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Supplementary material for this article is available [online](#)

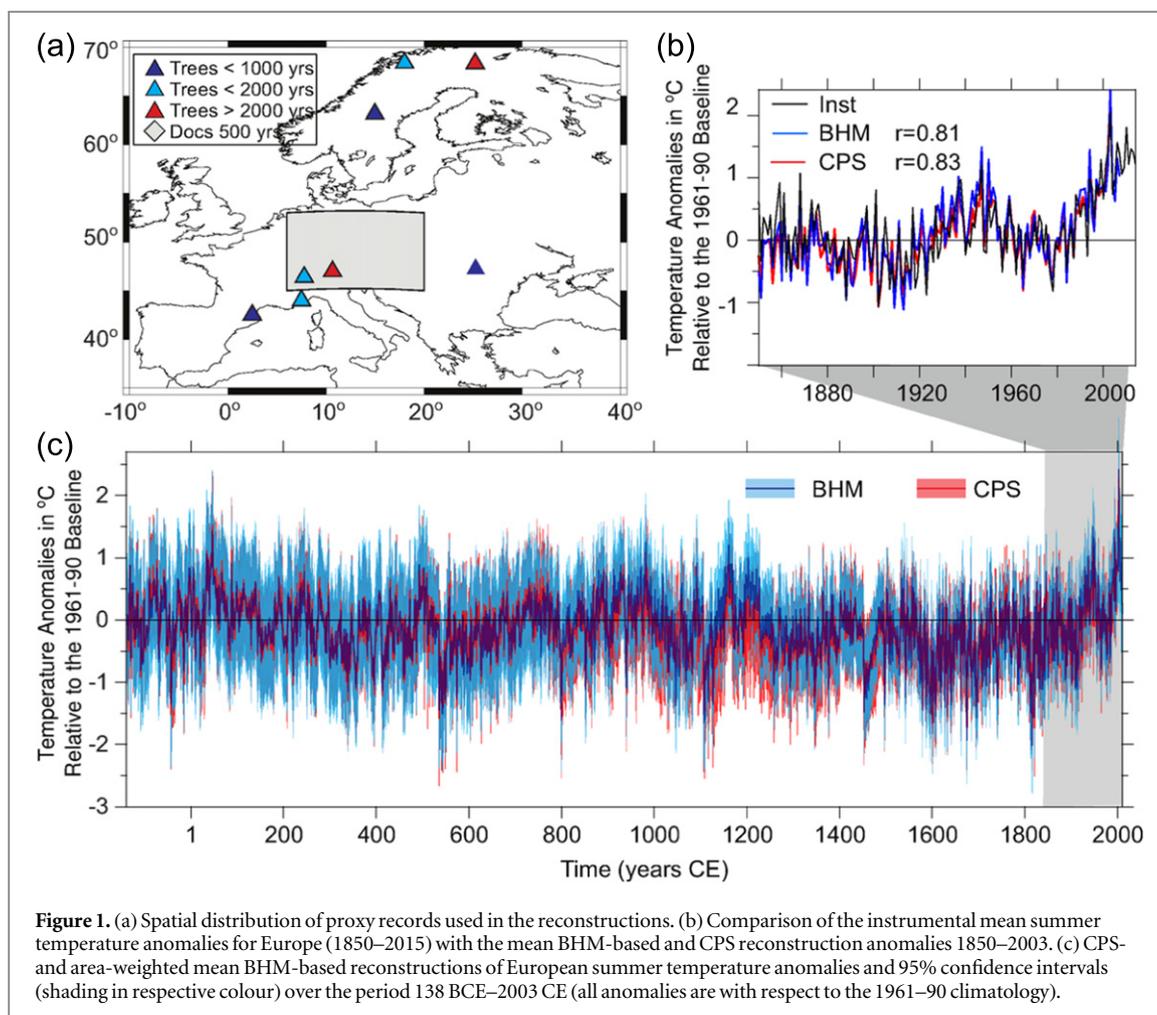
## Abstract

The spatial context is critical when assessing present-day climate anomalies, attributing them to potential forcings and making statements regarding their frequency and severity in a long-term perspective. Recent international initiatives have expanded the number of high-quality proxy-records and developed new statistical reconstruction methods. These advances allow more rigorous regional past temperature reconstructions and, in turn, the possibility of evaluating climate models on policy-relevant, spatio-temporal scales. Here we provide a new proxy-based, annually-resolved, spatial reconstruction of the European summer (June–August) temperature fields back to 755 CE based on Bayesian hierarchical modelling (BHM), together with estimates of the European mean temperature variation since 138 BCE based on BHM and composite-plus-scaling (CPS). Our reconstructions compare well with independent instrumental and proxy-based temperature estimates, but suggest a larger amplitude in summer temperature variability than previously reported. Both CPS and BHM reconstructions indicate that the mean 20th century European summer temperature was not significantly different from some earlier centuries, including the 1st, 2nd, 8th and 10th centuries CE. The 1st century (in BHM also the 10th century) may even have been slightly warmer than the 20th century, but the difference is not statistically significant. Comparing each 50 yr period with the 1951–2000 period reveals a similar pattern. Recent summers, however, have been unusually warm in the context of the last two millennia and there are no 30 yr periods in either reconstruction that exceed the mean average European summer temperature of the last 3 decades (1986–2015 CE). A comparison with an ensemble of climate model simulations suggests that the reconstructed European summer temperature variability over the period 850–2000 CE reflects changes in both internal variability and external forcing on multi-decadal time-scales. For pan-European temperatures we find slightly better agreement between the reconstruction and the model simulations with high-end estimates for total solar irradiance. Temperature differences between the medieval period, the recent period and the Little Ice Age are larger in the reconstructions than the simulations. This may indicate inflated variability of the reconstructions, a lack of sensitivity and processes to changes in external forcing on the simulated European climate and/or an underestimation of internal variability on centennial and longer time scales.

## Introduction

Europe has experienced a pronounced summer (June–August) warming of approximately 1.3 °C over the 1986–2015 period (figure 1b), accompanied by an increase of severe heat waves (length, frequency and persistency), most notably in 2003, 2010 and 2015 (Luterbacher *et al* 2004, Schär *et al* 2004, Beniston 2004, 2015, Della-Marta *et al* 2007, García-Herrera *et al* 2010, Barriopedro *et al* 2011, Rahmstorf and Coumou 2011, IPCC 2012, Russo *et al* 2015). The likelihood of occurrence of heatwaves and extremely hot summers in Europe has risen significantly in the first part of the 21st century—a trend mainly attributed to anthropogenic forcing (Stott *et al* 2004, Christidis *et al* 2015). Initiatives to benchmark European summer warming and the occurrence of extreme events have been launched to improve our understanding of the climate system and thus reduce and quantify uncertainties in the magnitude of projected future climate change (Hegerl *et al* 2011, Christidis *et al* 2012, 2015, Goosse *et al* 2012a). Paleoclimatic data covering the past 2000 yr provide a crucial perspective for characterizing natural decadal to centennial time-scale changes and to put recent climate change into a long-term perspective. Paleoclimatological advances over the past decade include: (i) the production of new proxy records and

new compilations on a regional basis (e.g. PAGES 2k Consortium 2013, 2014, Büntgen *et al* 2016, Schneider *et al* 2015); (ii) developments in multi-proxy reconstruction methodologies (e.g. Tingley and Huybers 2010a, 2010b, Smerdon 2012, Werner *et al* 2013, Neukom *et al* 2014, Guillot *et al* 2015, Werner and Tingley 2015); and (iii) development of comparison strategies between model experiments and reconstructions to assess the role of external forcing, feedbacks, and internal variability on the historical course of climate (e.g. Hegerl *et al* 2011, Bothe *et al* 2013a, 2013b, Fernández-Donado *et al* 2013, 2015, Schmidt *et al* 2014, Barboza *et al* 2014, Coats *et al* 2015, Moberg *et al* 2015, PAGES2k-PMIP3 Group 2015, Stoffel *et al* 2015, Tingley *et al* 2015). Additionally, new standards have been reached regarding the collection and archiving of proxy data (e.g. PAGES 2k Consortium 2013, 2014), estimation methods for past climate variability and associated uncertainties, and the analysis of uncertainties related to model forcing (Fernández-Donado *et al* 2013, 2015 and references therein). In a coordinated effort, the PAGES 2k Consortium (2013) presented a global dataset of proxy records and associated temperature reconstructions for seven continental-scale regions, including Europe and the Mediterranean region. Eleven annually resolved tree-ring width (TRW) and density records and documentary records from ten European locations were



used in an ensemble composite-plus-scale (CPS) reconstruction of mean European summer land temperature for the past two millennia. Here we build upon these results and provide new estimates of European summer temperature variability over more than the past two millennia. We present: (i) annually-resolved gridded summer temperature fields over Europe for the period 755–2003 of the Common Era (CE) based upon Bayesian hierarchical modelling (BHM; Tingley and Huybers 2010a, 2010b, 2013, Werner *et al* 2013; see methods and supplementary online material, SOM, for details) integrating a number of recently developed millennium length tree-ring records and historical documentary proxy evidence including a comparison with independent long-instrumental and proxy based regional summer temperature reconstructions (see data section; SOM); (ii) two reconstructions of mean European (weighted average over European land areas, see data) summer temperatures back to 138 BCE based on the CPS method and the averaged ensemble BHM. The CPS based reconstruction is similar to the one published for Europe by the PAGES 2k Consortium (2013), although it employs a slightly different proxy set (see data and SOM); (iii) a comparison between our new reconstructions and an ensemble of millennium-length climate model experiments (Masson-Delmotte

*et al* 2013) in order to assess consistency with changes in external forcing and the simulated climate variability over Europe; and (iv) spatial differences between simulated and reconstructed European summer temperature for the periods of the ‘Medieval Climate Anomaly’ (MCA, 900–1200 CE), the ‘Little Ice Age’ (LIA, 1250–1700 CE), and present-day (1950–2003 CE).

## Data

### Proxy and instrumental data

Nine annually resolved tree-ring width (TRW, Popa and Kern 2009, Büntgen *et al* 2011, 2012), maximum latewood density (MXD; Büntgen *et al* 2006, Gunnarsson *et al* 2011, Esper *et al* 2012, 2014), combined MXD and TRW (Dorado Liñán *et al* 2012) and documentary historical records (Dobrovlný *et al* 2010) were used for the reconstructions (table S1). Their locations encompass the region from 41° to 68° N and from 1° to 25° E (figure 1(a); SOM). The reconstructions target the period 138 BCE to 2003 CE, the last year for which all proxies are available. Records were selected based upon their seasonal summer temperature signals, their record length (700+ years for tree-ring records), and sample replication. We excluded the PAGES 2k

Consortium (2013) TRW records from Slovakia (Büntgen *et al* 2013) and Albania (Seim *et al* 2012) that were found to lack significant correlations with European summer temperature variability. Furthermore, the Torneträsk MXD record of Briffa *et al* (1992) that originally ends in 1980 CE, was substituted with the updated and newly processed data of Melvin *et al* (2013) and Esper *et al* (2014).

Calibration data for the European summer temperature reconstructions were derived from the CRU-TEM4v data product, comprising monthly mean surface air temperature anomalies (with respect to 1961–1990 CE) on a  $5^\circ \times 5^\circ$  land-only grid spanning the period 1850–2010 CE (Jones *et al* 2012). The region  $35^\circ\text{--}70^\circ\text{N}/10^\circ\text{W--}40^\circ\text{E}$  was selected, excluding grid cells over Iceland and small North Atlantic islands. Thus, 61 grid cells were retained. Missing months in the selected cells were infilled using the regularised expectation maximisation algorithm with ridge regression (Schneider 2001) to yield a time-continuous monthly anomaly grid over the period 1850–2010 CE (see SOM for details). The resulting data were used to calculate mean June–August (JJA) temperatures of each year and each grid cell, from which an area-weighted (North *et al* 1982) mean summer temperature index was computed. For the BHM based reconstruction, the original, non-infilled data were used (see methods and SOM for details). A comparison between the seasonal mean temperatures for the European domain using the raw (non-infilled) data and the temporally and spatially continuous (infilled) field is presented in figure S1 (SOM). Correlation coefficients between the proxy data and both the European mean summer temperature and local JJA grid cell temperatures from the infilled dataset for the period 1850–2003 CE are given in table S2 (SOM).

#### Atmosphere-ocean general circulation model (AOGCM) data

The European summer temperature reconstructions are compared with fully coupled state-of-the-art AOGCM simulations. The model-data comparison is based on 37 millennium-length simulations (see table S14) performed with 13 different AOGCMs. The ensemble includes eleven simulations from the Coupled Model Intercomparison Project Phase 5—Paleo Model Intercomparison Project Phase 3 (CMIP5/PMIP3; Braconnot *et al* 2012, Taylor *et al* 2012, Masson-Delmotte *et al* 2013) and 26 pre-PMIP3 additional simulations discussed in Fernández-Donado *et al* (2013). Aside from differences in model complexity and resolution, the most notable asset of the ensemble is the range of variation in applied external forcing configurations. The models consider different forcing factors and are also based on different forcing reconstructions. The CMIP5/PMIP3 simulations follow the forcing protocol outlined in Schmidt *et al* (2011, 2012), while the pre-PMIP3

simulations use a larger variety of forcing reconstructions (see Fernández-Donado *et al* 2013). The range in the applied external forcing configurations is largest for total solar irradiance (TSI). This relates most to the re-scaling and conversion of raw estimates (e.g.  $^{10}\text{Be}$  or  $^{14}\text{C}$ ) into changes in incoming shortwave radiation in units of  $\text{Wm}^{-2}$  (Solanki *et al* 2004, Steinhilber *et al* 2012) rather than the character of the temporal evolution over the past 2000 yr. The re-scaled TSIs used for the climate simulations can be classified into two groups according to the magnitude of their low frequency variations, thus leading to two sub-ensembles of simulations (Fernández-Donado *et al* 2013): one involving stronger solar forcing variability (used in some pre-PMIP3 simulations) with a percentage of TSI change between the Late Maunder Minimum (LMM; 1675–1715 CE) and present  $>0.23\%$ , denoted here  $\text{SUN}_{\text{WIDE}}$ ; another, with weaker solar forcing scaling (used by the CMIP5/PMIP3 experiments and some pre-PMIP runs) characterised by a TSI change between LMM and present  $<0.1\%$ , denoted here  $\text{SUN}_{\text{NARROW}}$  (see SOM for more details). On hemispheric scales, the highest estimates of solar forcing seems to yield a discrepancy between forced simulations and reconstructions (Schurer *et al* 2014). Regionally and seasonally the effect of solar forcing may be enhanced due to dynamic feedbacks that are largely missing in models (see Gray *et al* 2010).

## Methods

European mean summer temperature reconstructions covering more than 2000 yr were created by using BHM and CPS. The two methods are based on different statistical assumptions regarding the proxy records and their associated temperature signals. Both methods provide uncertainty estimates and have been tested with synthetic data in pseudo-proxy experiments (Werner *et al* 2013, Schneider *et al* 2015). BHM was applied to derive spatial fields of summer temperature. We show the area-weighted mean back to 138 BCE, but limit the analysis of the spatial results to the period 755–2003 CE due to the low number of proxies before that period.

#### Composite-plus-scaling

A nested CPS (e.g. Jones *et al* 2009, PAGES 2k Consortium 2013, Schneider *et al* 2015) reconstruction was computed using eight nests reflecting the availability of predictors back in time (see table S1 for the initial year of each nest). A CPS reconstruction was computed for each nest by normalising and centring the available predictor series over the calibration interval (1850–2003 CE). A composite for each nest was then calculated by weighting each proxy series by its correlation with the European mean summer temperature. Finally, each composite was centred and scaled to have the same variance as the target index

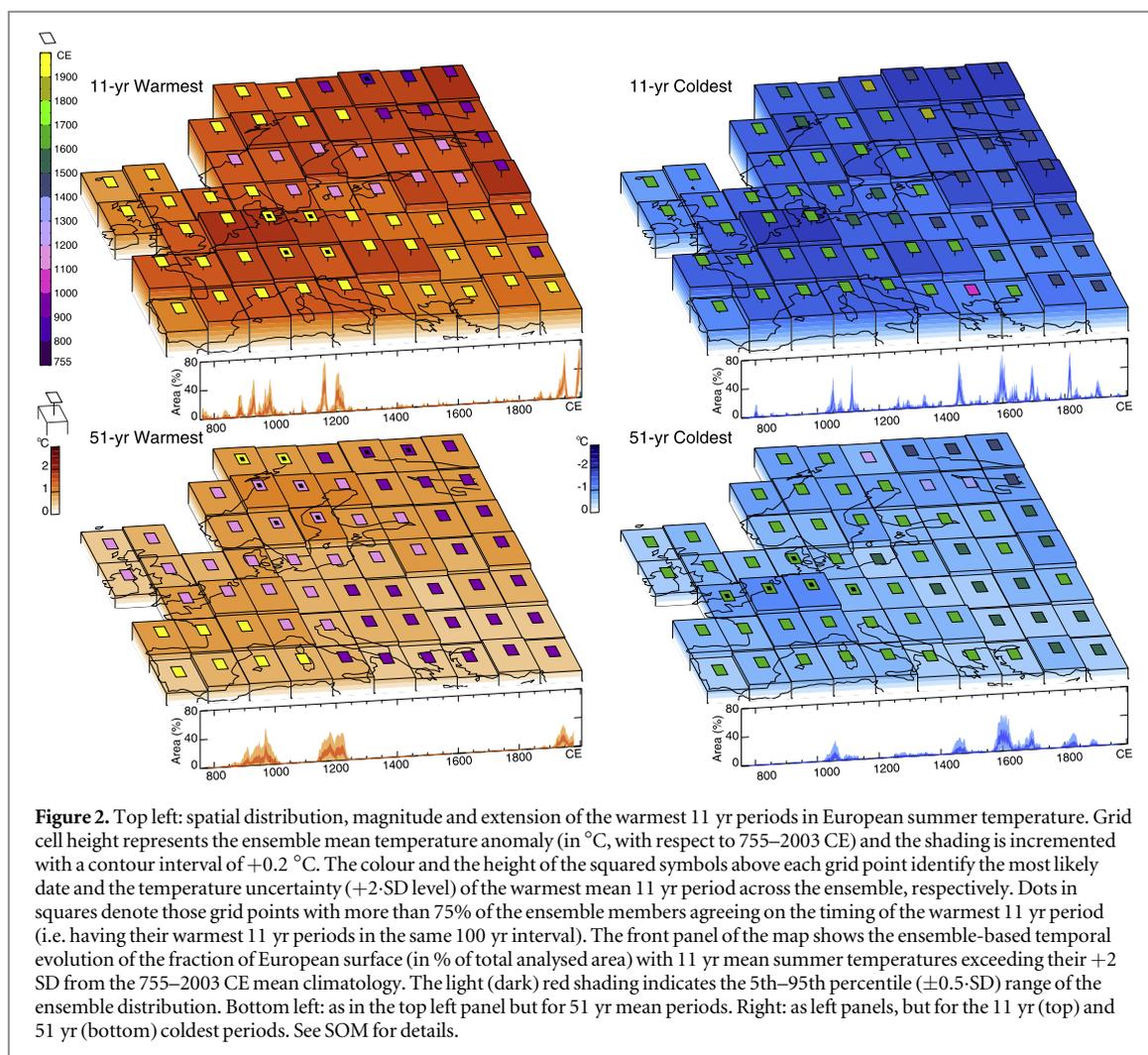
during the calibration period. CPS was implemented using a resampling scheme for validation and calibration (e.g. McShane and Wyner 2011, Schneider *et al* 2015) based on 104 yr for calibration and 50 yr for validation (the last year of the uniformly available predictor series is 2003, providing 154 yr of overlap with the target index, see SOM for details). Detailed validation statistics, with associated information across all reconstruction ensemble members within each nest, are provided in the SOM (tables S3 and S4). The limited number of proxies might be an important caveat for the reconstructions. Figure S3 shows the comparison of the eight nests in the CPS-based reconstructions of mean European summer temperature anomalies for the period 138 BCE–2003 CE. There are small differences between nests, but the covariance among each nest is remarkably consistent across all of the nests during their periods of overlap. The new CPS reconstruction, in the absence of the two predictors used by the PAGES 2k Consortium (2013) and employing the updated Torneträsk MXD record (Esper *et al* 2014), is virtually identical to the original PAGES 2k reconstruction over the full duration of the two reconstructions (Pearson's correlation coefficient of 0.99; figure S2).

