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ORIGINAL PAPER

# Atlantic and Mediterranean synoptic drivers of central Spanish juniper growth

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**Abstract** Atlantic and Mediterranean air masses influence the climate over the Iberian System mountain range. The relatively short instrumental records in central Spain though limit any long-term assessment of these synoptic systems. We here evaluate the potential to analyze such changes using ring width data from *Juniperus thurifera* trees growing in the northwestern and southeastern regions of the Iberian System, exposed to Atlantic and Mediterranean cyclonic activity, respectively. Comparison of tree rings with regional precipitation, temperature, and Palmer Drought Severity Index (PDSI) data indicates that juniper trees contain information on late spring and early summer drought conditions. Calibration trials using spatially resolved, gridded climate data reveal that the northwestern sampling site is predominantly controlled by Atlantic weather, while the southeastern site mainly reflects Mediterranean climate patterns. The strength and position of the blocking Azores high during spring to early summer is of particular importance for the distinct growth reactions in the Iberian System. The climate signal is remarkably strong in the southeastern site, where we developed the longest and best-replicated juniper tree ring record of the Iberian Peninsula. Data from this site allowed the reconstruction of May-June PDSI variability back to the early eighteenth century, indicating severe drought (PDSI<−9) in southeastern Spain in 1782, 1828, 1869, 1981, and 2005. The new PDSI record coheres well with historical rogation ceremony data from eastern Spain, indicating that common information on past drought events is inherent in both proxy archives.

## 1 Introduction

General circulation models indicate an increasing risk for severe summer drought in the western Mediterranean Basin

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toward the end of the twenty-first century (Giorgi and Lionello 2008). These conditions will likely be triggered by a well-developed and persistent high-pressure cell, the Azores high, blocking the advection of moisture from the Atlantic Ocean and Mediterranean Sea on the Iberian Peninsula (Altava-Ortiz et al. 2011). The tendency toward aridification is accompanied by rising temperatures accelerating a warm season moisture deficit, severely impacting regional vegetation and crop production (IPCC 2013). While the statistical certainty of such regional climate simulations, particularly for precipitation and drought, is rather low, it seems advisable to study the magnitude of drought events over longer time periods and work toward an extended dataset for assessing drought frequency in the Circum-Mediterranean area (Luterbacher et al. 2014).

Regional drought reconstructions, extending prior to instrumental observations, are largely missing in Iberia (Luterbacher et al. 2012). No regional precipitation reconstruction has been developed from tree ring chronologies, and the only local information on past drought events over the past several hundred years can be derived from documentary evidence (Martín-Vide and Barriendos 1995). Seasonal drought variability has been studied over the past 500 years in designated Iberian locations (Barriendos 1997; Domínguez-Castro et al. 2008; Vicente-Serrano and Cuadrat 2007), and an assessment of historical rogation ceremonies from several villages and cities in Spain enabled the reconstruction drought events and association with regional synoptic drivers (Domínguez-Castro et al. 2010, 2012).

From a tree ring perspective, the Iberian System, a mountain range separating Atlantic from Mediterranean influences and encompassing areas in northern, central, and eastern Spain (Rodriguez-Puebla et al. 1998), offers the opportunity to (i) potentially differentiate between western and eastern synoptic influences over longer timescales and (ii) reconstruct regional drought events associated with changes in large scale circulation patterns. In the Iberian System, most plateaus and lowlands covered with calcareous soils are subjected to a continental Mediterranean climate dominated by widespread *Juniperus thurifera* stands (Gauquelin et al. 1999). Previous work on tree ring width (TRW) and wood density data from *J. thurifera* in Spain indicated this species to be responsive to spring and early summer hydroclimatic conditions (Camarero et al. 2014; DeSoto et al. 2011, 2014). A TRW network analysis of 13 juniper sites in Spain revealed significant positive correlations with May and June precipitation totals and negative associations with June and July temperatures (DeSoto et al. 2012). Other work indicated only minor growth differences between female and male individuals (Montesinos et al. 2012; Rozas et al. 2009), corroborating the potential of this tree species to be considered for climate variability assessments and reconstruction of drought events (Esper et al. 2007).

We here address this objective and present two well-replicated TRW chronologies reaching back to the early nineteenth and late seventeenth centuries from *J. thurifera* sites located in northwestern and southeastern areas of the Iberian System. We assess the climate signal at these sites and demonstrate that the derived proxy data are influenced by late spring/early summer precipitation and temperature patterns toward the Atlantic Ocean and Mediterranean Sea, respectively. Exceptionally negative and positive TRW deviations are compared with mid-tropospheric geopotential high variations, and the significant May-June drought signal is utilized and transferred into a regional Palmer Drought Severity Index (PDSI) (Palmer 1965) reconstruction back to AD 1708.

