Holocene climates of the Iberian Peninsula: pollen-based reconstructions of changes in the west-east gradient of temperature and moisture

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Ms for: *Climate of the Past*

Abstract

The Iberian Peninsula is characterised by a steep west-east moisture gradient today, reflecting the dominance of maritime influences along the Atlantic coast and more Mediterranean-type climate further east. Holocene pollen records from the Peninsula suggest that this gradient was less steep during the ~~early to~~ mid-Holocene, possibly reflecting the impact of orbital changes on circulation and thus regional patterns in climate. Here we use ~~7121~~7214 pollen samples from 117 sites covering part or all of the last 12,000 years to reconstruct changes in seasonal temperature and in moisture across the Iberian Peninsula quantitatively. We show that there is an increasing trend in winter temperature at a regional scale, consistent with known changes in winter insolation. However, summer temperatures do not show the decreasing trend through the Holocene that would be expected if they were a direct response to insolation forcing. We show that summer temperature is strongly correlated with plant-available moisture (α), as measured by the ratio of actual evapotranspiration to equilibrium evapotranspiration, which declines through the Holocene. The reconstructions also confirm that the west-east gradient in moisture was considerably less steep than today during the ~~early to~~ mid-Holocene, indicating that atmospheric circulation changes (possibly driven by orbital changes) have been important determinants of the Holocene climate of the region.

1. Introduction

The Iberian Peninsula is characterised by a steep west-east gradient in temperature and moisture today, reflecting the dominance of maritime influences along the Atlantic coast and more Mediterranean-type climate further east. Projections of future climate change suggest that the region will become both warmer and drier, but nevertheless show that this west-east differentiation is maintained (Andrade et al., 2021a). The changes in temperature are projected to be larger and the occurrence of extreme temperature episodes more frequent in the south-central and eastern parts of Iberia than in Atlantic coastal areas (Carvalho et al., 2021). Similar gradients are seen in future projections of precipitation change, with largest reductions in precipitation in the south-central region (Andrade et al., 2021b). However, the stability of these west-east gradients during the Holocene has been questioned. In particular, the west-east gradient in moisture appears to have been less pronounced during the middle Holocene (8-4 ka) when cooler summers and wetter conditions in the Atlantic zone (e.g. Martínez-Cortizas et al., 2009; Mauri et al., 2015) coincided with the maximum development of mesophytic vegetation further east and south (Aranbarri et al., 2014, 2015; Carrión et al., 2010, 2009; González-Sampériz et al., 2017).

~~However, much of the evidence for Holocene climates is based on qualitative interpretations of vegetation changes, generally interpreted as reflecting changes in moisture availability (Morellón et al., 2018). Although these records are extensive, they seem to indicate fairly complex spatial patterns of change. Iberia was included in the quantitative pollen-based reconstructions of European climate though the Holocene (Mauri et al., 2015). However, most of the ca 50 sites from Iberia were from the Pyrenees and the inferred patterns across the Peninsular are therefore largely extrapolated. Furthermore, quantitative reconstructions of summer temperature made at individual sites using chironomid data (Muñoz Sobrino et al., 2013; Tarrats et al., 2018) are not consistent with reconstructed changes based on pollen for the same sites.~~ However, much of the evidence for Holocene climates of the Iberian Peninsula is based on qualitative interpretations of vegetation changes, generally interpreted as reflecting changes in moisture availability (Morellón et al., 2018). These records are extensive and they seem to indicate fairly complex spatial patterns of change. ~~(~~Kaufman et al.~~,~~ (2020) provides quantitative reconstructions of summer and winter temperature in their compilation of Holocene climate information, but there are only 5 terrestrial sites from the Iberian Peninsula. Iberia was also included in the quantitative pollen-based reconstructions of European climate through the Holocene (Mauri et al., 2015). However, the geographical distribution of sites included is uneven and a large fraction of the records were from the Pyrenees and the Cantabrian mountains, with additional clustering of sites in coastal regions. Thus, the inferred patterns of climate over most of the central part of the Peninsula are therefore largely extrapolated. ~~(~~Tarroso et al.~~,~~ (2016) has provided reconstructions of summer and winter temperature and mean annual precipitation since the Last Glacial Maximum for the Iberian Peninsula, by using modern species distribution data to develop climate probability distribution functions (PDFs) and applying these to 31 fossil records. However, although they identified trends in precipitation during the Holocene, the temperature reconstructions do not seem to be reliable since they show no changes through time (9 ~ 3 ka), either for the Iberian Peninsula as a whole or for individual sub-regions, in contra-distinction to the other reconstructions. The current state of uncertainty about Holocene climate changes in Iberia is further exacerbated because quantitative reconstructions of summer temperature made at individual sites using chironomid data (Muñoz Sobrino et al., 2013; Tarrats et al., 2018) are not consistent with reconstructed summer temperatures based on pollen for the same sites.

Here we re-examine the trends in summer and winter temperature and plant-available moisture through the Holocene across Iberia, using a new and relatively comprehensive compilation of pollen data (Shen et al., 2021) with age models based on the latest radiocarbon calibration curve (IntCal20: Reimer et al., 2020). We explicitly test whether there are significant differences in the west-east gradient of moisture and temperature through time. We then analyse the relationships between the changes in the three climate variables and how trends in these variables are related to external climate forcing. These analyses allow us to confirm that the west-east gradient in moisture was less steep during the mid-Holocene and indicate the importance of changes in atmospheric circulation in explaining observed patterns of climate change across the region.

~~We analyse how these trends are related to external forcing and quantify whether there are significant differences in west-east gradients through time.~~

2. Methods

Multiple techniques have been developed to make quantitative climate reconstructions from pollen (see reviews in Bartlein et al., 2011; Chevalier et al., 2020; Salonen et al., 2011). Modern analogue techniques (MAT: Overpeck et al., 1985) tend to produce rapid shifts in reconstructed values corresponding to changes in the selection of the specific analogue samples, although this tendency is less marked in the conceptually analogous response surface technique (Bartlein et al., 1986). Regression-based techniques, including weighted averaging methods such as Weighted Average Partial Least-Squares (WAPLS: ter Braak and Juggins, 1993), do not produce step-changes in the reconstructions but suffer from the tendency to compress the reconstructions towards the central part of the sampled climate range. However, this tendency can be substantially reduced by accounting for the sampling frequency (fx) and the climate tolerance of the pollen taxa present in the training data set (fxTWA-PLS: Liu et al., 2020). Bayesian approaches have also been applied to derive climate reconstructions from pollen assemblages (Peyron et al., 1998). However, comparison of fxTWA-PLS with the Bayesian model BUMPER (Holden et al., 2017), shows that fxTWA-PLS performs better in capturing the climate of the modern training data set from Europe (Liu et al., 2020).

Although fxTWA-PLS has clear advantages over other quantitative reconstructions techniques, there is still a slight tendency towards compression. We have therefore made a further modification to the approach as described in Liu et al. (2020). In the original version of fxTWA-PLS, the fx correction is applied as a weight with the form of $1/fx^2$ in the regression (step 7 in Table 1 in Liu et al., 2020). Here (see Appendix A) we make a further modification of fxTWA-PLS by (a) applying the fx correction separately in both the taxon calculation and the regression (step 2 and 7 in Table 1 in Liu et al., 2020) as a weight with the form of 1/fx and (b) applying P-splines smoothing (Eilers and Marx, 2021) in order to reduce the dependence of the fx estimation on bin width. The modified version further reduces the biases at the extremes of the sampled climate range. We used this modified version of fxTWA-PLS to reconstruct three climate variables: mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and plant-available moisture represented by α, an estimate of the ratio of actual evapotranspiration to equilibrium evapotranspiration. The individual and joint effects of MTCO, MTWA and α were tested explicitly using canonical correspondence analysis (CCA).

The modern pollen training dataset was derived from the SPECIAL Modern Pollen Data Set (SMPDS: Harrison, 2019). The SMPDS consists of relative abundance records from 6458 terrestrial sites from Europe, northern Africa, the Middle East and northern Eurasia (SI Figure S1) assembled from multiple different published sources. The pollen records were taxonomically standardized, and filtered (as recommended by Chevalier et al., 2020) to remove obligate aquatics, insectivorous species, introduced species, and taxa that only occur in cultivation. Taxa (mainly herbaceous) with only sporadic occurrences were amalgamated to higher taxonomic levels (genus, sub-family or family) after ensuring consistency with their distribution in climate space. As a result of these amalgamations, the SMPDS contains data on 247 pollen taxa. For our analysis, we use the 195 taxa that occur at more than 10 sites.

Modern climate data at each of the sites in the training data set were obtained from Harrison (2019). This data set contains climate reconstructions of MTCO, growing degree days above a baseline of 0° C (GDD_0) and a moisture index (MI), defined as the ratio of annual precipitation to annual potential evapotranspiration. The climate at each site was obtained using geographically-weighted regression of the CRU CL v2.0 gridded dataset of modern (1961-1990) surface climate at 10 arc minute resolution (New et al., 2002) in order to correct for elevation differences between each pollen site and the corresponding grid cell. The geographically-weighted regression used a fixed bandwidth kernel of 1.06 ° (~140km) to optimize model diagnostics and reduce spatial clustering of residuals relative to other bandwidths. The climate of each pollen site was then estimated based on its longitude, latitude, and elevation. MTCO and GDD_0 was taken directly from the GWR regression and MI was calculated for each pollen site using code modified from SPLASH v1.0 (Davis et al., 2017) based on daily values of precipitation, temperature and sunshine hours again obtained using a mean-conserving interpolation of the monthly values of each. For this application, we used MTCO directly from the data set but calculated MTWA from MTCO and GDD_0, based on the relationship between MTCO, MTWA and GDD_0 given by Appendix 2 of Wei et al. (2021). We derived α from MI following Liu et al. (2020). The modern training data set provides records spanning a range of MTCO from – 42.4 °C to 14.8 °C, of MTWA from 4.2 °C to 33.5 °C, and of α from 0.04 to 1.25 (Figure 1, SI Fig. S1).

The fossil pollen data from the Iberian Peninsula were compiled by Shen et al. (2021) and the data set (Harrison et al., 2022) was obtained from https://doi.org/10.17864/1947.000369. ~~We used a modified version of Tolerance-weighted Weighted Averaging Partial Least-Square with a sampling frequency correction (fxTWA-PLS: Liu et al., 2020) to reconstruct three climate variables: mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and plant-available moisture represented by α, an estimate of the ratio of actual evapotranspiration to equilibrium evapotranspiration. The individual and joint effects of MTCO, MTWA and α were tested explicitly using canonical correspondence analysis (CCA).~~

~~fxTWA-PLS is a modification of the Weighted Average Partial Least Square (WA-PLS) approach. The modification produces less compression of reconstructions towards the centre of the climatic range sampled by the training dataset, by accounting for the climatic tolerances of individual pollen taxa and the frequency of the sampled climate variable (fx) in the training dataset (Liu et al., 2020). The fx correction is applied as a weight with the form of $1/fx^2$ in the regression (step 7 in Table 1 in Liu et al., 2020). Here (see Appendix A) we make a further modification of fxTWA-PLS by (a) applying the fx correction separately in both the taxon calculation and the regression (step 2 and 7 in Table 1 in Liu et al., 2020) as a weight with the form of 1/fx and (b) applying P-splines smoothing (Eilers and Marx, 2021) in order to reduce the dependence of the fx estimation on bin width. The modified version further reduces the biases at the extremes of the sampled climate range.~~

~~The modern pollen training dataset was derived from the SPECIAL Modern Pollen Data Set (SMPDS: Harrison, 2019). The SMPDS consists of relative abundance records of the 247 most important pollen taxa from 6458 terrestrial sites from Europe, the Middle East and northern Eurasia (SI Figure S1). For our analysis, we use the 195 taxa that occur at more than 10 sites. Modern climate data at each of the sites in the training data set were obtained from Harrison (2019). The fossil pollen data from the Iberian Peninsula were compiled by Shen et al. (2021) and obtained from http://dx.doi.org/10.17864/1947.294.~~ The taxonomy used by Shen et al. (2021) is consistent with that employed in the SMPDS. Shen et al. (2021) provides consistent age models for all the records based on the IntCal20 calibration curve (Reimer et al., 2020) and the BACON Bayesian age-modelling tool (Blaauw et al., 2021; Blaauw and Christeny, 2011) using the supervised modelling approach implemented in the `ageR` package (Villegas-Diaz et al, 2021). We excluded individual pollen samples with large uncertainties (standard error larger than 100 years) on the attributed in the new age model. As a result, the climate reconstructions are based on a fossil data set of 7384 pollen samples from 117 records covering part or all of the last 12,000 years (Figure 2), with 42 individual records provided by the original authors, 73 records obtained from the European Pollen Database (EPD, www.europeanpollendatabase.net) and 2 records from PANGAEA (www.pangaea.de/). Details of the records are given in SI Table S1. The average temporal resolution of these records is 101 years. ~~We excluded individual pollen samples with large age uncertainties (standard error larger than 100 years).~~ W~~W~~e then ~~also~~ excluded a few samples where the reconstructed values ~~-~~of α exceed the natural limit of 0 and 1.26. Finally, 7214 samples from 117 records are used for the analyses of the climate reconstructions.~~. As a result, the climate analyses are based~~

~~on a fossil data set of 7121 pollen samples from 117 sites covering part or all of the last 12,000 years (Figure 1).~~

~~In addition to examining the reconstructions for individual sites, we constructed composite curves for the Iberian Peninsula as a whole. These curves were constructed after binning the site-based reconstructions using ±500-year bins. We did 1000 bootstrap resampling of the reconstructed climate values in each ±500-year bin to avoid the influence of a single value or a single site on the mean climate value in this bin, and use the standard deviation of the 1000 values to represent the uncertainty of the mean climate value. We constructed linear regression plots to examine the longitudinal and elevational patterns in the reconstructed climate variables, and assessed the significance of differences in these trends through time compared to 0.5 ka based on *p* values, with the customary threshold of 0.05.~~ In addition to examining the reconstructions for individual sites, we constructed composite curves for the Iberian Peninsula as a whole. The composite curves provide a way of comparing the relationship between trends in the reconstructed climate changes and insolation changes. The curves were constructed after binning the site-based reconstructions using ± 500-year bins. We did 1000 bootstrap resampling of the reconstructed climate values in each ± 500-year bin to avoid the influence of a single value or a single site on the mean climate value in this bin, and use the standard deviation of the 1000 values to represent the uncertainty of the mean climate value. We constructed linear regression plots to examine the longitudinal and elevational patterns in the reconstructed climate variables, and assessed the significance of differences in these trends through time compared to the most recent bin (0.5 ka ± 500 years) based on *p* values, with the customary threshold of 0.05. We then compared the climate trends with changes in summer and winter insolation.

