New insights into the reconstructed temperature in Portugal over the last 400-years

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Abstract

The consistency of an existing reconstructed annual (December–November) temperature series for the Lisbon region (Portugal) from 1600 onwards, based on a European-wide reconstruction, with: (1) five local borehole temperature-depth profiles; (2) synthetic temperature-depth profiles, generated from both reconstructed temperatures and two regional paleoclimate simulations in Portugal; (3) instrumental data sources over the twentieth century; and (4) temperature indices from documentary sources during the late Maunder Minimum (1675–1715) is assessed. The low-frequency variability of the reconstructed temperature in Portugal is not entirely consistent with local borehole temperature-depth profiles and with the simulated response of temperature in two regional paleoclimate simulations driven by reconstructions of various climate forcings. Therefore, the existing reconstructed series is calibrated by adjusting its low-frequency variability to the simulations (first-stage adjustment). The annual reconstructed series is then calibrated in its location and scale parameters, using the instrumental series and a linear regression between them (second-stage adjustment). This calibrated series shows clear footprints of the Maunder and Dalton minima, commonly related to changes in solar activity and explosive volcanic eruptions, and a strong recent-past warming, commonly related to human-driven forcing. Lastly, it is also in overall agreement with annual temperature indices over the late Maunder Minimum in Portugal. The series resulting from this post-reconstruction adjustment can be of foremost relevance to improve the current understanding of the driving mechanisms of climate variability in Portugal.

Keywords: Reconstructed temperature, borehole climatology, paleoclimate simulations, historical climatology, non-linear long-term trend, Portugal

1. Introduction

Climate reconstructions allow further insight into the climatic variability beyond the relatively short instrumental period, being commonly based on early instrumental records, documentary evidence, namely memoirs, diaries, chronicles, weather logs, ship logbooks, and natural proxies, such as boreholes, tree-rings, corals, ice-cores, speleothem records, pollen-profiles (Brázdil et al., 2010; Brázdil et al., 2005; Camuffo et al., 2010; Li et al., 2010; Luterbacher et al., 2006; Pollack and Huang, 2000). Historical climatology is critical for understanding the driving processes of climate variability not only in the past, but also in the future. This is particularly important when developing climate change projections for the future under emission scenarios (IPCC, 2013).

Climate variability in Europe over the last millennium was reconstructed based on both documentary evidence and natural proxies (e.g. Alcoforado et al., 2000; Brázdil et al., 2010; Brázdil et al., 2005; Camuffo et al., 2013; González-Rouco et al., 2009; Luterbacher et al., 2006). European-wide temperature reconstructions since 1500 were already developed (Luterbacher et al., 2004; Xoplaki et al., 2005), as well as continental-wide reconstructions for the last two millennia by Ahmed et al. (2013). Temperature reconstructions in some European sites, based on both documentary data and instrumental records since the 16th century, were carried out by Camuffo et al. (2010). A temperature reconstruction for southern Portugal during the late Maunder Minimum (LMM; 1675-1715) was presented by Alcoforado et al. (2000). However, in Portugal, most of the pre-instrumental records show numerous temporal gaps and there is a substantial lack of natural proxies with clear climatic signals (Alcoforado et al., 2012; Camuffo et al., 2010; Luterbacher et al., 2006).

Borehole temperature-depth profiles can be used as paleoclimate proxies for climate reconstruction (e.g. Bodri and Čermák, 1997; González-Rouco et al., 2009; Majorowicz et al., 1999; Šafanda et al., 2007), as they provide independent information on long-term temperature variability (Jones et al., 2009). Borehole measurements are a complementary temperature record to high-frequency air temperature series recorded at weather stations and, through profile inversion methods, may also enable validating low-frequency variability in these series (e.g. Beltrami and Bourlon, 2004; Beltrami and Mareschal, 1995; Beltrami et al., 2011; Chouinard and Mareschal, 2007; González-Rouco et al., 2006; Gouirand et al., 2007; Harris and Chapman, 1998; Harris and Gosnold, 1999; Nielsen and Beck, 1989; Pollack et al., 2006). Some studies have been carried out using borehole temperature logs measured in southern Portugal (e.g. Correia and Šafanda, 2001; Correia and Šafanda, 1999; Šafanda et al., 2007). Borehole reconstructions can also be compared to paleoclimate simulations generated by Earth system models for validation purposes (Beltrami et al., 2006; González-Rouco et al., 2009; Stevens et al., 2008).

The present study aims at analysing the consistency between the Luterbacher et al. (2004) and Xoplaki et al. (2005) temperature reconstructions for the Lisbon region (Portugal) and over the period of 1600–1999 using: 1) five local borehole temperature-depth profiles; 2) synthetic temperature-depth profiles, generated from gridded near-surface temperatures produced by regional paleoclimate reconstructions and simulations; 3) instrumental data recorded in Lisbon over the twentieth century; and 4) temperature indices from early instrumental and documentary sources during the LMM (1675-1715). This analysis allows a validation of the annual mean reconstructed temperature in Portugal over the last 400 years. The identification of possible inconsistencies with the above-referred data sources enables a post-reconstruction adjustment of this time series. In effect, this calibrated time series may help understanding past climate variability in Portugal and its main driving mechanisms, namely the role of external vs. internal forcing mechanisms on temperature variability. This attribution analysis provides critical information for model validation and for assessing the reliability of regional climate change projections. The datasets and methods are presented in section 2, the results are discussed in section 3 and the main conclusions are summarized in section 4.