## 2 Data and methods

Eighty-seven and 58 tree trunk core samples were collected in two *J. thurifera* sites in central Spain (Fig. 1). The sites are situated above 1,000 m asl. in the northwest (NW-J) and southeast (SE-J) Iberian System, ~30 km west of the city Soria and ~35 km east of the city Teruel. In these sites, juniper trees reach heights from 4–8 m and develop open forests on shallow, calcareous soils, where drought stress was expected to be the dominating climate signal.

The 5-mm-diameter core samples were prepared, visually crossdated, and TRW measured following standard procedures (Schweingruber 1983). The resulting time series were detrended using 100-year spline high-pass filters (Cook and Peters 1981) to remove tree age-related trends from the data (Cook and Kairiukstis 1990). The detrended measurements series were averaged using the arithmetic mean to form site chronologies reaching back to 1,809 in NW-J and 1,681 in SE-J (Table 1). Inter-series correlations in these sites are fairly high (Rbar=0.50 and 0.58), indicating a good coherence among the measurement series and suggesting that a common climatic forcing synchronized the TRW variations among trees. The temporally changing quality of the site chronologies was assessed by calculating the expressed population signal (EPS; Wigley et al. 1984) in 30-year windows shifted along the time series.

The sampling sites are subjected to a continental Mediterranean climate characterized by summer drought, increasing from northwestern to southeastern Spain, and winter cold including frost and snowfall. NW-J is classified subhumid (Rivas-Martínez 1983) with 516 mm annual precipitation, of which 102 mm are recorded during May-June at the nearby meteorological station in Soria, predominately originating from cyclone advection from the Atlantic Ocean. The SE-J site is dryer, recording only 414 mm at the nearby station in Teruel and 101 mm during May-June, with most of the precipitation originating from Mediterranean cyclonic activity (Esteban-Parra et al. 1998; Rodriguez-Puebla et al. 1998).

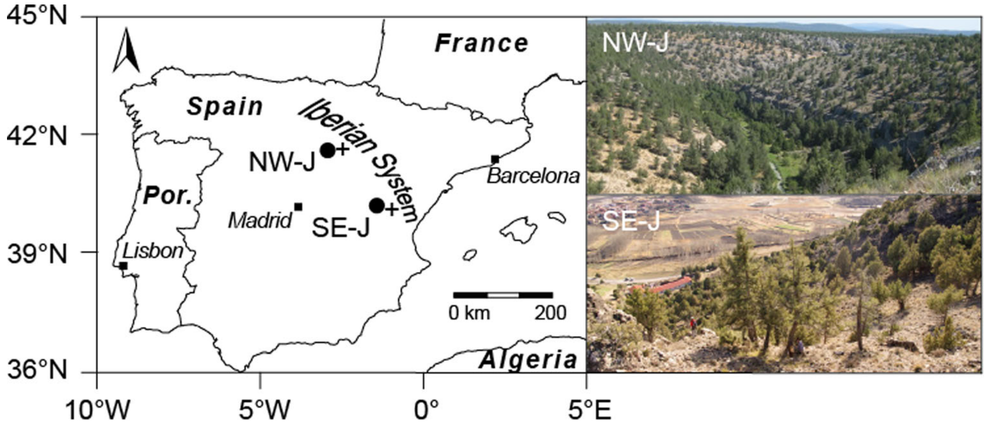


**Fig. 1** *Juniperus thurifera* sampling sites in northwestern (*NW-J*) and southeastern (*SE-J*) Iberian System. *Crosses* indicate climate stations in Soria near NW-J and Teruel near SE-J

For calibration of the NW-J and SE-J site chronologies, we used the observational precipitation and temperature data from Soria and Teruel reaching back to 1944 and 1948, respectively (Table 1). Monthly data from previous year October to current year September as well as a seasonal mean integrating May and June (MJ) were considered for the calculation of Pearson correlation coefficients with the tree ring data. In addition to the station readings, we used gridded PDSI data (2–3° E and 41–42° N for NW-J and 1–2° E and 40–41° N for SE-J; Van der Schrier et al. 2006) reaching back to 1901, though the early portions of these time series must be considered with caution as the station network in central Spain was rather patchy before 1950. PDSI is a widely used metric of relative drought and wetness (Cook et al. 2004) integrating observational precipitation and temperature data as well as regional soil type information (Dai et al. 2004). The latter component adds considerable seasonal persistence to this drought index, resulting in high correlations between consecutive months (Palmer 1965). All correlations with tree ring data were calculated over full periods of overlap with instrumental data as well as over a common period 1948–2002.