#### Bayesian hierarchical modelling (BHM)

Bayesian inference from a localised hierarchical model (Tingley and Huybers 2010a, 2010b, 2013) was used to derive a gridded summer temperature reconstruction from 138 BCE to 2003 CE. However, the drop-off in proxy availability prior to 755 CE led to an increase in uncertainty back in time (Werner *et al* 2013), especially in locations remote from the remaining available proxy sites. Thus, we only present a gridded BHM reconstruction between 755 and 2003 CE, and a mean European summer temperature index from 138 BCE to 2003 CE. The BHM approach follows that of Tingley and Huybers (2010a, 2010b, 2013), Werner *et al* (2013, 2014) and Werner and Tingley (2015), with minor modifications. A simple stochastic description of the local (gridded) temperature anomalies is used to model the spatial and temporal correlations of the true temperature field (see SOM for details). Additionally, the proxy response function for TRW data was changed to include a low-frequency response term (SOM, Werner *et al* 2014). Recent studies by Zhang *et al* (2015) indicate, that, when using TRW as a climate proxy, the low-frequency of the climate reconstructions is generally intensified due to higher long-term persistence in TRW data compared to instrumental data. As suggested by Tingley and Huybers (2013), we use the results of a predictive run (without the instrumental data as input) as the reconstruction product (see SOM).

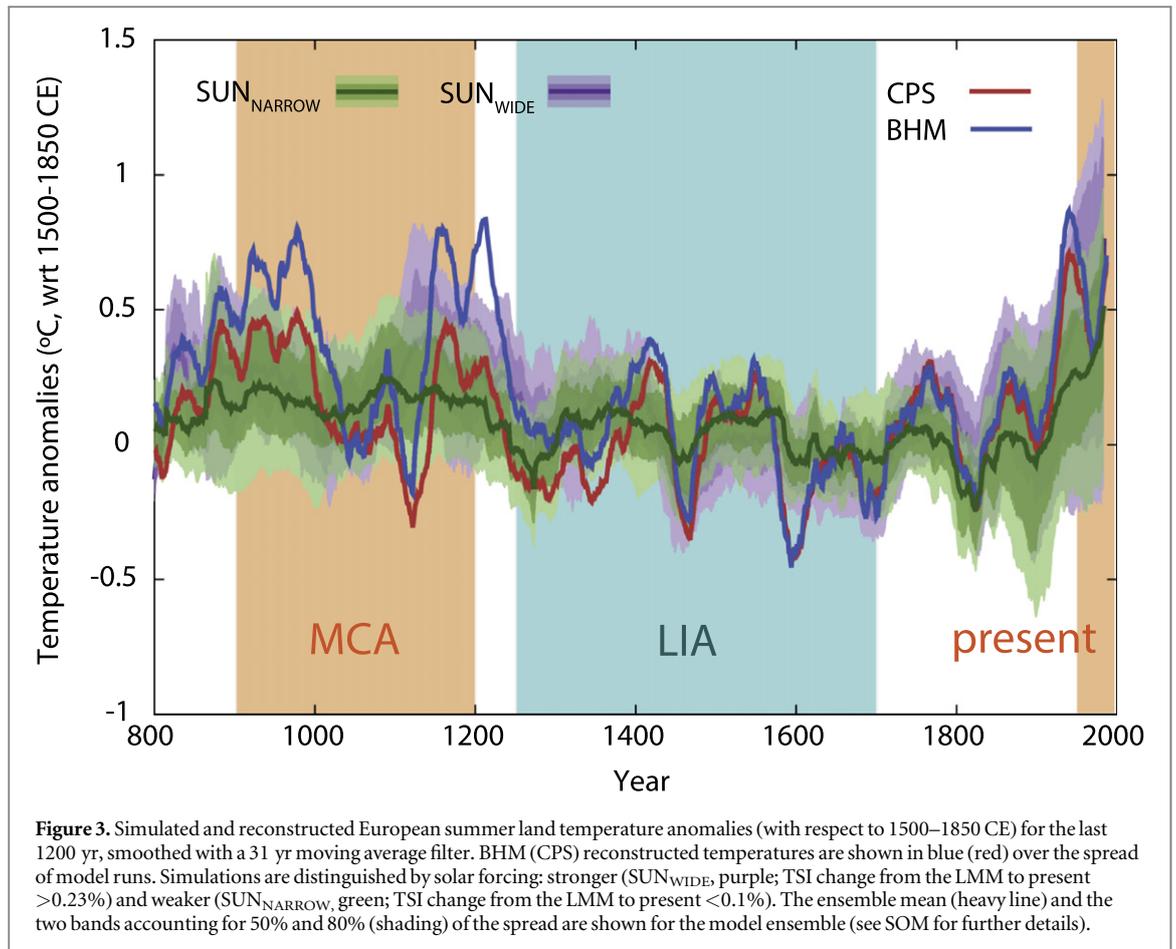
## Results and discussion

Comparison of the European temperature reconstructions with instrumental data indicates skilful reconstructed representations of interannual to multi-decadal variability over the calibration period (1850–2003 CE, figure 1(b), the Pearson correlation coefficient is 0.81 and 0.83 for BHM and CPS, respectively; see tables S3 and S4 and SOM for additional validation statistics). The reconstructions also compare well with long, independent station temperature series (table S13; figures S8), and reasonably well with summer temperature reconstructions from various high and low temporal resolution proxy records and gridded field reconstructions (table S13, figure S9). Our BHM-based reconstruction shows more pronounced changes in mean summer temperatures over Europe than previously reported (Luterbacher *et al* 2004, Guiot *et al* 2010; figures S10 and S11), which can partly be attributed to its better performance in the preservation of variance. The reconstructions indicate that on a multi-decadal time-scale (31 yr means) warm European summer conditions prevailed from the beginning of the reconstructed period until the 3rd century, and were followed by generally cooler conditions from the 4th to the 7th centuries (figure 1(c)). Warm periods also occurred during the 9th–12th centuries, peaking during the 10th century, and again in the late 12th to early 13th centuries. The timing of the European warm anomaly agrees with medieval-period warmth detected in most reconstructions of NH mean temperature (e.g. Esper *et al* 2002, D'Arrigo *et al* 2006, Frank *et al* 2007, 2010, Esper and Frank 2009, Ljungqvist *et al* 2012, Schneider *et al* 2015). Summers are more anomalously warm in Europe in the medieval period than reconstructed for annual NH data (see Masson-Delmotte *et al* 2013, figure 5.7), suggesting at least in part a dynamic origin. It is presently unclear to what extent relatively low volcanism (Sigl *et al* 2015), elevated solar forcing (Steinhilber *et al* 2009) and higher obliquity (orbital forcing) may have contributed to the unusual regional summer warmth. The warmer medieval period was followed by relatively cold summer conditions, persisting into the 19th century (figure 1(c)), with a notable return to somewhat warmer conditions during the middle portion of the 16th century. Finally, the reconstruction reproduces the pronounced instrumentally observed warming in the early and late part of the 20th century. The warmest century in both the CPS and BHM reconstructions is the 1st century CE (for BHM also the 10th century). It is  $<0.2$  °C warmer than the 20th century and multiple testing reveals the difference is not statistically significant (tables S5 and S6; see also SOM for details on testing how anomalous the recent warm conditions are in the context of the full reconstruction for 50-year and 30-year periods; tables S7–S12).



The gridded BHM reconstruction also reveals the marked sub-continental scale spatial variability back to 755 CE. Some of the warmer summer periods during medieval times (see also figure 1(c)) mask a substantial spatial heterogeneity. For example, the 11th century displayed multi-decadal periods characterised by pronounced warm conditions over Northern Europe, but relatively cold conditions in central and Southwestern Europe (figure 2). In addition, the decades around 1100 CE were cold in large parts of Europe (figure 2 right, top). The European cold conditions between the 13th and 19th centuries (figure 1(c)) also entail substantial temporal and spatial variability. The mid-13th century, for instance, was characterised by cooling in Northeastern Europe, but warming in Southwestern regions (figure 2). An exceptionally cold period occurred also in the late 16th century and early 17th century, with negative temperature anomalies over nearly half of Europe at decadal and multi-decadal time scales (figure 2 right panels). Cold summers were also prominent in the mid-15th century over Northeastern Europe, in the late 17th and the first half of the 19th century over central and Southern Europe (figure 2 right, top panel). Thus, the coldest intervals across Europe spread between the 15th and 17th centuries, depending on the region,

with poor temporal agreement at local scales across the ensemble (figure 2 right, top panel). In large parts of Europe, the summer temperatures of the latest 11 yr period (1993–2003 CE) are either similar to the warm intervals of medieval times or even warmer than any other period during the last 1250 yr (figure 2 left, top panel). Northeastern Europe shows the warmest decades of the last 1250 yr during medieval times, when large areas of Europe experienced recurrent and long-lasting warm periods punctuated by cold intervals during the 11th century (figure 2, top panels). If we consider 51 yr mean periods (figure 2 left, bottom), the largest, warm multi-decadal anomalies occurred during different intervals within medieval times (exceeding recent 51 yr averages in most of Europe). However, due to the competing level of warmth between the 10th and 12th–13th centuries and the higher uncertainties in reconstructed temperatures during medieval times, the temporal agreement across the ensemble for the 51 yr maximum is low. For the coldest intervals, we do not find the same degree of dependence on timescale (figure 2 right). The coldest decadal as well as multi-decadal (51 yr) periods occurred in the 16th and 17th centuries over most of Europe, but with better agreement on longer time-scales. To further assess how exceptional the warmest decadal and



multi-decadal periods of the 20th century were, we calculated (backwards in time) the number of years through which the warmest interval of the 20th century has remained unprecedented (figure S12). The ensemble indicates with high agreement that the late 20th century has the warmest decades since 755 CE in the Mediterranean region, while Northeastern Europe shows comparable warmth during the MCA, although with low agreement. Thus, at multi-decadal time-scales the warmest periods of the 20th century do not have equals since medieval times in most of Europe (figure S12).

Joint evaluation of reconstructions and AOGCM simulations covering the period 850–2000 CE allows for comparative assessments of these two independent sources of information of past climate variability. It further provides insights into the relative contributions of estimated external forcing and internal dynamics. For both the  $SUN_{WIDE}$  and  $SUN_{NARROW}$  solar variability sub-ensembles, figure 3 shows the ensemble average and the 10, 25, 75 and 90 percentiles. Purple and green shading in figure 3 represent measures of the overlap among the ensemble of simulations, taking into account the uncertainty due to internal climate variability. The overlap was calculated according to Jansen *et al* (2007). The scores are summed over all simulations and scaled to add one for a given year. The simulated range of internal variability

is ideally estimated based on SD from long control simulations with constant external forcing, however, these were not available for all models. Therefore, SDs were estimated from the high-pass (51 yr) filtered temperature outputs of the forced simulations. The attribution of climate response to external forcing in the multi-model ensemble is complicated by the heterogeneous choices of forcing agents (table S14). For example, some pre-PMIP3 simulations did not include anthropogenic aerosols or orbital forcing. With this caution in mind, the mean European temperature reconstructions using BHM and CPS correlate with the  $SUN_{WIDE}$  ensemble ( $r = 0.61$ ,  $p < 0.05$ , accounting for serial autocorrelation; figure 3) as well as with the  $SUN_{NARROW}$  ensemble mean ( $r = 0.55$  and  $0.57$  for BHM and CPS, respectively, both at  $p < 0.05$ ). Reconstructed cold conditions (mid-13th, mid-15th, and early 19th century) at multi-decadal time-scales mostly agree with simulated temperature minima attributed to solar and volcanic forcing (Hegerl *et al* 2011). The reconstructed minima at the beginning of the 12th century and around 1600 CE have no counterpart in the climate model data (figure 3), suggesting either an important role of internal variability (Goosse *et al* 2012b) or inaccuracies in model forcing (Fernández-Donado *et al* 2013, 2015). An alternative interpretation of the discrepancies as being related to shortcomings in the reconstructions is

unlikely due to considerable support for these temperature minima from other NH proxy evidence. Colder conditions in the decades around 1100 CE were also observed in other parts of the world, e.g. Russian plains (Klimenko and Sleptsov 2003, SOM, figure S9), East China (Ge *et al* 2003), the Tibetan Plateau (Thompson *et al* 2003, Liu *et al* 2006) and the Eastern Canadian Arctic (Moore *et al* 2001). Glacier advances are reported around this time for the Alps, Western Canada, the Canadian Arctic, Greenland, the Tibetan Plateau, and the Antarctic Peninsula (for a review, see Solomina *et al* 2015). Additionally, proxy-based evidence supports the cold conditions of the 16th–17th centuries (figure S9). Local proxy records of various types (see figure 2 in Christiansen and Ljungqvist 2012), inferences of glacier expansions around the world (e.g. Solomina *et al* 2015), continental multi-proxy reconstructions (e.g. PAGES 2k Consortium 2013), and extra-tropical NH tree-ring based summer temperature reconstructions (Briffa *et al* 2004, Masson-Delmotte *et al* 2013 and references therein; Schneider *et al* 2015, Stoffel *et al* 2015) support the existence of a strong and geographically widespread very cold episode around 1600 CE.