2. Data and Methods

2.1 Reconstructed temperatures

The reconstructed seasonal mean temperature in the gridbox (38.5–39.0˚N, 8.0–8.5˚W), which is located in the area of Lisbon (Portugal), and for the period of 1600-1999 was extracted from the Luterbacher et al. (2004) and Xoplaki et al. (2005) European-wide reconstructions (Lut2004 henceforth). Data is originally defined on a 0.5˚ latitude × 0.5˚ longitude grid. From 1901 onwards this dataset is based on instrumental data from New et al. (2000). For the selected gridbox, it is largely based on temperature records from Lisbon. Since the present study focuses on annual series, annual mean temperatures were obtained by averaging the four values corresponding to winter (DJF), spring (MAM), summer (JJA) and autumn (SON) mean temperatures (no monthly data is available). Hence, annual means refer to the period from December of the previous year to November of that year (e.g. annual mean of 1710 corresponds to the average taken from December 1709 to November 1710).

2.2 Borehole data

The consistency of the Lut2004 reconstruction with borehole measurements, retrieved from the only geothermal-paleoclimatological observatory in Portugal (38.34° N; 7.58° W), is assessed. This observatory is located about 5 km northwestwards of Évora (southern Portugal) and about 100 km eastwards of Lisbon. More detailed information can be found in Correia and Šafanda (2001) and Šafanda et al. (2007). Although the borehole measurements were not taken in Lisbon, the variability in the 11-yr moving averages of annual mean temperatures in Évora and Lisbon is quite similar (not shown). In fact, the correlation coefficient is of about 0.98 in their common instrumental period (1941-1999). The means for Lisbon and Évora are of 16.8ºC and 15.8ºC, respectively, while both standard deviations are of ca. 0.3ºC. Hence, these borehole measurements are assumed to be representative of the measurements made in Lisbon, as they mostly capture long-term variability.

Five measurements (temperature logs) in the same borehole TGQC1 are considered herein, which were carried out on 24 March 1997 (M1), 27 March 2000 (M2), 14 November 2002 (M3), 26 November 2003 (M4), and 28 October 2004 (M5), respectively. These five temperature logs were obtained by measuring the equilibrium temperature with a thermistor every 5.0 m (M1), 1.0 m (M2), 2.5 m (M3 and M4) and 2.0 m (M5), along the ~190 m depth in the borehole. The borehole is located in a region where the typical vegetation is old cork trees. This vegetation type has not changed in the last hundred years and the topography is subdued, with small elevation variations of tens of meters in the nearest few kilometres. The rock type in the area is hercynian age granite. Its thermophysical properties were measured in four samples, collected in a quarry located in the same granitic body and 1.5 km eastwards of the borehole. Thermal conductivity values of 2.8 ± 0.2 W mK^{-1} and thermal diffusivity values of 1.3 ± 0.1 m^2 s^{-1} were measured on polished surfaces of rock samples. Heat production was calculated as 2 ± 1 W m^{-3} (Correia and Šafanda, 2001). The estimated heat flux density for the borehole is 60 mW m^{-2}, which was confirmed as an *a posteriori* value of 58 ± 13 mW m^{-2} using the Functional Space Inversion method of Shen and Beck (1992).

The borehole temperature-depth profiles are herein compared to synthetic temperature profiles (forward model), generated from both Lut2004 and annual mean near-surface temperatures from two paleoclimate simulations, rather than applying the conventional procedure of inverting temperature logs to reconstruct ground surface temperatures (e.g. Correia and Šafanda, 2001). However, the uncertainties inherent to these inversion models (Hartmann and Rath, 2005), mostly due to errors in the estimation of subsurface parameters, are also present in these forward models. The profiles were generated following the methodology described by Beltrami et al. (2011), as explained below.

The temperature anomaly at depth *z* and time *t*, due to a step change in surface temperature T_0, is given by the solution of the one-dimensional heat diffusion equation (Carslaw and Jaeger, 1959):

$$T(z,t)=T_0 erfc\left(\frac{z}{2\sqrt{kt}}\right), \tag{1}$$

where *erfc* is the complementary error function and *k* is the subsurface thermal diffusivity (Cermak and Rybach, 1982). It has a value of 1.3×10^{-6} m^2s^{-1}, according to measurements on cut and polished surfaces of local rock samples (Correia and Šafanda, 2001). Generalizing this solution for a series of *K* step changes at the surface, the induced temperature anomalies at depth *z* are given by Mareschal and Beltrami (1992):

$$T_t(z)=T_i(z)+\sum_{j=1}^{K} T_j\left[erfc\left(\frac{z}{2\sqrt{kt_j}}\right)-erfc\left(\frac{z}{2\sqrt{kt_{j-1}}}\right)\right], \tag{2}$$

where $T_i(z)$ is the initial temperature profile.