~~The individual and joint effects of MTCO, MTWA and α were tested explicitly using canonical correspondence analysis (CCA).~~

3. Results

The modified version of fxTWA-PLS reproduces the modern climate reasonably well (Table 1). The performance is best for MTCO (R^2 0.75, RMSEP 4.70, slope 0.91) but is also good for α (R^2 0.68, RMSEP 0.16, slope 0.78) and MTWA (R^2 0.57, RMSEP 3.47, slope 0.71). The correlations between pollen records and each of the three bioclimate variables, as assessed by

CCA, were strong for both modern climate data and fossil reconstructions (Table 2). The variance inflation factor scores are all less than 6, so there are no multicollinearity problems (Table 2). Furthermore, the taxa that contribute most strongly to reconstructing colder/warmer or wetter/drier climates show predictable patterns consistent with their known ecological preferences (SI Table S2).

Winters were generally colder than present during the early to mid-Holocene, as shown by the coherent patterns of reconstructed anomalies at individual sites (~~Fig. 2~~Fig. 3a, 3~~2~~d). Here "present" means the most recent pollen bin (0.5 ka ± 500 years). The composite curve also shows a general increase in winter temperatures through time (~~Fig. 3~~Fig. 4a), consistent with the trend in winter insolation (~~Fig. 3~~Fig. 4d). The composite curve shows that it was ca 4°C cooler than today at 11.5 ka and conditions remained cooler than present until ca 2.5 ka. Winter temperature anomalies show no spatial differentiation between western and eastern Iberia (Table 3, SI Fig. S2). The similarity of the changes compared to present geographically is consistent with the idea that the changes in winter temperature are driven by changes in winter insolation.

Summers were somewhat hotter than present in the west and cooler than present in the east during the early and middle Holocene, as shown by the reconstructed anomalies at individual sites (~~Fig. 2~~Fig. 3b, 3~~2~~e). This west-east difference could not arise if the changes in summer temperatures were a direct reflection of the insolation forcing (~~Fig. 3~~Fig. 4e). Indeed, the composite curve shows relatively little change in MTWA (~~Fig. 3~~Fig. 4b), confirming that there is no direct relationship to insolation forcing (~~Fig. 3~~Fig. 4e).

There is a strong west-east gradient in α at the present day (~~Fig. 1~~Fig. 2), with wetter conditions in the west and drier conditions in the east. However, the reconstructed anomalies at individual sites (~~Fig. 2~~Fig. 3c, 3~~2~~f) suggest that west was drier and the east was wetter than present in the mid-Holocene, resulting in a flatter west-east gradient. The west-east gradient is significantly different from present between 9.5 ~ 3.5 ka (~~Fig. 4~~Fig. 5, Table 3), implying stronger moisture advection into the continental interior during the mid-Holocene. The change in gradient is seen in both high and low elevation sites (SI Fig. S3). There is also significant change in α with elevation between 9.5 ~ 4.5 ka (Table 3, SI Fig. S4).

Summer temperatures are strongly correlated with changes in α, both in terms of spatial correlations in the modern data set at a European scale and in terms of spatial and temporal correlations the fossil data set from Iberian Peninsula (Fig. 6). ~~Summer temperatures are strongly correlated with changes in α, both in the modern data set at a European scale and in the fossil data set from Iberia (Fig. 5).~~ The patterns of reconstructed anomalies in MTWA and α at individual sites are also coherent (~~Fig. 2~~Fig. 3b, 3~~2~~c, 3~~2~~e, 3~~2~~f), showing drier conditions and hotter summers than present in the west and wetter conditions with cooler summers in the east during the early to mid-Holocene. The west-east gradient in MTWA was significantly different from present between 9.5 and 3.5 ka except 8.5 ka (Table 3, SI Fig. S5), roughly the interval when the gradient in α was also significantly different from present. Again, the change in the east-west gradient is registered at both high and low elevation sites (SI Fig. S6). However, there is no significant change in MTWA with elevation except 8.5 and 7.5 ka (Table 3, SI Fig. S7).

4. Discussion

We have shown that there was a gradual increase in MTCO over the Holocene, both for most of the individual sites represented in the data set and for Iberia as a whole. Colder winters in southern Europe during the mid-Holocene (6 ka) are a feature of many earlier reconstructions (e.g. Cheddadi et al., 1997; Wu et al., 2007). A general warming trend over the Holocene is seen in gridded reconstructions of winter season (December, January, February) temperatures as reconstructed using the modern analogue approach by Mauri et al. (2015), although there is somewhat less millennial-scale variability in these reconstructions (SI Fig. S8). Nevertheless, their reconstructions show a cooling of 3°C in the early Holocene, ~~are~~ comparable in magnitude to the ca 4°C cooling at 11.5 ka reconstructed here. Although they show conditions slightly cooler than present persisting up to 1 ka, the differences are very small (ca 0.5°C) after 2 ka, again consistent with our reconstructions of MTCO similar to present by 2.5 ka. ~~Quantitative reconstructions of winter temperature are available for 5 terrestrial sites from the Iberian Peninsula in the Kaufman et al. (2020) compilation of Holocene climate information. These sites all show a general trend of winter warming over the Holocene, but the magnitude of the change at some of the individual sites is much larger (ca 10°C) and there is no assessment off the uncertainty on these reconstructions. The composite curve of Kaufman et al. (2020) shows an increasing trend in MTCO through the Holocene but with large uncertainties (SI Fig. S8). Our reconstructed trend in winter temperature is consistent with the changes in insolation forcing at this latitude during the Holocene, and is also consistent with transient climate model simulations of the winter temperature response to changing insolation forcing over the late~~

~~Holocene in this region (SI Fig. S9). Thus, we suggest that changes in winter temperatures are a direct consequence of insolation forcing.~~Quantitative reconstructions of winter temperature for the 5 terrestrial sites from the Iberian Peninsula in the Kaufman et al. (2020) compilation all show a general trend of winter warming over the Holocene, but the magnitude of the change at some of the individual sites is much larger (ca 10°C) and there is no assessment of the uncertainty on these reconstructions. The composite curve of Kaufman et al. (2020) shows an increasing trend in MTCO through the Holocene although with large uncertainties (SI Fig. S8). In contrast to the consistency of the increasing trend in MTCO during the Holocene between our reconstructions and those of Mauri et al. (2015) and Kaufman et al. (2020), there is no discernible trend in MTCO during the Holocene reconstruction of ~~(~~Tarroso et al. (~~,~~2016). Indeed, there is no significant change in their MTCO values after ca 9 ka, either for the Peninsula as a whole (SI Fig. S8) or for any of the four sub-regions they considered. Our reconstructed trend in winter temperature is consistent with the changes in insolation forcing at this latitude during the Holocene, and is also consistent with transient climate model simulations of the winter temperature response to changing insolation forcing over the late Holocene in this region (SI Fig. S9). Thus, we suggest that changes in winter temperatures are a direct consequence of insolation forcing.

We have shown that there is no overall trend in MTWA during the Holocene. According to our reconstructions, summer temperatures fluctuated between ca 0.5°C above or below modern temperature. The lack of coherent trend in MTWA is consistent with the gridded reconstructions of summer (June, July, August) temperature in the Mauri et al. (2015) data set and also with the 5 terrestrial sites from Iberia included in the Kaufman et al. (2020) data set. However, the patterns shown in the three data sets are very different from one another. Mauri et al. (2015) suggest the early Holocene was colder than today, and although temperatures similar to today were reached at 9 ka, most of the Holocene was characterised by cooler summers. Kaufman et al. (2020), however, showed warmer than present conditions during the early Holocene although they also show cooler conditions during the later Holocene. The differences between the three data sets probably reflect differences in the number of records used, but the lack of coherency points to there not being a strong, regionally coherent signal of summer temperature changes during the Holocene. Tarroso et al. (2016) also showed no significant changes in MTWA after ca 9 ka (SI Fig. S8).

The chironomid record from Laguna de la Roya covers the late glacial and terminates at 10.5

ka (Muñoz Sobrino et al., 2013). The reconstructed July temperature during the early Holocene is ca 12~13 °C, which is considerably cooler than today at this site. However, the authors caution that these samples have poor analogues and the record should be interpreted with caution. Chironomid-based reconstructions of July temperature at Basa de la Mora (Tarrats et al., 2018), a high elevation site in the Pyrenees, indicate temperatures within ± 0.5° C of the modern during the early to mid-Holocene (10~6 ka), similar to our regional composite reconstructions. However, they show persistently conditions cooler than present by ca 1.5 °C between 4.5 and 2 ka~~they show a persistent cooling of 1.5 °C compared to present between 4.5 and 2 ka~~, not seen in ~~these~~ our reconstructions. Furthermore, direct comparison of our reconstructions of MTWA at Basa de la Mora (SI ~~Fig. S10~~Fig. S11) to the chironomid-based reconstructions highlights that the two records show very different trajectories, since the pollen-based reconstruction of this site shows a consistent warming trend throughout the Holocene. Although Tarrats et al. (2018) argue that discrepancies between their temperature reconstructions and pollen-based reconstructions reflects the fact that the vegetation of Iberia, including the mountain areas, is largely driven by moisture changes and perhaps is not a good indicator of temperature, we have shown that there is sufficient information in the pollen records to reconstruct temperature and moisture independently (Table 2, Table S2). Thus, the cause of the differences between the pollen-based and chironomid-based reconstructions at Basa de la Mora is presumably related to methodology. In particular, the chironomid reconstructions use a training data set that does not include samples from the Pyrenees, or indeed the Mediterranean more generally, and may therefore not provide good analogues for Holocene changes at this site.

The lack of a clear trend in MTWA in our reconstructions is not consistent with insolation forcing, which shows a declining trend during the Holocene nor is it consistent with simulated changes in MTWA in transient climate model simulations (see supplementary materials for detailed description) of the summer temperature response to changing insolation forcing over the ~~late~~ Holocene in this region (SI Fig. S9). The change in moisture gradient during the mid-Holocene, however, suggests an alternative explanation whereby changes in summer temperature are a response to land-surface feedbacks associated with changes in moisture. Specifically, the observed increased advection of moisture into eastern Iberia would have created wetter conditions there, which in turn would permit increased evapotranspiration, implying less allocation of available net radiation to sensible heating, and resulting in cooler air temperatures. ~~Specifically, the increased advection of moisture into eastern Iberia created~~

~~wetter conditions leading to increased evapotranspiration, less allocation of available net radiation to sensible heating, and resulting in cooler air temperatures.~~ Our reconstructions show that the west-east moisture gradient in mid-Holocene was significantly flatter than the steep moisture gradient today, implying a significant increase in moisture advection into the continental interior during this period. Mauri et al. (2015) also showed that summers were generally wetter than present in the east but drier than present in the west at early to mid-Holocene, supporting the idea of a flatter west-east gradient. ~~Stronger moisture advection is not a feature of the transient climate model simulations, which may explain why these simulations do not show a strong modification of the insolation-driven changes in summer temperature. The failure of the current generation of climate models to simulate the observed strengthening of moisture transport into Europe and Eurasia during the mid-Holocene has been noted by other studies (e.g. Bartlein et al., 2017; Mauri et al., 2014). This data-model mismatch highlights the need for better modelling of land-surface feedbacks on atmospheric circulation and moisture.~~

We have shown that stronger moisture advection is not a feature of transient climate model simulations of the Holocene, which may explain why these simulations do not show a strong modification of the insolation-driven changes in summer temperature (Fig. S9). Although the amplitude differs, all of the models show a general decline in summer temperature. The failure of the current generation of climate models to simulate the observed strengthening of moisture transport into Europe and Eurasia during the mid-Holocene has been noted for previous versions of these models (e.g. Bartlein et al., 2017; Mauri et al., 2014) and also shown in Fig. S10. Mauri et al. (2014), for example, showed that climate models participating in the last phase of the Coupled Model Intercomparison Project (CMIP5/PMIP3) were unable to reproduce reconstructed climate patterns over Europe at 6000 yr B.P. and indicated that this resulted from over-sensitivity to changes in insolation forcing and the failure to simulate increased moisture transport into the continent. ~~(~~Bartlein et al.~~,~~ (2017) showed that the CMIP5/PMIP3 models simulated warmer and drier conditions in mid-continental Eurasia at 6000 yr B.P., inconsistent with palaeo-environmental reconstructions from the region, as a result of the simulated reduction in the zonal temperature gradient which resulted in weaker westerly flow and reduced moisture fluxes into the mid-continent. They also pointed out the strong feedback between drier conditions and summer temperatures. The drying of the mid-continent is also a strong feature of the mid-Holocene simulations made with the current generation of CMIP6/PMIP4 models (Brierley et al., 2020). The persistence of these data-model mismatches highlights the need for better modelling of land-surface feedbacks on atmospheric circulation and moisture.

