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

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Abstract

The reliability of an existing reconstructed annual (December–November) temperature series for the Lisbon region (Portugal) from 1600 onwards is assessed in the present study. The consistency of this series with: (1) five local borehole temperature-depth profiles; (2) synthetic temperature-depth profiles generated from both reconstructed temperatures and 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. It is found that reconstructed annual mean temperature series in Portugal, after European-wide reconstructions, is not consistent with both borehole profiles and paleoclimate simulations in their long-term variability and trends. Hence, the non-linear trend in the paleoclimate simulations is estimated and added to the reconstructed series (first-stage calibration). 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 calibration). The resulting calibrated series is then in clear accordance with the low-frequency variability of both borehole temperature-depth profiles and paleoclimate simulations. This calibrated series shows clear footprints of the Maunder and Dalton minima, mainly attributed to changes in solar activity and explosive volcanic eruptions, and a strong recent-past warming, attributed to human-driven forcing. Lastly, it is also in overall agreement with independently-derived annual temperature indices for the late Maunder Minimum. Thus, the series resulting of this re-calibration process for Lisbon can be of foremost relevance to improve the current understanding of the driving mechanisms of climate variability in 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 (Pollack and Huang, 2000; Brázdil et al., 2005, 2010; Luterbacher et al., 2006; Camuffo et al., 2010; Li et al., 2010). 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., 2005, 2010; Luterbacher et al., 2006; González-Rouco et al., 2009; Camuffo et al., 2013). 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 (Luterbacher et al., 2006; Camuffo et al., 2010; Alcoforado et al., 2012).

Borehole temperature-depth profiles can be used as paleoclimate proxies for climate reconstruction (e.g. Bodri and Čermák, 1997; Majorowicz et al., 1999; Šafanda et al., 2007; González-Rouco et al., 2009), 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. Nielsen and Beck, 1989; Beltrami and Mareschal, 1995; Harris and Chapman, 1998; Harris and Gosnold, 1999; Beltrami and Bourlon, 2004; González-Rouco et al., 2006; Pollack et al., 2006; Chouinard and

Mareschal, 2007; Gouirand et al., 2007; Beltrami et al., 2011). Some studies have been carried out using borehole temperature logs measured in southern Portugal (e.g. Correia and Šafanda, 1999; 2001; Šafanda et al., 2007). Borehole reconstructions can also be compared to paleoclimate simulations generated by Earth system models in a two-way validation approach (Christian et al., 2003; Beltrami et al., 2006; Stevens et al., 2008; González-Rouco et al., 2009).

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. Thus, the identification of inconsistencies with the above-referred data sources enables a rebuilt of this time series by applying suitable calibration techniques. In effect, this calibrated time series may help understanding past climate variability in Portugal and its main driving mechanisms. The datasets and methods are presented in Sect. 2, the results are discussed in Sect. 3 and the main conclusions are summarized in Sect. 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 (Lut2004 henceforth) was extracted from the Luterbacher et al. (2004) and Xoplaki et al. (2005) European-wide reconstructions. Data is originally defined on a 0.5°

latitude × 0.5° longitude grid. From 1901 onwards this dataset was based on instrumental data from Mitchell and Jones (2005). 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. It is located about 5 km northwestwards of Évora (southern Portugal) and about 100 km eastwards of Lisbon. More detailed information about this observatory 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 years 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 16.8 and 15.8 °C, respectively, while both SD are of ca. 0.3 °C. 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 temperature-depth profiles are herein compared to synthetic temperature profiles, generated from both Lut2004 and annual mean near-surface temperatures from paleoclimate simulations, rather than applying the conventional procedure of inverting temperature logs to reconstruct ground surface temperatures (e.g. Correia and Šafanda, 2001). In this manner, uncertainties inherent to these inversion methods (Hartmann and Rath, 2005) are avoided in the present study. 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):