2.3 Paleoclimate simulations

The two paleoclimate simulations were carried out with the Global Circulation Model (GCM) – ECHO-G, and then dynamically downscaled with the Regional Climate Model (RCM) – MM5. ECHO-G combines the HOPE-G ocean model (Legutke and Voss, 1999) with the ECHAM4 atmospheric model (Roeckner et al., 1996). The regional model employs a limited area domain that spans completely the Iberian Peninsula with a spatial resolution of 30 km. Three reconstructed external forcings were used to consistently drive both models: solar variability, atmospheric greenhouse gas concentrations and radiative effects of stratospheric volcanic aerosols. The skill of the MM5/ECHO-G setup to reproduce the climate in the Iberian Peninsula has been previously evaluated by Gómez-Navarro et al. (2011), particularly with respect to the ability of the regional model to reduce the warm bias and to correct the winter variability over western Iberia in the GCM run. Two paleoclimate simulations (Sim1 and Sim2), only differing in their initial conditions, were used as a broad estimation of the effect of internal variability (cf. Gómez-Navarro et al., 2012; González-Rouco et al., 2003; Zorita et al., 2007; Zorita et al., 2005). Near-surface (2 m) temperatures for the period of 1600-1989 are extracted from these simulations. Their daily mean fields were bilinearly interpolated from the original MM5 grid to the reconstructed temperature grid (0.5° latitude × 0.5° longitude) and extracted for the above-defined Lisbon gridbox (38.5–39.0°N, 8.0–8.5°W). Annual (December–November) means were then computed from the raw 6-hourly data.

In order to identify low-frequency variability and trends in the paleoclimate simulations, a data-adaptive filtering, based on a singular spectral analysis (SSA), is applied (Ghil and Vautard, 1991). SSA is based on the well-known principal component analysis, in which the multiple dimensionality is achieved by including time-lagged replicas of the original time series. The resulting principal components are thus linear combinations of different lags of this series, which is equivalent to a time filtering with filter-coefficients that are related to the eigenvectors of the lagged-covariance matrix. More formally, SSA corresponds to an eigenvalue decomposition of a lagged-covariance matrix, with a Toeplitz structure, obtained from the original time series of the paleoclimatic simulations. The rank, M, of this matrix is the average of (N/4–N/3), where N is the time series length (Plaut and Vautard, 1994). For the paleoclimatic simulations M=113 (N=390). In this methodology, the original time series can also be decomposed into a sum of M additive components and can be partially rebuilt using only the leading ‘signal modes’, thus filtering out background noisy components (Elsner and Tsonis, 1996; Vautard et al., 1992). In n-order SSA filtering, the leading n modes are used to rebuild the original time series. The lower the number of retained modes, the stronger is the time series smoothing. If all M modes are used, the original time series is fully recovered.

Under the assumption that the aforementioned external forcings used in the paleoclimate simulations are mainly manifested by long-term temperature trends in western Iberia, as suggested by Gómez-Navarro et al. (2012), similar trends of reconstructed and simulated temperatures should be expected. As SSA enables isolating data-adaptive non-linear trends in the time series (Ghil and Vautard, 1991), it can be used to correct discrepancies between long-term trends of reconstructed and simulated temperature series. In the present study, this approach was used to adjust the low-frequency variability in the reconstructed series to the paleoclimate external forcings obtained from the simulations (adjustment of the Lut2004 reconstruction). Therefore, instead of developing a new reconstruction, an adjustment of the already existing reconstruction was carried out herein (post-reconstruction adjustment).

2.4 Instrumental data and indexed temperatures

The consistency of the Lut2004 reconstruction with the corresponding instrumental series (InstT) for the available period of 1901–1999, recorded at the Lisboa-Geofísico meteorological station and supplied by the European Climate Assessment & Dataset project (Klein Tank et al., 2002), was also assessed. It should be stressed that Lut2004 is heavily dependent on InstT, as previously referred, and a high temporal correspondence between these two time series is thereby expected. A transfer-function between InstT and Lut2004 was determined by using a linear regression analysis. The resulting first-order regression polynomial was applied so as to calibrate the Lut2004 reconstruction in the extended period from 1600 onwards, thus correcting its location and scale parameters. Lastly, annual indexed temperatures for southern Portugal over the pre-instrumental period of 1675–1715 (LMM), developed by Alcoforado et al. (2000), were also analysed for consistency assessment.

3. Results

3.1 Consistency with borehole measurements and paleoclimate simulations

The consistency of the Lut2004 reconstruction with borehole temperature-depth profiles and with paleoclimate simulations is assessed in this section. The five logs of borehole measurements (M1, M2, M3, M4 and M5) are shown in Fig. 1a. Their corresponding inverse geothermal gradients were estimated using linear regressions applied to the bottom 140–180 m data (Fig. 1b). Owing to the deposition of fine material at the bottom of the borehole, there is locally a change in thermal conductivity at about 180 m. As the borehole was drilled in a very homogeneous granite batholith, these changes are not due to changes in the geological formation. In the present study, depths >180m are not used for gradient estimations. These gradients approximately range from 46 to 48 m ºC^{-1} (ca. 0.021 ºC m^{-1}). The corresponding root-mean squared error (RMSE) of each estimated linear model is always <0.01ºC (R-square adjusted >99.9%), which means that the errors in the estimation of the geothermal gradients have only minor impacts on the subsequent temperature-depth anomalies. The low borehole depths require a word of caution, as some authors have indicated that 200 m of depth may be too shallow for climate change assessments (Beltrami et al., 2011; Hamza et al., 2007; Majorowicz et al., 1999). The Global Database of Borehole Temperatures and Climate Reconstructions from the University of Michigan and the World Data Center for Paleoclimatology indeed consider a 200 m depth as a minimum requirement for past climate reconstruction (Pollack and Huang, 2000). Beltrami et al. (2011) also demonstrated that the maximum depth of borehole profiles can have a large impact on temperature-depth anomalies. Since no other geothermal-paleoclimatological observatory is available in Portugal, the conclusions derived from these borehole profiles may be provisional.