Speleothem oxygen-isotope data from the Iberian Peninsula provide support for our pollen-based reconstructions of changes in the west-east gradient of moisture through the Holocene. The speleothem records show a progressive increase in temperature from the Younger Dryas onwards, although the trend is less marked in the west than the east (Baldini et al., 2019). This warming trend is consistent with our reconstructions of changes in MTCO through the Holocene. ~~However,~~ S~~s~~peleothem records also show distinctly different patterns in moisture availability, with sites in western Iberia indicating wetter environments during early Holocene and a transition to drier conditions from ca 7.5 cal ka BP to the present (Stoll et al., 2013; Thatcher et al., 2020) while eastern sites record wetter conditions persisting from 9 to 4 cal ka (Walczak et al., 2015). This finding would support the weaker west to east moisture gradient shown by our results.

Pollen data are widely used for the quantitative reconstruction of past climates (see discussion in Bartlein et al., 2011). Nevertheless, climate is not the only driver of vegetation changes. On glacial-interglacial timescales, changes in CO_2 have a direct impact on plant physiological processes and reductions in plant water-use efficiency at low CO_2 result in vegetation appearing to reflect drier conditions than~~t~~ were experienced in reality (Farquhar, 1997; Gerhart and Ward, 2010; Prentice et al., 2017; Prentice and Harrison, 2009). The difference between post- and pre-industrial CO_2 levels could also influence the reliability of moisture reconstructions based on modern training data sets. ~~We have not accounted for the impact of changing CO_2 in our reconstructions of α, although there are techniques to do this (Prentice et al., 2011, 2017; Wei et al., 2021).~~ However, the change in CO_2 over the Holocene was only 40 ppm. ~~Prentice et al. (2021) (~~Prentice et al.~~,~~ (2022) shows that this change relative to modern levels has only a small impact on pollen-based reconstructed moisture indices. The magnitude of this impact is within the uncertainties on our reconstructions. Furthermore, accounting for the effect of this change in CO_2 or~~would~~ not won't affect the reconstructed west-east gradient through time. Therefore, w~~W~~e have not accounted for the impact of changing CO_2 in our reconstructions of α, although there are techniques to do this (Prentice et al., 2011, 2017; Wei et al., 2021). A more serious issue for our reconstructions may be the extent to which the vegetation cover of Iberia was substantially modified by human activities during the Holocene. While there is no doubt that anthropogenic activities were important at the local scale and particularly in the later Holocene (e.g. Abel-Schaad and López-Sáez, 2013; Connor et al., 2019; Fyfe et al., 2019; Mighall et al., 2006; Revelles et al., 2015), most of the sites used for our reconstructions are not associated with archaeological evidence of agriculture or substantial landscape modification. Furthermore, the consistency of the reconstructed changes in climate across sites provides support for these being largely a reflection of regional climate changes.

We have used a modified version of fxTWA-PLS to reconstruct Holocene climates of the Iberian Peninsula because this modification reduced the compression bias in MTCO and MTWA, and specifically reduces the maximum bias in MTCO, MTWA and α. Although this modified approach produces better overall reconstructions (Appendix A), its use does not change the reconstructed trends in these variables through time (SI Fig. S12~~1~~). Thus, the finding that winter temperatures are a direct reflection of insolation forcing whereas summer temperatures are influenced by land-surface feedbacks and changes in atmospheric circulation is robust to the method used. However, while we use a much larger data set than previous reconstructions, the distribution of pollen sites is uneven and the northern part of the Peninsula is better sampled than the southwest, which could lead to some uncertainties in the interpretation of changes in the west-east gradient of moisture. It would, therefore, be useful to specifically target the southwestern part of the Iberian Peninsula for new data collection. Alternatively, it would be useful to apply the approach used here to the whole of Eurasia, given that the failure of state-of-the-art climate models to advect moisture into the continental interior appears to be a feature of the whole region (Bartlein et al., 2017) and not the Peninsula alone.

5. Conclusion

We have used a pollen data set representing 117 sites across the Iberian Peninsula to make quantitative reconstructions of summer and winter temperature and an index of annual moisture through the Holocene. We show that the trends in winter temperature broadly follow the changes orbital forcing. Summer temperatures, however, do not follow the changes in orbital forcing but appear to be influenced by land-surface feedbacks associated with changes in moisture. The west-east gradient in moisture was considerably less pronounced during the mid-Holocene (8-4 ka).

Data and Code Availability

All the data used are public access and cited here. The code used to generate the climate reconstructions is available at https://github.com/ml4418/Iberia-paper.git.

Supplement. The supplement related to this article is available online.

Competing interests. We declare that we have no conflict of interest.

Author Contributions. ML, ICP and SPH designed the study. ML, ICP and CJFtB designed the modifications to fxTWA-PLS. PG-S and GG-R provided pollen data and insights into the regional palaeoclimate histories. ML carried out the analyses. ML and SPH wrote the first draft of the paper and all authors contributed to the final draft.

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Figure and Table Captions

Figure 1. Climate space represented by mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA), and plant-available moisture as represented by α, an estimate of the ratio of actual evapotranspiration to equilibrium evapotranspiration. The grey points show climate values for a rectangular area (21° W ~ 150° E, 29° N ~ 82° N) enclosing the SMPDS data set, derived from the Climate Research Unit CRU CL 2.0 database (New et al., 2002). The black points show climate values of the SMPDS dataset. The red points show climate values of the Iberian Peninsula region in the SMPDS dataset.

Figure 2~~1~~. Map showing the location of the 117 fossil sites in the Iberian Peninsula used for climate reconstructions. Sites lower than 1000 m above sea level are shown as squares, sites higher than 1000 m above sea level are shown as triangles. The base maps show modern (a) mean temperature of the coldest month (MTCO), (b) mean temperature of the warmest month (MTWA), and (c) plant-available moisture as represented by α, an estimate of the ratio of actual evapotranspiration to equilibrium evapotranspiration.

Figure 3~~2~~. Reconstructed anomalies in climate at individual sites through time. The sites are grouped into high (>1000m) and low (<1000m) elevation sites and organised from west to east. Grey cells indicate periods or longitudes with no data. The individual plots show the anomalies in reconstructed (a,d) mean temperature of the coldest month (MTCO), (b,e) mean temperature of the warmest month (MTWA), and (c,f) plant-available moisture as represented by α, an estimate of the ratio of actual evapotranspiration to equilibrium evapotranspiration. The anomalies are expressed as deviations of the mean value in each bin (± 500 years) from the value at 0.5 ka at each site.

Figure 4~~3~~. Reconstructed composite changes (anomalies to 0.5 ka) in (a) mean temperature of the coldest month (MTCO), (b) mean temperature of the warmest month (MTWA) and (c) plant-available moisture as represented by α, through the Holocene compared to changes in (d) winter and (e) summer insolation for the latitude of the Iberian Peninsula, using ± 500 years as the bin. The black lines show mean values across sites, with vertical line segments showing the standard deviations of mean values using 1000 bootstrap cycles of site resampling.

Figure 5~~4~~. Changes in the west-east gradient of plant-available moisture as represented by anomalies in α relative to 0.5 ka at individual sites through the Holocene. The red lines show the regression lines. The shades indicate the 95 % confidence intervals of the regression lines

Figure 6~~5~~. The relationship between mean temperature of the warmest month (MTWA) and plant-available moisture as represented by α (a) in the modern climate data set, and (b) in the Holocene reconstructions.

Table 1. Leave-out cross-validation (with geographically and climatically close sites removed) fitness of the modified version of fxTWA-PLS, for mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and plant-available moisture (α), with p-spline smoothed fx estimation, using bins of 0.02, 0.02 and 0.002, showing results for all the components. RMSEP is the root-mean-square error of prediction. ΔRMSEP is the per cent change of RMSEP using the current number of components than using one component less. p assesses whether using the current number of components is significantly different from using one component less, which is used to choose the last significant number of components (indicated in bold) to avoid over-fitting. The degree of overall compression is assessed by linear regression of the cross-validated reconstructions onto the climate variable, b1, b1.se are the slope and the standard error of the slope, respectively. The closer the slope (b1) is to 1, the less the overall compression is.

Table 2. Canonical Correspondence Analysis (CCA) result of modern and fossil-reconstructed MTCO, MTWA and α. The summary statistics for the ANOVA-like permutation test (999 permutations) are also shown. VIF is the variance inflation factor, Df is the number of degrees of freedom, χ^2 ~~-~~is the constrained eigenvalue (or the sum of constrained eigenvalues for the whole model)~~-~~, F is significance, and Pr (>F) is the probability.

Table 3. Assessment of the significance of anomalies to 0.5 ka through time with latitude and elevation. The slope is obtained by linear regression of the anomaly onto the longitude or elevation. p is the significance of the slope (bold parts: $p < 0.05$). x_0 is the point where the anomaly is 0 in the linear equation, which indicates longitude or elevation where the anomaly changes sign.

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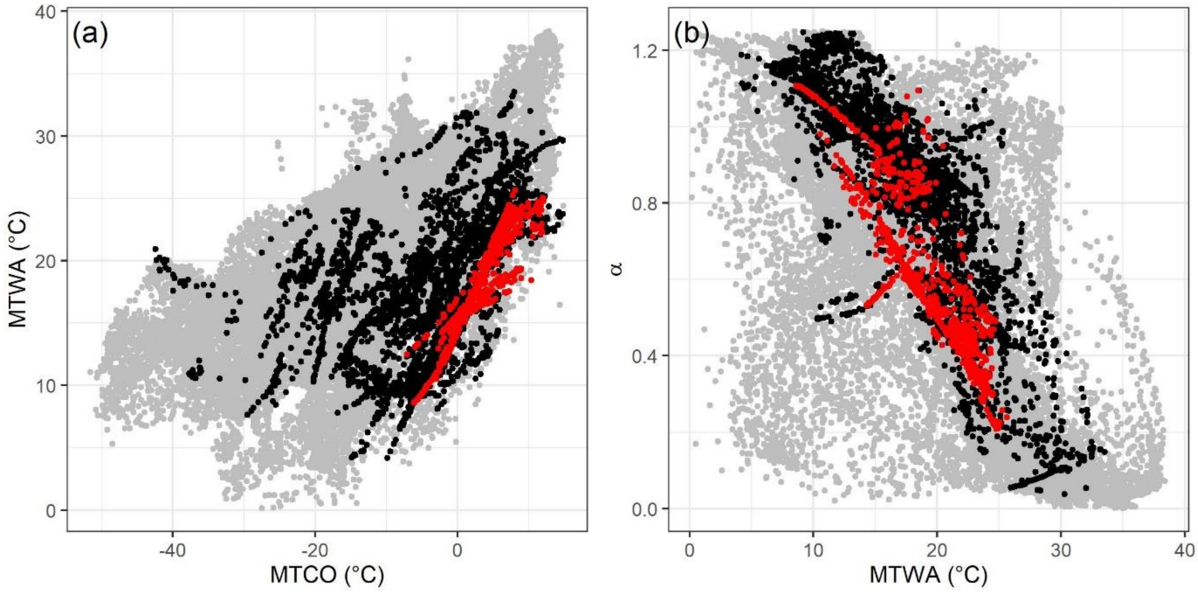

