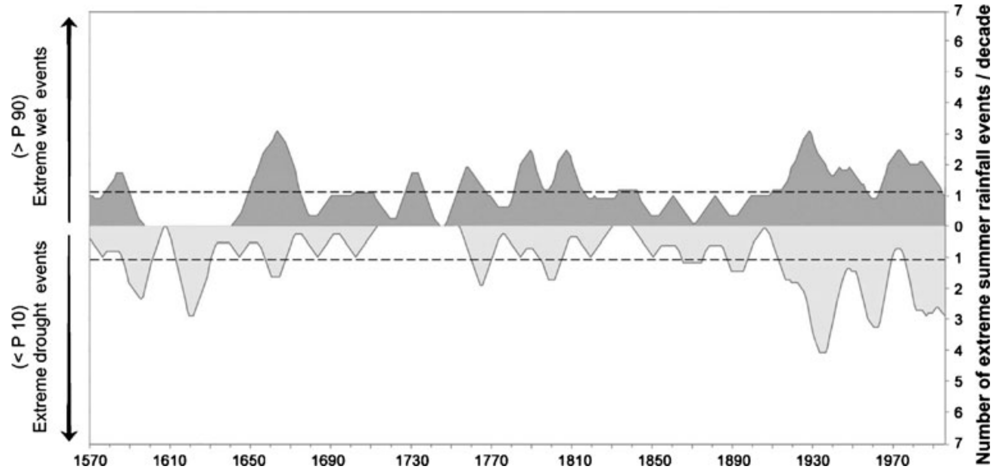


Fig. 5 Temporal evolution of summer rainfall extremes for the 1570–1990 period in the Guadarrama Mountains. The extreme event years are defined through the following percentile thresholds (P): severe wet events (summer rainfall>P 90 %), severe drought (<P 10 %). It shows the running 10-year cumulative number of events per decade



2006) (Fig. 6). The correlation coefficients $0.5<x<-0.5$ are significant at the $P<0.005$ level.

Discussion

Our results indicate a significant correlation between summer rainfall (May–August) and a composite tree ring chronology based upon two species of *Pinus*. The significant correlation between the growth of *P. sylvestris* and of *P. nigra* ssp. *salzmannii* with summer rainfall enabled reconstruction of this climate variable with a model that explains much of the total variance (adjusted R^2=0.49, P< 0.000001). The reconstruction performed herein is currently the most accurate for the Central Mountains of the Iberian Peninsula.

The spatial correlation patterns between instrumental and reconstructed values (Fig. 6a) show how the reconstruction captures the regional signal of drought variability in the target region of the northeastern mountains of the Iberian Peninsula (correlations of up to 0.6). The May–August pressure map (Fig. 6b) shows that this area is influenced in summer by the thermal low pressure zones induced in the northeastern areas of the Iberian Peninsula. This indicates that the summer rainfall recorded in this region is basically of convective origin and results from this low pressure (Fernández 1986; Ruiz-Labourdette et al. 2011a).

Most of the reconstructed series (sixteenth to the twentieth century) is within the dry, wet and irregular rainfall period described by other authors for the Iberian Peninsula (Sanz 2003; Font 1988; Martín-Vide and Barriendos 1995; Rodrigo et al. 1999). Rainfall minima of the reconstruction were