The five temperature-depth anomaly profiles (M1–5), after removing their estimated geothermal gradients, are reproduced in Fig. 2a. M1, M2, M3 and M4 show a more pronounced near-surface warming than M5. Overall, these profiles suggest strong recent-past warming trends in near-surface air temperatures.

The synthetic temperature-depth anomaly profiles, generated from the Lut2004 reconstruction and from the two paleoclimate simulations, are also shown in Fig. 2a. The 11–year running means of their anomalies over the period 1600–1989 are plotted in Fig. 2b. The chronograms of the two simulations, as well as their individual profiles, are indeed very similar to the corresponding ensemble mean chronograms and profiles (not shown). In fact, the correlation coefficient between the 11-yr running means of the two simulations is as high as +0.82. This is indicative of the large influence of external forcings in the long-term variability of temperature. Conversely to the simulations, which exhibit a strong warming trend since the 1830s, Lut2004 only depicts a recent-past upward trend and a cooling trend during the nineteenth century (Fig. 2b). Although the recent-past warming trend in Lut2004 is clearly corroborated by InstT, the cooling trend is neither supported by simulations (Fig. 2b) nor by any scientific evidence from previous studies. As a result, the synthetic temperature-depth anomaly profile obtained from Lut2004 is clearly different from the profiles obtained from the five borehole measurements and from the paleoclimate simulations (Fig.2a).

The discussion above hints at a remarkable agreement between the low-frequency variability of near-surface temperature from two independent sources (borehole measurements and paleoclimate simulations driven by reconstructed forcing). However, whereas the paleoclimate simulations agree well with the borehole temperature-depth profiles, the reconstructed temperature for Portugal (Lut2004) is not entirely consistent with the long-term trends revealed by these new sources. In fact, its linear trend is nearly zero over the whole period and there is no signature of cool/warm periods. This disagreement between simulations and Lut2004 was already reported by Gómez-Navarro et al. (2011). As such, the low-frequency variability of the Lut2004 reconstruction are herein adjusted to be more coherent with the borehole data and simulations. Towards this aim, the ensemble mean temperature from the two simulations was low-pass filtered by a 2-order SSA. The filtered series (SSA-trend in Fig. 2b) highlights the signature of the external forcings on near-surface temperature and was then added to the Lut2004 reconstruction. The resulting calibrated series (CalT = Lut2004 + SSA-trend) is also shown in Fig. 2b.

The SSA-trend clearly shows a warming trend since the 1830s and a relatively cool period during the LMM (1670–1730). This is also in line with previous studies on the impact of solar activity on global temperatures (e.g. Eddy, 1983; Frenzel, 1994). The period from 1730 to 1800 recorded annual mean temperatures close to the baseline, being followed by an anomalously cold period until the 1830s, which is associated with the Dalton Minimum, also a period of low solar activity (Wagner and Zorita, 2005). The strong upward trend in CalT from the 1830s onwards is now in clear agreement with the paleoclimate simulations and InstT (in the twentieth century). The LMM (ca. 1670–1730) and Dalton minimum (ca. 1790–1830) are also clearly depicted in CalT. Furthermore, the temperature-depth anomaly profile from CalT is similar to the profiles from the five borehole measurements and paleoclimate simulations (Fig. 2a). This represents an important validation of CalT.

3.2 Consistency with instrumental data

The consistency between InstT and CalT has been assessed by a linear regression in their common period (1901–1989). The corresponding scatterplot shows that linear regression provides a good fitting, with a correlation coefficient above 0.90 (Fig. 3), explaining about 82% of the total variance (R-square adjusted), and a RMSE of 0.22. According to the Fisher's test, this least-squares linear regression model is statistically significant at a 99% confidence level ($p<0.01$). A bootstrap procedure with 10,000 resamples shows that the 95% confidence interval for the correlation coefficient between InstT and CalT is [0.87, 0.93], supporting the Fisher's test. Therefore, CalT clearly reproduces the observed temperature in Portugal in the instrumental period (InstT). A 3-order polynomial fitting, with a robust regression using the bisquare weighting method, provides a slightly better adjustment (R-square adjusted of 83% and RMSE of 0.21), but its extrapolation for the lowest temperatures (outside the range of values used in the model fitting, not shown) is not reliable and was discarded. The corresponding linear regression polynomial is applied for a second-stage adjustment of location and scale parameters in CalT. This allows expressing CalT in absolute temperature values instead of anomalies (Fig. 4a). Additionally, taking into account the high coherency between CalT and InstT, CalT was extended from 1989 to 1999 using InstT values. In order to confirm long-term trends in CalT, the non-parametric progressive Mann-Kendall test is applied (Sneyers, 1990, 1992). The forward and backward Kendall t parameters for CalT jointly depict a warming trend from the 1830s onwards, being particularly noteworthy since the 1930s (Fig.4b).