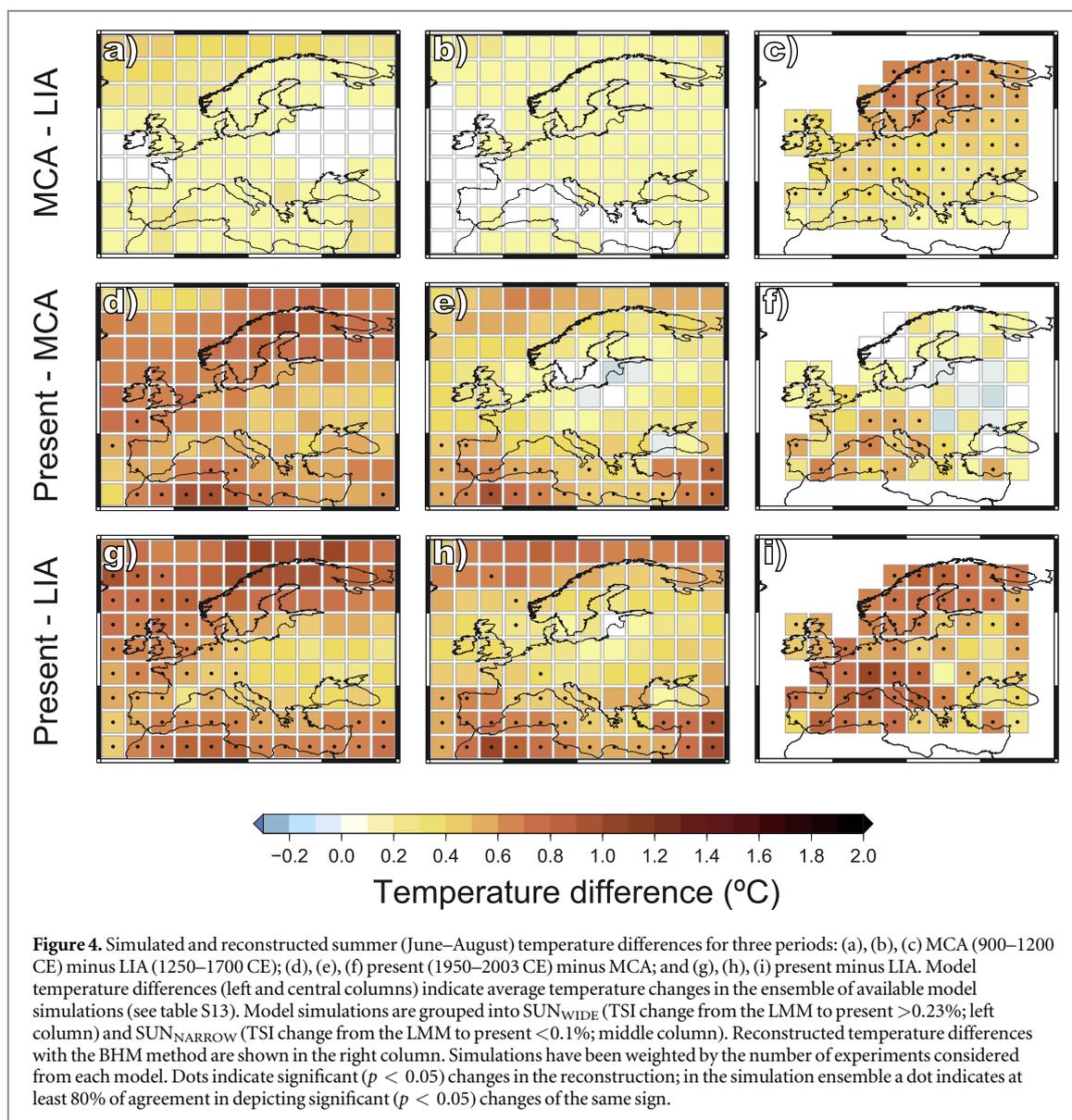
In agreement with the results of Hegerl *et al* (2011) using temperature reconstructions from Luterbacher *et al* (2004), our findings suggest that changes in external forcing have had a pronounced influence on past European summer temperature variations. A more in-depth detection and attribution analysis of temperature changes over Europe, as well as those over other PAGES 2k regions (PAGES 2k Consortium 2013) can be found in PAGES2k-PMIP3 Group (2015). The marginally better agreement with the SUN<sub>WIDE</sub> ensemble lends tentative support to both the importance of changes in solar forcing in driving continental past climate variations as well as a potentially greater role for solar forcing in driving European summer temperatures than is currently present in the CMIP5/PMIP3 simulations. This might be evidence for an enhanced sensitivity to solar forcing in this particular region due to dynamics, as has been suggested by modelling studies (see e.g. Ineson *et al* 2015). However, this is beyond the current scope of this paper. It should also be noted, that most periods with anomalously low solar activity during the last millennium coincide with clustering of medium-to-strong tropical volcanic eruptions, thus complicating a clear separation of individual forcing contributions to large-scale temperature variations (Zanchettin *et al* 2013a, Schurer *et al* 2014).

The European summer temperature response to strong tropical volcanic events is analysed through Superposed Epoch Analysis (SEA, e.g. Fischer *et al* 2007, Hegerl *et al* 2011) for the PMIP3 model simulations and the BHM reconstructions (figures S13–S14). For each volcanic forcing, the 12 strongest volcanic events are selected, following the same approach as in PAGES2k-PMIP3 group (2015). The SEA for the reconstruction is performed for the 13 strongest tropical volcanic eruptions ( $> = \text{VEI } 5$ ) published in Esper

*et al* (2013). The selected eruptions all occurred during the time period covered by the gridded BHM reconstruction (figure S14). We show the anomalies during the year of the eruptions and the 3 yr delayed post-eruption anomalies evaluated with respect to the pre-eruption climatology, defined as the average state over the five summers preceding the eruption. Using the PMIP3 climate models the multi-model response after the strongest volcanoes over the last millennium shows an overall European summer cooling (figure S13), though much stronger than in the reconstructions (figure S14) and peaking during the year of the eruption and the first year thereafter. The composite analysis from the reconstructions clearly reveals that the European summer cooling is strongest in the first and second year after the eruptions. The average anomalies are of the order of  $0.5^\circ\text{C}$ .

The summer cooling is confirmed by a separated analysis for a selection of strong tropical (Samalas 1257, Huaynaputina 1600, Parker 1641 and Tambora 1815) and non-tropical (Laki 1783/1784) eruptions (figure S15, Lavigne *et al* 2013, Sigl *et al* 2015, Stoffel *et al* 2015) in the BHM reconstructions.

Patterns of past sub-continental climate variability contain information about the influence of external factors that affect the climate system and, together with climate models, can be used to better understand how internal dynamics contribute to determining the regional climate response to external forcing. Figure 4 shows the spatial differences between the MCA, LIA, and present-day averages for simulated and reconstructed European summer temperatures. Note that the following results do not differ significantly if alternative definitions of periods are chosen (not shown). Overall, simulated differences are statistically significant at the 5% level only at a few grid-points, even without correction for multiple testing, and are not clearly consistent across the model ensemble (figure 4). The models tend to simulate the largest changes for all the three periods over Northern Europe, resembling the typical pattern of temperature response to changes in forcing (e.g. Zorita *et al* 2005) and the possible signature of Arctic amplification (see Masson-Delmotte *et al* 2013). While the simulated pattern for both model groups qualitatively matches the reconstruction of the MCA to LIA transition, its amplitude is smaller (figures 4(a)–(c)) for both sub-ensembles. The differences between the reconstructed spatial patterns averaged during the MCA and the present day (figure 4(f)) are distinct from the same simulated metric (figures 4(d) and (e)), particularly over North–Eastern Europe. The reconstructed MCA is slightly warmer than recent decades in many parts of (primarily) Northern and Eastern Europe, while the simulations reveal a more generalised and warmer present day over the whole spatial domain (figures 4(d)–(f)), with the SUN<sub>NARROW</sub> simulations appearing closer to the reconstructions than SUN<sub>WIDE</sub>. Also the SUN<sub>NARROW</sub> ensemble fails to fully reproduce the magnitude of the reconstructed temperature differences between the LIA and present day (figures 4(g)–(i))



for which the agreement between different simulations is regionally limited to Southern and Western parts of the target region.

If we assume the BHM reconstruction to be our best available evidence regarding the MCA–LIA transition, the amplitude mismatch between the multi-model ensemble and the reconstructions suggest either a reduced model sensitivity, or an underestimation of model forcings, or that internal variability may play a dominant role. Alternatively a combination of all these factors may be at play. The fact that different simulations agree with each other only in a limited part of the domain indicates a hint that the response to forcing can be model-dependent and that ensemble members may diverge depending on initial and boundary conditions (Zanchettin *et al* 2013b). Concerning the latter, changes in ocean circulation may be important, including aspects of variability such as the state of the Atlantic Multi-decadal Oscillation (AMO; Kerr 2000, Alexander

*et al* 2014) and dynamical implications of phasing between the AMO and North Pacific sea-surface temperatures for hemispheric-scale teleconnections (i.e. Zanchettin *et al* 2013a). Additionally, some of the models may not be able to reproduce the dynamical mechanisms shaping the regional responses to forcing variations (e.g. Ineson *et al* 2015), owing to, for example, a lack of horizontal resolution or the absence of a well-resolved stratosphere (Mitchell *et al* 2015).

## Conclusions and outlook

In this study, we have updated and extended reconstructions of European summer temperature variation for the CE using a suite of proxy records and a BHM approach. We also jointly analysed the new summer temperature reconstruction with several state-of-the-art reconstructions and AOGCM simulations in order to clarify the relative role of external forcing and internal variability for the evolution of European

summer temperatures at different spatial and temporal scales. Reconstructions of mean European summer temperatures compare well for both the CPS and the BHM methods, strengthening our confidence in the derived results. Our European summer temperature reconstructions compare well with independent instrumental and lower resolution proxy-derived temperature estimates but show larger amplitudes in summer temperature variability than previously reported. There is thus merit in further studies combining instrumental series with low and high-resolution summer temperature proxies in a Bayesian hierarchical framework (Werner and Tingley 2015). Our primary findings indicate that the 1st and 10th centuries CE could have experienced European mean summer temperatures slightly but not statistically significantly (5% level) warmer than those of the 20th century. However, summer temperatures during the last 30 yr (1986–2015) have been anomalously high and we find no evidence of any period in the last 2000 years being as warm (tables S11, S12). The anomalous recent warmth is particularly clear in Southern Europe where variability is generally smaller, and where the signal of anthropogenic climate change is expected to emerge earlier (e.g. Mahlstein *et al* 2011). European summer mean temperatures appear to reflect the influence of external forcing during periods with sustained sub-decadal (volcanic) and multi-decadal (volcanic, solar, GHG) changes. Reconstructed summer temperature anomalies for the Roman period and MCA in Europe, which are not reflected to the same extent in large-scale means have important implications for predicting the magnitude and frequency of extremes. Our results show that subcontinental regions may undergo multi-decadal (and longer) periods of sustained temperature deviations from the continental average indicating that internal variability of the climate system is particularly prominent at sub-continental scales, in accordance with results from simulations of future anthropogenic-driven climate change (Deser *et al* 2012). The new reconstructions provide the basis for future comparison with extended simulations beyond the last millennium that are currently underway. A significant advantage of the gridded reconstructions is that they will allow an in-depth analysis of the spatial co-variability within the European realm in comparison to higher resolution climate simulations capable of mimicking the complex geographical and climatic structure of Europe. Further, forcings such as volcanic aerosols, solar and land-use change are expected to have unique fingerprints of temperature change, potentially affecting some areas of Europe more than others. In future analyses we will use the long-timescale sub-continental information presented here to try to disentangle these different factors from internal variability.

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# **Supplementary Online Material, SOM**

## *European summer temperatures since Roman times*

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*Environmental Research Letters*

# Data

## *Proxy and instrumental data*

We provide herein a short overview of the nine annually resolved tree-ring width (TRW), tree-ring maximum latewood density (MXD) and documentary records used for the reconstructions (Table S1).

The MXD-based summer temperature reconstruction from Northern Scandinavia (Nsc12, see Table S1) is derived from living and sub-fossil *Pinus sylvestris* trees from Finnish and Swedish Lapland. The record is longer and better replicated than any previously existing MXD-based temperature reconstruction, and has been used to assess inter-annual to millennial (Milankovitch) scale climate variability in Northern Scandinavia back to 138 BCE (Esper et al. 2012). Nsc12 integrates data from trees that fell into shallow lakes in Finnish Lapland with measurement series from living trees growing at the lake shores (to avoid ecological shifts that can limit the reliability of composite chronologies integrating relic material; see Tegel et al. 2010, D uthorn et al. 2013, 2015; Linderholm et al. 2014). The second tree-ring chronology spanning the past two millennia has been developed from records in the European Alps (Aus11, B untgen et al. 2011). It has been truncated in 138 BCE to enable comparison with the long-term record from Scandinavia. Additional records, that were recently developed and have not been integrated into any large-scale reconstructions include an updated MXD record from J amtland in central Sweden (Jae11, Gunnarson et al. 2011) extending back to 1107 CE, a TRW reconstruction from the French Alps (Fra12, B untgen et al. 2012) extending back to 969 CE and a composite record integrating MXD and TRW data from the Spanish Pyrenees back to 1260 CE (Pyr12, Dorado Li an n et al. 2012b). These time series as well as the TRW record from Romania (Car09; Popa and Kern, 2009) and the MXD record from Switzerland (Swi06, B untgen et al. 2006) all extend into the 21st century and enable an assessment of proxy-based temperature variability until 2003 CE. All tree-ring chronologies used in this study have been detrended using the RCS technique (Esper et al. 2003) to avoid loss of low-frequency variance that can limit the assessment of temperature variations on centennial time scales (Cook et al. 1995; Esper et al. 2002). Table S1 provides information about the proxy data used.

**Table S1:** Proxy data information used for the European summer temperature reconstructions

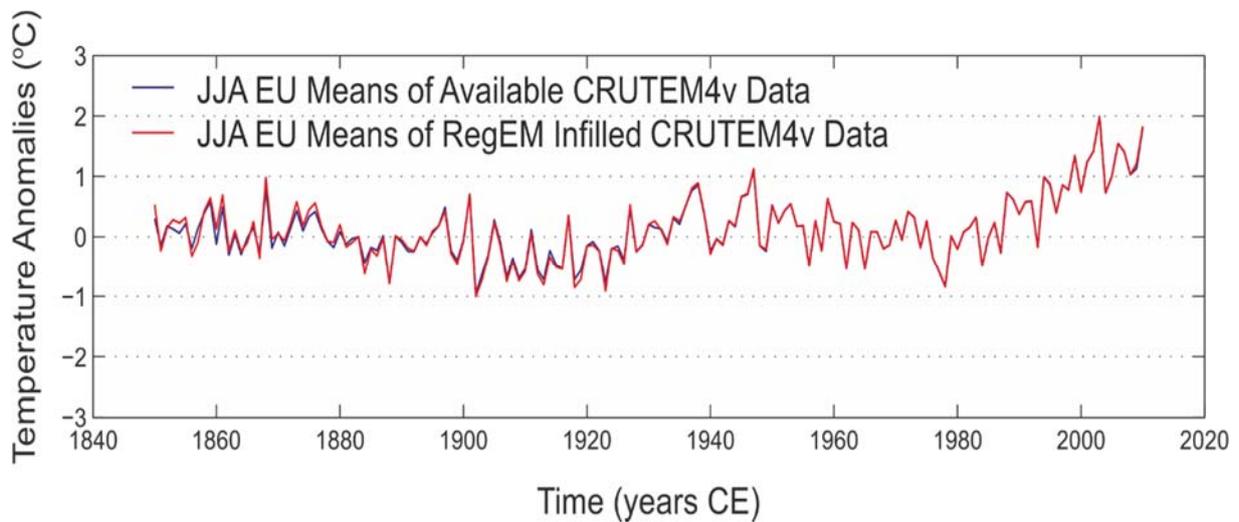
Site	Country	Lon./Lat.	Elevation	Archive	Tree species	Proxy	Period	Reference
Tor13	Sweden	19.6° E/68.25° N	400 m	Tree-rings	Pine	MXD	500-2004	Melvin et al. (2013); Esper et al. (2014)
Jae11	Sweden	15° E/63.10° N	800-1000 m	Tree-rings	Pine	MXD	1107-2007	Gunnarson et al. (2011)
Nsc12	Finland	25° E/68° N	300 m	Tree-rings	Pine	MXD	138 BCE-2006	Esper et al. (2012)
Car09	Romania	25.3° E/47° N	1800 m	Tree-rings	Pine	TRW	1163-2005	Popa and Kern (2009)
Aus11	Austria	10.7° E/47° N	1450-2300 m	Tree-rings	Larch/Pine	TRW	500 BCE-2003	B�untgen et al. (2011)
Swi06	Switzerland	7.8° E/46.4° N	1600-2300 m	Tree-rings	Larch	MXD	755-2004	B�untgen et al. (2006)
Fra12	France	7.5° E/44° N	2100-2300 m	Tree-rings	Larch	TRW	969-2007	B�untgen et al. (2012)
Pyr12	Spain	1° E/42.5° N	1500-2500 m	Tree-rings	Pine	MXD/TRW	1260-2005	Dorado Li�an�n et al. (2012)
CEu10	Central Europe	45°-53° N, 6°-20° E	500-1500 m	Historical documents	–	–	1500-2007	Dobrovoln�y et al. (2010)

Compared to the European mean summer reconstructions in PAGES 2k Consortium (2013) we excluded the TRW records from Slovakia (Büntgen et al. 2013) and Albania (Seim et al. 2012), as they are not significantly correlated with the selected target of European summer temperature variability. Furthermore, the Torneträsk MXD record of Briffa et al. (1992) that ends in 1980, has been exchanged with the updated and newly processed data by Melvin et al. (2013) and Esper et al. (2014).

As in PAGES 2k Consortium (2013), we use the seasonally-resolved Central European temperature series (CEu10, Dobrovolný et al. 2010) that combines documentary and early instrumental data. A Central European index temperature series (the seven ordinaly scaled ranks from -3 to 3) was created from documentary-based indices from Germany, Switzerland and the Czech Lands for the period 1500–1854 CE. The instrumental temperature series from 1760–2007 CE was taken as an average of eleven homogenized series: Kremsmünster, Vienna and Innsbruck (Austria), Basel, Geneva and Bern (Switzerland), Regensburg, Karlsruhe, Munich and Hohenpeissenberg (Germany) and Prague-Klementinum (the Czech Republic). These series were corrected for insufficient radiation protection (summer half-year) of early thermometers, and for the growth of the urban heat island effect before being used in the temperature reconstruction. Verification statistics indicated high reconstruction skill for all seasons (Dobrovolný et al. 2010).

### ***Comparison between seasonal European mean temperatures using the raw data and the time and space continuous field infilled with the RegEM-Ridge algorithm***

Figure S1 shows the differences between raw (with gaps) and infilled mean summer temperature indices derived from the CRUTEM4v temperature grid over the European domain. The differences are small and appear primarily prior to 1900 CE when the amount of missing data, particularly in the Mediterranean land region, is highest. The Pearson correlation coefficients between the proxy data and both European mean summer temperature and the local JJA grid cell temperatures in the infilled dataset were calculated over the 1850-2003 CE period and are shown in Table S2.



***Figure S1:*** Comparison between the area-weighted JJA mean temperature anomalies (1961-1990 climatology) for the European domain using the raw (with gaps) data and the time and space continuous field infilled with the RegEM-Ridge algorithm (Schneider 2001).

**Table S2:** Start years, proxy abbreviation and Pearson's correlation coefficients ( $r$ ) between the proxies and either the European regional mean summer temperature or the mean summer temperature of the grid containing the proxy (the latter number is given in parentheses) using the RegEM-Ridge infilled temperature data. All correlations were computed for the 1850-2003 CE period. The null hypothesis of no correlation can be rejected at the 5% and 1% levels for correlations above 0.13 and 0.19, respectively (assuming a one-tailed PDF).