The spatial patterns of climate signals inherent to the juniper site chronologies were evaluated considering 0.5° gridded (CRU3.1) precipitation, temperature, and PDSI data, and correlation fields plotted using the KNMI Climate Explorer at http://climexp.knmi.nl. The typical pressure patterns associated with wide and narrow tree rings were assessed by averaging 500 hPa geopotential heights over Europe (Luterbacher et al. 2002) during the twentieth century TRW deviations exceeding ±1 standard deviation. Since the MJ PDSI signal in SE-J turned out to be particularly strong and the TRW data from that site reach back to the late seventeenth century, we also transferred this site chronology into a drought reconstruction by scaling (Esper et al. 2005) the proxy record over 1901–2002 against the nearest grid point PDSI record. The reconstruction is accompanied by uncertainty estimates derived from the standard error (SE) of the calibration model.

The tree ring-based PDSI reconstruction was subsequently compared with historical rogation dates considering the spring and summer ceremonies in five cities in eastern Spain (Barcelona, Tarragona, Teruel, Tortosa, Zaragoza) available over the 1750–1850 period (Domínguez-Castro et al. 2012). The data were expressed in percent reaching from no rogation in a particular year in any of the five cites (0 %) to 100 %, indicating that rogations took place in all five cities during spring and summer of a particular year. We aligned the reconstructed MJ PDSI estimates, using superposed epoch analysis (SEA; Panofsky and Brier 1958), considering the seven driest years characterized by >50 % rogation events during the 1750–1850 period as well as 22 likely pluvial years where no rogation was documented in any of the five cities. In the SEA, the four pre- and post-rogation (no rogation) PDSI estimates are also displayed.

**Table 1** Tree ring sites and meteorological stations. MSL is the mean segment length of all series included in a site chronology. AGR is the average growth rate of all trees in a site. Rbar is the correlation between all measurement series within a site, after removing the age trend from the series

| Site/station | Latitude | Longitude | Elevation [m] | Period | Series | MSL [year] | AGR [mm] | Rbar |
|---|---|---|---|---|---|---|---|---|
| NW-J | 41° 42′ 29″ N | 2° 48′ 22 ″W | 1,040–1,090 | 1809–2010 | 87 | 115 | 0.76 | 0.50 |
| SE-J | 40° 22′ 51‴ N | 1° 31′ 14″ W | 1,220–1,320 | 1681–2010 | 58 | 197 | 0.74 | 0.58 |
| Soria | 41° 46′ 30″ N | 2° 28′ 59″ W | 1,082 | 1944–2010 | | | | |
| Teruel | 40° 21′ 2″ N | 1° 7′ 27″ W | 900 | 1948–2003 | | | | |

## 3 Results and discussion

### 3.1 Climatic drivers of NW-J and SE-J

The *J. thurifera* chronologies show good coherence over the past 200–300 years with EPS values exceeding 0.81 back to the mid-nineteenth century in NW-J and back to the mid-eighteenth century in SW-J (Fig. 2). While replication in NW-J decreases rapidly in the late nineteenth century, the number of measurement series in SE-J declines more gradually back in time, indicating that this latter record might contain reconstruction skill well before the onset of instrumental measurements. The two chronologies, NW-J and SE-J, correlate at $r$=0.18 over the 1829–2010 period of overlap (replication >4 series).

The climate signal inherent to these chronologies is characterized by positive correlations with May precipitation and negative correlations with early and high summer temperatures (Fig. 3). These results are in line with previous work on *J. thurifera* stands in central Spain (DeSoto et al. 2012), indicating the dominating significance of water availability to maintain cell division and enlargement at the onset of the vegetation period during earlywood formation (Camarero et al. 2010, 2014). Late spring/early summer water supply is again negatively impacted by subsequent summer warmth (most significant in June in NW-J and in July in SE-J) evapotranspirating humidity from the shallow calcareous soils and thereby constraining radial stem growth in these subhumid and dry sites.

These conditions are summarized in the PDSI integrating precipitation, temperature, and soil parameters (Van der Schrier et al. 2006). The correlations with this climate parameter gradually increase from previous year October reaching maximum values in current year May (Fig. 3, bottom panel). The correlations are persistently larger in the dryer SE-J site (compared to NW-J) and when omitting the early twentieth century data from the calibration trials. The latter indicates a loss of skill in the meteorological network due to missing observational data prior to the 1940s. Maximum values of $r$=0.62 during May and $r$=0.61 during MJ indicate the feasibility of considering the SE-J TRW chronology as a reconstruction of spring/summer drought. Split-period calibration (1948–1975) and verification (1976–2002) against instrumental MJ PDSI data reveal correlations between $r$=0.44 and 0.70. A possible secondary seasonal response peak, as would be expected from sub-seasonal growth monitoring data, demonstrating a bimodal xylogenesis including an autumn reactivation of cambial activity in lowland *J. thurifera* (Camarero et al. 2010), is not revealed in our monthly response patterns. Secondary growth and latewood formation in our higher elevation sites is likely <10 % of the total ring width (Olano et al. 2012), thereby constraining the seasonality of the climate signal to late spring/early summer.