The uncertainties in the CalT series are a combination of the original uncertainties in the Lut2004 dataset plus additional uncertainties related to the non-linear trend used in the adjustment. The former are discussed in Luterbacher et al. (2004), but are only available for the European mean reconstruction. Hence, it is not possible to have a local estimate of these uncertainties. The latter can be estimated through the assessment of the consistence between Sim1 and Sim2. For this purpose, the SSA filtering was applied separately to Sim1 and Sim2. The mean absolute difference between the two non-linear trends obtained from Sim1 and Sim2 provides a measure of the uncertainty related to the simulations. It has an approximate value of 0.05ºC. However, this number provides just a lower bound, since it does not explicitly consider uncertainties related to the simulation itself, which are difficult to assess due to the limited number of available simulations with similar characteristics.

3.3 Consistency with precipitation indices

In previous studies, temperature in southern Portugal was analysed during the LMM (1675–1715) by Alcoforado et al. (2000), and during the eighteenth century by Taborda et al. (2004) and Alcoforado et al. (2012). In these studies, research was based on documentary evidence, such as diaries, ecclesiastical rogation ceremonies (*pro-pluvia* and *pro-serenitate*), *Misericórdias* and municipal institutional sources, as well as on early instrumental data. From this documentary evidence, basic data were transformed into indices on an ordinal scale, following the methodology developed by Pfister (1995). Monthly temperatures were originally indexed on a scale from 0 to ±1. Annual indices (December–November) can then vary from 0 to ±12. The consistency between CalT and the corresponding annual indexed temperatures is assessed by their respective scatterplots (Fig. 5). For a perfect agreement, the documented temperature extremes (cold/hot years) should be reflected by coherent CalT anomalies, i.e. all data pairs in the scatterplots should be either on top-right or bottom-left quadrants (positively aligned series). There is an overall agreement between CalT and the annual temperature index (>80% of all years are on top-right or bottom-left quadrants, with a correlation coefficient of 0.76). Therefore, this agreement also provides a validation of CalT for the period of 1675–1715. However, as the SSA-filtering does not significantly modify the interannual variability within this relatively short time period (LMM), the aforementioned agreement also applies between Lut2004 and the annual temperature index (not shown).

4. Summary and conclusions

The consistency of the reconstructed annual temperature series in Portugal (Lut2004) is assessed by using five borehole temperature-depth profiles, synthetic temperature-depth profiles generated from both the Lut2004 reconstruction and paleoclimate simulations, instrumental data (InstT) and indexed temperatures during the LMM. While the paleoclimate simulations agree well in the long-term variability with the borehole temperature-depth profiles, the same does not apply to the Lut2004 reconstruction. In fact, the long-term trends in Lut2004 are not fully consistent with borehole data and simulations. The late Maunder and Dalton minima, clearly reflected in the paleoclimate simulations and well-documented in the literature, in association with changes in solar activity (Eddy, 1983), are absent from the Lut2004 reconstruction. Moreover, there is a cooling trend throughout the nineteenth century that is not supported by previous studies. Therefore, the Lut2004 reconstruction was calibrated by adjusting its low-frequency variability to the paleoclimatic simulations, also in agreement with local borehole data. Documentary sources in Portugal during the LMM (1675–1715) also show high agreement with CalT, thus providing an additional validation over the LMM.

These results suggest some inconsistencies in the low-frequency variability of temperature in Portugal between the Lut2004 reconstruction and borehole data or simulations. In effect, the absence of clear long-term trends in Lut2004 is not coherent with the significant changes in the radiative forcing throughout the last 400 years and the important role played by these external forcings on temperature variability over western Iberia (Gómez-Navarro et al., 2012).

The frequent temporal gaps in the pre-instrumental records and the substantial lack of natural proxies with clear climatic signals in Portugal (Alcoforado et al., 2012; Camuffo et al., 2010; Luterbacher et al., 2006) may partially explain this limitation in the reproduction of the low-frequency variability in the Lut2004 reconstruction. An important loss of low-frequency variance caused by the method used in Lut2004 was also found by von Storch et al. (2009). Nevertheless, a more detailed assessment of the causes for this shortcoming is out of the scope of the present study, as it does not develop a new reconstruction for comparison, but rather an adjustment of an existing reconstruction.

CalT adjusts the low-frequency variability in the Lut2004 reconstruction so as to be more consistent with local borehole measurements and regional climate simulations. It can thus be of foremost relevance in forthcoming research on climatic variability in Portugal. A reliable representation of the low-frequency variability of temperature in Portugal, including its long-term trends, is critical for understanding the role played by external vs. internal forcings on the regional climate variability and change. Due to the relatively coarse spatial resolution of data generated by state-of-the-art GCMs, they are not suitable for regional-scale assessments. Since such scales are precisely the focus of this study, temperature series from two high-resolution regional paleoclimatic simulations (Sim1 and Sim2) are employed instead of GCM runs. These two simulations were documented and validated in previous studies. Unfortunately, there are only two available simulations covering Portugal with such high-resolution characteristics. Hence, it is not possible to increase the ensemble size of model simulations, though it would be very useful for uncertainty assessments. In forthcoming research, new regional paleoclimatic simulations over Portugal, also using different models, should be used to enhance the robustness and evaluate the significance of the current adjustment.