\* includes instrumental data

<b>Nest</b>	<b>Start Year (CE)</b>	<b>Proxy</b>	<b>Correlation (r)</b>
1	-138	Nsc12	0.44 (0.76)
		Aus11	0.53 (0.69)
2	441	Tor13	0.51 (0.70)
3	755	Swi06	0.35 (0.61)
4	969	Fra12	0.45 (0.49)
5	1107	Jae11	0.47 (0.66)
6	1163	Car09	0.37 (0.41)
7	1260	Pyr10	0.13 (0.45)
8	1500	Ceu10	0.73 (0.96*)

## Reconstruction Methods and Validation

### *Composite plus Scaling (CPS)*

Multiple studies have previously applied the CPS method and validated its skill as a method for index reconstructions (e.g. Mann et al. 2008; PAGES 2k Consortium 2013). The initial calibration interval extended from 1850–1953 CE and was incremented by one year until reaching the final period of 1900–2003 CE, yielding a total of 51 reconstructions for each nest of Table S2. Within each calibration step, the 50 years excluded from calibration were used for validation. For each nest, the final CPS reconstruction was computed as the median reconstructed value in each year within the 51-member reconstruction ensemble.

Uncertainties were estimated based on the mean standard deviation (SD) of the residuals across all of the validation intervals by adding 1.96 times the SD estimate to the maximum and minimum ensemble values in each year, thereby providing the 95% confidence intervals of the median reconstruction. The final nested index reconstruction was combined by splicing together the median reconstruction and estimated uncertainties of each nest such that every reconstructed year is derived from the nest with the maximum number of possible predictors. Validation statistics across all reconstruction ensemble members within each nest indicate skilful CPS summer temperature reconstructions: The mean Reduction of Error (RE; Cook et al. 1994) and Coefficient of Efficiency (CE; Cook et al. 1994) cross validation statistics across the 51 intervals in each nest are positive (Table S3). Benchmarking experiments (Wahl and Smerdon 2012) with 1000 realizations of AR(1) red noise time series as predictors and autocorrelations approximating those of the available proxy records were also performed. These experiments yielded maximum mean RE and CE benchmark values below the mean values achieved for the actual reconstruction across all nests (Table S3). The mean Pearson's correlation coefficients for each nest were all above the 95% significance level ( $r=0.245$ ) assuming a one-tailed test. Similar to the RE and CE results, the mean correlation coefficient across all validation intervals was also higher in each reconstruction nest than the maximum mean correlation achieved in the red noise benchmarking experiments (Table S3). Cross correlations between each of the derived nests during their period of overlap reflect strong coherence among the estimates (Table S4) and lend further support to the robustness of the reconstruction estimates of the individual nests.

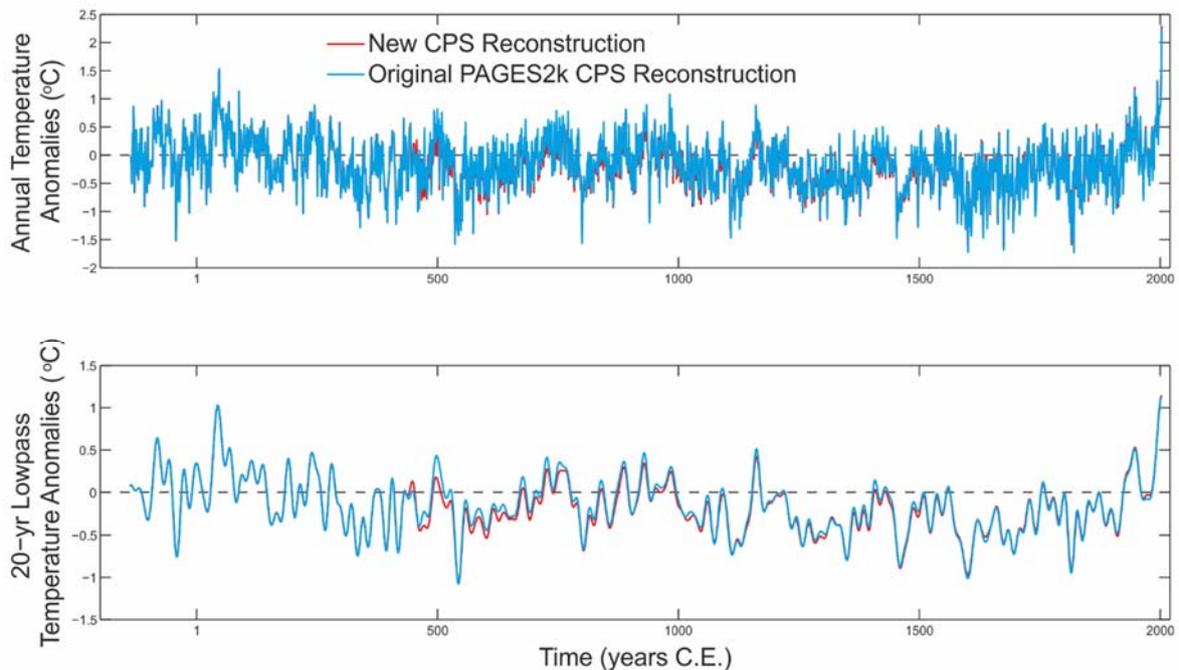
**Table S3:** Mean validation statistics (in bold) for each nest of the CPS reconstruction. Numbers given in parentheses represent the mean, standard deviation and maximum mean validation statistics for 1000 benchmarking experiments performed for each nest using AR(1) red noise time series equal to the number of proxies in each nest and autocorrelations that approximate the estimated persistence of each proxy record.

Nest	Mean Correlation (r)	Mean RE	Mean CE
1	<b>0.75</b> (0.01, 0.16, 0.52)	<b>0.53</b> (-0.63, 0.32, 0.11)	<b>0.40</b> (-1.15, 0.44, -0.15)
2	<b>0.74</b> (-0.01, 0.16, 0.47)	<b>0.47</b> (-0.63, 0.31, 0.12)	<b>0.31</b> (-1.15, 0.41, -0.15)
3	<b>0.76</b> (0.02, 0.16, 0.54)	<b>0.47</b> (-0.59, 0.31, 0.29)	<b>0.32</b> (-1.10, 0.42, 0.06)
4	<b>0.78</b> (0.00, 0.17, 0.55)	<b>0.50</b> (-0.60, 0.33, 0.27)	<b>0.36</b> (-1.12, 0.44, 0.04)
5	<b>0.79</b> (0.00, 0.17, 0.55)	<b>0.44</b> (-0.60, 0.33, 0.23)	<b>0.27</b> (-1.11, 0.44, -0.01)
6	<b>0.80</b> (0.00, 0.17, 0.48)	<b>0.50</b> (-0.58, 0.34, 0.25)	<b>0.35</b> (-1.10, 0.46, 0.03)
7	<b>0.80</b> (0.01, 0.17, 0.55)	<b>0.50</b> (-0.57, 0.32, 0.34)	<b>0.35</b> (-1.07, 0.42, 0.13)
8	<b>0.85</b> (0.02, 0.16, 0.48)	<b>0.63</b> (-0.53, 0.30, 0.18)	<b>0.52</b> (-1.03, 0.40, -0.09)

**Table S4:** Pearson's correlation coefficients between each CPS nest during the 1500-1849 CE common interval.

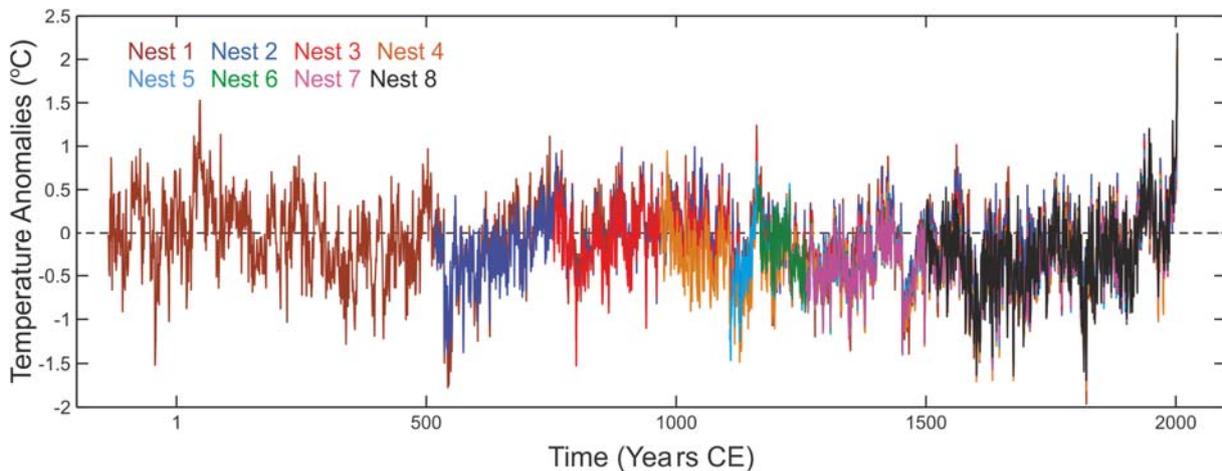
	Nest1	Nest2	Nest3	Nest4	Nest5	Nest6	Nest7	Nest8
Nest1	1	0.91	0.89	0.85	0.84	0.85	0.85	0.74
Nest2		1	0.96	0.93	0.92	0.93	0.92	0.76
Nest3			1	0.98	0.97	0.97	0.97	0.85
Nest4				1	0.97	0.97	0.97	0.85
Nest5					1	0.99	0.99	0.87
Nest6						1	0.99	0.88
Nest7							1	0.89
Nest8								1

Figure S2 shows a comparison between the new CPS based reconstruction (without two tree ring predictors including the updated Torneträsk MXD record) and the one published in PAGES 2k Consortium (2013). The two reconstructions are virtually identical and have a Pearson's correlation coefficient of 0.99 over the full reconstruction period.



**Figure S2:** Comparison between the new CPS based European summer mean reconstruction and the one published in PAGES 2k Consortium (2013). Bottom: as in the top panel but for 20-year low-pass filtered time-series.

The limited number of proxies might be an important caveat for the reconstructions. Figure S3 presents the sensitivity of the reconstruction to the number of underlying proxies. The descriptions of the nests and their quantitative comparisons are given in Tables S2-S4. While there are small differences between some nests, the covariance among each nest is remarkably consistent across all of the nests during their periods of overlap.



**Figure S3:** Comparison of the eight nests in the CPS-based reconstructions of mean European summer temperature anomalies for the period 138 BCE-2003 CE. The descriptions of the nests and their quantitative comparisons are given in Tables S2-S4.

In addition to the CPS methodology, alternative techniques were explored for application to the longest nest in the European mean summer temperature reconstruction (not shown). Ordinary least squares (OLS) regression was employed by using the same resampling scheme discussed in the methods section of the article. OLS was also tested with a static validation/calibration interval of 1850-1899 /1900-2003 CE and the residual modelling and Monte Carlo resampling described in Wahl and Smerdon (2012). While both iterations of OLS were similar to the corresponding CPS scenarios, the validation statistics for the OLS reconstructions were overall poorer than for CPS. Additionally, OLS reduced the variability more than CPS, although the difference of the validation period mean temperature was reconstructed too cold in the static-period OLS exercises. The RegEM-EIV method (Mann et al. 2008) was also tested using the same static validation/calibration intervals of 1850-1899 / 1900-2003 CE (not shown). This approach returned similar results as the CPS or the OLS methods in corresponding scenarios. Despite the above-described differences in validation statistics, the general characteristics of all derived reconstructions were comparable and provide further validation of the CPS nested temperature reconstruction.

## ***Bayesian Hierarchical Modelling (BHM)***

For the summer temperature reconstruction at grid point scale, we used a slightly modified version of the simple hierarchical model implemented by Werner et al. (2013) and Tingley and Huybers (2013). Here, we provide details on temperature field  $\mathbf{T}_t$  to be reconstructed, the field of the instrumental records  $\mathbf{I}_t$ , as well as the field of the temperature proxies  $\mathbf{P}_t$ . The assumptions on the inter-annual variability of each field and their interdependencies are subsequently given. Proxy data are centred to have zero mean during the 1500–2000 CE period to facilitate data processing. In contrast to the CPS application, the data-infilling step for the instrumental temperature observations was not necessary.

The hierarchical model in a paleoclimate reconstruction consists of a process-level model, describing the spatio-temporal evolution of the climate field, and a data-level that describes how proxies and instrumental data record the climate anomalies. The temperatures drive the realizations of the instrumental observations and the proxies through linear stochastic response functions. From these model assumptions, the corresponding conditional probability densities for both the temperature field and the model parameters can be derived. These are then combined with prior probability densities reflecting knowledge on the system using Bayes' rule. Here, the prior distributions are left as being very broad and uninformative (see parameters of Tingley and Huybers 2010a; Werner et al. 2013). The resulting posterior probability densities are estimated by using a Gibbs sampler. In contrast to Werner et al. (2013) and Tingley and Huybers (2013), in which all proxies of one type were constructed equally and thus shared a common proxy response function with one set of parameters, the reconstructions derived herein use a distinct parameter for each single proxy.

The equations as used also by Tingley and Huybers (2013) are:

$$\mathbf{T}_{t+1} - \mu = \alpha(\mathbf{T}_t - \mu) + \boldsymbol{\varepsilon}_{T,t} \quad (1a)$$

$$\mathbf{I}_t = \mathbf{H}_t(\mathbf{T}_t + \boldsymbol{\varepsilon}_{I,t})^T \quad (1b)$$

$$\mathbf{P}_t = \mathbf{H}_t(\beta_0 + \beta_1 \mathbf{T}_t + \beta_2 \mathbf{P}_{t-1} + \boldsymbol{\varepsilon}_{P,t})^T \quad (1c)$$

$$\boldsymbol{\varepsilon}_{T,t} \sim N(\mathbf{0}, \boldsymbol{\Sigma}), \boldsymbol{\Sigma}_{i,j} = \sigma^2 \exp(-\varphi |x_i - x_j|) \quad (1d)$$

$$\boldsymbol{\varepsilon}_{I,t} \sim N(\mathbf{0}, \mathbf{I} \tau_I^2) \quad (1e)$$

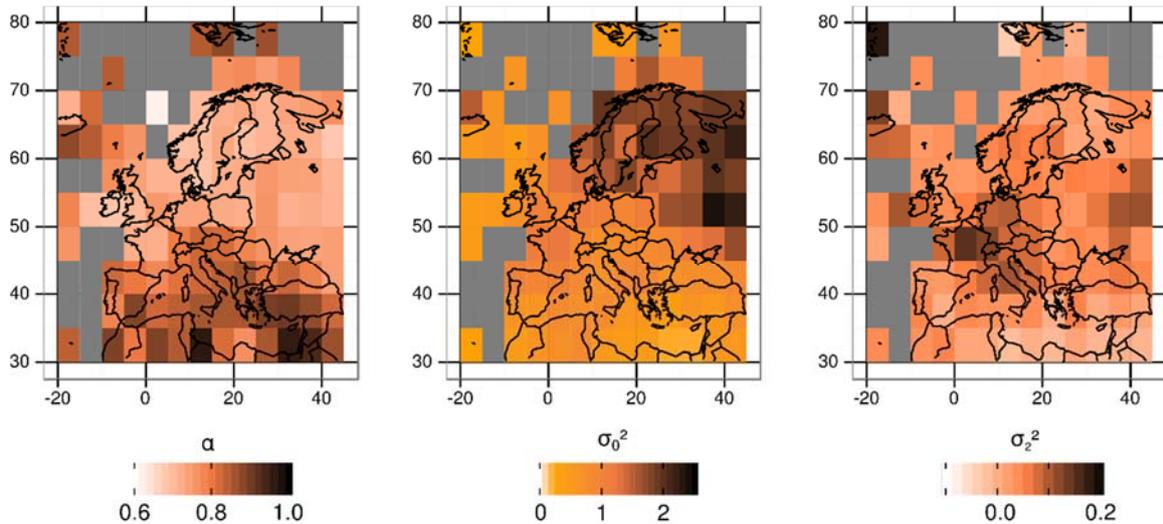
$$\boldsymbol{\varepsilon}_{P,t} \sim N(\mathbf{0}, \mathbf{I} \tau_P^2) \quad (1f)$$

Equation (1a) describes the process-level model, the temporal evolution of the temperature field  $\mathbf{T}_t$  for time index  $t$ , using an AR(1) process with uniform persistence  $\alpha$  and mean  $\mu$ . The inter-annual variability of the temperature field  $\boldsymbol{\varepsilon}_{T,t}$  is multivariate normal with zero mean and covariance matrix  $\boldsymbol{\Sigma}$ , eq. (1d). The spatial covariance matrix is homogeneous and decreases exponentially with orthodromic distance with a spatial correlation length of  $\varphi$ . The variance of the inter-annual local fluctuation is given by  $\sigma^2$ . The instrumental observations  $\mathbf{I}_t$  are assumed to be noisy representations of the true temperature at the location of observation (eq. 1b) with noise strength (variance)  $\tau_I^2$  (eq. 1e). The natural climate archives  $\mathbf{P}_t$  are modelled with a linear stochastic response function (eq. 1c) for latewood density and documentary evidence. The tree-ring width of one year is influenced, however, by the previous year's growth (Frank et al. 2007), which might be responsible for the additional long term memory as observed by Zhang et al (2015). The term  $\beta_2$  was therefore included to estimate this influence for TRW data. It was held fixed at zero for the other proxy types. The proxy noise strength is  $\tau_P^2$ . While the model does allow for one proxy type to be used at more than one location we have chosen to estimate all coefficients for each proxy series. This is in contrast to the original articles by Tingley and Huybers (2010a,b) and also Tingley and Huybers (2013), in which a single proxy transfer function with only one set of global parameters was used for more than one location. The  $\mathbf{H}_t$  matrices contain ones at locations where proxy or instrumental data are present at time step  $t$ , and zero otherwise.