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

where erfc is the complementary error function and k is the subsurface thermal diffusivity (Cermak and Rybach, 1982). It has a value of $1.3 \times 10^{-6}\,\mathrm{m}^2\,\mathrm{s}^{-1}$, 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):

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

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

2.3 Paleoclimate simulations

The paleoclimate simulations were carried out with the Global Circulation Model ECHO-G, and then dynamically downscaled with the Regional Climate Model 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. González-Rouco et al., 2003; Zorita et al., 2005, 2007; Gómez-Navarro et al., 2012). 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). In this methodology, the original time series is decomposed into a sum of additive components and can be partially rebuilt using only "signal modes", thus filtering out background noisy components (Vautard et al., 1992; Elsner and Tsonis, 1996). Under the assumption that the aforementioned external forcings used in the paleoclimate simulations are mainly manifested though 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. This approach has been used to correct the low-frequency variability in the reconstructed series, rendering it more consistent with the paleoclimate external forcings.

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 140–190 m data (Fig. 1b). These gradients approximately range from 47 to 49 $\mathrm{m\,^{\circ}C^{-1}}$ (ca. 0.021 $\mathrm{^{\circ}C\,m^{-1}}$). 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 (Majorowicz et al., 1999; Hamza et al., 2007; Beltrami et al., 2011). The Global Database of Borehole Temperatures and Climate Reconstructions from 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. Nonetheless, not disregarding the aforementioned limitations, no other geothermal-paleoclimatological observatory is available in Portugal, but the conclusions derived from their analysis 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. There are two meters of difference between M5 (12 m) and the other profiles (10 m), which may partially explain this difference. 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 years 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 years 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 remarkably 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), thus supporting each other. However, whereas the paleoclimate simulations agree well with the borehole temperature-depth profiles, the reconstructed temperature for Portugal (Lut2004) fails to capture the long-term trends. In fact, its linear trend is nearly zero over the whole period and there is no signature of cool/warm periods. This striking disagreement between simulations and Lut2004 was already reported by Gómez-Navarro et al. (2011). As such, the Lut2004 reconstruction needs to be adequately adjusted for climate research purposes. Towards this aim, the ensemble mean temperature from the two paleoclimate simulations was low-pass filtered. A 2-order SSA filtering was applied in order to improve the signal-to-noise ratio and to highlight the signature of external forcings. The resulting SSA filtered series (SSA-trend) is depicted in Fig. 2b.

The SSA-trend corresponds to a non-linear data-adaptive long-term trend (Fig. 2b). It 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). Hence, this long-term trend clearly reflects the main external (radiative) forcings on near-surface temperature and was added to the Lut2004 reconstruction. The resulting calibrated series (CalT) is also shown in Fig. 2b. 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 much clearer than in the Lut2004 reconstruction. 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 a noteworthy cross-validation of CalT.

4 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 and regression equation reveal they are linearly related, with a correlation coefficient above 0.90 (Fig. 3), explaining about 82 % of the total variance. Therefore, CalT clearly reproduces the observed temperature in Portugal in the instrumental period (InstT). Further, the corresponding regression polynomial is applied for a second-stage calibration of location and scale. 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. This final time series can then be used, with high confidence, in upcoming studies of climate variability in Portugal.

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). Aiming at identifying regularities (oscillations) in CalT, a wavelet spectrum, using Morlet estimation (Torrence and Compo, 1998), as well as the corresponding global power spectrum are determined (Fig. 4c). The results show significant power for periods beyond 130–190 years and from the 1725s onwards. This is indeed a clear manifestation of the non-linear trend added for CalT calibration. In fact, the wavelet spectrum for the trend is quite similar to that for CalT (not shown).

5 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

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documentary evidence, such as diaries, ecclesiastical rogation ceremonies (*pro-pluvia* and *pro-serenitate*), *Misericórdias* and municipal institutional sources, as well as on early intrumental 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). Overall, there is a general agreement between CalT and temperature indices ($>80\,\%$ 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.