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Figure Captions

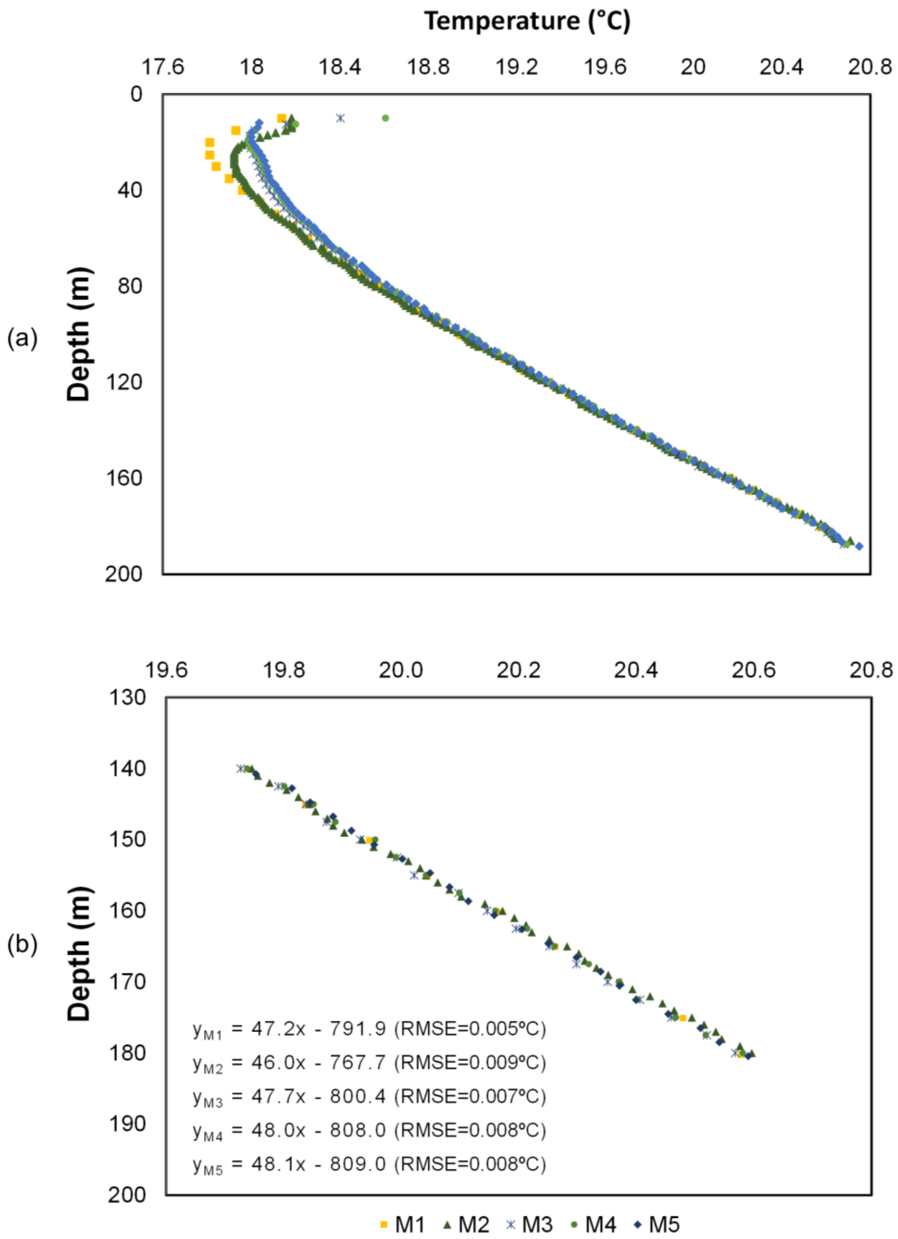
Fig. 1. (a) Borehole temperature logs (temperature vs. depth) for: M1, M2, M3, M4 and M5 from the Évora observatory (cf. legends). (b) The same as on (a), but only for the bottom 140–180 m data. The outlined equations of the respective regression lines (omitted) represent the corresponding estimated geothermal gradients (slope of the linear regression line).

Fig. 2. (a) Temperature-depth anomaly profiles for: M1, M2, M3, M4 and M5, with respect to the estimated geothermal gradients in Fig. 1b, along with the synthetic profiles generated from: Lut2004 – reconstructed temperature; CalT – calibrated temperature; and Sim1/Sim2 – paleoclimate simulations, retrieved for a gridbox near Lisbon, Portugal (cf. legends). (b) Chronograms of the 11-yr running mean anomalies of Lut2004, CalT and Sim1/Sim2 for the period of 1600–1989. The SSA filtered ensemble mean temperature from the two simulations (SSA-trend) is also displayed. The 11-yr running means of InstT (instrumental annual mean temperature) anomalies are depicted for the period of 1901-1999, along with the respective linear trend. Note that anomalies in each series are with respect to their common period (1901-1989).