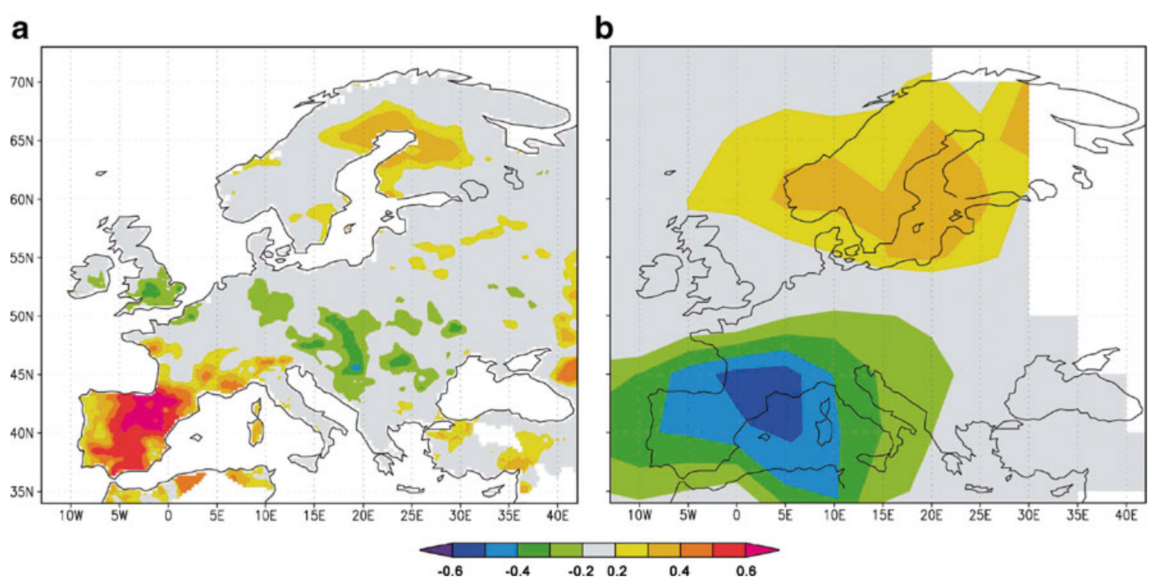


Fig. 6 Spatial correlation patterns between **a** the E-OBS 3.0 (Haylock et al. 2008) 0.25°×0.25° gridded May–August precipitation and the reconstructed May–August precipitation for the 1950–1992 period. **b** The HadSLP2 (Allan and Ansell 2006) 2°×2° gridded May–August sea level pressure and the reconstructed summer precipitation for the 1942–1992 period. Correlation coefficients $0.5<x<-0.5$ are significant at the $P<0.005$ level

observed in the 1600–1630, 1750–1770, 1940 and 1965 periods. Maximum precipitation was observed during the 1650–1680, in the 1780s and in the 1970–1990 periods. The reconstruction precipitation maximum of the 1780s, coinciding with the rainfall maximum detected on the Iberian Peninsula, was identified by different authors (Font 1988; Fernández et al. 1996; Sanz and Creus 1999) by means of historic documentary sources as one of the periods exhibiting the greatest climatic extremes of the last few centuries in the area. The instrumental data records show an abrupt change to drier conditions during the 1990s (Fig. 3). This last abrupt decadal scale change is the largest of the 1570–2005 series, coinciding with the decrease in rainfall detected on the peninsula by Rodrigo et al. (1999, 2000), De Luis et al. (2000), Sanz (2003) and Lehner et al. (2006) and with the summer warming of the Central Mountains of the peninsula as from the 1980s (Raso 1997; Granados and Toro 2000; Agustí-Panareda and Thompson 2002).

The low-frequency climatic variability of the reconstructed series shows that one of the most important oscillatory modes involves a quasi-periodicity of approximately 25 years. This pattern is mostly constant throughout the series and is only interrupted in the second half of the 1600s and halfway through the 1800s. Currently, no studies demonstrate this quasi-periodicity of the rainfall pattern in Europe. Other authors have detected rhythms in tree growth related with drought conditions every 18.6 years in the North America (Currie 1984; Cook et al. 1997) or with the 22-year Hale solar cycle (Murphy et al. 1994; Villalba et al. 1996). The other oscillatory mode, exhibiting a short periodicity (<4 years) observed in Europe (Burroughs 1992; Jiménez et al. 2001), presents no significant correlations with the return periods of the North Atlantic Oscillation or the El Niño Southern Oscillation climatic indices. The relationship between this quasi-periodicity and climate forcings requires further investigation.

Reconstruction (1950–1992) and climatic records (1942–2005) also show an apparent increase in the recurrence of extreme dry events from the start of the twentieth century in these mountains, which becomes sharper in the 1990s. This increase is consistent with that observed by Manrique and Fernández-Cancio (2000), Tardif et al. (2003), Camarero and Gutiérrez (2004), Andreu et al. (2007) and Macias et al. (2006) in the Pyrenees and by Ceballos et al. (2004) and Galán et al. (1999) on Spain's Central Plateau. We believe that the value of the present paper lies in the first combination of the six sites studied in two composite chronologies and in the joint analysis thereof in order to obtain regional chronologies that can be useful for understanding past climate in southwestern Europe.

This supports the results indicating a global tendency towards a greater recurrence of extreme drought and heat waves in southern Europe (Easterling et al. 2000; Goodess and Jones 2002; Beniston et al. 2007; Lehner et al. 2006; Giorgi and Lionello 2008; Fischer and Schär 2010).