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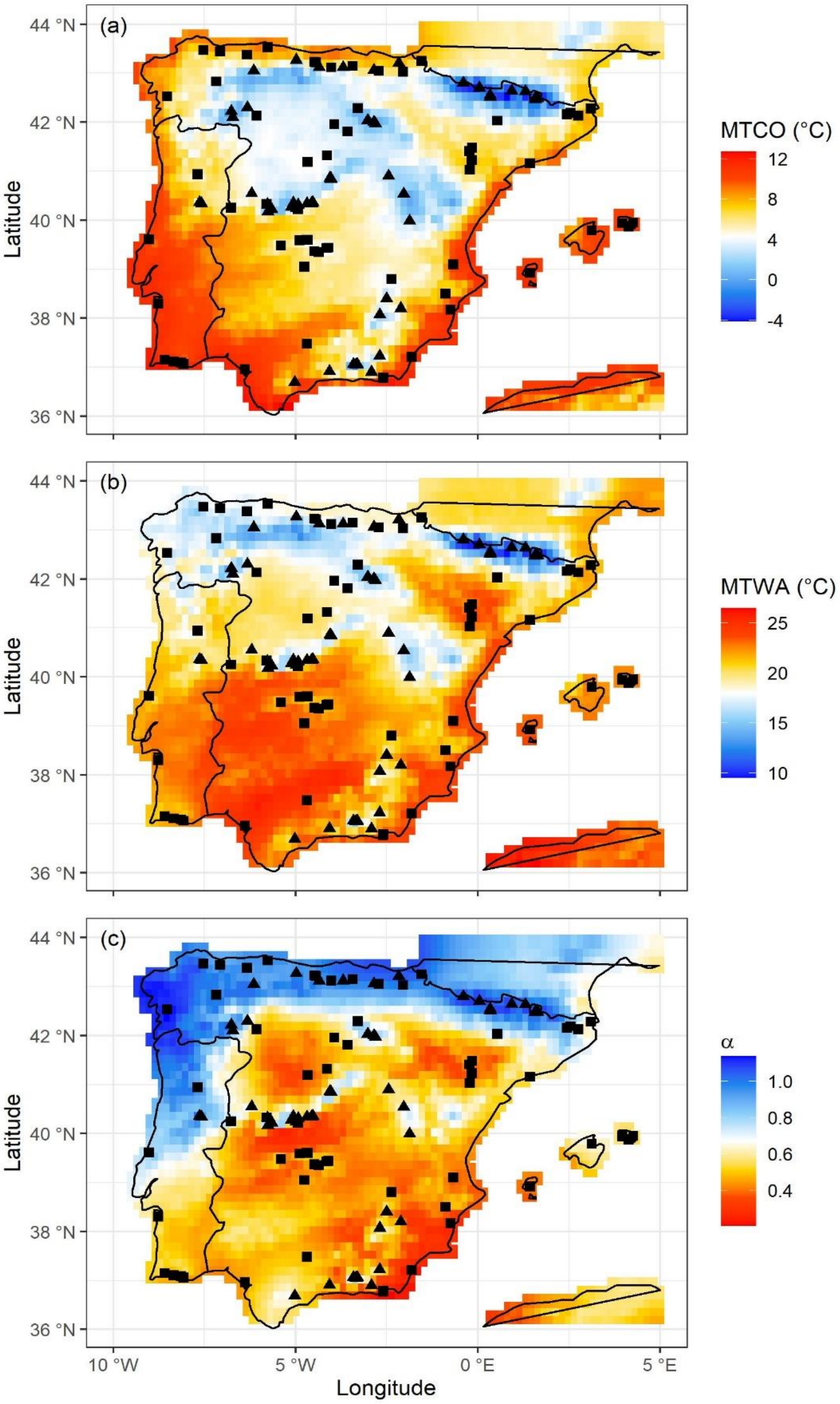
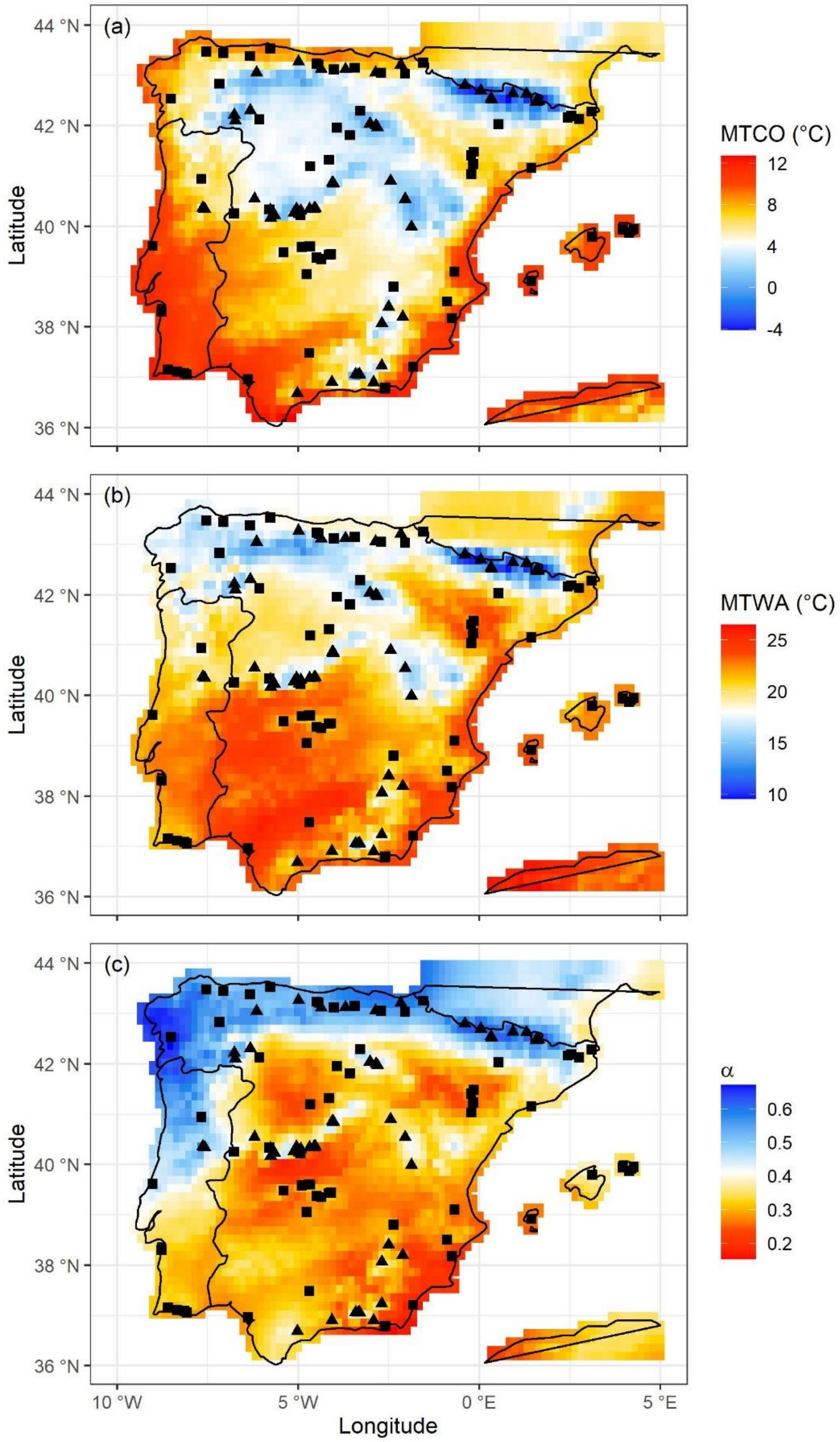

(a)
(b)
(c)
44 °N
42 °N
40 °N
38 °N
36 °N
Latitude
10 °W
5 °W
0 °E
5 °E
Longitude
MTCO (°C)
12
8
4
0
-4
MTWA (°C)
25
20
15
10
α
1.0
0.8
0.6
0.4

767


(a)
(b)
(c)
44 °N
42 °N
40 °N
38 °N
36 °N
Latitude
10 °W
5 °W
0 °E
5 °E
Longitude
MTCO (°C)
12
8
4
0
-4
MTWA (°C)
25
20
15
10
α
0.6
0.5
0.4
0.3
0.2

768

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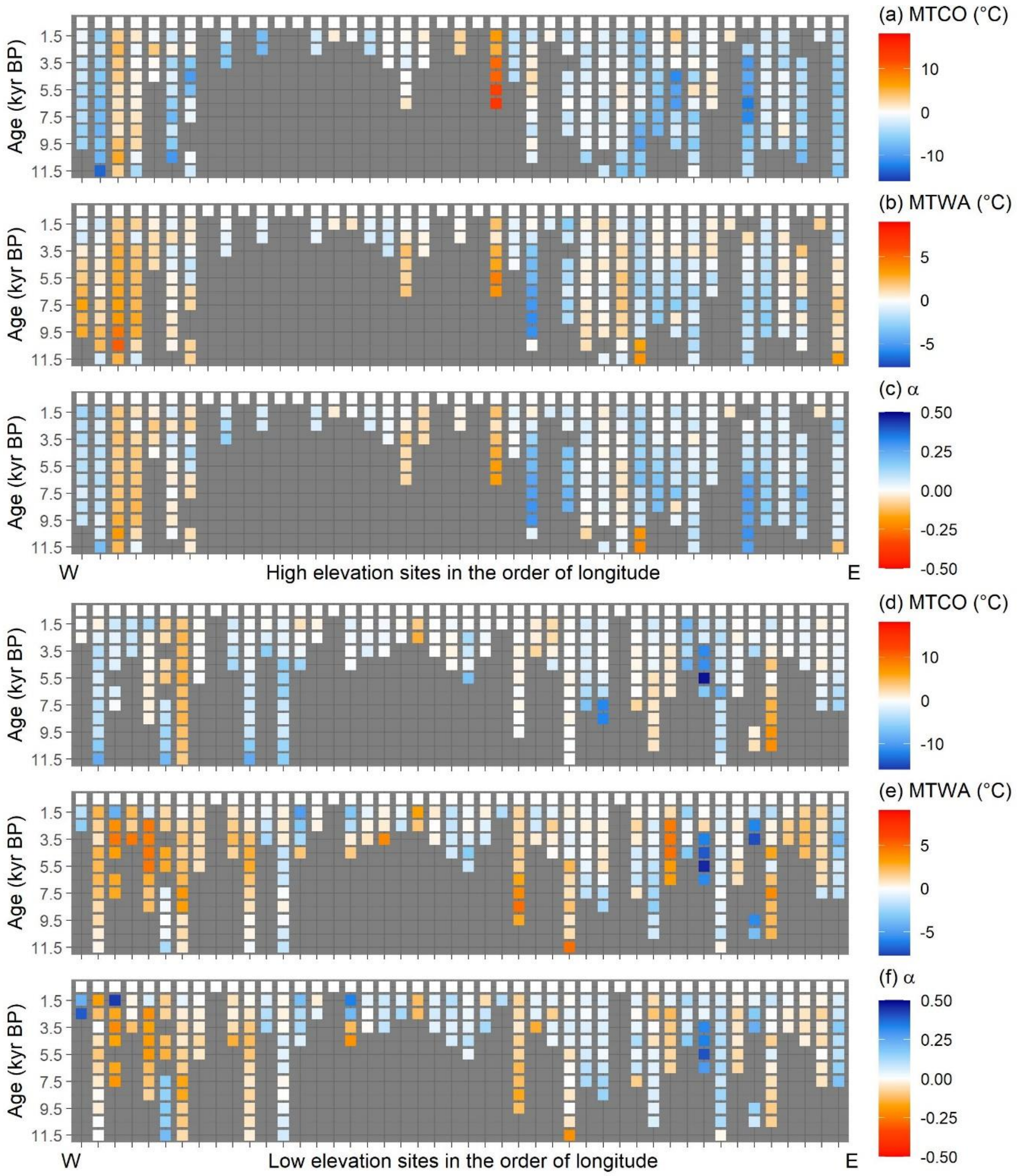
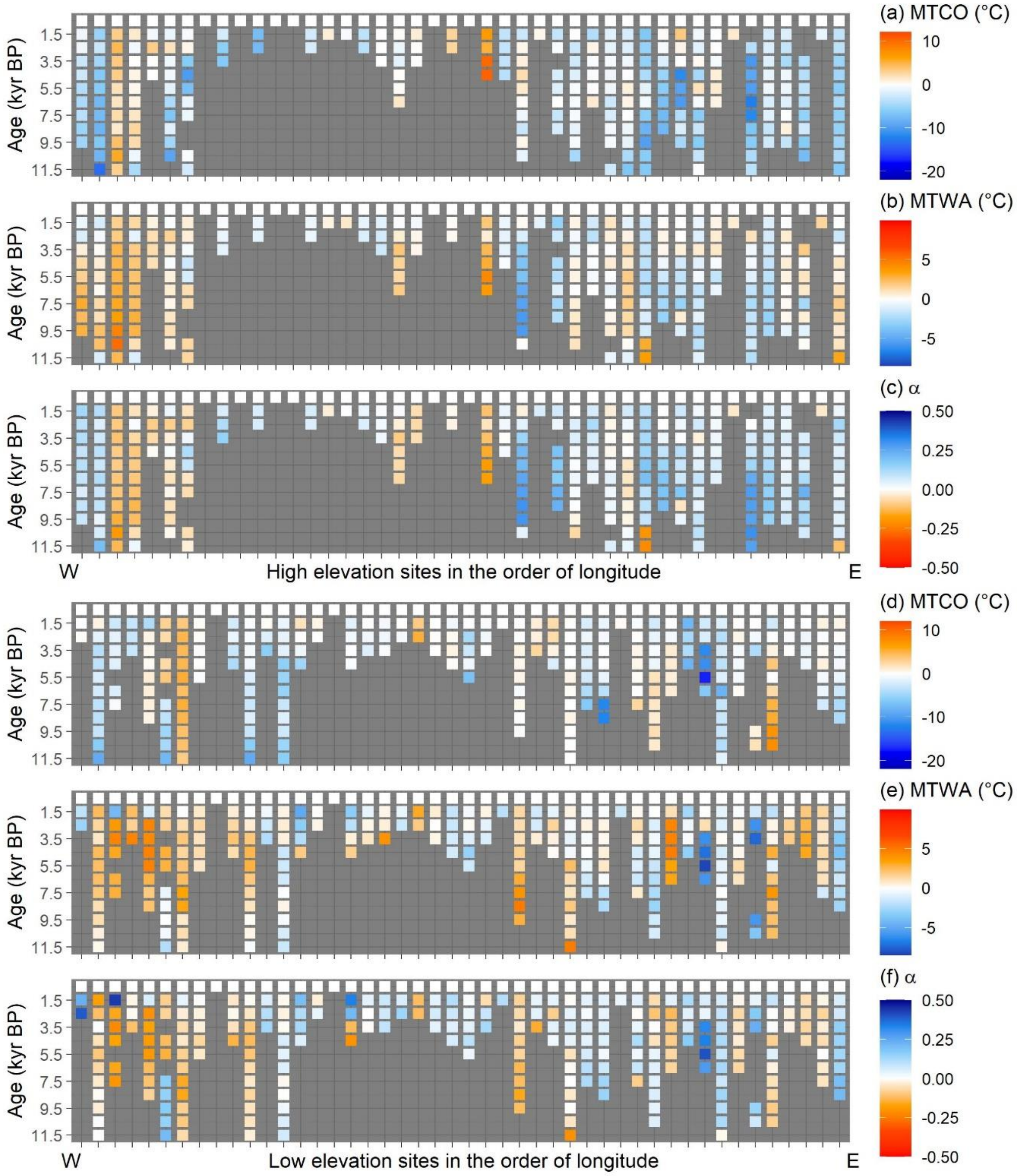
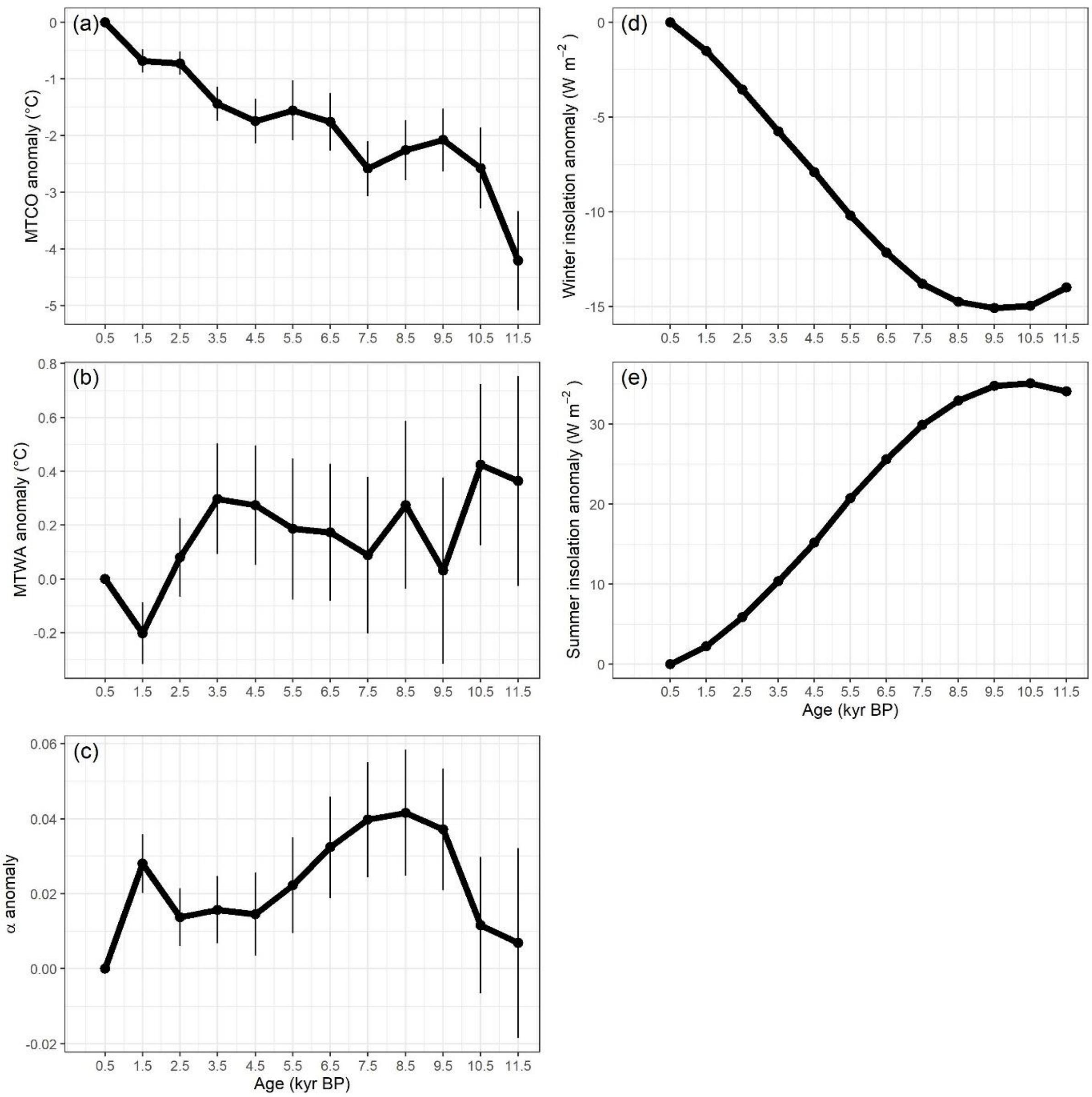