Fig. 3. Scatterplot between InstT and CalT anomalies over their common period (1901–1989). The corresponding regression line, calibration equation and R-squared measure (determination coefficient) are also pointed out.

Fig. 4. Chronogram of: (a) CalT – calibrated annual mean temperature – in the period of 1600–1999 and InstT in the period of 1901–1999. Estimated errors are grey shaded, with a mean error of 0.05ºC (b) Forward – u(t) – and backward – u'(t) – series of the normalised Kendall t parameter from the progressive Mann-Kendall analysis of CalT. 95% confidence interval for the no trend hypothesis in grey shading.

Fig. 5. Scatterplot of CalT in the period of 1675–1715 as a function of the annual temperature indices. Light (dark) grey circles represent cold (hot) years from documentary evidence. Circles with black edges indicate agreement between the two datasets. Years with '0' index are omitted for the sake of readability of the plot. The horizontal line corresponds to CalT mean. Some labels are omitted for the sake of clarity.



(a)
Temperature (°C)
17.6
18
18.4
18.8
19.2
19.6
20
20.4
20.8
Depth (m)
0
40
80
120
160
200
(b)
19.6
19.8
20.0
20.2
20.4
20.6
20.8
Depth (m)
130
140
150
160
170
180
190
200
y_M1 = 47.2x - 791.9 (RMSE=0.005ºC)
y_M2 = 46.0x - 767.7 (RMSE=0.009ºC)
y_M3 = 47.7x - 800.4 (RMSE=0.007ºC)
y_M4 = 48.0x - 808.0 (RMSE=0.008ºC)
y_M5 = 48.1x - 809.0 (RMSE=0.008ºC)
M1 M2 M3 M4 M5

Fig. 1

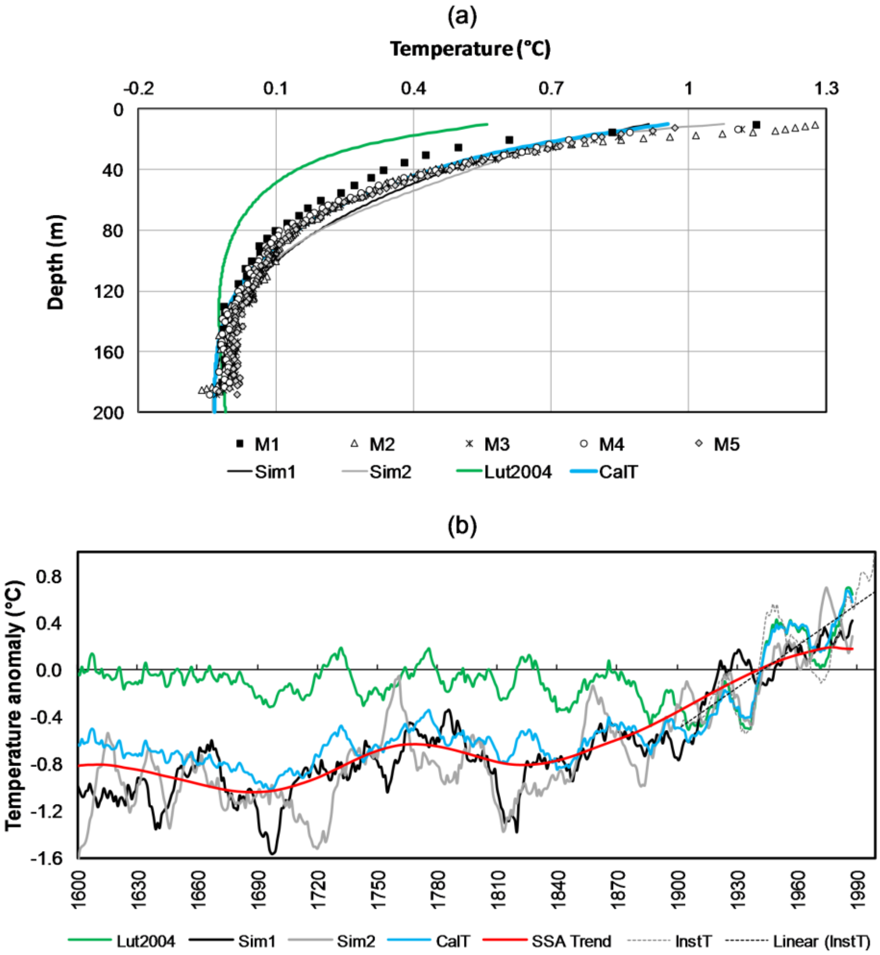

(a)
Temperature (°C)
-0.2
0.1
0.4
0.7
1
1.3
0
40
80
120
160
200
Depth (m)
M1
M2
M3
M4
M5
Sim1
Sim2
Lut2004
CalT
(b)
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.6
Temperature anomaly (°C)
1600
1630
1660
1690
1720
1750
1780
1810
1840
1870
1900
1930
1960
1990
Lut2004
Sim1
Sim2
CalT
SSA Trend
InstT
Linear (InstT)