6 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 with the borehole temperature-depth profiles, the same does not apply to the Lut2004 reconstruction. In fact, it fails to reproduce the long-term trend from the 1830s onwards. The late Maunder and Dalton minima, also clearly reflected in the paleoclimate simulations and well-documented in the literature, in association with changes in solar activity (Eddy, 1983), are both 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 reconstruc-

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tion was calibrated by adding a non-linear long-term trend, estimated from a low-pass SSA filtering of the average temperature series from two paleoclimate simulations.

As a result of the calibration method, CalT shows an overall agreement with the long-term variability of the simulations. In addition, its temperature-depth anomaly profile is highly coherent with synthetic profiles obtained from both borehole and paleoclimate simulations. These outcomes correspond to a validation of CalT. As this analysis was carried out in the temperature anomalies, a location and scale calibration of CalT, using InstT as a baseline, is applied. To identify regularities in CalT series, a wavelet spectral analysis was undertaken. Important oscillations are identified from the eighteenth century onwards, which are in accordance with the non-linear long-term trend. Documentary sources in Portugal during the LMM (1675–1715), not incorporated in Lut2004/CalT, are used to determine annual temperature indices. A high correspondence is also found between CalT and these indices, thus providing an additional validation of CalT, at least over the LMM.

These results are not only a two-way validation of borehole data and paleoclimate simulations, as their temperature-depth profiles are in clear agreement, but also suggest the inability of the Lut2004 reconstruction to properly capture the warming trend in Portugal. Despite the presence of a warming trend in Lut2004 over the twentieth century and the high consistency with InstT, there is a cooling trend in the nineteenth century that is not supported by borehole measurements, regional paleoclimate simulations and literature. In effect, the absence of clear long-term trends in Lut2004 is very unlikely, taking into account 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). Similar results were also obtained on a seasonal basis. The long-term non-linear trends of the seasonal temperature series from paleoclimate simulations are analogous to that of the annual mean series, whilst Lut2004 seasonal series are not able to properly capture the corresponding low-frequency variability (not shown). Hence, the present study calibrated

CalT series overcomes an important limitation of the Lut2004 reconstruction and can thus be of foremost relevance in forthcoming research on climatic variability in Portugal.

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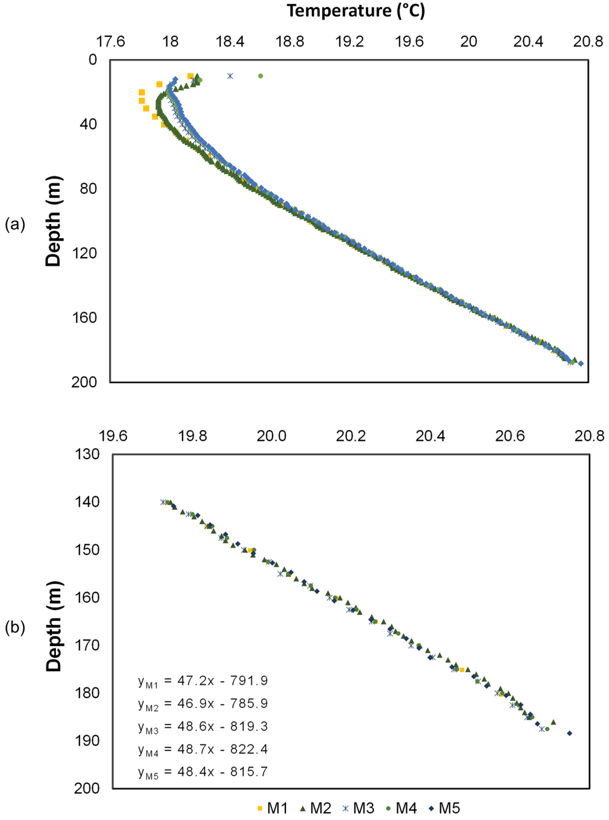

Figure 1. (a) Borehole temperature logs (temperature vs. depth) for: M1, M2, M3, M4 and M5 from the Évora observatory (cf. legends). **(b)** The same as on **(a)**, but only for the bottom 140–190 m data. The outlined equations of the respective regression lines (omitted) represent the corresponding steady-state geothermal gradients (slope of the linear regression line).

