Original

Santos, J.A.; Carneiro, M.F.; Alcoforado, M.J.; Leal, S.; Luz, A.L.;
Camuffo, D.; Zorita, E.:

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In: The Holocene (2015) SAGE

DOI: 10.1177/0959683614566250

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The Holocene
2015, Vol. 25(4) 663–676
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sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0959683614566250
hol.sagepub.com
SAGE

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Abstract

A calibration of reconstructed winter, spring and autumn precipitation series in Portugal from 1600 onwards is undertaken in the present study using new instrumental sources for the period of 1815–2012. As summer precipitation in Portugal is scarce and irregular, it is not considered. A consistency analysis of the calibrated time series is then undertaken using: (1) precipitation indices for Portugal in 1675–1799; (2) teleconnections between seasonal precipitation and large-scale atmospheric flow; (3) two paleoclimatic experiments (ERIK1 and ERIK2), generated from a global/regional climate model chain (ECHO-G/MM5); and (4) tree-ring records from oak trees in Portugal (Serra do Buçaco). These are the first multi-centennial records of tree-ring growth in Portugal (the earliest series begin in 1675). General agreement is found between indices and calibrated precipitation for their common period on an annual basis. Overall, the atmospheric teleconnection patterns are dynamically coherent between the instrumental and pre-instrumental periods. The inter-annual to inter-decadal variability in the calibrated series reveals similar distributions as in the paleoclimatic simulations. Low-frequency variability in spring precipitation is validated by 12 tree-ring series. This study provides calibrated seasonal precipitation series in Portugal from 1600 onwards, revealing high consistency with several independent sources for winter and spring, enabling future applications to climate research.

Keywords

long-term variability, paleoclimatic simulations, Portugal, precipitation proxies, reconstructed precipitation, tree-rings

Received 28 March 2014; revised manuscript accepted 1 December 2014

Introduction

Climate change and its impacts on environment, human health and socio-economic sectors are a main concern among the general population, scientists and governments. Special attention has been devoted to changes in climate variability and extremes under future scenarios of anthropogenic forcing in Europe (e.g. Santos and Corte-Real, 2006; Santos et al., 2007b; Sillmann et al., 2013) and in Portugal (Andrade et al., 2014; Costa et al., 2012). However, a better understanding of past climates and its implications are crucial for a reliable assessment of the climate change impacts over the next decades (Brázdil et al., 2005). As such, several studies have been carried out in recent decades on historic climatology (e.g. Brázdil et al., 2005, 2010; Camuffo et al., 2013; Luterbacher et al., 2006), including studies of extreme events in Europe and their impacts (Brázdil et al., 2004; Mauch and Pfister, 2009; Pfister et al., 2010; Wetter and Pfister, 2013). Although climate variability can be assessed over the last two to three centuries from instrumental records at some specific locations, there are numerous spatial and temporal gaps, particularly in the pre-instrumental period (before the mid-19th century). For this period, past climate can be reconstructed from documentary evidence (diaries, memoirs, weather logs, ship logbooks, administrative and ecclesiastic archives, among others) and from natural proxies, such as tree-rings, corals, boreholes and ice-cores (e.g. Alcoforado et al., 2000; Brázdil et al., 2005, 2010; Camuffo et al., 2010a).

By using a multi-source approach, a European-wide precipitation reconstruction has been developed since 1500 (Pauling et al., 2006). Data from 1901 to 2000 are based on the reanalysis from Mitchell and Jones (2005), while data prior to 1901 are reconstructed amounts. Three data types are used for this reconstruction:

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instrumental records, documentary evidence and natural proxies. Using similar multivariate approaches as in Pauling et al. (2006), the North Atlantic Oscillation (NAO) index (Luterbacher et al., 2002a) and sea level pressure fields within a North Atlantic–European sector (Luterbacher et al., 2002b) were extended back to 1500. Sea level pressure for the same region and from 1750 onwards was reconstructed by Kuttel et al. (2010). Other winter NAO reconstructions were also undertaken (e.g. Cook et al., 2002; Trouet et al., 2009). European-wide temperature reconstructions are also available since 1500 (Luterbacher et al., 2004; Xoplaki et al., 2005). Continental-wide reconstructed temperatures were also developed for the last two millennia (Ahmed et al., 2013). A European pattern climatology for 1766–2000 was also developed (Casty et al., 2007). Although these reconstructions are commonly based on the stationarity of the relationships between large-scale connections and regional/local climatic conditions, several recent studies have highlighted their potential non-stationarity (Raible et al., 2014; Vicente-Serrano and López-Moreno, 2008), which is an important shortcoming of these reconstructions.

Climate variability in Portugal, including extreme value and trend analyses, has been widely studied for the period of regular meteorological observations (Santos and Leite, 2009). The key role of North Atlantic large-scale atmospheric forcing on Portuguese precipitation has been demonstrated (e.g. Santos et al., 2005), mostly through the NAO and East Atlantic (EA) pattern (Hurrell et al., 2013; Marshall et al., 2001; Pinto and Raible, 2012; Rodríguez-Puebla et al., 1998, 2001; Santos et al., 2007b; Wanner et al., 2001). Furthermore, droughts were associated with the development of strong equivalent barotropic ridges over the Eastern North Atlantic (Santos et al., 2009a, 2009b), as well as with North Atlantic jet stream regimes (Woollings et al., 2011) that underlie the occurrence of recent extremely dry and wet winters (Santos et al., 2013). Nonetheless, the lack of early instrumental and documentary information has hampered climate reconstructions in Portugal for the 17th and 18th centuries (Alcoforado et al., 2012; Camuffo et al., 2010a, 2010b; Luterbacher et al., 2006). The lack of information over Southwestern Europe is stressed by Luterbacher et al. (2000). A regional reanalysis for the Iberian Peninsula was also carried out by Pauling et al. (2006), but largely relying on precipitation reconstructions for Southern Spain (Rodrigo et al., 1999). Precipitation reconstructions in Portugal were undertaken for the period from 1675 to 1715 (Alcoforado et al., 2000) and over the 18th century (Taborda et al., 2004), but these data were not incorporated in Pauling et al.'s (2006) reconstructions.