As proposed by Gelman et al. (2003), the reconstruction using Bayesian inference is done in two steps. The first step is the actual inference step, performed with a Gibbs sampler over a subset of the proxy data and the full instrumental data. The second step consist of a predictive experiment following Gelman et al. (2003); the parameters are sampled from the results in the inference step and temperatures are predicted while withholding the instrumental data, resulting in the full, two millennia long climate field reconstruction.

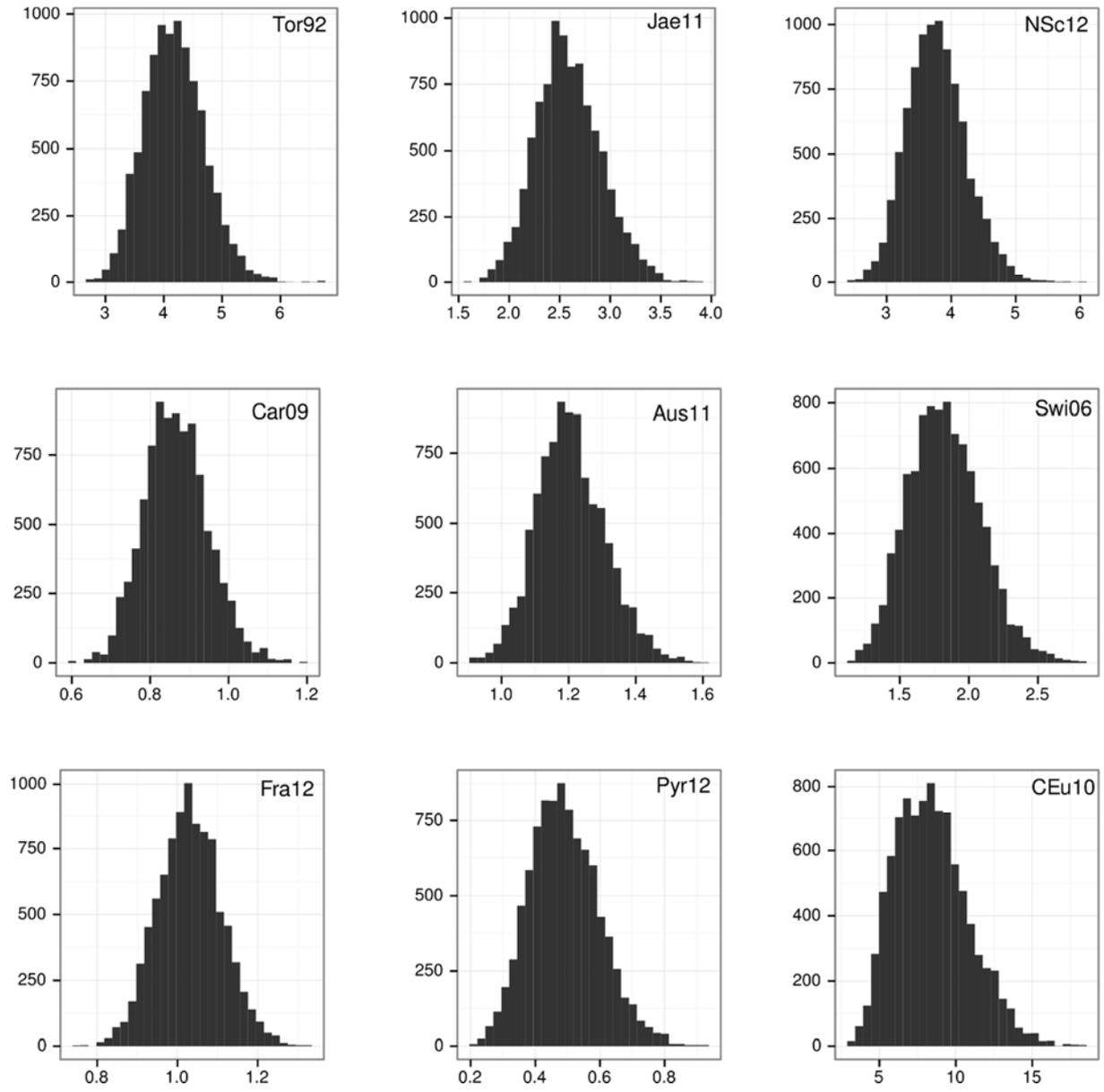
For the inference step, input data are first truncated to start at 755 CE, when four proxy series are available, and end at 2003 CE. The truncation helps avoid convergence issues prior to 754 CE when only two proxies are available. The Bayesian inversion is done using five chains of the Gibbs sampler that are run for 5000 steps each. The last half is checked for convergence using the Potential Scale Reduction Factor *Rhat* measure as defined in Gelman et al. (2003). All four chains converge after about 2000 steps and the *Rhat* values do not deviate more than  $10^{-3}$  from unity. These Gibbs sampler runs are used to create a set of likely model parameter distributions. These are then used to perform predictive experiments for the temperature field over the full reconstruction period 138 BCE to 2003 CE using the complete proxy data while withholding the instrumental observations. The predictive experiment is run as a (simplified) Gibbs sampler, initialized with estimates from the first run. The parameters are sampled from the distributions estimated in the inference step and the temperatures are estimated conditional on these. In this way the parameter estimation is not influenced by a data set that is too sparse in the past (before 755 CE). Additionally, the reconstructions over the instrumental period can be checked against the instrumental dataset. Again, only the last iterations of the Gibbs sampler are used, this time as the final ensemble of gridded temperature reconstructions. From this ensemble we calculate measures, usually showing the ensemble mean of the result as well as the upper and lower 2.5% quantiles of the distribution as uncertainty estimates.

To assess whether a uniform persistence term  $\alpha$  is appropriate in this context, we apply the Kramers-Moyal-Expansion (KME, Risken 1989, Stemler et al. 2007, Werner et al. 2014) to the instrumental data on the grid scale. From the drift term in the stochastic function we can derive the persistence term  $\alpha$ . The results are shown in Fig. S3 (left panel). The persistence is roughly uniform over the landmass. The local strength of the inter-annual variability,  $\sigma$ , of summer temperatures is presented in Fig. S4 (center panel). Local inter-annual variability is strongest in the Scandinavian/western Russian regions. Deviations from the additive white noise model (eq. 1a) are shown in Fig. S4 (right panel). The results support our approach of first rescaling the instrumental data to zero mean and uniform standard deviation and then assuming homogenous model parameters in the reconstruction, but note that the amount of data used in the KME is insufficient to obtain exact values for the second and higher-order terms.



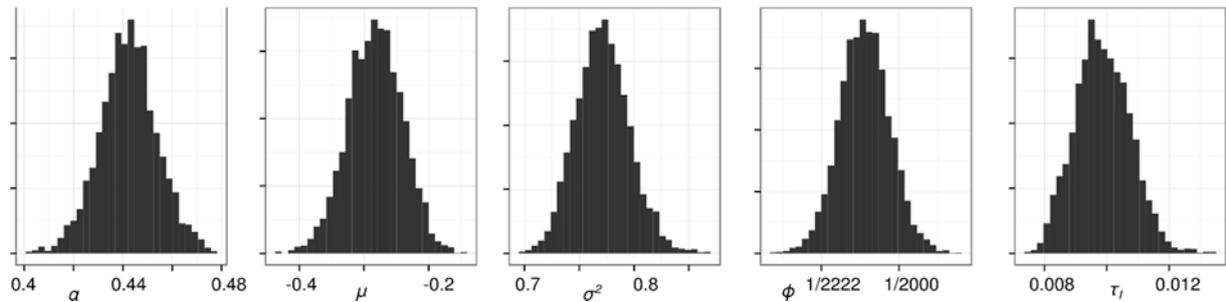
**Figure S4:** Persistence, inter-annual variability and deviation from additive white noise model (left, center and right panel respectively), estimated through Kramers-Moyal-Expansion from instrumental data CRUTEM 4v (Jones et al. 2012), JJA, 1850-2010 CE. Persistence is close to 0.7 for most of the grid cells. The difference in variability is removed by standardization of data prior to the reconstruction. Deviations from the additive white noise model are small.

Histograms of the proxy Signal to Noise Ratio (SNR) calculated from the drawn parameters are shown in Fig. S5. Most of the tree-ring data show high SNR values, above and exceeding 1, with the exception of the data from the Pyrenees. Of the natural climate archives, the MXD tree-ring series from Torneträsk (Melvin et al. 2013; Esper et al. 2014) and Northern Scandinavia (Esper et al. 2012) show the strongest values. The SNR of the documentary data is artificially inflated, as it contains instrumental data in the calibration period.



**Figure S5:** Histograms of estimated SNR for each proxy calculated from the parameters inferred from the BHM. Details on the proxy data can be found in Table S1.

Figure S6 shows draws of the parameters for the spatiotemporal temperature model (eq. 1a), the persistence  $\alpha$ , the mean  $\mu$ , the strength of the inter-annual variability  $\sigma$ , and the spatial correlation length  $\phi$ , as well as the instrumental noise variance  $\tau^2$ . The model parameters are close to the results of the preliminary analysis in Fig. S4.



**Figure S6:** Histograms of the model parameters (first four panels, eq. 1a) and the strength of the instrumental noise (right panel, eq. 1b).

Using all of the predictors used in the European reconstruction of PAGES 2k Consortium (2013) results in zero signal content for the two here excluded (Tatra and Albanian) tree ring series. Thus, the resulting reconstruction is virtually identical – that is, the posterior distributions of the temperatures at all locations cannot be distinguished. The BHM algorithm was therefore able to filter out a posteriori unsuitable set of proxy data.

## ***Comparison of recent and earlier warm periods***

To test whether recent warm conditions are unusual in the context of the two full reconstructions presented in Fig. 1C we made a series of simple comparisons using 2-sample t tests. We present results for individual t tests, but also for tests that have been corrected for first order autocorrelation by adjusting the variance and estimating the equivalent sample size and thus the adjusted degrees of freedom. To take account of the increased likelihood of ‘false positive’ results that arise with multiple testing, we use two methods: a false discovery rate controlling method (FDR; Benjamini and Hochberg, 1995) and the much harsher Bonferroni correction (Dunn, 1961; Field, 2013). We use two-tail tests because we did not predict the sign of the differences in advance.

Comparing the mean temperature anomaly of the 20th century with every other century the two reconstructions differ only slightly. In the CPS reconstruction only the 1st century CE has a mean temperature anomaly higher than that of the 20th century and the difference is statistically significant at the 5% level using the simple t test and remains so when first order autocorrelation is taken into account (Table S5). However, after correction for multiple testing the difference is not significant. In the BHM reconstruction (Table S6) there are two century means that are very slightly ( $<0.1$  °C) warmer but neither is significantly different from the 20th century even using a simple t test with no corrections. The pattern of cold centuries is similar but not identical in the two reconstructions. Using the CPS data 14 centuries are significantly different from (colder than) the 20th using the FDR correction and 12 remain so even using the Bonferroni correction. Using the BHM data the equivalent values are 14 and 11. In both reconstructions the first four centuries of the first millennium and the 8th and 10th centuries are not significantly different from the 20th. The centuries within the Little Ice Age are strongly significantly different from the 20th century in both reconstructions.

The same procedure was repeated using the second half of the 20th century as the reference period and comparing with every other half century. In the CPS reconstruction (Table S7) there are four half centuries, all in the early first millennium, that are very slightly warmer but the differences are not statistically significant even using simple t tests with no corrections. Using the BHM data (Table S8), there are three half centuries that are slightly warmer but again the differences are not significant even using simple t tests with no corrections. The pattern of significant cold half centuries largely mirrors the pattern shown for warm centuries.

The last 30 years in both reconstructions are very warm relative to the full records and when compared to contiguous sets of 30 years (Tables S9 and S10) there is only one interval (24 to 53CE) that is slightly warmer. These samples are too short to apply a correction for autocorrelation, but after applying a simple t test the warmest 30-year interval is not significantly different from the last 30 years of the proxy records.

Although the proxy-based climate reconstructions only extend as far as 2003, the equivalent instrumental data used for calibration and scaling extends to cover the summer of 2015. The mean temperature of the past 30 years in the instrumental data (1986-2015 CE) is much higher than that of any 30-year period over the last two millennia. When compared with the same contiguous 30-year periods used above (Tables S11 and S12) there is only one, in the 1st century (24-53 CE), that is not significantly colder even when using the harshest correction for family-wise error. It is extremely likely that the average European summer temperatures of the last 30 years have been anomalously warm with respect to the last two millennia.

**Table S5.** Mean temperature anomaly for each century and the difference (Diff) from the 20th century using the CPS reconstruction. Significance levels are given for each individual two-tail t-test, for tests taking account of first order autocorrelation (Cor AC) and then using two corrections for multiple testing; the False Discovery Rate ( $\alpha = 0.05$ ) and the Bonferroni correction for family-wise error ( $\alpha = 0.05$ ). Warmer periods and significant differences are identified in orange, significant cooler periods in blue ( $p < 0.05$ ).

CPS data: centuries						
C	Mean	Diff	T test	Cor AC	FDR	Bonf
20	<b>0.09</b>					
19	-0.32	-0.41	<0.001	<0.001	Yes	Yes
18	-0.24	-0.34	<0.001	<0.001	Yes	Yes
17	-0.52	-0.61	<0.001	<0.001	Yes	Yes
16	-0.29	-0.38	<0.001	<0.001	Yes	Yes
15	-0.26	-0.35	<0.001	<0.001	Yes	Yes
14	-0.41	-0.50	<0.001	<0.001	Yes	Yes
13	-0.33	-0.42	<0.001	<0.001	Yes	Yes
12	-0.24	-0.33	<0.001	<0.001	Yes	Yes
11	-0.26	-0.35	<0.001	<0.001	Yes	Yes
10	0.08	-0.01	0.823	0.850	No	No
9	-0.10	-0.20	0.001	0.006	Yes	No
8	0.09	-0.01	0.922	0.936	No	No
7	-0.18	-0.27	<0.001	<0.001	Yes	Yes
6	-0.26	-0.36	<0.001	<0.001	Yes	Yes
5	-0.13	-0.22	<0.001	0.005	Yes	No
4	-0.37	-0.46	<0.001	<0.001	Yes	Yes
3	0.02	-0.07	0.245	0.340	No	No
2	0.04	-0.06	0.340	0.439	No	No
1	0.27	0.17	0.011	0.043	No	No
0	0.06	-0.03	0.635	0.708	No	No

**Table S6.** As Table S5 but for the BHM reconstruction

<b>BHM data: centuries</b>						
C	Mean	Diff	T test	Cor AC	FDR	Bonf
20	<b>0.16</b>					
19	-0.32	-0.48	<0.001	<0.001	Yes	Yes
18	-0.25	-0.42	<0.001	<0.001	Yes	Yes
17	-0.51	-0.68	<0.001	<0.001	Yes	Yes
16	-0.31	-0.47	<0.001	<0.001	Yes	Yes
15	-0.24	-0.40	<0.001	<0.001	Yes	Yes
14	-0.32	-0.48	<0.001	<0.001	Yes	Yes
13	-0.07	-0.23	0.001	0.010	Yes	No
12	0.00	-0.17	0.036	0.101	No	No
11	-0.20	-0.36	<0.001	<0.001	Yes	Yes
10	0.25	0.08	0.227	0.316	No	No
9	-0.02	-0.19	0.005	0.022	Yes	No
8	0.04	-0.13	0.051	0.102	No	No
7	-0.21	-0.37	<0.001	<0.001	Yes	Yes
6	-0.33	-0.49	<0.001	<0.001	Yes	Yes
5	-0.12	-0.28	<0.001	0.001	Yes	Yes
4	-0.34	-0.50	<0.001	<0.001	Yes	Yes
3	-0.03	-0.19	0.003	0.015	Yes	No
2	0.02	-0.14	0.022	0.065	No	No
1	0.26	0.09	0.185	0.299	No	No
0	0.07	-0.09	0.195	0.311	No	No

**Table S7.** As Table S5 but for the mean temperature anomaly of each half century and the difference (Diff) from the second half of the 20th century using the CPS reconstruction

<b>CPS data: half centuries</b>						
C	Mean	Diff	T test	Cor AC	FDR	Bonf
20	<b>0.18</b>					
20	0.01	-0.17	0.072	0.151	No	No
19	-0.19	-0.37	<0.001	<0.001	Yes	Yes
19	-0.44	-0.62	<0.001	<0.001	Yes	Yes
18	-0.14	-0.31	<0.001	0.001	Yes	Yes
18	-0.35	-0.52	<0.001	<0.001	Yes	Yes
17	-0.47	-0.65	<0.001	<0.001	Yes	Yes
17	-0.56	-0.74	<0.001	<0.001	Yes	Yes
16	-0.40	-0.58	<0.001	<0.001	Yes	Yes
16	-0.17	-0.35	<0.001	<0.001	Yes	Yes
15	-0.50	-0.68	<0.001	<0.001	Yes	Yes
15	-0.02	-0.19	0.007	0.010	Yes	No
14	-0.34	-0.52	<0.001	<0.001	Yes	Yes
14	-0.47	-0.65	<0.001	<0.001	Yes	Yes
13	-0.48	-0.66	<0.001	<0.001	Yes	Yes
13	-0.18	-0.36	<0.001	<0.001	Yes	Yes
12	0.03	-0.15	0.063	0.129	No	No
12	-0.50	-0.68	<0.001	<0.001	Yes	Yes
11	-0.25	-0.42	<0.001	<0.001	Yes	Yes
11	-0.27	-0.45	<0.001	<0.001	Yes	Yes
10	0.11	-0.07	0.379	0.440	No	No
10	0.05	-0.13	0.142	0.243	No	No
9	-0.02	-0.19	0.024	0.069	No	No
9	-0.19	-0.37	<0.001	<0.001	Yes	Yes
8	0.03	-0.14	0.110	0.205	No	No
8	0.14	-0.04	0.638	0.687	No	No
7	-0.11	-0.29	<0.001	0.002	Yes	No
7	-0.24	-0.42	<0.001	<0.001	Yes	Yes
6	-0.28	-0.46	<0.001	<0.001	Yes	Yes
6	-0.25	-0.42	<0.001	0.002	Yes	No
5	-0.10	-0.28	0.002	0.012	Yes	No
5	-0.16	-0.34	<0.001	0.004	Yes	No
4	-0.33	-0.50	<0.001	<0.001	Yes	Yes
4	-0.41	-0.58	<0.001	<0.001	Yes	Yes