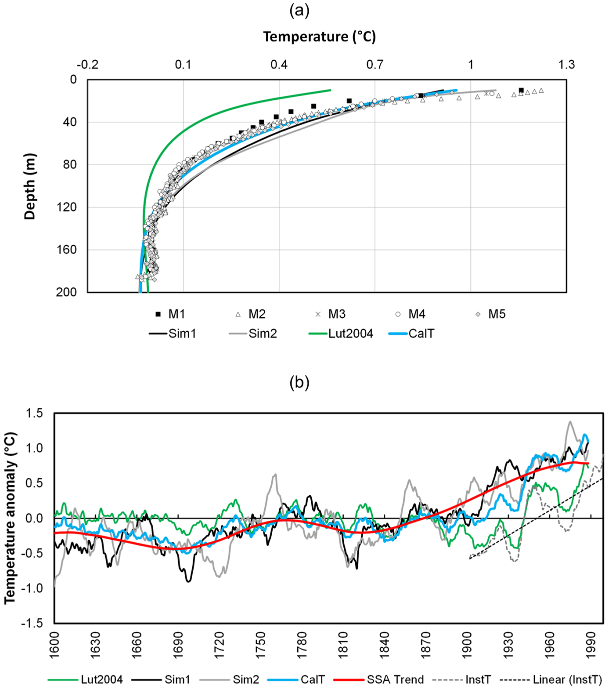

Figure 2. (a) Temperature-depth anomaly profiles for: M1, M2, M3, M4 and M5, with respect to the estimated geothermal gradients in Fig. 1b, along with the synthetic profiles generated from: Lut2004 – reconstructed temperature; CalT – calibrated temperature; and Sim1/Sim2 – paleoclimate simulations, retrieved for a gridbox near Lisbon, Portugal (cf. legends). **(b)** Chronograms of the 11 years 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 years 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 its full period.

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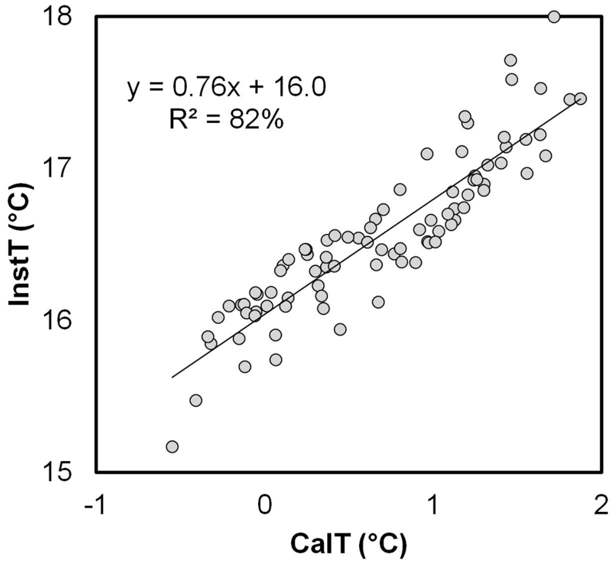

Figure 3. Scatterplot between InstT and CalT anomalies over their common period (1901–1989). The corresponding regression line, calibration equation and *R*-squared measure (determination coefficient) are also pointed out.