Climate model experiments simulate data for the same past periods as in the reconstructed series (e.g. Gouirand et al., 2007; Gómez-Navarro et al., 2013; Kiktev et al., 2003; Zorita et al., 2005), but there is no calendar correspondence between simulated and reconstructed time series (Fischer et al., 2007). Nevertheless, the multi-decadal variability is mostly associated with long-term changes, e.g., driven by external forcings, enabling the comparison between multi-decadal variability in reconstructed and simulated data. Recent paleoclimatic simulations highlight the preponderant role of internal variability on precipitation in Portugal, as the external forcings are largely undetectable and the uncertainty levels are very high (González-Rouco et al., 2009).

Tree-rings have been widely used as natural archives (Leal et al., 2004) and are one of the most successful proxies for past climate reconstruction (e.g. Anchukaitis et al., 2012; Briffa et al., 2013; Cullen and Grierson, 2009; Davi et al., 2006; Lara and Villalba, 1993; Leland et al., 2013; Touchan et al., 2011). No chronologies are available over Portugal in the International Tree-Ring Data Bank (ITRDB, <http://www.ncdc.noaa.gov/paleo/treering.html>). Up to now, studies have been focussed on seasonal dynamics of vascular cambium and tree-ring growth (Luz et al., 2014; Vieira et al., 2014a, 2014b), or on relationships between growth

features and climate over short-term series (e.g. Campelo et al., 2013; Leal et al., 2004, 2008) that do not extend beyond instrumental data. The longest published tree-ring chronologies for Portugal spread over 100 (Vieira et al., 2010) and 126 years (Campelo et al., 2009). However, long-living and undisturbed trees in Portugal are rare. The current Portuguese forest is very recent owing to the progressive replacement of natural species with non-native ones, affecting more than one half of the forested territory (ICNF, 2013). In the middle ages, oak trees prevailed in the Portuguese endemic forests (Azevedo, 1997). The evergreen oak species (*Quercus suber* L. and *Quercus ilex* L.) are still widespread, but show limited potential for dendrochronology (weak definition of ring boundaries and occurrence of false rings). The remaining deciduous oak trees represent only 2% of total forest area and grow in isolated stands. Due to the lack of economic interest, these stands are not appropriately inventoried. Although dendrochronology studies for Portugal have given evidence for climate signals in tree-rings, namely positive correlations with precipitation (e.g. Abrantes et al., 2013; Campelo et al., 2013; Leal et al., 2008), they extend only a few decades back in time. In the present study, the very first multi-centennial tree-ring-width (TRW) series for Portugal is analysed.

This study aims to calibrate and analyse the consistency of the Pauling et al. (2006) reconstruction of precipitation in Portugal, using (1) independent precipitation indices, (2) teleconnection patterns in reconstructed large-scale flow within the Euro-Atlantic sector, (3) state-of-the-art regional paleoclimatic simulations and (4) new tree-ring data from Portugal.

Data and methods

The Portuguese historic precipitation series (HistPT) from Camuffo et al. (2013) are used as a reference for calibrating the reconstructed precipitation data from Pauling et al. (2006) over Portugal. As the Portuguese precipitation regime is characterized by strong seasonality, winter (DJF), spring (MAM) and autumn (SON) are considered separately. Summer precipitation is scarce and irregular and may then lead to erratic results. HistPT is available for 1815–2012, but with a data gap in 1826–1835, related to the Napoleonic Wars and the Spanish Civil War during the first half of the 19th century (Camuffo et al., 2013). As this time series is based on instrumental measurements mainly collected in the Lisbon area (Camuffo et al., 2013), it is more representative of the precipitation in that part of the country. A previous correlation analysis of HistPT with the gridded Pauling precipitation, defined on a 0.5° latitude $\times$ 0.5° longitude grid, revealed a maximum correlation coefficient (>0.99) with the closest gridbox to Lisbon (38.5° – 39.0° N, 8.0° – 8.5° W) for all seasons in their 1815–2000 common period. Precipitation for this gridbox was thereby extracted (PaulingPT). The correlation coefficients >0.70 throughout the country highlight that HistPT is also largely representative of the inter-annual variability of precipitation in the mainland, in spite of the strong climate-mean precipitation gradients (>1500 mm in Northwestern Portugal and <500 mm in the very South).

Linear regression analyses were applied to determine transfer-functions between HistPT and PaulingPT in their common period. Calibrated precipitation series (CalPT) are then achieved by applying the transfer-functions to PaulingPT in the period of 1600–2000. The 16th century is not considered herein, as reconstruction errors are expected to be relatively high over Portugal (cf. Pauling et al. (2006), their Figure 3(a)) and there is a substantial lack of data for consistency analysis. For 2001–2012, the HistPT series are used to extend CalPT, which is not a strong assumption as the correlation coefficient between HistPT and PaulingPT in 1961–2000 is greater than 0.99.