Fig. 2

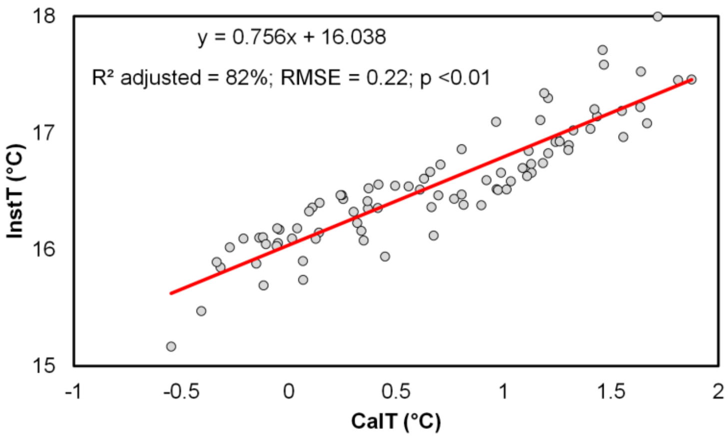

y = 0.756x + 16.038
R² adjusted = 82%; RMSE = 0.22; p <0.01
InstT (°C)
CalT (°C)
18
17
16
15
-1
-0.5
0
0.5
1
1.5
2

Fig. 3

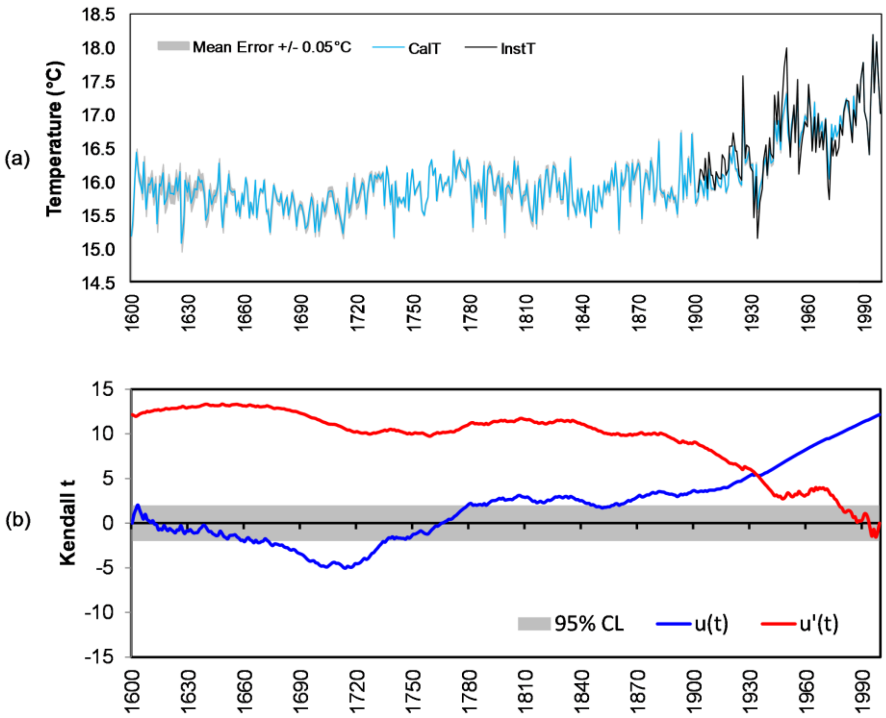

(a)
Temperature (°C)
Mean Error +/- 0.05°C
CalT
InstT
(b)
Kendall t
95% CL
u(t)
u'(t)

Fig. 4

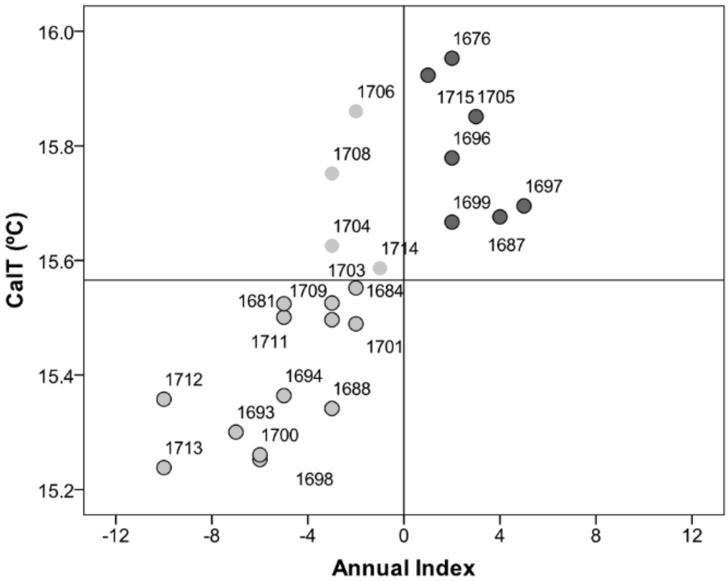

1676
1706
1715 1705
1696
1708
1697
1699
1704
1714
1687
1703
1709
1684
1681
1711
1701
1712
1694
1688
1693
1700
1713
1698
16.0
15.8
15.6
15.4
15.2
CalT (ºC)
-12
-8
-4
0
4
8
12
Annual Index

Fig. 5