3	-0.04	-0.22	0.011	0.042	No	No
3	0.08	-0.09	0.266	0.379	No	No
2	-0.11	-0.29	<0.001	0.006	Yes	No
2	0.19	0.01	0.869	0.878	No	No
1	0.25	0.07	0.397	0.491	No	No
1	0.28	0.11	0.288	0.419	No	No
0	-0.10	-0.28	0.004	0.026	Yes	No
0	0.22	0.04	0.607	0.694	No	No

**Table S8.** As Table S7 but for the BHM reconstruction

<b>BHM data: half centuries</b>						
C	Mean	Diff	T test	Cor AC	FDR	Bonf.
20	<b>0.22</b>					
20	0.11	-0.11	0.326	0.432	No	No
19	-0.16	-0.38	<0.001	<0.001	Yes	Yes
19	-0.47	-0.69	<0.001	<0.001	Yes	Yes
18	-0.17	-0.39	<0.001	<0.001	Yes	Yes
18	-0.34	-0.55	<0.001	<0.001	Yes	Yes
17	-0.47	-0.69	<0.001	<0.001	Yes	Yes
17	-0.56	-0.77	<0.001	<0.001	Yes	Yes
16	-0.43	-0.65	<0.001	<0.001	Yes	Yes
16	-0.19	-0.41	<0.001	<0.001	Yes	Yes
15	-0.46	-0.68	<0.001	<0.001	Yes	Yes
15	-0.01	-0.23	0.003	0.003	Yes	No
14	-0.25	-0.47	<0.001	<0.001	Yes	Yes
14	-0.38	-0.60	<0.001	<0.001	Yes	Yes
13	-0.34	-0.55	<0.001	<0.001	Yes	Yes
13	0.20	-0.02	0.801	0.846	No	No
12	0.28	0.06	0.506	0.597	No	No
12	-0.28	-0.50	<0.001	<0.001	Yes	Yes
11	-0.21	-0.43	<0.001	0.001	Yes	Yes
11	-0.19	-0.40	<0.001	<0.001	Yes	Yes
10	0.30	0.08	0.363	0.440	No	No
10	0.20	-0.02	0.813	0.851	No	No
9	0.02	-0.19	0.042	0.106	No	No
9	-0.07	-0.29	<0.001	0.003	Yes	No
8	-0.01	-0.23	0.013	0.046	No	No
8	0.09	-0.13	0.089	0.142	No	No
7	-0.14	-0.36	<0.001	<0.001	Yes	Yes
7	-0.28	-0.50	<0.001	<0.001	Yes	Yes
6	-0.38	-0.60	<0.001	<0.001	Yes	Yes
6	-0.27	-0.49	<0.001	0.001	Yes	Yes
5	-0.10	-0.31	0.001	0.006	Yes	No
5	-0.14	-0.36	<0.001	0.003	Yes	No
4	-0.27	-0.48	<0.001	<0.001	Yes	Yes
4	-0.41	-0.63	<0.001	<0.001	Yes	Yes
3	-0.08	-0.30	0.001	0.004	Yes	No

3	0.03	-0.19	0.026	0.073	No	No
2	-0.12	-0.34	<0.001	0.002	Yes	No
2	0.16	-0.06	0.464	0.523	No	No
1	0.21	-0.003	0.969	0.974	No	No
1	0.30	0.08	0.426	0.547	No	No
0	0.00	-0.21	0.026	0.086	No	No
0	0.15	-0.07	0.408	0.523	No	No

**Table S9.** As Table S5 but for the mean temperature anomaly of contiguous 30-year periods and the difference (Diff) from the last 30 years of the record using the CPS reconstruction.

CPS data: 30 years						
Start	End	Mean	Diff	t test	FDR	Bonf.
1974	2003	<b>0.39</b>				
1944	1973	0.19	-0.20	0.156	No	No
1914	1943	0.07	-0.32	0.019	Yes	No
1884	1913	-0.34	-0.73	<0.001	Yes	Yes
1854	1883	-0.13	-0.51	<0.001	Yes	Yes
1824	1853	-0.33	-0.71	<0.001	Yes	Yes
1794	1823	-0.46	-0.85	<0.001	Yes	Yes
1764	1793	-0.22	-0.60	<0.001	Yes	Yes
1734	1763	-0.17	-0.55	<0.001	Yes	Yes
1704	1733	-0.36	-0.74	<0.001	Yes	Yes
1674	1703	-0.59	-0.98	<0.001	Yes	Yes
1644	1673	-0.31	-0.70	<0.001	Yes	Yes
1614	1643	-0.49	-0.87	<0.001	Yes	Yes
1584	1613	-0.79	-1.18	<0.001	Yes	Yes
1554	1583	-0.24	-0.63	<0.001	Yes	Yes
1524	1553	-0.19	-0.58	<0.001	Yes	Yes
1494	1523	-0.18	-0.56	<0.001	Yes	Yes
1464	1493	-0.40	-0.78	<0.001	Yes	Yes
1434	1463	-0.41	-0.79	<0.001	Yes	Yes
1404	1433	0.01	-0.37	0.004	Yes	No
1374	1403	-0.29	-0.68	<0.001	Yes	Yes
1344	1373	-0.47	-0.85	<0.001	Yes	Yes
1314	1343	-0.36	-0.75	<0.001	Yes	Yes
1284	1313	-0.47	-0.86	<0.001	Yes	Yes
1254	1283	-0.50	-0.88	<0.001	Yes	Yes
1224	1253	-0.34	-0.72	<0.001	Yes	Yes
1194	1223	-0.03	-0.42	0.001	Yes	No
1164	1193	-0.03	-0.42	0.002	Yes	No
1134	1163	-0.08	-0.47	0.001	Yes	No
1104	1133	-0.64	-1.02	<0.001	Yes	Yes
1074	1103	-0.24	-0.63	<0.001	Yes	Yes
1044	1073	-0.26	-0.65	<0.001	Yes	Yes
1014	1043	-0.29	-0.68	<0.001	Yes	Yes
984	1013	-0.03	-0.41	0.002	Yes	No

954	983	0.11	-0.27	0.042	No	No
924	953	0.18	-0.21	0.135	No	No
894	923	-0.08	-0.47	0.001	Yes	Yes
864	893	0.14	-0.25	0.069	No	No
834	863	-0.13	-0.52	<0.001	Yes	Yes
804	833	-0.28	-0.67	<0.001	Yes	Yes
774	803	-0.21	-0.60	<0.001	Yes	Yes
744	773	0.26	-0.13	0.330	No	No
714	743	0.19	-0.20	0.118	No	No
684	713	-0.11	-0.50	<0.001	Yes	Yes
654	683	-0.06	-0.45	0.001	Yes	No
624	653	-0.25	-0.63	<0.001	Yes	Yes
594	623	-0.26	-0.65	<0.001	Yes	Yes
564	593	-0.29	-0.68	<0.001	Yes	Yes
534	563	-0.55	-0.93	<0.001	Yes	Yes
504	533	0.00	-0.38	0.004	Yes	No
474	503	0.06	-0.33	0.022	Yes	No
444	473	-0.20	-0.58	<0.001	Yes	Yes
414	443	-0.27	-0.65	<0.001	Yes	Yes
384	413	-0.22	-0.60	<0.001	Yes	Yes
354	383	-0.25	-0.64	<0.001	Yes	Yes
324	353	-0.46	-0.85	<0.001	Yes	Yes
294	323	-0.28	-0.66	<0.001	Yes	Yes
264	293	-0.06	-0.45	0.002	Yes	No
234	263	0.23	-0.15	0.259	No	No
204	233	-0.05	-0.44	0.002	Yes	No
174	203	0.01	-0.38	0.005	Yes	No
144	173	-0.26	-0.65	<0.001	Yes	Yes
114	143	0.26	-0.13	0.293	No	No
84	113	0.15	-0.24	0.074	No	No
54	83	0.29	-0.10	0.455	No	No
24	53	0.55	0.17	0.274	No	No
-7	23	0.08	-0.30	0.030	Yes	No
-37	-8	-0.05	-0.44	0.002	Yes	No
-67	-38	-0.08	-0.47	0.003	Yes	No
-97	-68	0.29	-0.10	0.460	No	No
-127	-98	-0.10	-0.49	0.001	Yes	Yes

**Table S10.** As Table S9 but for the BHM reconstruction.

<b>BHM data: 30 years</b>						
Start	End	Mean	Diff	t test	FDR	Bonf
1974	2003	<b>0.42</b>				
1944	1973	0.27	-0.15	0.334	No	No
1914	1943	0.20	-0.22	0.129	No	No
1884	1913	-0.34	-0.76	<0.001	Yes	Yes
1854	1883	-0.10	-0.52	<0.001	Yes	Yes
1824	1853	-0.35	-0.77	<0.001	Yes	Yes
1794	1823	-0.48	-0.90	<0.001	Yes	Yes
1764	1793	-0.24	-0.66	<0.001	Yes	Yes
1734	1763	-0.23	-0.65	<0.001	Yes	Yes
1704	1733	-0.32	-0.74	<0.001	Yes	Yes
1674	1703	-0.62	-1.04	<0.001	Yes	Yes
1644	1673	-0.28	-0.70	<0.001	Yes	Yes
1614	1643	-0.52	-0.94	<0.001	Yes	Yes
1584	1613	-0.79	-1.20	<0.001	Yes	Yes
1554	1583	-0.24	-0.66	<0.001	Yes	Yes
1524	1553	-0.19	-0.61	<0.001	Yes	Yes
1494	1523	-0.24	-0.66	<0.001	Yes	Yes
1464	1493	-0.29	-0.71	<0.001	Yes	Yes
1434	1463	-0.43	-0.85	<0.001	Yes	Yes
1404	1433	0.00	-0.42	0.002	Yes	No
1374	1403	-0.19	-0.61	<0.001	Yes	Yes
1344	1373	-0.38	-0.80	<0.001	Yes	Yes
1314	1343	-0.32	-0.74	<0.001	Yes	Yes
1284	1313	-0.34	-0.76	<0.001	Yes	Yes
1254	1283	-0.35	-0.77	<0.001	Yes	Yes
1224	1253	-0.05	-0.47	0.001	Yes	Yes
1194	1223	0.45	0.03	0.812	No	No
1164	1193	0.14	-0.28	0.050	No	No
1134	1163	0.30	-0.12	0.399	No	No
1104	1133	-0.54	-0.96	<0.001	Yes	Yes
1074	1103	-0.08	-0.50	0.001	Yes	No
1044	1073	-0.39	-0.81	<0.001	Yes	Yes
1014	1043	-0.16	-0.58	<0.001	Yes	Yes
984	1013	0.11	-0.31	0.029	Yes	No
954	983	0.36	-0.06	0.648	No	No

924	953	0.27	-0.15	0.316	No	No
894	923	0.04	-0.38	0.009	Yes	No
864	893	0.19	-0.23	0.123	No	No
834	863	-0.05	-0.47	0.001	Yes	No
804	833	-0.15	-0.57	<0.001	Yes	Yes
774	803	-0.14	-0.56	<0.001	Yes	Yes
744	773	0.10	-0.32	0.021	Yes	No
714	743	0.15	-0.27	0.040	No	No
684	713	-0.18	-0.60	0.000	Yes	Yes
654	683	-0.06	-0.48	0.001	Yes	Yes
624	653	-0.29	-0.71	<0.001	Yes	Yes
594	623	-0.35	-0.77	<0.001	Yes	Yes
564	593	-0.37	-0.79	<0.001	Yes	Yes
534	563	-0.64	-1.06	<0.001	Yes	Yes
504	533	-0.01	-0.43	0.002	Yes	No
474	503	0.08	-0.34	0.024	Yes	No
444	473	-0.22	-0.64	<0.001	Yes	Yes
414	443	-0.24	-0.66	<0.001	Yes	Yes
384	413	-0.17	-0.59	<0.001	Yes	Yes
354	383	-0.19	-0.61	<0.001	Yes	Yes
324	353	-0.45	-0.87	<0.001	Yes	Yes
294	323	-0.31	-0.73	<0.001	Yes	Yes
264	293	-0.10	-0.52	<0.001	Yes	Yes
234	263	0.13	-0.29	0.041	No	No
204	233	-0.06	-0.48	0.001	Yes	No
174	203	-0.03	-0.45	0.001	Yes	No
144	173	-0.25	-0.67	<0.001	Yes	< Yes
114	143	0.23	-0.19	0.143	No	No
84	113	0.13	-0.29	0.035	Yes	No
54	83	0.24	-0.18	0.185	No	No
24	53	0.56	0.14	0.336	No	No
-7	23	0.12	-0.30	0.046	No	No
-37	-8	0.03	-0.39	0.007	Yes	No
-67	-38	-0.04	-0.45	0.004	Yes	No
-97	-68	0.16	-0.26	0.071	No	No
-127	-98	-0.11	-0.53	<0.001	Yes	Yes

**Table S11.** As Table S5 but for the mean temperature anomaly of contiguous 30-year periods and the difference (Diff) from the last 30 years of the instrumental record using the CPS reconstruction.

<b>CPS data: instrumental data for last 30 years</b>						
Start	End	Mean	Diff	t test	FDR	Bonf.
1986	2015	<b>0.90</b>				
1944	1973	0.19	-0.71	<0.001	Yes	Yes
1914	1943	0.07	-0.83	<0.001	Yes	Yes
1884	1913	-0.34	-1.24	<0.001	Yes	Yes
1854	1883	-0.13	-1.03	<0.001	Yes	Yes
1824	1853	-0.33	-1.23	<0.001	Yes	Yes
1794	1823	-0.46	-1.36	<0.001	Yes	Yes
1764	1793	-0.22	-1.12	<0.001	Yes	Yes
1734	1763	-0.17	-1.07	<0.001	Yes	Yes
1704	1733	-0.36	-1.26	<0.001	Yes	Yes
1674	1703	-0.59	-1.49	<0.001	Yes	Yes
1644	1673	-0.31	-1.21	<0.001	Yes	Yes
1614	1643	-0.49	-1.39	<0.001	Yes	Yes
1584	1613	-0.79	-1.69	<0.001	Yes	Yes
1554	1583	-0.24	-1.14	<0.001	Yes	Yes
1524	1553	-0.19	-1.09	<0.001	Yes	Yes
1494	1523	-0.18	-1.08	<0.001	Yes	Yes
1464	1493	-0.40	-1.30	<0.001	Yes	Yes
1434	1463	-0.41	-1.31	<0.001	Yes	Yes
1404	1433	0.01	-0.89	<0.001	Yes	Yes
1374	1403	-0.29	-1.19	<0.001	Yes	Yes
1344	1373	-0.47	-1.37	<0.001	Yes	Yes
1314	1343	-0.36	-1.26	<0.001	Yes	Yes
1284	1313	-0.47	-1.37	<0.001	Yes	Yes
1254	1283	-0.50	-1.40	<0.001	Yes	Yes
1224	1253	-0.34	-1.24	<0.001	Yes	Yes
1194	1223	-0.03	-0.93	<0.001	Yes	Yes
1164	1193	-0.03	-0.93	<0.001	Yes	Yes
1134	1163	-0.08	-0.98	<0.001	Yes	Yes
1104	1133	-0.64	-1.54	<0.001	Yes	Yes
1074	1103	-0.24	-1.14	<0.001	Yes	Yes
1044	1073	-0.26	-1.16	<0.001	Yes	Yes
1014	1043	-0.29	-1.19	<0.001	Yes	Yes

984	1013	-0.03	-0.93	<0.001	Yes	Yes
954	983	0.11	-0.79	<0.001	Yes	Yes
924	953	0.18	-0.72	<0.001	Yes	Yes
894	923	-0.08	-0.98	<0.001	Yes	Yes
864	893	0.14	-0.76	<0.001	Yes	Yes
834	863	-0.13	-1.03	<0.001	Yes	Yes
804	833	-0.28	-1.18	<0.001	Yes	Yes
774	803	-0.21	-1.11	<0.001	Yes	Yes
744	773	0.26	-0.64	<0.001	Yes	Yes
714	743	0.19	-0.71	<0.001	Yes	Yes
684	713	-0.11	-1.02	<0.001	Yes	Yes
654	683	-0.06	-0.96	<0.001	Yes	Yes
624	653	-0.25	-1.15	<0.001	Yes	Yes
594	623	-0.26	-1.16	<0.001	Yes	Yes
564	593	-0.29	-1.19	<0.001	Yes	Yes
534	563	-0.55	-1.45	<0.001	Yes	Yes
504	533	0.00	-0.90	<0.001	Yes	Yes
474	503	0.06	-0.84	<0.001	Yes	Yes
444	473	-0.20	-1.10	<0.001	Yes	Yes
414	443	-0.27	-1.17	<0.001	Yes	Yes
384	413	-0.22	-1.12	<0.001	Yes	Yes
354	383	-0.25	-1.15	<0.001	Yes	Yes
324	353	-0.46	-1.36	<0.001	Yes	Yes
294	323	-0.28	-1.18	<0.001	Yes	Yes
264	293	-0.06	-0.96	<0.001	Yes	Yes
234	263	0.23	-0.67	<0.001	Yes	Yes
204	233	-0.05	-0.95	<0.001	Yes	Yes
174	203	0.01	-0.89	<0.001	Yes	Yes
144	173	-0.26	-1.16	<0.001	Yes	Yes
114	143	0.26	-0.64	<0.001	Yes	Yes
84	113	0.15	-0.75	<0.001	Yes	Yes
54	83	0.29	-0.61	<0.001	Yes	Yes
24	53	0.55	-0.35	0.015	Yes	No
-7	23	0.08	-0.82	<0.001	Yes	Yes
-37	-8	-0.05	-0.95	<0.001	Yes	Yes
-67	-38	-0.08	-0.98	<0.001	Yes	Yes
-97	-68	0.29	-0.61	<0.001	Yes	Yes
-127	-98	-0.10	-1.00	<0.001	Yes	Yes