In order to analyse the consistency of CalPT, gridded datasets of reconstructed 2-m air temperature (Luterbacher et al., 2004;

Xoplaki et al., 2005), 500-hPa geopotential height and sea level pressure (Luterbacher et al., 2002b) are also used. Correlation patterns between CalPT and these atmospheric fields are computed for the instrumental (1871–1999) and pre-instrumental (1659–1870) periods separately. The non-parametric Spearman-rank correlation coefficients, which are more robust to non-Gaussian variables, are used for this purpose. All correlations in the present study are computed between departures of each variable from their corresponding means. These patterns unveil teleconnections between CalPT and the atmospheric flow (Wilks, 2011). In precipitation and temperature, the statistical significance is assessed at 5% significance level. The reconstructed NAO index (Luterbacher et al., 2002a) is also used to establish relationships between precipitation and large-scale atmospheric circulation over the North Atlantic. The reconstructed sea level pressure by Kuttel et al. (2010) begins in 1750, while the dataset used in the present study initiates in 1659, but the results are in clear agreement for both instrumental and pre-instrumental periods, mainly in winter, apart from some slight differences in detail (not shown).

Two simulations (ERIK1 and ERIK2), generated by two independent runs of a global/regional climate model chain, are also used for the consistency analysis of CalPT. The global model ECHO-G comprises an atmospheric model (ECHAM4; Roeckner et al., 1996) and an ocean model (HOPE-G; Legutke and Voss, 1999). A more recent version than in Cubasch et al. (1997) is used herein. The two experiments were driven by the same historical forcings (greenhouse gases, total solar irradiance and volcanic eruptions). The fifth-generation *Pennsylvania State University – National Center for Atmospheric Research Mesoscale Model* (MM5) is used for dynamical downscaling over a high-resolution domain covering the Iberian Peninsula. A two-way nesting scheme between two domains of the regional model is used. Precipitation data from these simulations are available on a 30-km grid resolution. A detailed description of these experiments can be found in Gómez-Navarro et al. (2012), Zorita et al. (2005, 2007) and González-Rouco et al. (2003). The corresponding physical parameterizations can be found in Jerez et al. (2013). In order to be comparable to CalPT, the simulated precipitation is bilinearly interpolated from the original MM5 Gaussian grid (Gómez-Navarro et al., 2012) to the Pauling dataset grid (0.5° latitude $\times$ 0.5° longitude). The same gridbox of PaulingPT (38.5° – 39.0° N, 8.0° – 8.5° W) is then extracted for ERIK1 and ERIK2. Temporal changes in variability ranges are tracked by 31-year moving window percentiles (non-parametric variability measures).

Finally, TRW series, from a total of 74 wood cores of 37 trees, extracted at breast height with an increment borer, are considered. These samples were obtained from healthy oak trees of the species *Quercus robur* L. (QR), grown in the natural park of Buçaco (central Portugal). Two sites were chosen: one at the mountain top (QR1 at an elevation of about 500m; 32 samples from 16 trees) and another at the base (QR2 approx. 300m; 42 samples from 21 trees). The cores were fixed with glue on a wooden support, with the transverse wood surface facing upwards, and left to dry in air. The core surfaces were then polished, electrically and manually, using progressively finer grits of sand paper. Vessels were then filled with white wax in order to highlight tree-ring limits. TRWs were measured, with a 1/100mm resolution, using an increment measurement table LINTAB 560mm/2.5mm, connected to a LEICA® M80 stereo microscope and software TSAP-Win Scientific 4.68e from Rinntech®. The earliest records begin in 1675, and they all end in the 21st century. Only samples with a continuous record covering at least the instrumental period (1871–1999) are considered for validation purposes (23 from QR1 and 42 from QR2), being the first multi-centennial tree-ring series collected in Portugal.

A singular spectral analysis (SSA) is applied in order to filter out background noise in the precipitation variability and TRW

series, retaining only significant components. This methodology allows an increase in the signal-to-noise ratio (Ghil and Vautard, 1991). The original time series is split into a sum of reconstructed components in the time domain (Vautard et al., 1992), and it is possible to partially rebuild the raw series with only ‘signal modes’. The first modes are commonly recognized as ‘oscillating pairs’ in the eigenspectrum (Elsner and Tsonis, 1996). This decomposition is applied not only to the time domain, but also to the frequency domain (Vautard et al., 1992). The data-adaptive reconstructed components make SSA preferable over other filtering methods, with large application to climate research (e.g. Corte-Real et al., 1998; Sezginer Unal and Ghil, 1995; Ribera et al., 2000). SSA corresponds to an eigenvalue decomposition of a Toeplitz lagged-covariance matrix of rank M . The rank is the average of $(N/4 - N/3)$, where N is the time series length (Plaut and Vautard, 1994). The Burg algorithm is used for power spectral density estimation (Burg, 1975), widely applied to climatic parameters (Leite and Peixoto, 1995; Pardo-Igúzquiza and Rodríguez-Tovar, 2006; Santos and Leite, 2009). To fulfil SSA basic assumptions, i.e., weak stationarity and symmetry, the time series needed preliminary transformations. First, each time series was linearly detrended to warrant stationarity in mean. Second, an automatic Box–Cox transformation was applied to enhance symmetry. Third, all series were scaled to the range [0–1] to be directly comparable.