### 3.2 Spatial response patterns

The local calibration results are supported by larger-scale correlation fields, indicating an overall stronger signal in SE-J compared to NW-J, particularly with the PDSI data (Fig. 4). This approach, however, additionally reveals a distinct spatial differentiation between the juniper sites, with the NW-J signals clearly oriented toward Portugal and the Atlantic Ocean,

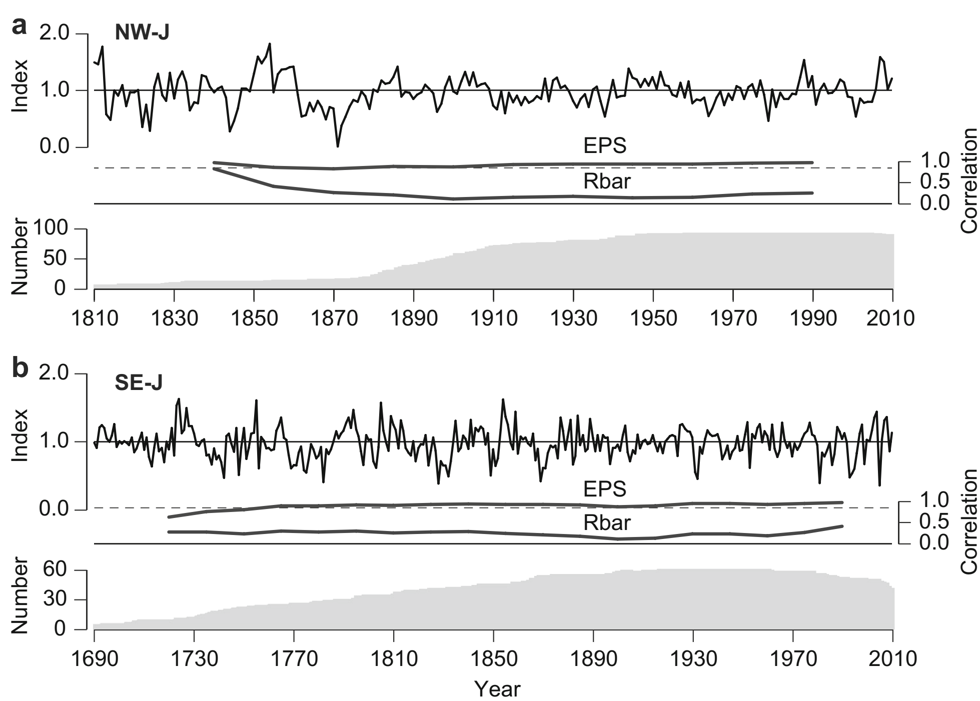


**Fig. 2** *Juniperus thurifera* site chronology characteristics. **a** The 100-spline detrended *NW-J* chronology (*top panel*) shown together with the temporally changing expressed population signal (*EPS*) and inter-series correlation (*Rbar*) and the number of TRW measurement series included in the chronology (*bottom panel*). **b** Same as in (**a**) but for the *SE-J* data. *Dashed lines* indicate EPS=0.85 above which a chronology might contain some predictive skill