*Table S12. As Table 11 but for the BHM reconstruction.*

<b>BHM reconstruction: instrumental data for last 30 years</b>						
Start	End	Mean	Diff	t test	FDR	Bonf.
1986	2015	<b>0.90</b>				
1944	1973	0.27	-0.63	<0.001	Yes	Yes
1914	1943	0.20	-0.70	<0.001	Yes	Yes
1884	1913	-0.34	-1.24	<0.001	Yes	Yes
1854	1883	-0.10	-1.00	<0.001	Yes	Yes
1824	1853	-0.35	-1.25	<0.001	Yes	Yes
1794	1823	-0.48	-1.38	<0.001	Yes	Yes
1764	1793	-0.24	-1.14	<0.001	Yes	Yes
1734	1763	-0.23	-1.13	<0.001	Yes	Yes
1704	1733	-0.32	-1.22	<0.001	Yes	Yes
1674	1703	-0.62	-1.52	<0.001	Yes	Yes
1644	1673	-0.28	-1.18	<0.001	Yes	Yes
1614	1643	-0.52	-1.42	<0.001	Yes	Yes
1584	1613	-0.79	-1.69	<0.001	Yes	Yes
1554	1583	-0.24	-1.14	<0.001	Yes	Yes
1524	1553	-0.19	-1.09	<0.001	Yes	Yes
1494	1523	-0.24	-1.14	<0.001	Yes	Yes
1464	1493	-0.29	-1.19	<0.001	Yes	Yes
1434	1463	-0.43	-1.33	<0.001	Yes	Yes
1404	1433	0.00	-0.90	<0.001	Yes	Yes
1374	1403	-0.19	-1.09	<0.001	Yes	Yes
1344	1373	-0.38	-1.28	<0.001	Yes	Yes
1314	1343	-0.32	-1.22	<0.001	Yes	Yes
1284	1313	-0.34	-1.24	<0.001	Yes	Yes
1254	1283	-0.35	-1.25	<0.001	Yes	Yes
1224	1253	-0.05	-0.95	<0.001	Yes	Yes
1194	1223	0.45	-0.45	<0.001	Yes	Yes
1164	1193	0.14	-0.76	<0.001	Yes	Yes
1134	1163	0.30	-0.60	<0.001	Yes	Yes
1104	1133	-0.54	-1.44	<0.001	Yes	Yes
1074	1103	-0.08	-0.98	<0.001	Yes	Yes
1044	1073	-0.39	-1.29	<0.001	Yes	Yes
1014	1043	-0.16	-1.06	<0.001	Yes	Yes
984	1013	0.11	-0.79	<0.001	Yes	Yes
954	983	0.36	-0.54	<0.001	Yes	Yes

924	953	0.27	-0.63	<0.001	Yes	Yes
894	923	0.04	-0.86	<0.001	Yes	Yes
864	893	0.19	-0.71	<0.001	Yes	Yes
834	863	-0.05	-0.95	<0.001	Yes	Yes
804	833	-0.15	-1.05	<0.001	Yes	Yes
774	803	-0.14	-1.04	<0.001	Yes	Yes
744	773	0.10	-0.80	<0.001	Yes	Yes
714	743	0.15	-0.75	<0.001	Yes	Yes
684	713	-0.18	-1.08	<0.001	Yes	Yes
654	683	-0.06	-0.96	<0.001	Yes	Yes
624	653	-0.29	-1.19	<0.001	Yes	Yes
594	623	-0.35	-1.25	<0.001	Yes	Yes
564	593	-0.37	-1.27	<0.001	Yes	Yes
534	563	-0.64	-1.54	<0.001	Yes	Yes
504	533	-0.01	-0.91	<0.001	Yes	Yes
474	503	0.08	-0.82	<0.001	Yes	Yes
444	473	-0.22	-1.12	<0.001	Yes	Yes
414	443	-0.24	-1.14	<0.001	Yes	Yes
384	413	-0.17	-1.07	<0.001	Yes	Yes
354	383	-0.19	-1.09	<0.001	Yes	Yes
324	353	-0.45	-1.35	<0.001	Yes	Yes
294	323	-0.31	-1.21	<0.001	Yes	Yes
264	293	-0.10	-1.00	<0.001	Yes	Yes
234	263	0.13	-0.77	<0.001	Yes	Yes
204	233	-0.06	-0.96	<0.001	Yes	Yes
174	203	-0.03	-0.93	<0.001	Yes	Yes
144	173	-0.25	-1.15	<0.001	Yes	Yes
114	143	0.23	-0.67	<0.001	Yes	Yes
84	113	0.13	-0.77	<0.001	Yes	Yes
54	83	0.24	-0.66	<0.001	Yes	Yes
24	53	0.56	-0.34	0.009	Yes	No
-7	23	0.12	-0.78	<0.001	Yes	Yes
-37	-8	0.03	-0.87	<0.001	Yes	Yes
-67	-38	-0.04	-0.94	<0.001	Yes	Yes
-97	-68	0.16	-0.74	<0.001	Yes	Yes
-127	-98	-0.11	-1.01	<0.001	Yes	Yes

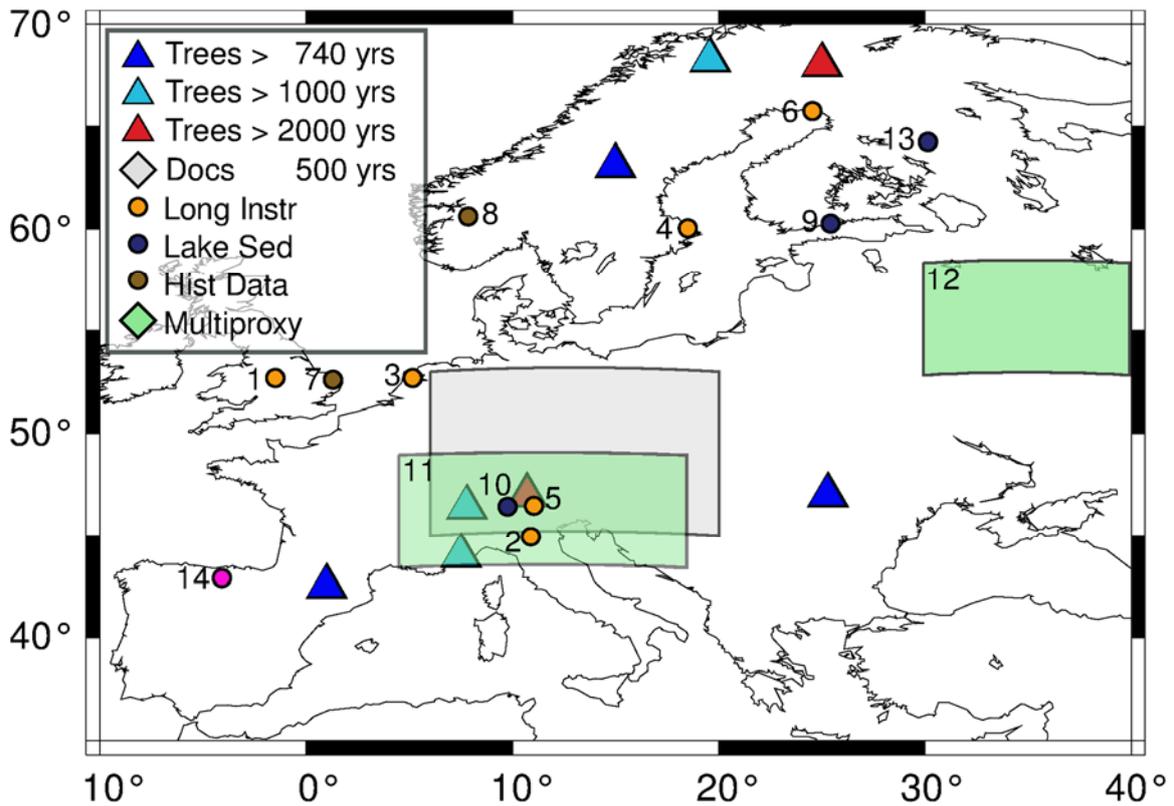
### ***Comparison between the new European summer temperature reconstruction and independent instrumental and low and high-resolution proxy based summer temperature estimates from Europe***

We compare the mean and the gridded BHM-based reconstruction with long independent station temperature series (Table S13; Figs. S7, S8) and summer temperature reconstructions from various proxy records (Table S13, Figs. S7, S9) which were not used for our reconstruction. In this context we evaluate the reconstruction skill by taking the results of the predictive run of the BHM reconstruction, estimated at the locations of the independent temperature data. Using all ensemble members, we calculate the Pearson's correlation coefficient and the standard deviation ratio (SDR) between the ensemble members of the predictive experiment and the independent summer temperature data prior to 1850 CE, the beginning of the CRUTEM 4v instrumental data (Jones et al. 2012). These are eventually averaged over all ensemble members. Where the temporal resolution of the reconstruction did not match that of the considered independent proxy data, the reconstruction was resampled and time averaged to match both the resolution and the averaging procedures used in these studies. Results are provided in Table S13 and shown in Figs. S8 and S9. Correlation coefficients are high between our reconstructed summer temperatures and long instrumental data from the Alps and Sweden close to proxy locations (Table S13; Fig. S8). Correlation coefficients with instrumental data from the Netherlands, Central England and Northern Italy are smaller but still statistically significant ( $p < 0.05$  level; Table S13; Fig. S8).

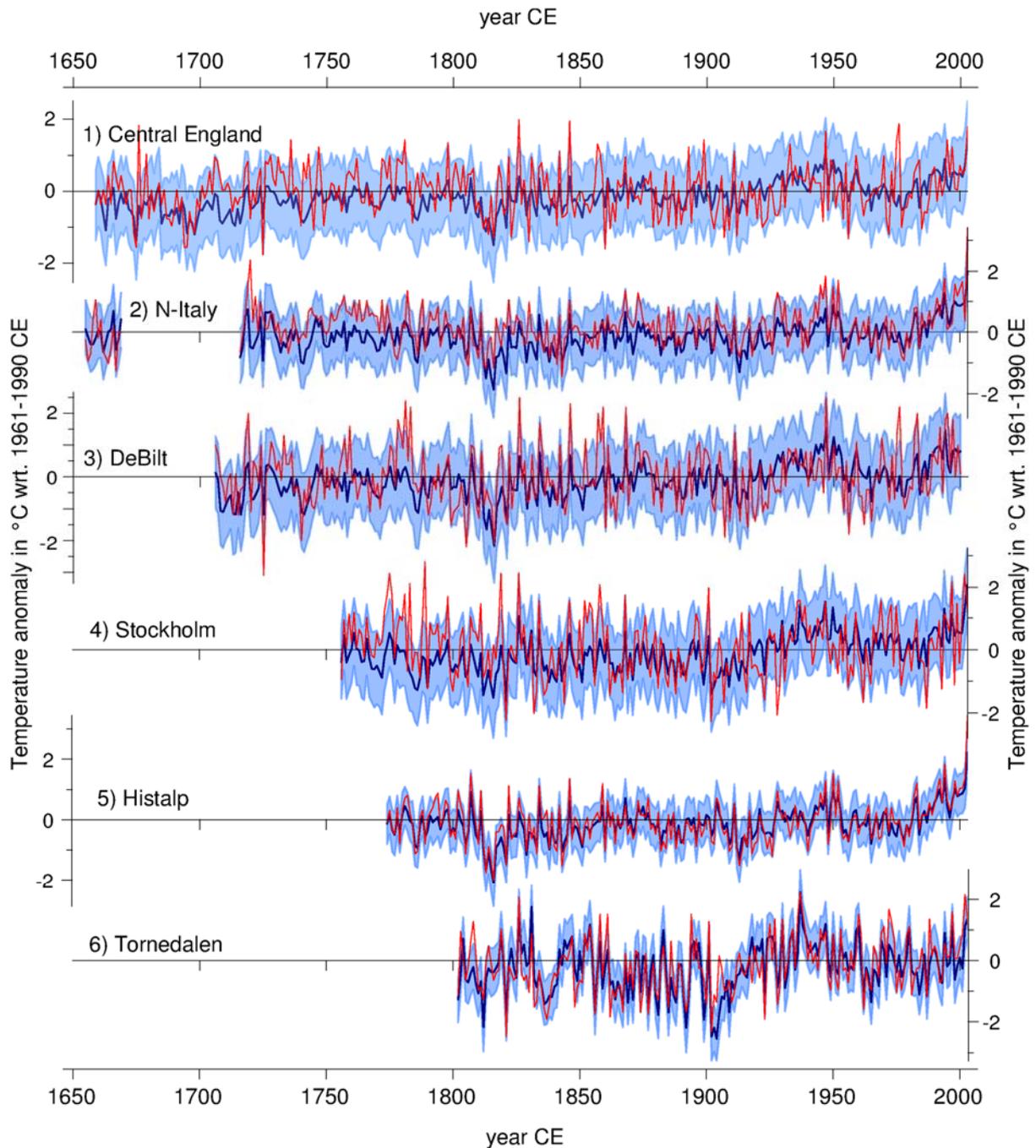
**Table S13:** Compilation of independent summer temperature reconstructions and long instrumental series used for comparisons with the BHM reconstruction. Mean correlation coefficients (\* significant at  $p < 0.05$  level) and mean standard deviation ratios (SDR) between reconstructed summer temperatures and independent proxy/instrumental data are shown together with coordinates and data type.  $\square$  not indicated in map, see Figs. S10 and S11

No, Region	East	North	r	SDR	Type	Period (CE)	Reference
1, CET	-1.5	52.7	0.28*	0.974	Long instrumental data	1659-2007	Manley (1974, updated)
2, N-Italy	11	45	0.35*	1.032	Long instrumental data	1655-2007 (with gaps)	Camuffo and Bertolin (2012a,b); Camuffo et al. (2010)
3, De Bilt	5.18	52.11	0.39*	0.887	Long instrumental data	1706-2003	van Engelen and Nellestin 1996, updated
4, Stockholm	18.0	59.3	0.42*	0.873	Long instrumental data	1756-2010	Moberg and Bergström, 1997; Moberg et al. (2002)
5, Histalp	11.7	46.3	0.77*	0.907	Long instrumental data	1774-2007	Böhm et al. (2009)
6, Tornedalen	24	66	0.71*	0.993	Long instrumental data	1802-2008	Klingbjer and Moberg (2003)
7, SE England	1	52.6	0.03	1.220	Grain harvest date (AMJJ temperature)	1256-1431	Pribyl et al. (2012)
8, Vestlandet	7	61	0.49*	1.163	Multi-proxy reconstruction (spring to summer)	1732-2003	Nordli et al. (2003)
9, Finland	25.4	60.3	0.24	0.606	Chironomid temperatures, lake sediment, irregular multidecadal resolution	1330-2000	Luoto et al. (2009)
10, Swiss Alps	9.76	46.43	0.16	0.704	Chironomid July temperature (3y average)	1780-1998	Larocque-Tobler et al. (2010)
10, Swiss Alps	9.76	46.43	0.4*	0.416	Chironomid July temperature (20y average)	1120-1990	Larocque-Tobler et al. (2010)
11, Alps	4-19	43-49	0.6*	1.034	Multi-proxy summer reconstruction (partly dependent, as it includes Büntgen et al. 2006) data	1067-1996	Trachsel et al. (2012)
12, Russian Plains	30-40	53-58	0.33*	1.693	Multi-proxy summer T reconstruction	605-1995	Klimenko and Slepsov (2003)
13, Finland	30.12	64.28	0.15	1.129	Temperature, lake sediment irregular multi-decadal resolution	470-1990	Luoto and Helama (2010)
14, Northern Spain	-4	43	0.117	3.022	Speleothem (low resolution)	-138-2003	Martín-Chivelet et al. (2011)
$\square$ 15, Western Europe	-10-40	35-70	0.1	0.910	Multi-proxy spring/summer T reconstruction	600-2007	Guiot et al. (2010)
$\square$ 16, Europe	-25-40	35-70	0.41*	1.27	Multi-proxy summer T reconstruction	1500-1899	Luterbacher et al. (2004)

In the earliest periods a number of series were composed of readings of imperfect instruments located in various locations and exposures. For instance, the earliest part of the (Central England Temperature (CET) series till 1672 is less reliable as it is composed of multi-proxy in combination with extrapolation from various readings (Parker et al, 1992). The subsequent instrumental period of CET consists of indoor observations, as recommended by the protocol of the Royal Medical Society, London (Jurin 1723) for three main reasons: to use non-weatherproof instruments, to smooth out the diurnal cycle, and for health purposes. In Europe, this recommendation that was followed by the observers that adhered to the Royal Network, flourished 1724-1735 CE. In the second half of the 18th century, the interest for health purposes was enhanced with the Network of the Société Royale de Médecine, Paris that flourished in 1776-1786 CE. Outdoor observations with weather and climate purposes returned with the Societas Meteorologica Palatina, Mannheim, in the period 1781-1792 CE. The indoor-outdoor change was responsible for dishomogeneities in the last quarter of the 18th century (Camuffo, 2002). The common bias prior to about 1850 CE for instrumental summer temperatures is generally higher than the reconstructions, though they are still within the uncertainty range (Fig. S8 b,c,g). This can be attributed to the well-known summer temperature warm bias due to missing Stevenson shielding (Moberg et al. 2003; Frank et al. 2007; Böhm et al. 2010). However, not all series were affected by this bias. In Italy the tradition was with a thermometer on the shade, hung on a North facing wall, following a recommendation of the Medici Network, Florence (1655 to 1670 CE; Camuffo and Bertolin, 2012a). It has been suggested (Middleton, 1966) that the solar screen was applied in 1830, but in Padua, Toaldo shielded his thermometer against the direct radiation of the summer sunrise and sunset since 1780, although the thermometer was hung outside of a North-facing window (Camuffo, 2002). In conjunction with the standard deviation ratio (SDR), the well-captured temperature amplitude between the early 19th century cold episode and the late 20th century warming, and the good qualitative agreement with the Tornedalen and Histalp temperature series (Table S13) indicate that inter-annual to decadal variability is very well preserved at least in areas that are close to proxy locations, while more data are needed in other regions where the skill is lower (e.g. British Isles).