Results

Reconstructed precipitation

Time series of seasonal historic precipitation totals in Portugal (HistPT) for 1815–2012, normalized by the 1961–1990 baseline, depict strong variability (Figure 1). The Portuguese Mediterranean-like climate is characterized by strong seasonality in precipitation. Winter is the rainiest season, while spring and autumn (transitional seasons) show more irregularity. The positive skewness in the empirical distributions of precipitation is highlighted by the corresponding boxplots (Figure 1). The 11-year centred running means of HistPT (low-pass filtered series) display long-term variability (Figure 1). Wintertime precipitation remains systematically below the baseline average until the 1950s, while from this decade to the 1990s, there is some stationarity around the baseline average. In contrast to winter, clear trends are identified in spring and autumn. The increase in spring precipitation in the 1835–1850 and 1870–1890 periods, as well as the subsequent downward trend until 1905, are noteworthy. The upward trend in autumn over 1870–1900, followed by a downward trend until the 1920s, is also notable. Finally, it is still worth mentioning the recent-past upward trend (from 1960s onwards) in autumn. Further discussion can be found in Camuffo et al. (2013).

The significance, sign and approximate periods of trends are assessed by the non-parametric Mann–Kendall test (Sneyers, 1990, 1992). Trends’ significance is also confirmed by the Spearman test (Sneyers, 1990). The Wald–Wolfowitz test for the serial correlation is also applied before the trend tests, as recommended by Sneyers (1990). For all these tests, the null hypothesis is tested at 5% significance level (Table 1). Only non-significant upward (downward) trends in autumn–winter (spring) are detected in HistPT. However, according to the progressive Mann–Kendall test, they are statistically significant over some time slices for spring and autumn (spring: upward trend in the period of 1870–1890 and downward trend in 1890–1900; autumn: downward trend in 1910–1950).

The strong connection between the North Atlantic large-scale atmospheric flow, reflected by the symmetric NAO index (Figure 1), and precipitation in Portugal (unsmoothed series) is attested by significant correlation coefficients (99% confidence level), particularly in winter (+0.52). These results are in agreement with

Figure 1. Right panels: historic seasonal precipitation totals in Portugal (HistPT) for 1815–2012, normalized by the mean over the baseline 1961–1990, for (a) DJF, (b) MAM and (c) SON. Note the data gap in 1826–1835. Thick black lines are 11-year running means of HistPT, and dashed lines are the 11-year running means of the corresponding symmetric NAO index (Luterbacher et al., 2002a). The Pearson correlation coefficients (R) between HistPT and $-NAO$ (unsmoothed series) are also plotted. Left panels: corresponding boxplots of HistPT. Medians correspond to the horizontal thick lines within each box, lower (upper) box limits to the 25th (75th) percentiles and lower (upper) whisker limits to the non-outlier minima (maxima). Outliers are indicated with circles.

Table 1. Statistics of the Wald–Wolfowitz serial correlation test (WW), Spearman (SP) and Mann–Kendall (MK) trend tests for HistPT and CalPT for each season (DJF, MAM and SON). Test statistics in bold when null hypothesis is rejected at 5% level.

	HistPT			CalPT		
	WW	SP	MK	WW	SP	MK
DJF	0.88	0.94	0.92	1.10	–0.83	–0.89
MAM	1.00	–0.96	–0.95	3.57	–2.84	–2.94
SON	0.23	0.94	0.91	1.75	1.39	1.41

previous studies, showing that an anomalously weak Azores anti-cyclone (negative NAO phase) is favourable to precipitation in Portugal, while a strong anticyclone (positive NAO phase) inhibits precipitation by diverting moist westerly flows towards Northern Europe (Andrade et al., 2011, 2012; Barnston and Livezey, 1987; Goodess and Jones, 2002; Santos et al., 2007a; Ulbrich et al., 1999).

The scatterplots between HistPT and PaulingPT (Figure 2) reveal quite strong correlations in their common period (1815–2000), with R -squared measure (determination coefficients) ranging from 68% (spring) to 80% (winter), i.e., Pearson product-moment correlation coefficients within the 0.82–0.90 range. These scatterplots also suggest that linear regressions provide better adjustments than polynomial or logarithmic fits. Therefore, PaulingPT reliably reproduces the observed precipitation in Portugal, mostly winter precipitation. The high skill in winter is in accordance with Pauling et al. (2006), which highlights the high reconstructive skill for winter precipitation in the Iberian Peninsula. In fact, the pressure gradients over the North Atlantic are more intense in winter, and thus the large-scale atmospheric circulation has a much larger impact on Portuguese precipitation (e.g. Ulbrich et al., 1999).

The linear regression equations (Figure 2) were used as calibration equations (transfer-functions) for PaulingPT. The location and scale parameters of PaulingPT are then corrected. Furthermore, new sources of instrumental data collected in Portugal from 1815 onwards, not incorporated in PaulingPT, were taken into account in this calibration. This is an improvement to the existing

Figure 2. HistPT–PaulingPT scatterplots in 1815–2000 for: (a) DJF, (b) MAM and (c) SON. The corresponding linear regression lines, their respective equations and *R*-squared measures are pointed out.

information on the long-term precipitation in Portugal, as it brings new historic sources to both the temporal extension of HistPT and the calibration of the Pauling dataset for Portugal. The calibrated series (CalPT) are a synthesis of previous series by combining instrumental, documentary and other proxy sources. CalPT for winter is presented in Figure 3a for 1600–2012 (413 years). For the sake of succinctness, spring and autumn panels are not discussed herein (Figures S1 and S2 in supplemental file, available online). The 11-year running mean depicts the multi-decadal variability, but its variance represents less than 10% of total variance. As a result of the calibration, the upward (downward) trends in autumn–winter (spring), already identified in HistPT, are also found in CalPT, but are now clearer and statistically significant in spring (Table 1). The consistency of CalPT series with different data sources is assessed in the next subsections.