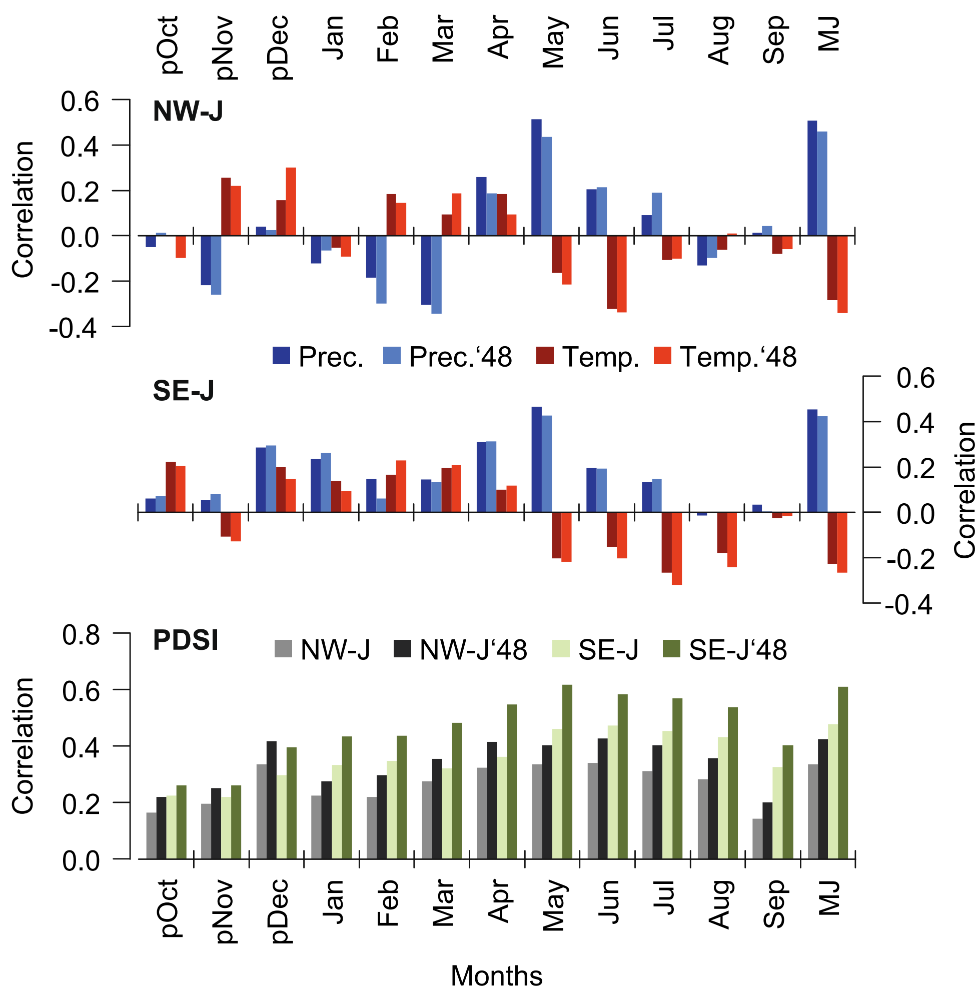


**Fig. 3** Climate signals in northwestern and southeastern central Spanish juniper growth. Correlation coefficients between monthly precipitation (*blue*) and temperature data (*red*) with NW-J and SE-J tree ring width data (*top and middle panels*). *Bottom panel* shows correlations with gridded PDSI data (*gray and green*). All correlations are computed over the (full) periods of overlap with instrumental data (see Table 1: 1944–2010 for Soria, 1948–2003 for Teruel, 1901–2002 for gridded PDSI) as well as over the period 1948–2002 common to all instrumental records (labeled '48 in the figure). *Bars* for pOct, pNov, and pDec indicate correlations with previous year's months. MJ is a seasonal mean integrating May and June data. For the common-period calculations, $p<0.05$ is reached at $r\approx0.3$

and the SE-J patterns extending southeast into northwest Africa. The SE-J PDSI pattern is spatially more restricted and confined to the Iberian Peninsula, whereas the NW-J PDSI signal appears largely insignificant when considering the extended 1901–2002 period. The correlation maps clearly reveal a spatially explicit influence of low-pressure systems, advected from the Mediterranean Sea, on the vegetation in the eastern Iberian System, and a dominating control of growth by the Westerlies in the western Iberian System.

This distinction into Atlantic and Mediterranean synoptic drivers is reinforced by the 500-hPa geopotential height maps associated with exceptionally narrow and wide tree rings in NW-J and SE-J (Fig. 5). Particularly, the negative TRW deviations show a differentiation, with NW-J being associated with an intensified Azores high extending along the southwest European continental lands and blocking Atlantic depressions and SE-J associated with high pressure in the western Mediterranean and extending north over the European Alps. In contrast, wide juniper tree rings are associated with low pressure centered over western Iberia and extending into the Atlantic (NW-J) and a more diffuse pattern of low pressure extending north into central and northern Europe (SE-J). The mid-tropospheric geopotential heights associated with tree growth in central Spain reveal the differential influence of Atlantic and Mediterranean air masses on the Iberian System, thereby indicating the ability of *J. thurifera* stands to support the reconstruction of competing synoptic influences in southern Europe, which could improve our understanding of changing long-term atmospheric dynamics at continental scales (Trouet et al. 2009).