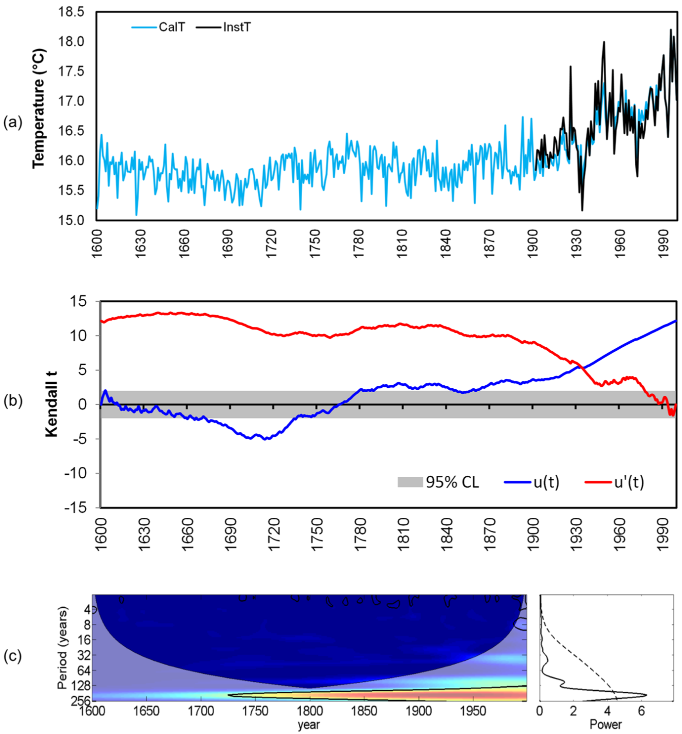

Figure 4. Chronogram of: **(a)** CalT – calibrated annual mean temperature – in the period of 1600–1999 and InstT in the period of 1901–1999. **(b)** Forward – $u(t)$ – and backward – $u'(t)$ – series of the normalised Kendall t parameter from the progressive Mann–Kendall analysis of CalT. 95 % confidence interval for the no trend hypothesis in grey shading. **(c)** Wavelet power spectra (left panels) and global wavelet spectra (right panels) of CalT over the period of 1600–1999 (Morlet estimation). Solid black lines in the wavelet spectra represent statistically significant power at a confidence level of 95 % and the cone of influence is white shaded. Dashed lines in the global spectra correspond to red noise significance level.

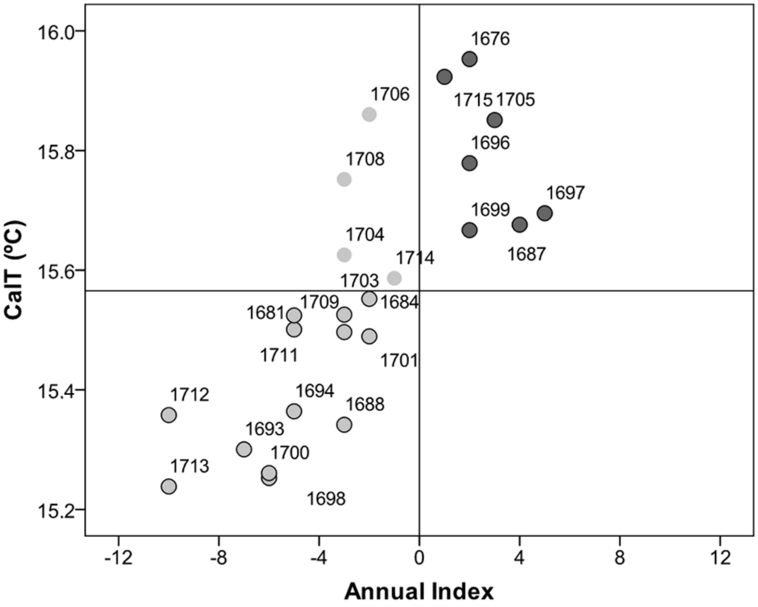

Figure 5. Scatterplot of CalT in the period of 1675–1715 as a function of the annual temperature indices. Light (dark) grey circles represent cold (hot) years from documentary evidence. Circles with black outer lines indicate agreement between the two datasets. Years with “0” index are omitted. The horizontal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