Consistency analysis using early instrumental and documentary data in Portugal

Precipitation in Southern Portugal during the late Maunder Minimum (LMM AD 1675–1715) was investigated by Alcoforado et al. (2000) and during the 18th century by Taborda et al. (2004) and Alcoforado et al. (2012). In these studies, from both documentary evidence (from diaries, ecclesiastical, *Misericórdias* and municipal institutional sources) and early instrumental data, precipitation indices were produced on seasonal and annual bases. The precipitation indices for the 1675–1715 period (Alcoforado et al., 2000), and for the 1715–1799 period (Taborda et al., 2004), were produced following the Pfister (1995) methodology. These precipitation indices are not assimilated in PaulingPT and are thus independent of CalPT. Annual precipitation is indexed in the scale from 0 to ± 9 for the period 1675–1799 (instead of ± 12 , as June–August precipitation is usually scarce in Portugal). The indexed annual precipitation is compared with September–May CalPT (Figure 4). For perfect agreement, all documented precipitation extremes (wet/dry years) should be associated with consistent anomalies of CalPT, i.e., all circles in the scatterplots should be in the first (top right) and third (bottom left) quadrants. In fact, CalPT is in good agreement with the precipitation index, since most of the years (>80%) are in the first or third quadrants (positively aligned). Some of the discrepancies found between the two datasets can be attributed not only to PaulingPT, but also to uncertainties in the early data sources in Portugal. Overall, it can be stated that CalPT is consistent with early instrumental and documentary sources in Portugal.

Consistency analysis using large-scale flow

The teleconnection patterns between CalPT and four atmospheric variables, namely precipitation, 2-m air temperature, 500-hPa geopotential height and mean sea level pressure, are discussed herein. As these datasets are available for different time periods, the common period of 1659–1999 is considered. In order to take the different sources used in the reconstruction of these atmospheric variables into account, the analysis is carried out for two separate non-overlapping periods, i.e., 1659–1870 and 1871–1999. The former (212 years) is predominantly based on proxy datasets (pre-instrumental) and the latter (129 years) on instrumental records.

The teleconnection patterns for winter precipitation (Figure 3b) show positive correlations with CalPT over Southern/Western Europe and negative correlations over most of Northern Europe and Southern/Southeastern Mediterranean Basin. These correlations are a clear reflection of the combination of both the NAO and EA forcing over precipitation in Europe (DeCastro et al., 2006; Hurrell, 1995; Qian et al., 2000; Rodríguez-Puebla et al., 1998, 2001). The highest correlation is found over Portugal and inner Iberia, but the eastward extension of the high correlation (>0.6) is noteworthy, particularly over the Genoa Gulf, where correlation is even higher than in some parts of Iberia. In fact, correlations with precipitation in the Northern and Eastern coasts of Iberia are generally low. This can be explained, on the one hand, by the complex orography (regions on the lee side of major mountain ranges) and, on the other, by the important role of Mediterranean weather systems on precipitation over Eastern Iberia. Furthermore, these westerly travelling disturbances reach the Western Mediterranean Basin through France, justifying the relatively high correlation in that region. In addition, the correlation is stronger in the pre- than in the instrumental period for all seasons, which may suggest an overestimation of the large-scale forcing on precipitation in Portugal during the pre-instrumental period. For spring and autumn, patterns are similar but weaker (Figures S1 and S2 available online). Temperature patterns essentially reflect the NAO forcing on precipitation in winter and

Figure 3. (a) Winter (DJF) CalPT for the 1600–2012 period, normalized by the 1961–1990 baseline mean, along with the respective 11-year running means (thick black line). *Left panels:* Spearman-rank correlation patterns between DJF CalPT and the corresponding gridded: (b) Pauling precipitation, (c) Luterbacher temperature, (d) Luterbacher geopotential height (500 hPa) and (e) Luterbacher sea level pressure for 1659–1870 (pre-instrumental period). *Right panels:* the same as in the left panels, but for 1871–1999 (instrumental period). Non-significant correlation coefficients at 95% confidence level are not displayed for precipitation and temperature (b and c).

spring, while in autumn much weaker patterns are found (Figure 3c). With respect to 500-hPa geopotential height (Figure 3d), the patterns clearly reflect the combined effect of NAO and EA, i.e., anomalously low geopotential heights north-westward of Iberia are favourable to precipitation in Portugal, mainly in winter. The sea level pressure patterns (Figure 3e) are dynamically coherent

with the 500-hPa geopotential height (Figure 3d). Although there is an eastward shift in the position of the centres-of-action between the two periods, the spatial correlations between the patterns in the pre- and instrumental periods show good consistency in winter and spring, with all correlation coefficients above +0.80 (Table 2).

Figure 4. September–May CalPT versus precipitation index scatterplot for 1675–1799. Light (dark) grey circles represent dry (wet) seasons from documentary evidence. Circles with black outer lines indicate agreement between the two datasets. Years with '0' index are omitted. The horizontal line corresponds to the median of the September–May CalPT distribution. Some labels are omitted for the sake of clarity.

Table 2. Spatial Spearman-rank correlation coefficients between the correlation patterns in the 1659–1870 and 1871–1999 periods (left and right panels in Figure 3 and in Figures S1 and S2, available online) for precipitation, temperature, sea level pressure and 500-hPa geopotential heights. Statistically significant correlations at 99% confidence level in bold (>0.80 in grey shading).