### 3.3 PDSI Reconstruction and assessment

We considered the SE-J chronology for the reconstruction of annual to multi-decadal MJ PDSI fluctuations back to 1708 (Fig. 6). The reconstruction focuses on May and June as these months revealed highest correlations with the juniper ring width chronologies and distinct positive temperature and negative precipitation responses. While the uncertainties of this reconstruction are quite large, as to the unexplained variance exceeding 60 % of the observed PDSI variability back to 1948 (here estimated considering 2xSE, smoothed in the figure), an

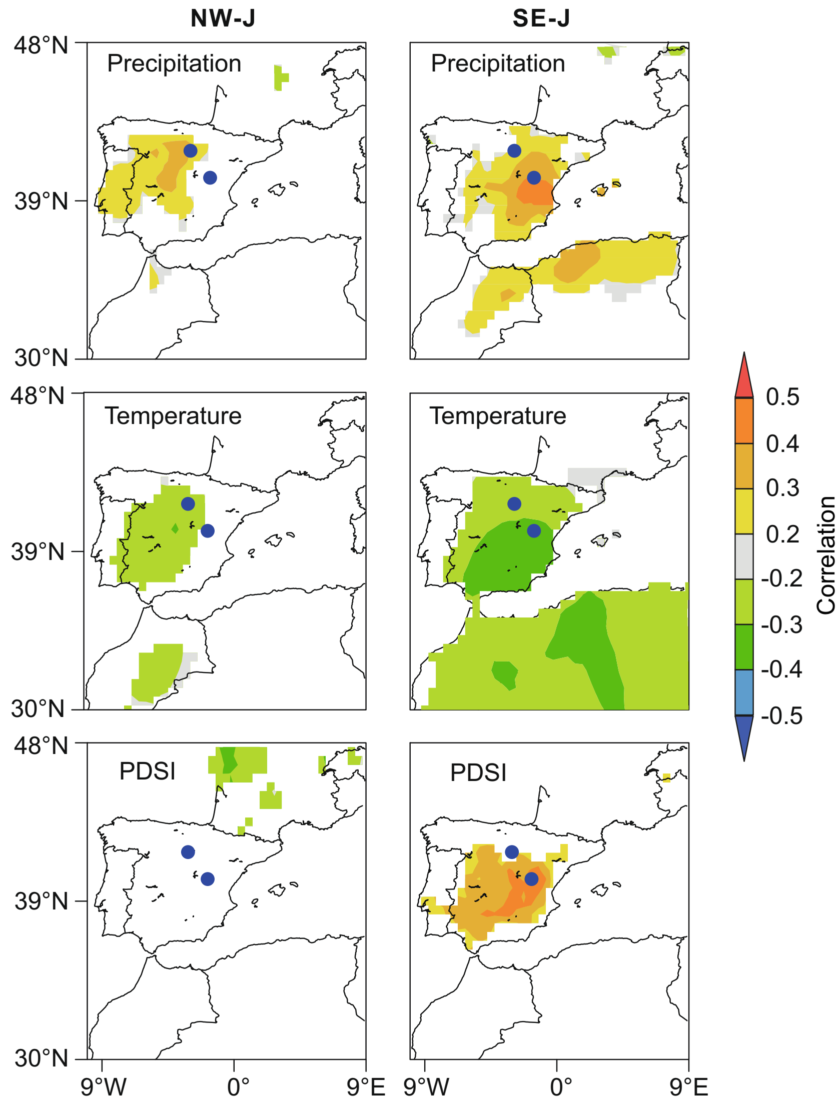


**Fig. 4** Climate fields associated with juniper growth in northwestern and southeastern Spanish sites. Correlation patterns of gridded May-June precipitation, temperature, and PDSI data with 1901–2002 TRW data in NW-J (*left column*) and SE-J (*right column*). *Blue dots* indicate the location of NW-J and SE-J

estimation of longer-term hydroclimate variability appeared useful in a region threatened by increasing drought impact. Severe drought beyond PDSI<−8, during the plant physiologically important late spring/early summer period, occurred in 9 years during the past 300 years (Table 2). These events were accompanied with regular pluvial conditions (exceeding +8 in 9 years), thereby emphasizing the variability of hydroclimate and vulnerability of vegetation and farming in central Spain.

Comparison of the MJ PDSI reconstruction with drought estimates derived from historical rogation ceremonies in five Spanish cities located toward the Mediterranean Sea (Domínguez-Castro et al. 2012) revealed only modest correlation ($r$=0.31) throughout 1750–1850 (Fig. 6b). These results are, however, constrained by the structure of the rogation data including 22 years with no rogation ceremony (0 %) in any city, for example. Aligning the tree ring-derived PDSI values by these likely pluvial years, as well as the dry years exceeding 49 % rogation events, using SEA, revealed a clear pattern of high and low PDSI estimates centered on the rogation data (year 0 in Fig. 6c). The average reconstructed PDSI exceeds +3.5 during years when no rogation ceremony in any of the five cities took place, but falls below −3 during years with maximum numbers of rogation ceremonies. While these findings appear encouraging and revalidate variability in both proxy records, there is also reason for expecting dissimilarity between these tree ring and documentary archives. Whereas the tree ring-based PDSI reconstruction is characterized by response maxima during MJ, the rogation data represent specific events that took place during a certain date in spring and summer of a particular year, and after which both continuous drought as well as rainfall could have happened. The tree ring and documentary proxy locations are also distributed over a region exceeding 300 km including coastal as well as mountainous sites.