(a) MTCO (°C)
(b) MTWA (°C)
(c) α
(d) MTCO (°C)
(e) MTWA (°C)
(f) α
Age (kyr BP)
1.5
3.5
5.5
7.5
9.5
11.5
10
0
-10
5
-5
0.50
0.25
0.00
-0.25
-0.50
W
High elevation sites in the order of longitude
E
Low elevation sites in the order of longitude

778


(a) MTCO (°C)
10
0
-10
-20
(b) MTWA (°C)
5
0
-5
(c) α
0.50
0.25
0.00
-0.25
-0.50
Age (kyr BP)
1.5
3.5
5.5
7.5
9.5
11.5
W
High elevation sites in the order of longitude
E
(d) MTCO (°C)
(e) MTWA (°C)
(f) α
Low elevation sites in the order of longitude

779

Figure 4~~3~~. Reconstructed composite changes (anomalies to 0.5 ka) in (a) mean temperature of the coldest month (MTCO), (b) mean temperature of the warmest month (MTWA) and (c) plant-available moisture as represented by α, through the Holocene compared to changes in (d) winter and (e) summer insolation for the latitude of the Iberian Peninsula, using ± 500 years as the bin. The black lines show mean values across sites, with vertical line segments showing the standard deviations of mean values using 1000 bootstrap cycles of site resampling.


(a)
MTCO anomaly (°C)
0
-1
-2
-3
-4
-5
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
(b)
MTWA anomaly (°C)
0.8
0.6
0.4
0.2
0.0
-0.2
(c)
α anomaly
0.06
0.04
0.02
0.00
-0.02
Age (kyr BP)
(d)
Winter insolation anomaly (W m^{-2})
0
-5
-10
-15
(e)
Summer insolation anomaly (W m^{-2})
30
20
10
0
Age (kyr BP)

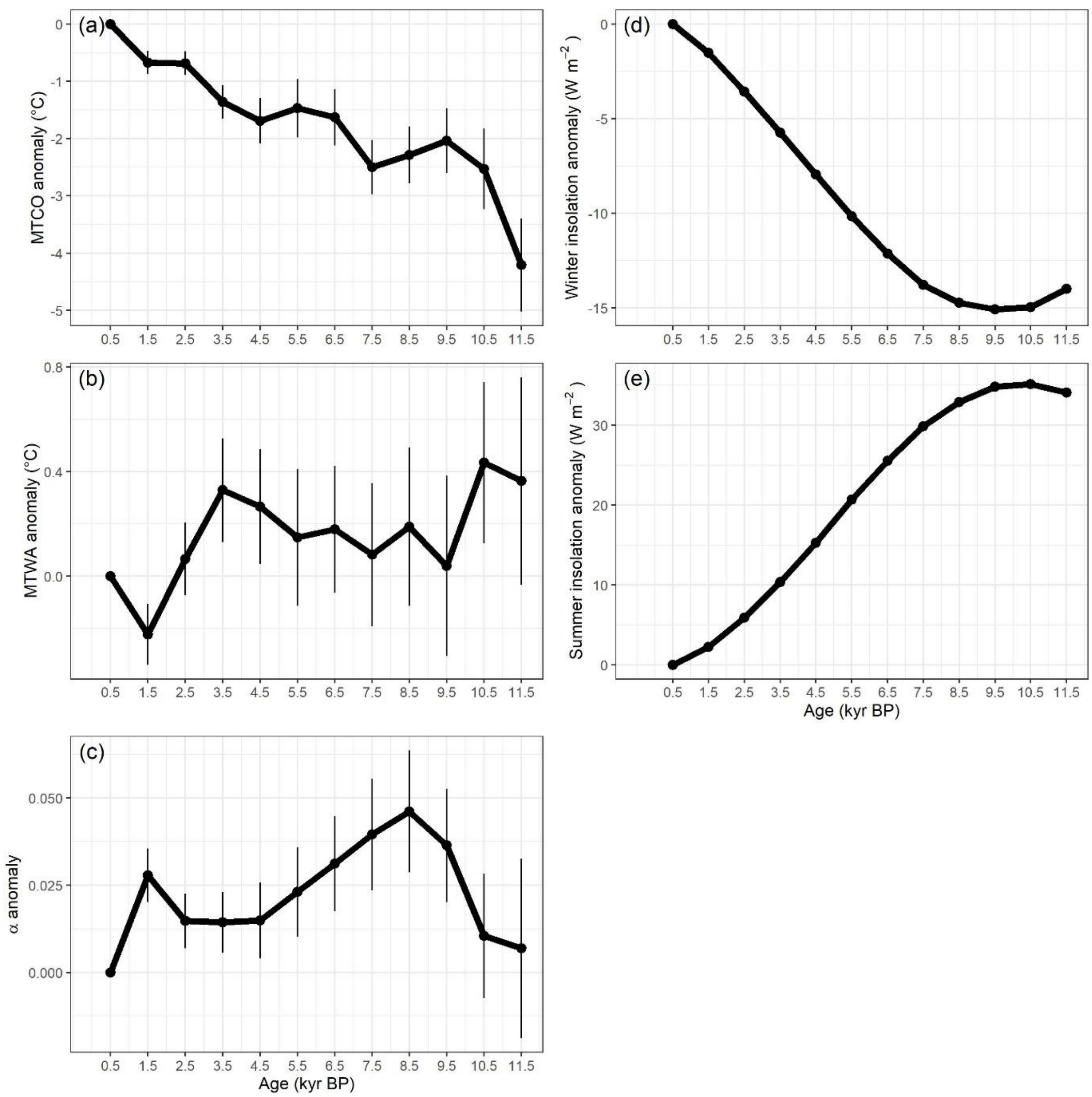
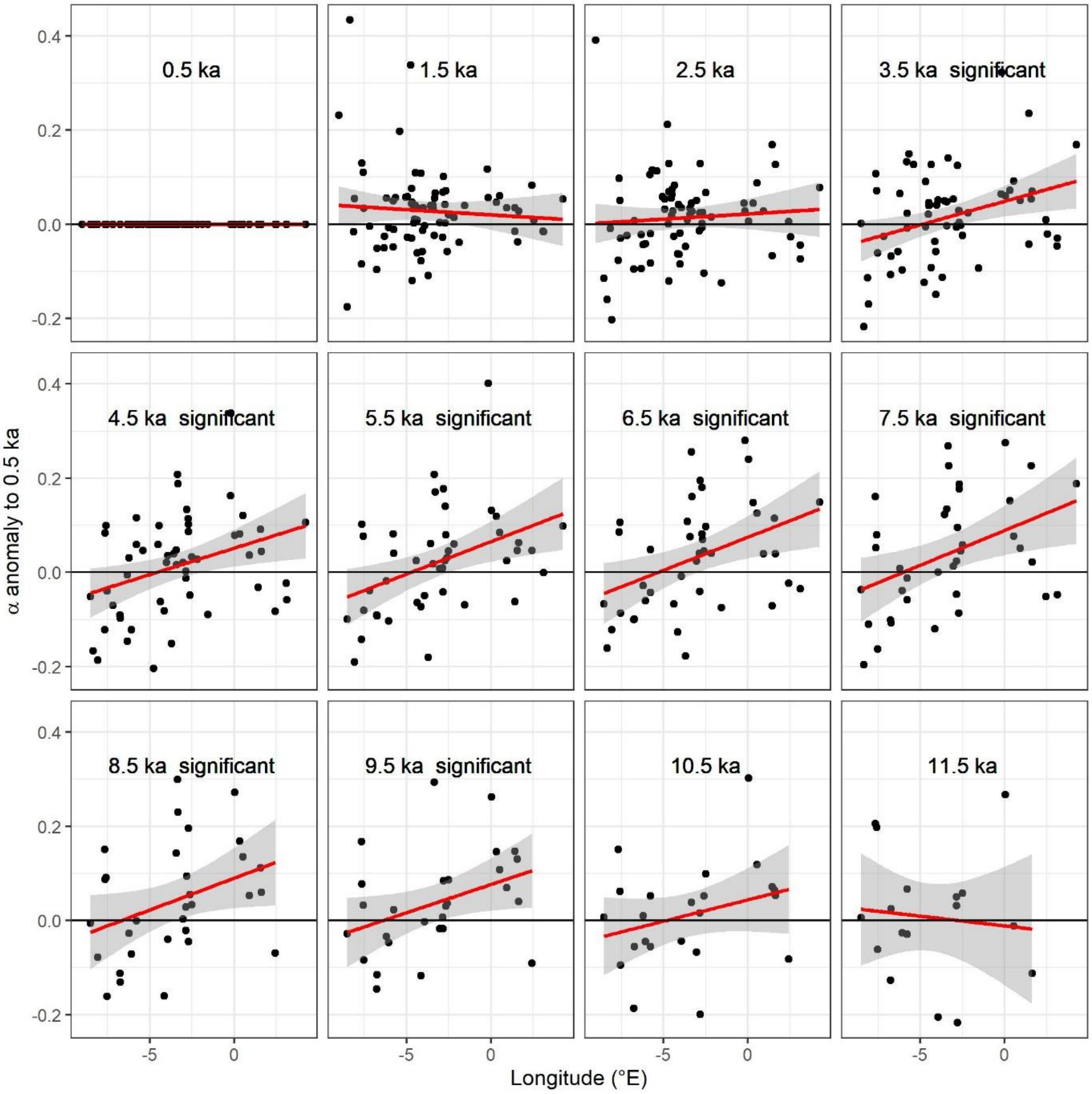
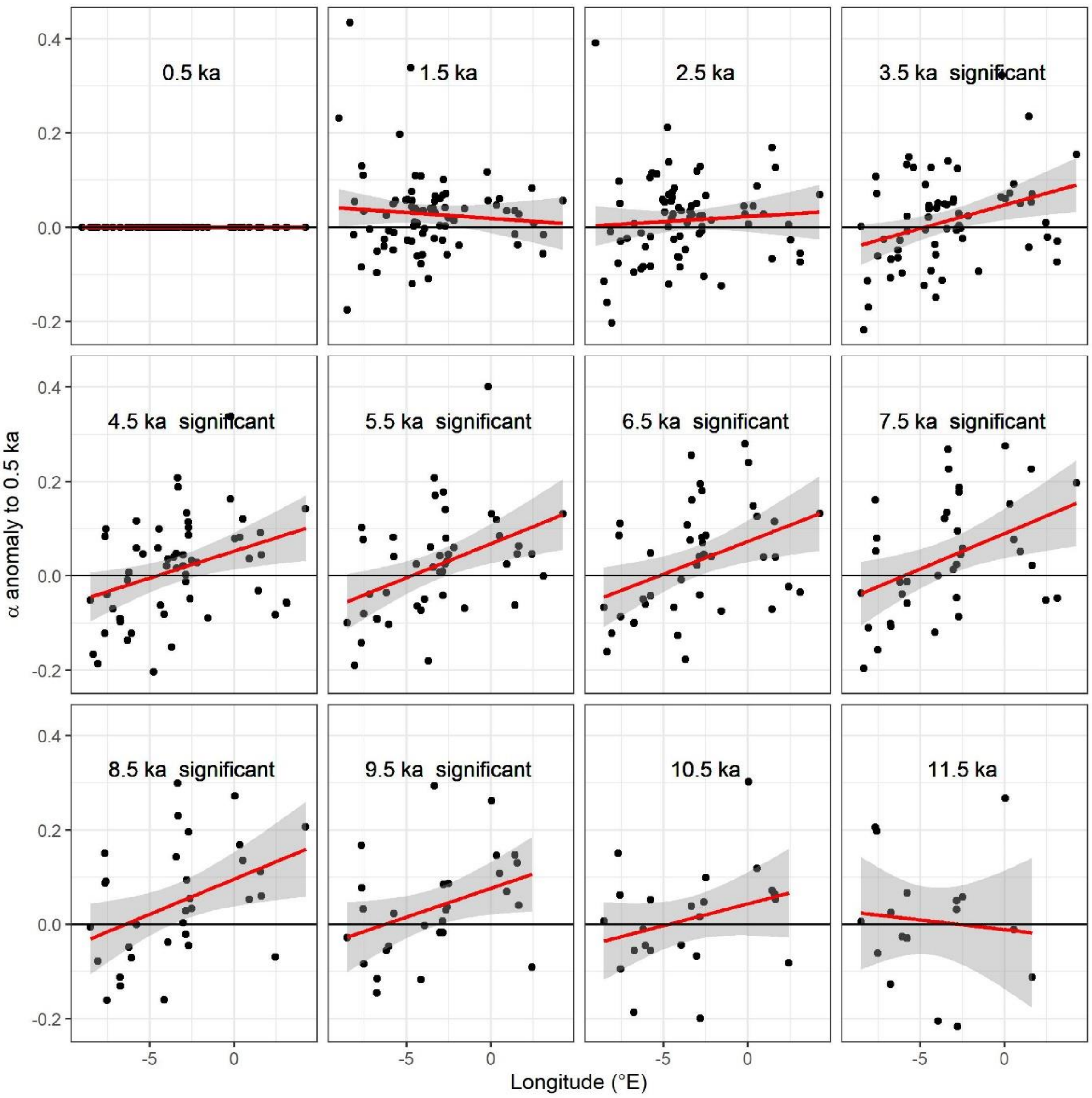