	DJF	MAM	SON
Precipitation	0.93	0.87	0.83
Temperature	0.87	0.88	0.93
Sea level pressure	0.92	0.85	0.67
Geopotential height	0.94	0.84	0.74

The previous correlation analysis highlights the consistency of CalPT series with the large-scale flow for both pre- and instrumental periods, particularly for winter and spring, as is also suggested by the correlation levels in Table 2. Similar results are found for the composites of each of the previous fields for the extreme seasonal precipitations (below/above the 10th/90th percentile, not shown). The consistency found between CalPT and the large-scale atmospheric flow for the pre- and instrumental periods was to some extent expected, as the reconstruction methodologies implicitly integrate large-scale teleconnections. However, the stationarity of these teleconnections and the stability of their centres-of-action is a relatively strong assumption, since it does not take into account, e.g., multi-decadal variability (Franzke et al., 2011; Moore et al., 2013). For instance, a number of different NAO reconstructions have shown incoherent behaviour and high uncertainties over the pre-instrumental period (Pinto and Raible, 2012). Therefore, in order to strengthen the consistency analysis of CalPT, other analyses have been carried out using paleoclimatic simulations and tree-ring measurements.

Consistency analysis using paleoclimatic simulations

ERIK1 and ERIK2 paleoclimatic simulations are an additional tool to assess the consistency of seasonal CalPT, despite no direct correspondence between model and real world time. Nevertheless, long-term trends driven by external forcings and variability ranges can be considered as climate change footprints in the time

series. For Portugal, the correlation coefficients either between ERIK1 and ERIK2 precipitation (different model initializations) or between ERIK1/2 and CalPT are <0.10 for all seasons (uncorrelated). The SSA of seasonal CalPT and of ERIK1/2 precipitation revealed no similar behaviour in both time and frequency domains (not shown). This outcome stresses the absence of temporal correspondence between simulated and reconstructed precipitation, not only on a yearly basis, but also on longer timescales. Hence, these results highlight the minor role played by external forcings on precipitation variability in Portugal, hinting at the leading role played by internal atmospheric processes (Gómez-Navarro et al., 2012). Therefore, for Portuguese precipitation, the high levels of natural climate variability are an important limitation to predictability, with all the resulting implications on the reliability of future climate change projections for precipitation under anthropogenic forcing scenarios. An explanation for this high unpredictability is the aforementioned strong dependence of Portuguese precipitation on large-scale patterns, also largely unpredictable, such as the NAO and EA. Similar conclusions have been drawn for other regions, including North America (Deser et al., 2012).

As the signal of external forcings on precipitation in Portugal is unclear, only the variability ranges can be compared between CalPT and ERIK1/2. Similar ranges suggest similar distributions, i.e., samples from the same statistical population. This also suggests that CalPT distributions are coherent with the physical state of the climate system simulated by the ECHO-G/MM5 model chain. Some discrepancies between simulated and reconstructed precipitation (Figure S3, available online) might be explained by model biases. By considering the anomalies (deviations) in each time series relative to the 1600–1990 mean, biases in central tendency are first corrected before subsequent analyses. For assessing changes in the variability ranges throughout the time series, the 5th, 25th, 50th, 75th and 95th percentiles of precipitation anomalies are computed for 31-year moving windows. The CalPT variability is clearly within the 5th–95th ranges outlined by the simulations (Figure 5). This agreement is quite acceptable, apart from some extreme years. Furthermore, the vast majority of these extreme years were recorded in the most recent decades, particularly since the mid-20th century, which may suggest some inability of the model in reproducing the well-documented recent-past trend for stronger and more frequent precipitation extremes in Europe and Portugal (e.g. Tank and Können, 2003). Additionally, no significant trends are detected in both ERIK simulations, with a gradual decrease in the 5th–95th range, while the opposite occurs in CalPT. Despite all the limitations and uncertainties inherent to these simulations, the CalPT distributions are coherent with the physical state of the simulated climate system.

Validation with tree-ring measurements

Mediterranean trees show a typical bimodal response to climate; tree-ring growth is influenced by both previous autumn/winter and current spring/summer conditions (Cherubini et al., 2003). The onset of tree growth (which takes place around March in the case of the present study) is controlled by the air temperature observed during the previous months (Begum et al., 2013), and the further development of the tree-ring often depends on accumulated precipitation since the previous autumn through spring (e.g. Campelo et al., 2009; Leal et al., 2008). Water stress conditions during summer (determined by high temperature and low precipitation) may also exert some influence over tree growth (e.g. Nicault et al., 2008). The cessation of cambial activity, leading to the end of the formation of a tree-ring, takes place around September in response to a decrease in air temperature (Gonzalez-Gonzalez et al., 2013).

Figure 5. Left panels: chronograms of the 31-year moving window 5th, 25th, 50th, 75th and 95th percentiles of the ERIK1 precipitation anomalies (in mm/day with respect to the corresponding means over the full period of 1600–1990) for: (a) DJF, (b) MAM and (c) SON. Time series are smoothed by 11-year running means. The corresponding CalPT series and their 31-year moving window 50th percentiles are also displayed (see legend). Right panels: the same as left panels, but for ERIK2.

In order to identify the strength of these climatic signals in the dendrochronologies, response functions (or individual correlations) are applied as standard dendroclimatological methods (Cook and Kairiukstis, 1990; Fritts, 1976). The tree-ring series are related to several series of monthly climatic variables, most commonly, precipitation sums and mean temperatures from previous year October to current year September (sometimes November). This is coincident with the hydrological year, which is biologically more meaningful than the calendar year. The results of this analysis show the most determinant seasons for tree growth (e.g. Campelo et al., 2009: using response functions; Leal et al., 2008: using single correlations).