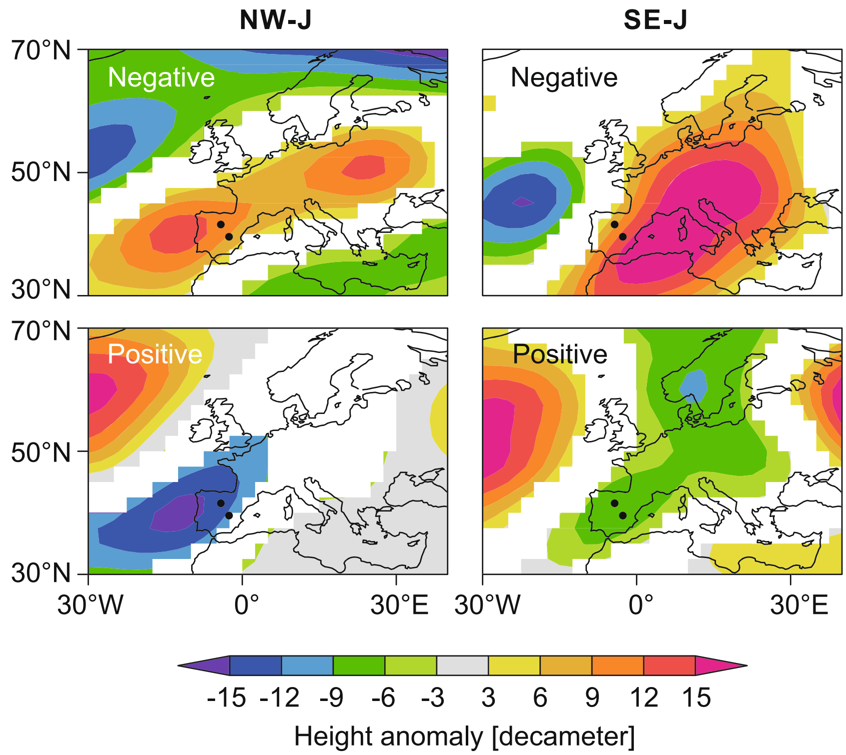


**Fig. 5** Large scale circulation patterns associated with negative and positive tree ring deviations. *Colors* indicate the mean May-June geopotential height deviations in the 500 hPa level (in decameters) in years with exceptionally narrow (*top panels*) and wide (*bottom panels*) tree rings in NW-J (*left*) and SE-J (*right*). *Green and blue* indicate areas with low pressure and *yellow and red* indicate areas with high pressure, relative to climatology