(a)
MTCO anomaly (°C)
0
-1
-2
-3
-4
-5
(b)
MTWA anomaly (°C)
0.8
0.4
0.0
(c)
α anomaly
0.050
0.025
0.000
0.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
Age (kyr BP)
(d)
Winter insolation anomaly (W m^{-2})
0
-5
-10
-15
(e)
Summer insolation anomaly (W m^{-2})
30
20
10
0
Age (kyr BP)

Figure 5~~4~~. Changes in the west-east gradient of plant-available moisture as represented by anomalies in α relative to 0.5 ka at individual sites through the Holocene. The red lines show the regression lines. The shades indicate the 95 % confidence intervals of the regression lines.


0.5 ka
1.5 ka
2.5 ka
3.5 ka significant
4.5 ka significant
5.5 ka significant
6.5 ka significant
7.5 ka significant
8.5 ka significant
9.5 ka significant
10.5 ka
11.5 ka
α anomaly to 0.5 ka
0.4
0.2
0.0
-0.2
Longitude (°E)
-5
0


0.5 ka
1.5 ka
2.5 ka
3.5 ka significant
4.5 ka significant
5.5 ka significant
6.5 ka significant
7.5 ka significant
8.5 ka significant
9.5 ka significant
10.5 ka
11.5 ka
α anomaly to 0.5 ka
Longitude (°E)
0.4
0.2
0.0
-0.2
-5
0

795

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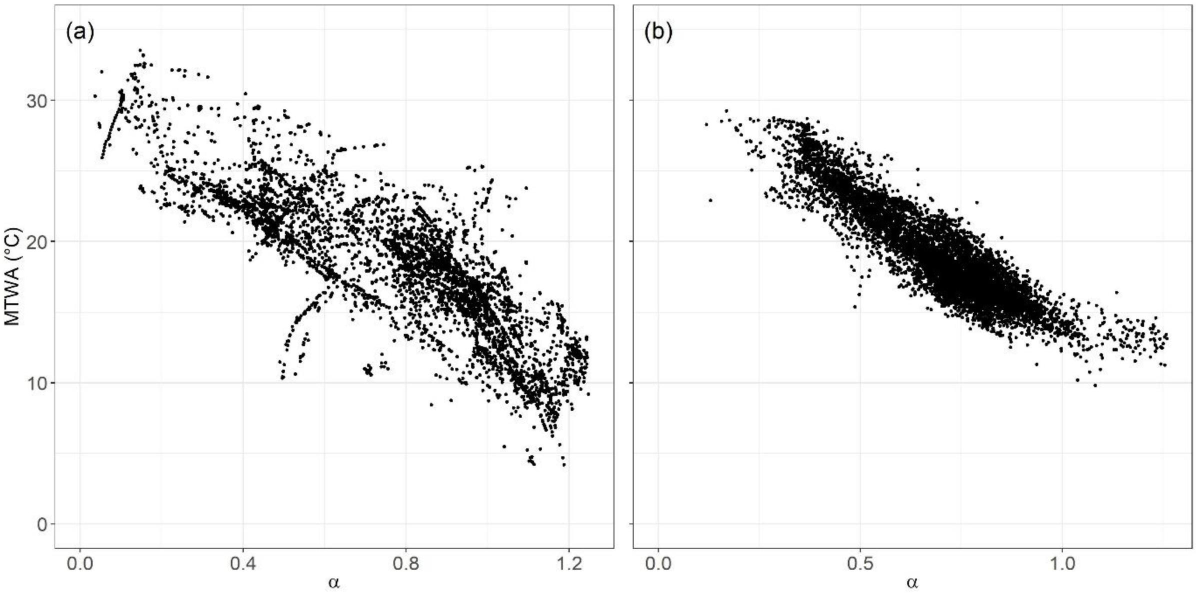

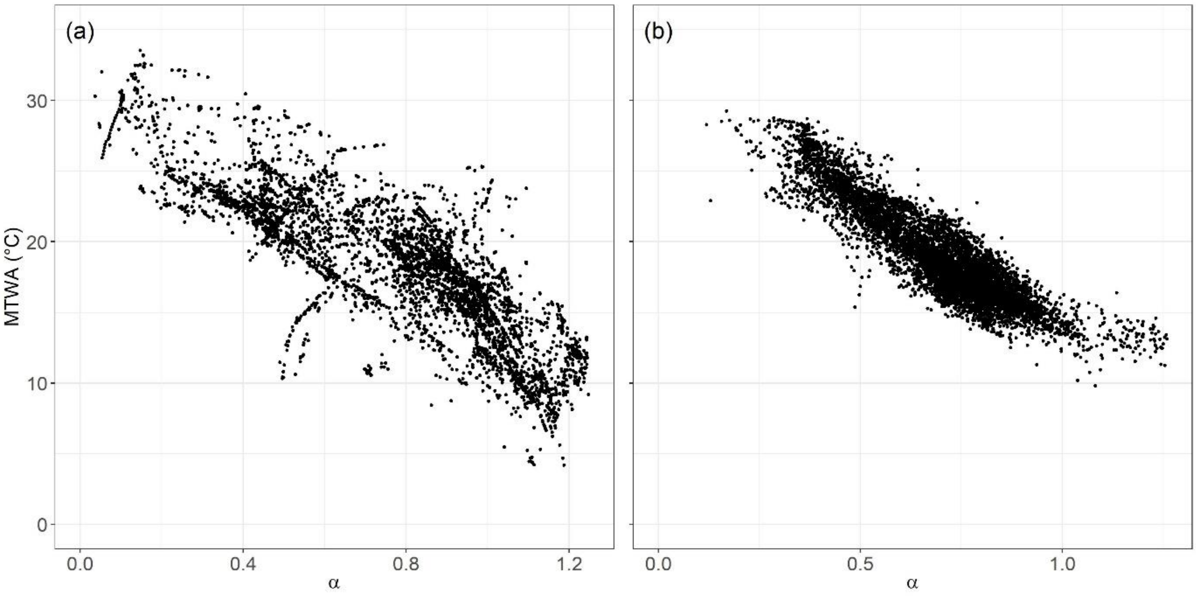

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	ncomp	R^2	avg. bias	max. bias	min. bias	RMSEP	ΔRMSEP	*p*	b_1	$b_1.se$
MTCO	1	0.70	−0.86	25.23	0.00	5.20	−39.97	0.001	0.89	0.01
	2	0.73	−0.73	25.00	0.00	4.87	−6.29	0.001	0.91	0.01
	3	0.74	−0.71	24.38	0.00	4.86	−0.32	0.001	0.91	0.01
	4	**0.75**	**−0.59**	**24.27**	**0.00**	**4.70**	**−3.26**	**0.001**	**0.91**	**0.01**
	5	0.74	−0.63	34.54	0.00	4.77	1.51	1.000	0.91	0.01
MTWA	1	0.52	−0.29	17.13	0.00	3.72	−26.88	0.001	0.69	0.01
	2	0.56	−0.14	17.20	0.00	3.53	−5.06	0.001	0.71	0.01
	3	0.56	−0.13	17.01	0.00	3.53	−0.20	0.008	0.71	0.01
	4	**0.57**	**−0.11**	**17.30**	**0.00**	**3.47**	**−1.56**	**0.001**	**0.71**	**0.01**
	5	0.57	−0.11	17.34	0.00	3.48	0.10	0.780	0.71	0.01
α	1	0.65	−0.014	0.787	0.000	0.165	−39.59	0.001	0.76	0.01
	2	0.68	−0.016	0.781	0.000	0.159	−3.55	0.001	0.77	0.01
	3	**0.68**	**−0.017**	**0.757**	**0.000**	**0.158**	**−0.61**	**0.023**	**0.78**	**0.01**
	4	0.69	−0.017	0.784	0.000	0.158	−0.43	0.108	0.79	0.01
	5	0.69	−0.017	0.850	0.000	0.158	0.26	0.985	0.80	0.01

Table 2. Canonical Correspondence Analysis (CCA) result of modern and fossil-reconstructed MTCO, MTWA and α. The summary statistics for the ANOVA-like permutation test (999 permutations) are also shown. VIF is the variance inflation factor, Df is the number of degrees of freedom, χ^2 ~~-~~is the constrained eigenvalue (or the sum of constrained eigenvalues for the whole model)~~-~~, F is significance, and Pr (>F) is the probability.