A preliminary correlation analysis between the yearly TRW series and seasonal CalPT was inconclusive (all correlation coefficients < 0.25). Additionally, the correlation coefficients among the different TRW samples are quite low. In fact, trees growing in Mediterranean environments often depict weak/unclear climatic signals, showing a mixture of forcings that are inconsistent in time. Furthermore, the connection between temperature and precipitation anomalies varied over the last centuries, ranging from correlation to anti-correlation, also including no-correlation periods (Camuffo et al., 2010b). Although TRW series cannot provide a validation of CalPT on a year-to-year timescale, they can still be useful for validating variability on longer timescales (decadal to

centennial scales). A SSA decomposition of CalPT series was undertaken to isolate low-frequency variability. As an illustration, the wavelet power spectrum, with Morlet estimation (Torrence and Compo, 1998), of spring CalPT and its SSA decomposition are shown in Figure 6.

The wavelet spectrum clearly depicts significant power within the 80–120-year range and throughout most of the time series (Figure 6a). A second significant oscillatory behaviour, with an approximate 30-year period is confined to the 19th century. Significant high-frequency oscillations are only detected in the 20th century. The analyses in both time and frequency of 10-order and 2-order filtered series clearly highlight the high skill of SSA in isolating the robust components and in filtering out noise (Figure 6b and c). In fact, the 10-order series already presents a significant enhancement of the signal-to-noise ratio, which is particularly clear in the corresponding spectrum; only four spectral bands, peaking at about 80–120, 30–40, 5 and 2 years, rather than the nearly white-noise spectrum of the total series (Figure 6b and c). However, the eigenspectrum (not shown) suggests that only the 2-order filtered series is significant. It essentially reflects the leading oscillation in the time series, with an approximate period of 150 years (Figure 6b and c). This leading periodicity is also clear in the spectra of the total and 10-order series, as well as in the time domain. Similar results are obtained for winter and

Figure 6. (a) Wavelet power spectrum (left panel) and global wavelet spectrum (right panel) of the MAM CalPT over the 1600–2012 period (Morlet estimation with serial correlation of 0.12). Solid black lines in the wavelet spectrum represent statistically significant power at a confidence level of 95% and the cone of influence is white shaded. The dashed line in the global spectrum corresponds to the red noise significance level. (b) SSA decomposition of the same time series. Total, 10-order and 2-order filtered series are depicted (see legends). (c) Corresponding Burg power spectral density (PSD) estimates for the same time series shown in the upper panel. Periodicities associated with PSD maxima are pointed out.

autumn, with the 2-order series mainly reflecting leading low-frequency oscillations, with peaks of periods longer than 100 years (not shown). For the sake of succinctness, the results obtained by applying SSA to TRW series are not presented herein, though similar conclusions can be drawn for most of the samples. Furthermore, the wavelet spectra for ERIK1 and ERIK2 reveal no correspondence with reconstructed precipitation and TRW series in both time and frequency domains (not shown).

From all tree-ring samples, 12 samples from 10 trees (4 from QR1 and 6 from QR2) reveal significant correlations with the 2-order SSA filtered CalPT in spring (Table 3). Their values vary from +0.50 to +0.80, thus being footprints of the low-frequency variability of spring precipitation on the tree-rings. These associations are also supported by the correlation coefficients

between the 31-year running mean spring CalPT and the TRW series (Table 3). Their chronograms clearly exhibit a common behaviour, i.e., a 120-year oscillation that is approximately in phase among the different variables, in both the 31-year running means and the 2-order SSA filtered series (Figure 7).

Conclusion

This study provides calibrated seasonal precipitation series in Portugal from 1600 onwards. As summer precipitation in Portugal is generally scarce and highly irregular, it was discarded from the analysis. The calibrated precipitation series revealed good consistency with several independent sources for winter and spring. Despite the existence of a European-wide precipitation

reconstruction from 1500 onwards (Pauling et al., 2006), the lack of local/regional data sources used in this specific reconstruction may hinder its application to Portugal. In this study, seasonal precipitation series for a gridbox near Lisbon (Portugal) were

Table 3. List of the selected 12 samples, from 10 trees and collected in two sites: QR1 and QR2. Their record periods and lengths are indicated. The correlation coefficients R_{MA}/R between the 31-year running mean/2-order SSA filtered spring CalPT and the TRV series in their common periods are also outlined. All correlation coefficients are statistically significant at 95% confidence level.

Site	Tree	Sample	Period	Length (years)	R_{MA}	R
QR1	2	QR1.02a	1769–2010	242	0.45	0.54
QR1	5	QR1.05a	1744–2010	267	0.47	0.69
QR1	5	QR1.05b	1752–2010	259	0.32	0.59
QR1	14	QR1.14a	1871–2011	141	0.44	0.53
QR1	15	QR1.15b	1775–2009	235	0.68	0.77
QR2	7	QR2.07b	1726–2011	286	0.31	0.59
QR2	10	QR2.10b	1773–2011	239	0.48	0.79
QR2	11	QR2.11a	1771–2011	241	0.35	0.68
QR2	11	QR2.11c	1794–2011	218	0.26	0.71
QR2	12	QR2.12a	1809–2011	203	0.64	0.65
QR2	20	QR2.20b	1820–2011	192	0.58	0.56
QR2	21	QR2.21b	1727–2011	285	0.54	0.65

extracted from this dataset (PaulingPT, 1600–2000) and long instrumental seasonal series for Portugal (HistPT, 1815–2012) were used to assess the reliability of PaulingPT. The high correlation coefficients between PaulingPT and HistPT demonstrate that PaulingPT realistically replicates the observed precipitation variability in Portugal, particularly in winter. Nonetheless, since early instrumental records in HistPT (19th century) were not incorporated in PaulingPT and some biases were detected, PaulingPT was calibrated over the full period (1600–2000). As such, calibrated precipitation (CalPT) is more archetypal of the precipitation in Portugal than PaulingPT, particularly of the precipitation in the Lisbon region, from where most early instrumental records were obtained. The consistency of CalPT series were then analysed with: (1) a precipitation index, (2) large-scale reconstructions of atmospheric flow, (3) paleoclimatic simulations and (4) tree-ring series.