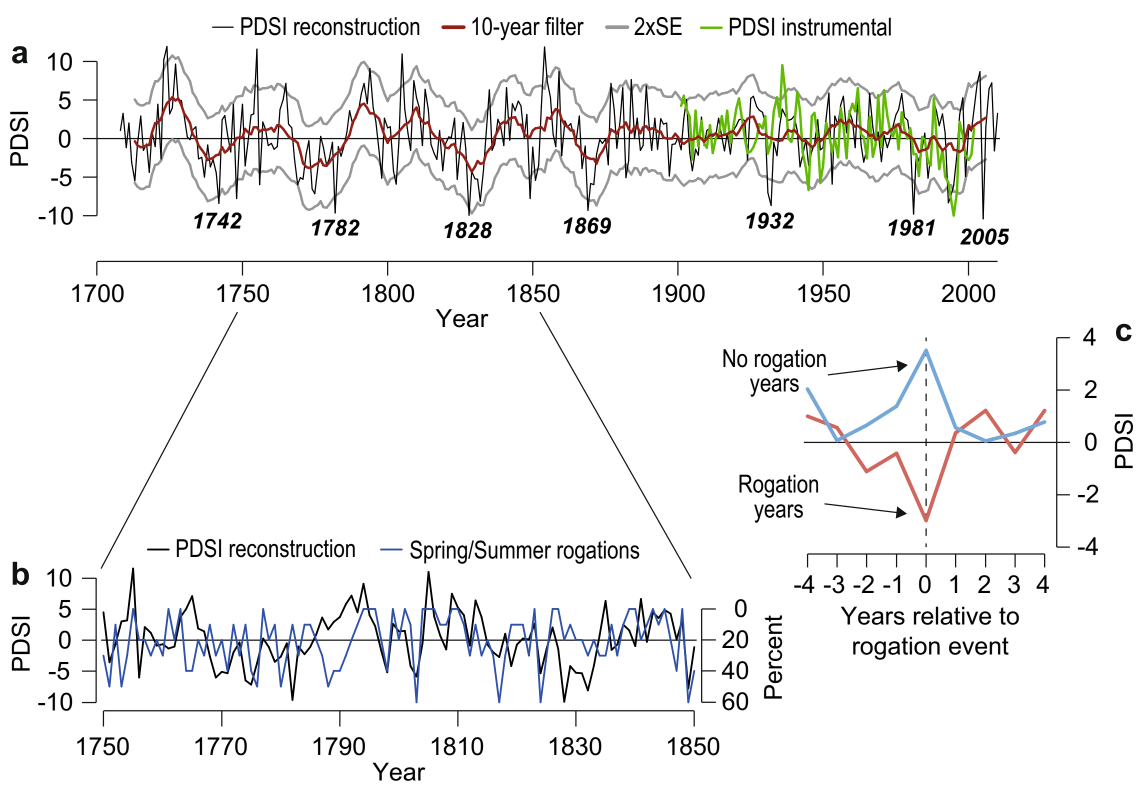


**Fig. 6** PDSI reconstruction and comparison with rogation ceremony data. **a** Annually resolved PDSI reconstruction back to 1708 (*black curve*), derived from scaling the SE-J chronology against instrumental PDSI data (*green*), shown together with a 10-year filter (*red*). Uncertainty is estimated considering the standard error (2xSE, *gray*) of the calibration model from 1948–2002. Seven reconstructed driest years exceeding PDSI<−8.5 are indicated (see Table 2). **b** The PDSI reconstruction shown together with the number of rogation events (*blue curve*, in percent) documented in five eastern Spanish cities over the 1750–1850 period. **c** SEA of the PDSI estimates centered on the seven driest years ≥50 % rogation events during 1750–1850 (*red curve*) and the 22 potentially wet years during which no rogation was documented (*blue curve*)

**Table 2** Ten highest and lowest reconstructed May-June PDSI values in southeastern Spain since 1708

| | Year | Wet | Year | Dry |
|---|---|---|---|---|
| 1 | 1724 | 12.0 | 2005 | −10.5 |
| 2 | 1854 | 11.8 | 1828 | −9.9 |
| 3 | 1755 | 11.6 | 1981 | −9.8 |
| 4 | 1805 | 11.0 | 1782 | −9.6 |
| 5 | 1723 | 10.2 | 1869 | −9.3 |
| 6 | 1727 | 9.6 | 1932 | −8.7 |
| 7 | 1794 | 9.1 | 1742 | −8.5 |
| 8 | 1859 | 8.7 | 1993 | −8.4 |
| 9 | 2004 | 8.6 | 1832 | −8.1 |
| 10 | 1884 | 7.6 | 1849 | −7.8 |

The PDSI reconstruction presented here best portrays conditions in the eastern Iberian System and southeastern Spain (right column in Fig. 4). Due to the chronology composition integrating wood samples from only living trees, as well as the necessary removal of tree age-related noise using individual detrending methods (Cook et al. 1995), the reconstruction does not contain lower frequency, centennial scale trends (Esper et al. 2002). Such an objective could be achieved by combining the living-tree samples with TRW measurements from historical buildings, which would also permit extending the reconstruction further back time over the past millennium. It is recommended working with disks rather than core samples in such a project to facilitate crossdating among trees and dating of historical wood.

## 4 Conclusions

Two well-replicated *J. thurifera* chronologies reaching back to 1809 and 1681 from the Iberian System mountain range in Spain are presented. The records contain significant climate signals and are most sensitive to late spring/early summer drought conditions. Due to their location toward the northwestern and southeastern margins of the Iberian System, and the application of spatial correlation maps, the newly developed time series permitted a distinct differentiation into Atlantic and Mediterranean synoptic drivers of juniper growth. This finding was further supported by analyzing lower tropospheric pressure patterns associated with exceptionally wide and narrow tree rings in central Spain, an assessment that revealed the feasibility of utilizing juniper tree ring chronologies to reconstruct the dynamics and interplay of Atlantic Westerlies and Mediterranean depressions over longer timescales. A subsequent reconstruction of PDSI variability back to the early eighteenth century revealed skill of the tree ring data to estimate regional drought variations, an achievement that we recommend could be extended back in time using wood samples from historical buildings. The new reconstruction agrees well with pluvial and dry events derived from historical rogation ceremony data, revalidating the drought estimates retained in *J. thurifera* growth variations from the Iberian System mountain range.

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