	Axes	**Axis 1**	**Axis 2**	**Axis 3**	**VIF**
Modern	Constrained eigenvalues	0.3819	0.1623	0.1087	/
	Correlations of the environmental variables with the axes:				
	MTCO	−0.815	0.579	0.012	1.31
	MTWA	−0.700	−0.203	0.685	3.34
	α	0.883	0.430	−0.187	3.39
		Df	**χ^2**	**F**	**Pr (>F)**
	Whole model	3	0.6530	78.113	0.001
	MTCO	1	0.3082	110.597	0.001
	MTWA	1	0.1602	57.489	0.001
	α	1	0.1846	66.252	0.001
	CCA 1	1	0.3819	137.076	0.001
	CCA 2	1	0.1623	58.252	0.001
	CCA 3	1	0.1087	39.011	0.001
Fossil-reconstructed	**Axes**	**Axis 1**	**Axis 2**	**Axis 3**	**VIF**
	Constrained eigenvalues	0.3601 ~~0.3594~~	0.2266 ~~0.2270~~	0.2037 ~~0.2043~~	/
	Correlations of the environmental variables with the axes:				
	MTCO	0.430 ~~0.417~~	0.776 ~~0.767~~	0.462~~0.488~~	1.34 ~~1.33~~
	MTWA	0.987 ~~0.987~~	0.141 ~~0.146~~	−0.076 ~~−0.068~~	5.40 ~~5.31~~
	α	−0.947~~−0.945~~	0.088 ~~0.095~~	−0.308~~−0.311~~	5.28~~5.19~~
		Df	**χ^2**	**F**	**Pr (>F)**
	Whole model	3	0.7905 ~~0.7906~~	226.98~~225.12~~	0.001
	MTCO	1	0.2465 ~~0.2446~~	212.34~~208.91~~	0.001
	MTWA	1	0.3298~~0.3309~~	284.07~~282.65~~	0.001
	α	1	0.2142~~0.2152~~	184.53~~183.79~~	0.001
	CCA 1	1	0.3601~~0.3594~~	310.19~~307.00~~	0.001
	CCA 2	1	0.2266 ~~0.2270~~	195.24~~193.88~~	0.001
	CCA 3	1	0.2037~~0.2043~~	175.51~~174.48~~	0.001

Table 3. Assessment of the significance of anomalies to 0.5 ka through time with latitude and elevation. The slope is obtained by linear regression of the anomaly onto the longitude or elevation. p is the significance of the slope (bold parts: $p < 0.05$). x_0 is the point where the anomaly is 0 in the linear equation, which indicates longitude or elevation where the anomaly changes sign.

		Longitude (°E)			Elevation (km)		
	age (ka)	slope	p	x_0	slope	p	x_0
MTCO (°C)	0.5	0.00~~0.00~~	/~~/~~	/~~/~~	0.00~~0.00~~	/~~/~~	/~~/~~
	1.5	−0.07~~−0.07~~	0.411~~0.453~~	−13.02~~−13.80~~	−0.30~~−0.39~~	0.411~~0.285~~	−1.21~~−0.71~~
	2.5	−0.15~~−0.14~~	0.095~~0.113~~	−8.56~~−8.52~~	−0.52~~−0.52~~	0.179~~0.170~~	−0.40~~−0.29~~
	3.5	−0.13~~−0.14~~	0.314~~0.253~~	−14.83~~−13.06~~	−0.81~~−0.79~~	0.142~~0.147~~	−0.77~~−0.72~~
	4.5	−0.12~~−0.12~~	0.444~~0.445~~	−17.28~~−16.97~~	−0.69~~−0.69~~	0.319~~0.315~~	−1.46~~−1.37~~
	5.5	−0.24~~−0.24~~	0.247~~0.260~~	−9.49~~−9.37~~	−0.61~~−0.63~~	0.503~~0.477~~	−1.43~~−1.17~~
	6.5	−0.18~~−0.17~~	0.372~~0.405~~	−12.74~~−12.79~~	−0.87~~−0.88~~	0.293~~0.281~~	−0.88~~−0.71~~
	7.5	−0.15~~−0.16~~	0.421~~0.391~~	−20.39~~−18.89~~	−1.38~~−1.43~~	0.080~~0.067~~	−0.67~~−0.55~~
	8.5	−0.03~~−0.08~~	0.890~~0.703~~	−77.87~~−33.59~~	−1.58~~−1.34~~	0.065~~0.101~~	−0.10~~−0.42~~
	9.5	0.01~~0.00~~	0.954~~0.992~~	156.31~~937.82~~	−1.79~~−1.81~~	0.060~~0.056~~	0.11~~0.14~~
	10.5	0.20~~0.19~~	0.474~~0.493~~	9.25~~9.85~~	−1.38~~−1.38~~	0.241~~0.232~~	−0.64~~−0.62~~
	11.5	0.23~~0.23~~	0.528~~0.528~~	13.77~~13.77~~	0.12~~0.12~~	0.947~~0.947~~	36.35~~36.35~~
MTWA (°C)	0.5	0.00~~0.00~~	/~~/~~	/~~/~~	0.00~~0.00~~	/~~/~~	/~~/~~
	1.5	−0.01~~0.00~~	0.862~~0.928~~	−26.38~~−51.95~~	−0.05~~−0.04~~	0.830~~0.859~~	−3.35~~−4.94~~
	2.5	−0.09~~−0.09~~	0.137~~0.164~~	−2.80~~−2.90~~	−0.45~~−0.48~~	0.092~~0.069~~	1.19~~1.15~~
	3.5	**−0.23~~−0.22~~**	**0.005~~0.007~~**	**−2.03~~−1.84~~**	−0.40~~−0.44~~	0.284~~0.236~~	1.74~~1.76~~
	4.5	**−0.21~~−0.22~~**	**0.016~~0.014~~**	**−2.01~~−2.08~~**	−0.58~~−0.57~~	0.126~~0.140~~	1.55~~1.56~~
	5.5	**−0.26~~−0.29~~**	**0.011~~0.005~~**	**−2.43~~−2.62~~**	−0.49~~−0.43~~	0.280~~0.340~~	1.53~~1.49~~
	6.5	**−0.24~~−0.24~~**	**0.017~~0.015~~**	**−2.30~~−2.28~~**	−0.62~~−0.61~~	0.137~~0.134~~	1.41~~1.43~~
	7.5	**−0.26~~−0.27~~**	**0.012~~0.010~~**	**−3.02~~−3.05~~**	**−1.05~~−1.03~~**	**0.019~~0.021~~**	**1.28~~1.28~~**
	8.5	−0.24~~−0.26~~	0.061~~0.024~~	−2.43~~−2.62~~	**−1.15~~−0.87~~**	**0.023~~0.079~~**	**1.57~~1.51~~**
	9.5	**−0.32~~−0.32~~**	**0.013~~0.012~~**	**−3.20~~−3.17~~**	−0.44~~−0.44~~	0.459~~0.457~~	1.34~~1.36~~
	10.5	−0.18~~−0.18~~	0.115~~0.110~~	−1.23~~−1.21~~	0.54~~0.54~~	0.276~~0.278~~	0.44~~0.42~~

	11.5	0.13~~0.13~~	0.453~~0.453~~	−7.25~~−7.25~~	0.37~~0.37~~	0.663~~0.663~~	0.22~~0.22~~
α	0.5	0.00~~0.00~~	/~~/~~	/~~/~~	0.00~~0.00~~	/~~/~~	/~~/~~
	1.5	0.00~~0.00~~	0.508~~0.453~~	8.99~~7.55~~	−0.01~~−0.01~~	0.393~~0.438~~	3.40~~3.67~~
	2.5	0.00~~0.00~~	0.517~~0.526~~	−9.89~~−10.41~~	0.02~~0.02~~	0.249~~0.211~~	0.19~~0.21~~
	3.5	**0.01~~0.01~~**	**0.006~~0.006~~**	**−4.91~~−4.78~~**	0.02~~0.02~~	0.191~~0.161~~	0.28~~0.38~~
	4.5	**0.01~~0.01~~**	**0.010~~0.009~~**	**−4.60~~−4.60~~**	**0.05~~0.05~~**	**0.008~~0.008~~**	**0.79~~0.79~~**
	5.5	**0.01~~0.01~~**	**0.005~~0.003~~**	**−4.75~~−4.73~~**	**0.05~~0.05~~**	**0.027~~0.031~~**	**0.67~~0.65~~**
	6.5	**0.01~~0.01~~**	**0.007~~0.007~~**	**−5.34~~−5.28~~**	**0.06~~0.06~~**	**0.004~~0.003~~**	**0.60~~0.64~~**
	7.5	**0.02~~0.02~~**	**0.009~~0.008~~**	**−6.05~~−5.99~~**	**0.09~~0.09~~**	**0.000~~0.000~~**	**0.75~~0.75~~**
	8.5	**0.01~~0.02~~**	**0.049~~0.018~~**	**−6.67~~−6.45~~**	**0.09~~0.08~~**	**0.000~~0.00~~4**	**0.88~~0.68~~**
	9.5	**0.01~~0.01~~**	**0.048~~0.046~~**	**−6.40~~−6.29~~**	**0.07~~0.07~~**	**0.012~~0.012~~**	**0.70~~0.72~~**
	10.5	0.01~~0.01~~	0.183~~0.173~~	−4.85~~−4.70~~	0.02~~0.02~~	0.535~~0.523~~	0.59~~0.67~~
	11.5	0.00~~0.00~~	0.713~~0.713~~	−2.76~~−2.76~~	0.03~~0.03~~	0.654~~0.654~~	0.93~~0.93~~

Appendix A

Theoretical basis:

The previous version of fxTWA-PLS (fxTWA-PLS1):

The estimated optimum ($\hat{u}_k$) and unbiased tolerance ($\hat{t}_k$) of each taxon are calculated from the modern training data set as follows:

$$\hat{u}_k = \frac{\sum_{i=1}^{n} y_{ik} x_i}{\sum_{i=1}^{n} y_{ik}} \tag{A1}$$

$$\hat{t}_k = \sqrt{\frac{\sum_{i=1}^{n} y_{ik} (x_i - \hat{u}_k)^2}{(1 - 1/N_{2k})\ \sum_{i=1}^{n} y_{ik}}} \tag{A2}$$

where

$$N_{2k} = \frac{1}{\sum_{i=1}^{n} \left(\frac{y_{ik}}{\sum_{i'=1}^{n} y_{i'k}} \right)^2} \tag{A3}$$

where *n* is the total number of sites; y_{ik} is the observed abundance of the k^{th} taxon at the i^{th} site; x_i is the observed climate value at the i^{th} site; N_{2k} is the effective number of occurrences for the k^{th} taxon.

fx correction is applied as weight in the form of $1/fx^2$ at regression at step 7 in Table 1 in Liu et al. (2020). The regression step uses robust linear model fitting by the R code:

$$rlm\left(x_i \sim comp_1 + comp_2 + \cdots + comp_{pls}, weights = {}^{1}\!/_{fx^2}\right) \tag{A4}$$

The modified version of fxTWA-PLS (fxTWA-PLS2):

The distribution of y_{ik} is influenced by the distribution of the climate variable, so we need to apply the fx correction when calculating optimum and tolerance for each taxon as follows:

$$\hat{u}_k = \frac{\sum_{i=1}^{n} \frac{y_{ik} x_i}{f_{x_i}}}{\sum_{i=1}^{n} \frac{y_{ik}}{f_{x_i}}} \tag{A5}$$

$$\hat{t}_k = \sqrt{\frac{\sum_{i=1}^{n} \frac{y_{ik} (x_i - \hat{u}_k)^2}{f_{x_i}}}{\left(1 - \frac{1}{N_{2k}}\right) \sum_{i=1}^{n} \frac{y_{ik}}{f_{x_i}}}} \tag{A6}$$

where

$$N_{2k} = \frac{1}{\sum_{i=1}^{n} \left(\frac{\frac{y_{ik}}{f_{x_i}}}{\sum_{i'=1}^{n} \frac{y_{i'k}}{f_{x_{i'}}}} \right)^2} \tag{A7}$$

The modified version of fxTWA-PLS applies fx correction separately at taxon calculation and regression (step 2 and 7 in Table 1 in Liu et al., 2020), both using weight in the form of 1/fx. The regression step (step 7) then becomes:

$$rlm\left(x_i{\sim}comp_1 + comp_2 + \cdots + comp_{pls}, weights = {}^{1}\!/_{fx}\right) \tag{A8}$$

The previous version uses fx values extracted from histograms, and different bin widths may result in different training results. The modified version applies P-splines histogram smoothing (Eilers and Marx, 2021) with third order difference penalty, which makes the fx values almost independent on the bin width. The optimal smoothing parameter of the P-spline penalty was determined by the HFS (Harville-Fellner-Schall) algorithm (Eilers and Marx, 2021) for the Poisson likelihood for the histogram counts.