Early instrumental and documentary sources in Portugal (1675–1799), also not incorporated in PaulingPT, were used for establishing an annual precipitation index. Good agreement was found between CalPT and this index. The teleconnection patterns controlling precipitation in Portugal, identified by teleconnection patterns between precipitation and 2-m air temperature, sea level pressure and 500-hPa geopotential heights, revealed good consistency throughout the full period with available data (1659–1999). This consistency is particularly remarkable for winter and spring. Despite the likely non-stationarity in these teleconnection patterns,

Figure 7. Chronograms of the (a) 31-year running means and (b) 2-order filtered MAM CalPT, along with the corresponding filtered tree-ring-width (TRV) series of the 12 outlined samples (see legend). All series are normalized to unit absolute maximum.

the coupling between precipitation and large-scale patterns in the Euro-Atlantic sector confirmed CalPT for winter and spring, but was not sufficiently conclusive for autumn. The consistency of CalPT is further analysed by ERIK1 and ERIK2 paleoclimatic simulations for the Iberian Peninsula. Even though no correspondence in the long-term variability between CalPT and simulated precipitation for Portugal was detected, a general agreement was found between their distributions (variability ranges). This outcome suggests that CalPT is coherent with the state of the climate system simulated by the ECHO-G/MM5 model chain, thus representing to some extent a confirmation of CalPT. The lack of temporal correspondence in the multi-decadal variability highlights the key role played by internal variability on precipitation in Portugal, in accordance with Gómez-Navarro et al. (2012).

Finally, the low-frequency variability of the reconstructed spring precipitation is validated by 12 TRW series from Portugal (ca. 250-year long). They share a common oscillation with a period of 80–120 years. For the other seasons no clear correspondence is detected between tree samples and precipitation. The inter-annual variability in tree-ring chronologies and its relationship to climate are often easy to assess. However, the reproduction of low-frequency trends in climate is critical in dendrochronological studies and a key feature for the reconstruction of the full range of climatic variability (Esper et al., 2002). The frequency in the response to climate is often restricted to timescales shorter than the half-mean length of a dendrochronological series (Björklund et al., 2013). It is therefore remarkable that the trees used for this study are suitable for validating low-frequency variability in precipitation.

The tree-ring series used herein do not show strong synchrony at inter-annual timescales. Due to missing or locally absent tree-rings and unclear ring boundaries, it is often impossible to cross-date cores retrieved from Mediterranean tree-rings (Cherubini et al., 2003). These authors recommend the use of whole stem discs to overcome this difficulty, which is impossible in the present study as it implies tree felling. Oak tree samples collected in inner Portugal show a common inter-annual synchrony (Abrantes et al., 2013; Campelo et al., 2009; Leal et al., 2008), while others sampled in coastal regions may not (Rodríguez-González et al., 2010). The trees in the present study were sampled at a location with a particular microclimate (approximately 40 km away from the coast), characterized by mild temperatures, high annual precipitation (>1000 mm) and frequent morning fogs. In effect, tree-rings collected at forested wetlands along the Portuguese western coast show low-pass filtered synchrony comparable to the present study (Rodríguez-González et al., 2010). Trees growing under Mediterranean environments often show a mixture of forcings in the climatic signal. Even so, there are several studies reporting dependence on water availability, although without seasonal consistency among locations and/or species: Nicault et al. (2008) present spring–summer drought reconstructions from Mediterranean tree-rings; in Leal et al. (2008) and Campelo et al. (2009), Mediterranean oaks' growth in Portugal depends on the storage of rainfall before the growing season onset; Campelo et al. (2010) found responses to different seasons depending on the tree-ring feature being analysed; and in Martín-Benito et al. (2013) two pine species growing in East-central Spain mountains respond differently to drought.

This study improves the reconstructed seasonal precipitation in Portugal by integrating new data and by providing a multi-source consistency analysis. CalPT can be of utmost relevance for upcoming studies of climate in Portugal, as well as a contribution for the improvement of the existing European reconstructions. Forthcoming research may also contribute to clarify the role of natural and anthropogenic forcing factors on past climate variability in Portugal. The present study outcomes might thus be used to improve our understanding of both past and future climatic variability in Portugal.

Acknowledgements

The authors would like to thank 'Fundação Mata do Buçaco' for tree sampling permission, Rosa Pinho and Lísia Lopes for guidance in the field and assistance in locating appropriate trees, and Umut Sen and Alexandra Lauw for assistance in the field.

Funding

This study was carried out under the project 'Reconstruction and model simulations of past climate in Portugal using documentary and early instrumental sources – Klimhist' and supported by FCT – Portuguese Foundation for Science and Technology (PTDC/AAC-CLI/119078/2010, PEst-OE/AGR/UI4033/2014, PTDC/AAC-CLI/103046/2008, SFRH/BPD/44493/2008, PTDC/HIS-ARQ/117099/2010).

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