Ecological perspective in the projected trend of global warming

Regional climate change projections for mountains on the Iberian Peninsula were conducted by Nogués-Bravo et al. (2007), AEMET (2008) and Giorgi and Lionello (2008). These simulations provide a collective picture of substantial drying and warming in the warm season—a precipitation decrease exceeding 25–30 % and warming exceeding 4–5 °C for the 2071–2100 period in relation to the 1961–1990 reference period, under the A2-IPCC emission scenario (medium–high emissions).

These forecasts invite us to imagine the consequences of these changes for the southerly limit of the distribution ranges of numerous Eurosiberian refugee species in the Mediterranean mountains. Here, the cause of stress is fundamentally water related (Kramer et al. 2000; Giménez-Benavides et al. 2007; Acosta et al. 2008) and warming and desiccation would cause radical re-ordination of plant communities in these mountains. Since the end of the last glaciation, relict Mediterranean populations of Eurosiberian and Boreal species that have found refuge in these mountains constitute one of the southernmost formations of these species in Eurasia. These populations are typical of shade-adapted species (unlike what occurs with this same species in forests in central and northern Europe), which favours survival of seedlings during summer (Escudero et al. 1997; Martínez-Vilalta and Piñol 2002; Castro et al. 2004). The conditions observed of exceptional soil moisture, similar to those in the regions of origin of these species in central and northern Europe, might constitute the key to their growth and reproduction. The exceptionally wet summers, with a recurrence of approximately 9 years, could give rise to mass recruitment episodes, sufficient to guarantee the medium- and long-term survival of these northern species in the Mediterranean climate (Rojo and Montero 1996; Castro et al. 2004). This might perhaps enable exceptional recruitment of root reserves that would be useful for subsequent growth cycles (Fritts 2001; Lara et al. 2005). The decrease in frequency of these wet events therefore implies a northward latitudinal displacement of these forests in the Mediterranean region, together with a substantial reduction thereof, as was modelled by Benito et al. (2006, 2008), García and Allué (2010), Keenan et al. (2011), Ruiz-Labourdette et al. (2011b), Engler et al. (2011) or Thuiller et al. (2011). Changes in this sense can perhaps be observed in Mediterranean mountains—*Pinus uncinata* (Camarero and Gutiérrez 2007), *Taxus baccata* (Sanz et al. 2009) or *Abies pinsapo* (Linares and Carreira 2009). Our results indicate that the direct and indirect effects of extreme events on Mediterranean ecosystems might be greater than those caused by the mean change trends (Peñuelas et al. 2000; Walther et al. 2002; Gutschick and BassiriRad 2003; Groom et al. 2004; Pausas 2004; Pausas and Fernández-Muñoz 2012).

The only vestiges of Eurosiberian and Boreal species on the central Iberian Peninsula might disappear with an increase in summer drought (Fernández-González et al. 2005). This loss of species might be intensified by isolation within a warm and dry matrix (Petit et al. 2005) at the southern limit of their biogeographical distribution. In consonance with the behaviour patterns observed in other Mediterranean mountains, there might be a progressive displacement of the cold humid conifers (*P. sylvestris*, *P. nigra*) and cold temperate deciduous species (*Q. petraea*, *F. sylvatica*, *Corylus avellana*, *F. excelsior*, *Betula* sp., etc.) by species exhibiting less water requirements—*Q. pyrenaica*, *Quercus faginea* and *Juniperus thurifera* (Sobrino et al. 2001; Peñuelas and Boada 2003; Sanz-Elorza et al. 2003; Valladares et al. 2005, 2008; Mendoza et al. 2006; Jump et al. 2006). In the same sense, the forests of Mediterranean mountains might be subjected to new disruptive factors resulting from increased temperature, summer desiccation, a greater recurrence of extreme drought and heat waves, such as the spread of exotic thermophilous or xerophyllous species (Brasier 1996; Gritti et al. 2006), perhaps increasing the frequency of natural and man-made fires (Piñol et al. 1998; Pausas 2004; Moriondo et al. 2006; Bowman et al. 2009; Pausas and Fernández-Muñoz 2012), or a higher incidence of pests heretofore only observed at lower elevations (Hódar et al. 2003). These changes can seriously affect biodiversity in these mountains, which constitute the low-latitude limit or rear edge of numerous Eurosiberian species (Hampe and Petit 2005) and Europe's highest rates of endemisms (Vennetier and Ripert 2009; Thuiller et al. 2011).

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