Table A1. Leave-out cross-validation (with geographically and climatically close sites removed) fitness of the previous and modified version of fxTWA-PLS (fxTWA-PLS1 and fxTWA-PLS2, respectively), for mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and plant-available moisture (α), using bins of 0.02, 0.02 and 0.002, respectively. n is the number of components used. RMSEP is the root mean square error of prediction. ΔRMSEP is the per cent change of RMSEP using the current number of components than using one component less. *p* assesses whether using the current number of components is significantly different from using one component less, which is used to choose the last significant number of components (indicated in bold) to avoid overfitting. The degree of overall compression is assessed by doing linear regression to the cross-validation result and the climate variable. b1, b1.se are the slope and the standard error of the slope, respectively. The closer the slope (b1) is to 1, the lower the overall compression is. fx correction is set intrinsic in functions in `fxTWAPLS` package for both versions in this paper, instead of relying on an outside input in Liu et al. (2020), so the values of fxTWA-PLS1 might be slighted different from values in Table 2 in Liu et al. (2020), but it doesn't affect the conclusion.

	Method	n	R^2	avg. bias	max. bias	min. bias	RMSEP	ΔRMSEP	*p*	b1	b1.se
MTCO	fxTWA-PLS1	1	0.66	−0.86	31.17	0.00	5.21	−39.87	0.001	0.76	0.01
		2	0.72	−0.52	36.65	0.00	4.70	−9.78	0.001	0.80	0.01
		3	0.73	−0.47	41.18	0.00	4.62	−1.63	0.001	0.82	0.01
		4	**0.73**	**−0.51**	**44.86**	**0.00**	**4.58**	**−1.01**	**0.006**	**0.82**	**0.01**
		5	0.73	−0.41	58.35	0.00	4.62	0.89	0.708	0.83	0.01
	fxTWA-PLS2	1	0.70	−0.86	25.23	0.00	5.20	−39.97	0.001	0.89	0.01
		2	0.73	−0.73	25.00	0.00	4.87	−6.29	0.001	0.91	0.01
		3	0.74	−0.71	24.38	0.00	4.86	−0.32	0.001	0.91	0.01
		4	**0.75**	**−0.59**	**24.27**	**0.00**	**4.70**	**−3.26**	**0.001**	**0.91**	**0.01**
		5	0.74	−0.63	34.54	0.00	4.77	1.51	1.000	0.91	0.01
MTWA	fxTWA-PLS1	1	0.50	−0.53	17.91	0.00	3.87	−24.09	0.001	0.67	0.01
		2	**0.56**	**−0.54**	**17.71**	**0.00**	**3.52**	**−8.98**	**0.001**	**0.69**	**0.01**
		3	0.57	−0.49	25.14	0.00	3.52	0.09	0.565	0.73	0.01
		4	0.57	−0.43	34.92	0.00	3.56	1.12	0.974	0.75	0.01
		5	0.57	−0.46	32.23	0.00	3.55	−0.23	0.139	0.74	0.01
	fxTWA-PLS2	1	0.52	−0.29	17.13	0.00	3.72	−26.88	0.001	0.69	0.01
		2	0.56	−0.14	17.20	0.00	3.53	−5.06	0.001	0.71	0.01
		3	0.56	−0.13	17.01	0.00	3.53	−0.20	0.008	0.71	0.01
		4	**0.57**	**−0.11**	**17.30**	**0.00**	**3.47**	**−1.56**	**0.001**	**0.71**	**0.01**
		5	0.57	−0.11	17.34	0.00	3.48	0.10	0.780	0.71	0.01
α	fxTWA-PLS1	1	0.63	−0.020	0.773	0.000	0.174	−36.23	0.001	0.78	0.01
		2	0.69	−0.012	0.902	0.000	0.157	−9.66	0.001	0.79	0.01
		3	**0.69**	**−0.011**	**0.820**	**0.000**	**0.155**	**−1.28**	**0.001**	**0.79**	**0.01**
		4	0.70	−0.010	0.786	0.000	0.156	0.25	0.867	0.81	0.01
		5	0.70	−0.010	0.786	0.000	0.156	0.09	1.000	0.81	0.01
	fxTWA-PLS2	1	0.65	−0.014	0.787	0.000	0.165	−39.59	0.001	0.76	0.01
		2	0.68	−0.016	0.781	0.000	0.159	−3.55	0.001	0.77	0.01
		3	**0.68**	**−0.017**	**0.757**	**0.000**	**0.158**	**−0.61**	**0.023**	**0.78**	**0.01**
		4	0.69	−0.017	0.784	0.000	0.158	−0.43	0.108	0.79	0.01
		5	0.69	−0.017	0.850	0.000	0.158	0.26	0.985	0.80	0.01

Figure A1. Training results using the last significant number of components. The left panel shows the previous version (fxTWA-PLS1) and the right panel shows the modified version of fxTWA-PLS (fxTWA-PLS2). The 1: 1 line is shown in black; the linear regression line is shown in red, to show the degree of overall compression. The horizontal dashed lines indicate the natural limit of α (0~1.26).

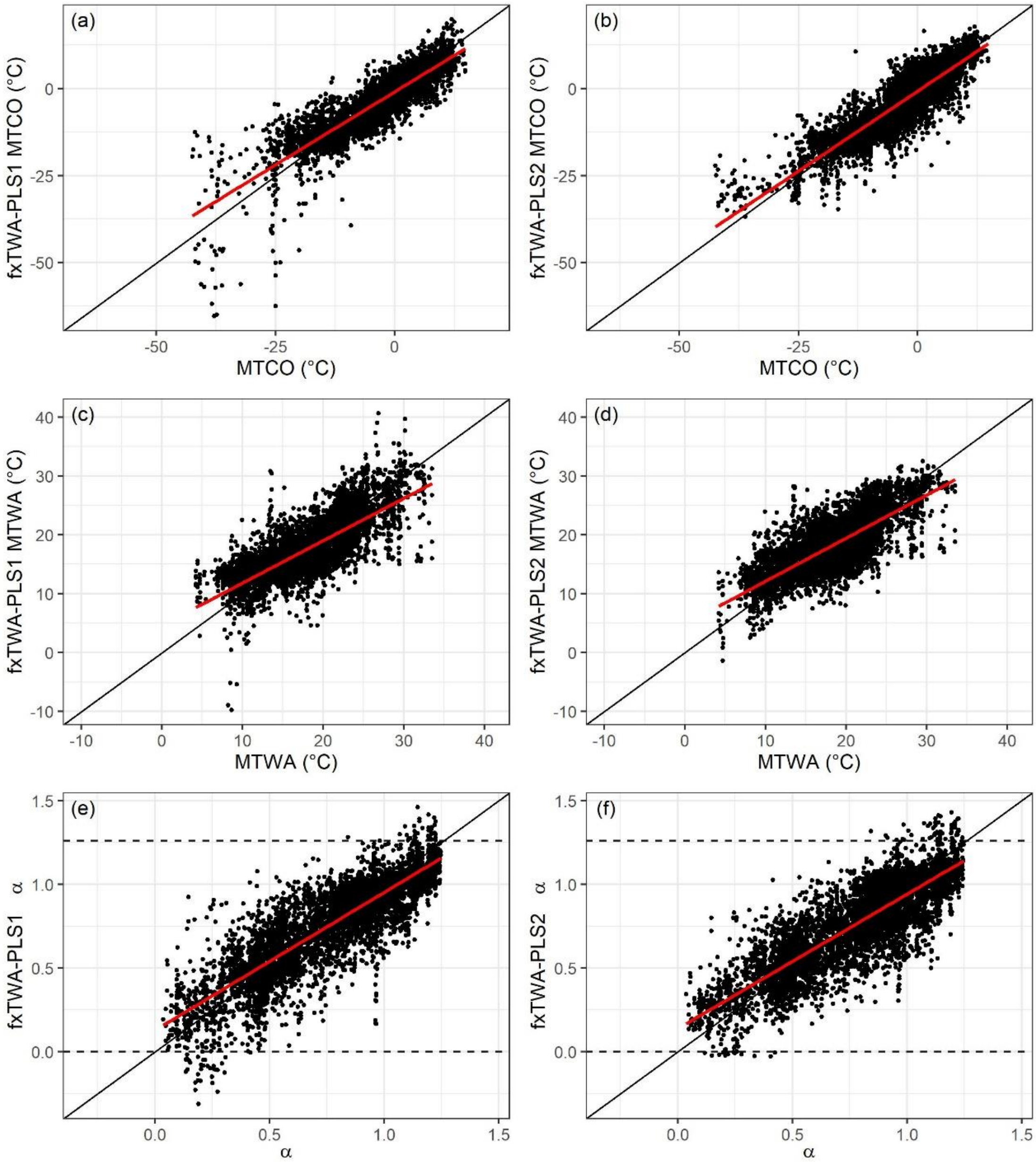
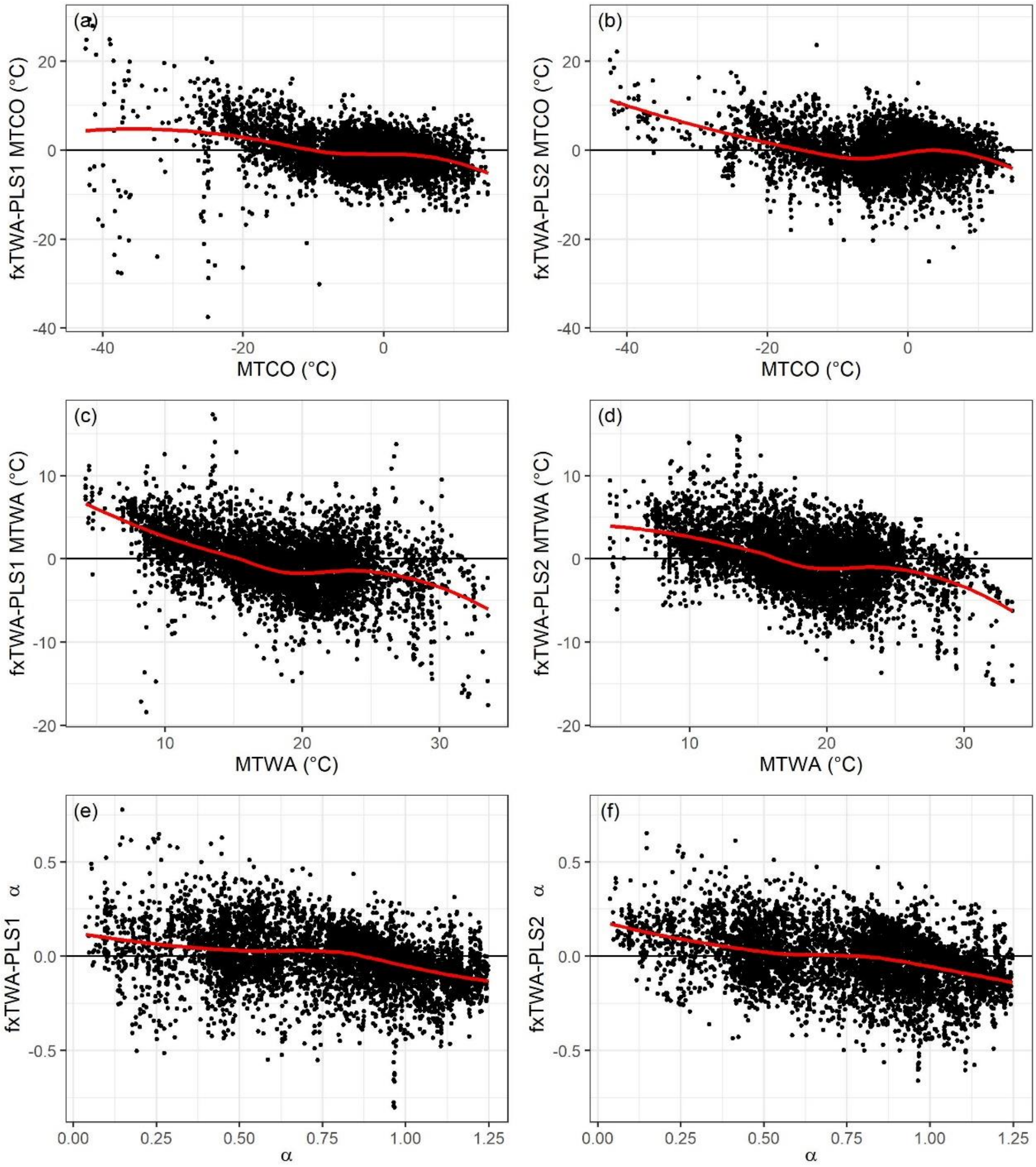


Figure A2. Residuals using the last significant number of components. The left panel shows the previous version (fxTWA-PLS1) and the right panel shows the modified version (fxTWA-PLS2) of fxTWA-PLS. The zero line is shown in black; the locally estimated scatterplot smoothing is shown in red, to show the degree of local compression.



As shown in Table A1, Figure A1 and A2, the modified version is able to further reduce the compression in MTCO and MTWA, and maximum bias in MTCO, MTWA and α. As shown in Figure A1 and A2, there is less scatter and there are less α values beyond the natural limit.