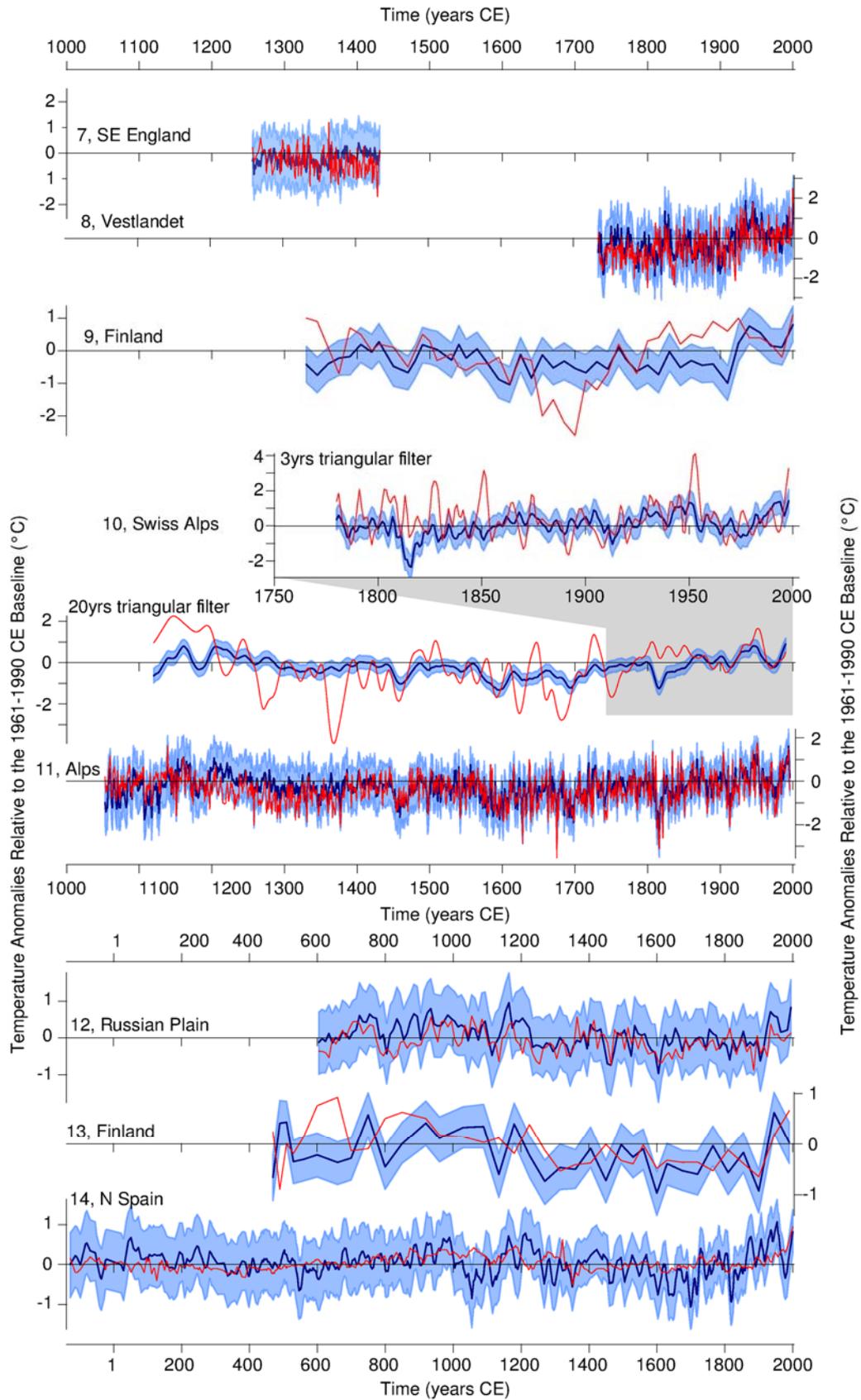
**Figure S7:** Locations of proxy data in this study (triangles for tree ring data and grey shaded area for documentary evidence, see Fig. 1) and independent local (circles) and regional (green shaded area) summer temperature evidence. See Table S13 for details.



**Figure S8:** Comparison of reconstructed BHM-based summer temperature anomalies (blue line) and uncertainties (shading) with independent summer temperature records (red lines) from different areas of Europe. All anomalies are computed with respect to 1961-1990 CE (see Table S13 and Fig. S7 for details).

The temperatures reconstructed from grain harvest data from the southeastern UK (Pribyl et al. 2012) bear little resemblance to our reconstruction (Fig. S9) but lie within the uncertainty range. Lake sediment data from Finland (Luoto et al., 2009; Luoto and Helama 2010) behave similarly to the reconstruction at decadal to multi-decadal time-scales, but minima and maxima of the longer time-series (Luoto and Helama 2010) are shifted by several decades, possibly indicating problematic age-depth models in these particular sediment data (Fig. S9).

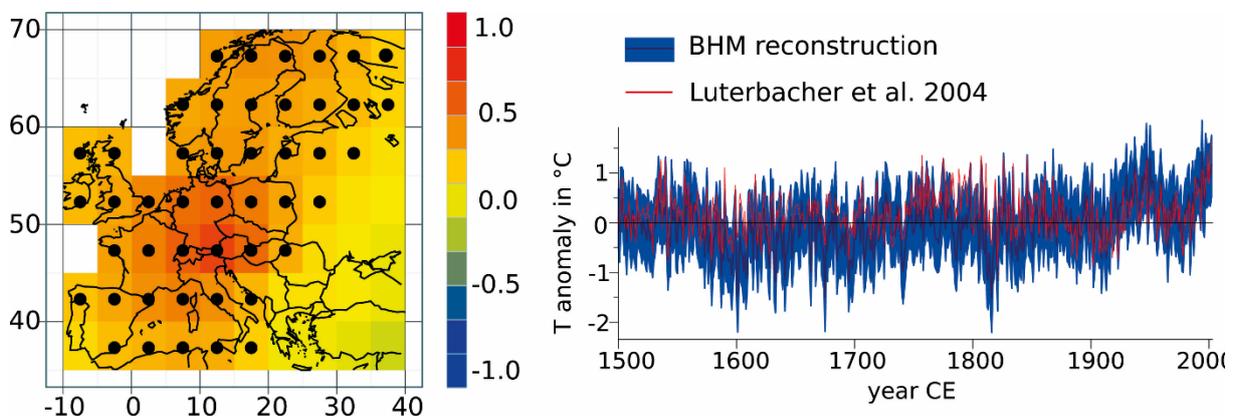
The reconstructed temperatures at Lake Silvaplana in the Alps were filtered with triangular filters (three and twenty years) to be more readily comparable with the chironomid-inferred temperature reconstruction from the lake sediments. While agreement of the data over the 20th century is good, coherence is low for the early 19th century cooling episode (Fig. S9). The 20-yr filtered lake sediment data indicates relative warming during the 11th century that is absent in our reconstructions, at least when using the same type of filter. The BHM reconstruction compares quite well with the decadal summer temperature reconstruction from the Russian Plain except for the early 19th century cooling, even though the BHM reconstruction does not include any proxy data from the Russian Plains target area 30-40° E 53-58° N (Fig. S9). The match with the low-resolution speleothem record from northern Spain is also quite good during the first millennium period 300-1000 CE (it should be noted that this record is the only reconstruction available for comparison to this period). The comparisons with these independent decadal-resolved proxy-based reconstructions indicate that the BHM reconstruction faithfully preserved decadal-to-centennial variability (Fig. S9).



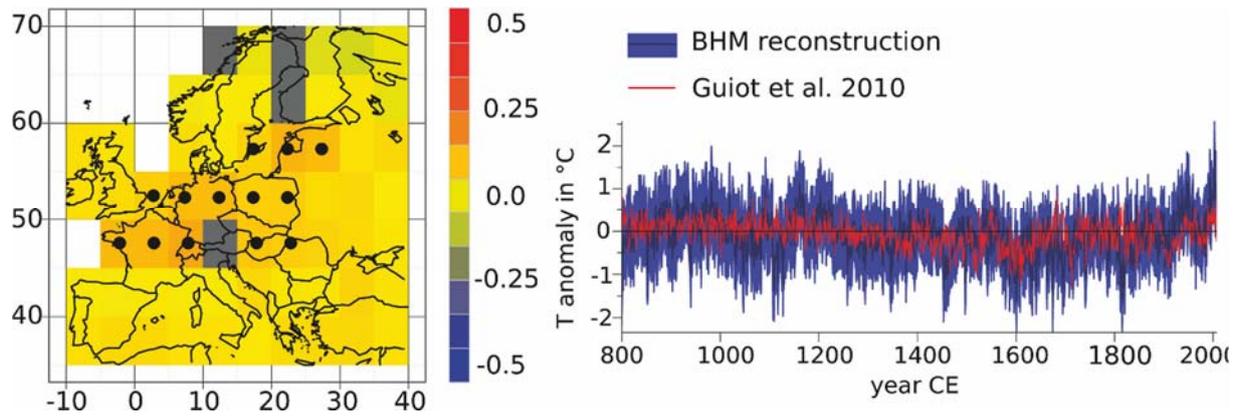
**Figure S9:** Comparison of reconstructed BHM-based summer temperature anomalies (blue line) and uncertainties (shading) with long independent summer temperature reconstructions (red lines) from proxies over different areas of Europe, all anomalies with respect to 1961-1990 CE, see Table S13 and Fig. S7 for details.

We find good agreement with the independent European mean and gridded summer temperature reconstructions by Luterbacher et al. (2004) covering the past five centuries (Table S13, Fig. S10). However, there is strong indication that the spatial mean of the earlier reconstruction has less low-frequency variability than the BHM reconstruction. The correlations over most of the grid are statistically significant, except for the southeastern part (Fig. S10), where no proxy data are available and the uncertainties are largest for both reconstructions. The ensemble mean of the SDR is displayed in Table S13. We also compare our reconstruction with the mean and gridded April-September temperature reconstruction by Guiot et al. (2010). The correlations between both data sets are generally very low (Table S13) though statistically significant in central Europe (Fig. S11). Some of the discrepancies are likely due to the different target seasons and match those found comparing summer (JJA) with warm season (May-October) averages in the instrumental CRUTEM data (Jones et al. 2012, not shown).

Many established reconstruction methods suffer from a loss of reconstructed temporal variability when reconstructing large-scale area means. For spatially resolved climate field reconstructions this effect is more pronounced (von Storch et al. 2004, Bürger et al. 2006; Christiansen et al. 2009; Smerdon and Kaplan, 2007, Smerdon et al. 2011; Christiansen 2011), although it is not present in spatially-resolved annual and February-March temperature reconstructions in western temperate North America (Wahl and Smerdon 2012) and a spatially-resolved precipitation reconstruction for California and western Nevada in the United States (Diaz and Wahl, 2015). However, BHM as implemented here has been shown to skilfully reconstruct much of the target variance in pseudo-proxy tests over Europe (Werner et al. 2012) and North America (Tingley and Huybers 2010a,b) and to estimate confidence intervals that faithfully include the target data. The above presented comparisons to data suggest that the results from pseudoproxy experiments are also applicable for real world applications.



**Figure S10:** Correlation at each grid cell between Luterbacher et al. (2004) gridded -summer reconstructions and the BHM JJA estimates. The black dots mark the locations where correlations are significant at  $p < 0.05$  level. Right: Comparison of area weighted averaged European temperature anomalies, red: Luterbacher et al. (2004), blue: mean BHM reconstruction.



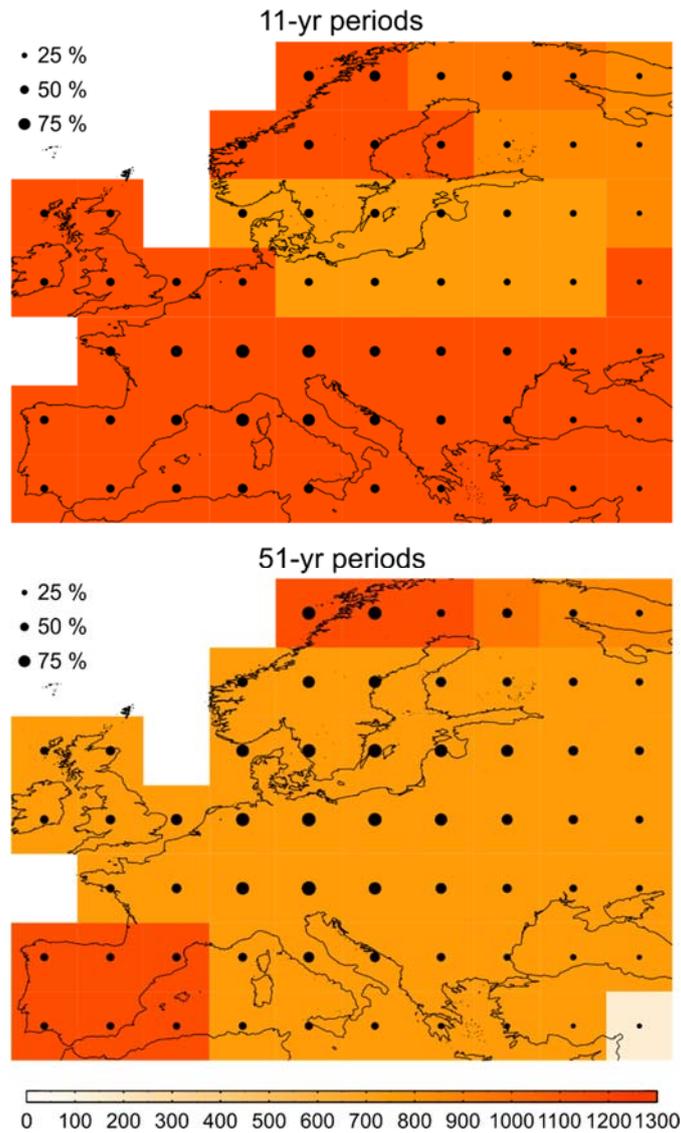
**Figure S11:** Left: Correlation at each grid cell between Guiot et al. (2010) gridded April-September reconstructions and the BHM JJA estimates. The black dots mark the locations where correlations are significant at  $p < 0.05$  level. The Guiot et al. (2010) reconstruction is not available within the grey shaded grids. Right: Comparison of area-weighted averaged European temperature anomalies, red: Guiot et al. (2010), blue: mean BHM reconstruction.

### ***Details on the computation of Figure 2, main text***

For each grid point and ensemble member, the BHM reconstructed summer temperature of each year is expressed as anomaly with respect to the 755-2003 CE period. 11-yr running centered means of the anomalies are then calculated at each grid point for 11-yr periods with complete data (i.e. from 755-765 CE to 1993-2003 CE). For each ensemble member, the local maximum and minimum 11-yr mean anomaly of 755-2003 CE is chosen and the corresponding ensemble mean is represented in Fig. 2 by the height of the bars and filled shading with contour interval of 0.2 °C starting at 0 °C. The height of each flag above the bar represents the associated temperature uncertainty at the grid point scale, defined as 2 standard deviations (SD) of the ensemble distribution of the warmest 11-yr mean temperatures.

To estimate the most likely date of the warmest and coldest 11-yr mean period across the ensemble, we constructed the frequency distribution of dates, taking the central year of the warmest 11-yr mean period of each member. By using centered running temporal windows of 100-yr width, we calculated the number of members having their warmest and coolest 11-yr mean period in the same 100-yr interval. The most populated bin is the most likely date of the warmest and coolest 11-yr mean period across the ensemble, and is indicated in the top of each grid point by colored squared symbols, according to the colour bar. Flags marked with a black square denote grid points where more than 75% of the ensemble members have the warmest (or coolest) 11-yr mean period in the same 100-yr bin (i.e. agree on the timing of the warmest and coolest period). Finally, for each ensemble member, the time series of the 11-yr mean summer temperature anomalies at each grid point,  $T_i$ , were normalized by dividing by the standard deviation  $SD = \sqrt{\sum (T_i - T)^2 / N - 1}$  where  $N$  equals the number of all available 11-yr periods of the 755-2003 CE record, and  $T$  is the local 755-2003 CE average of the 11-yr mean temperature series  $T_i$ . For each 11-yr period, we searched for those grid points with temperature anomalies above and below the local 2 SD value and calculated the percentage of the European area that they represent. This allows the construction of the time-evolving percentage of European area with 11-yr mean temperatures above and below 2 SD for each ensemble member. The light (dark) shading in the front plot of the map represents the ensemble spread, defined as the 5th-95th percentile range ( $\pm 0.5$  sigma interval). The bottom panels of Fig. 2 (main text) are the same as the top panels but for 51-yr mean periods.

We also explored the degree to which the 20th century summer temperatures in Europe was exceptional (Fig. S12). To do so, we selected for each ensemble member and each grid point the warmest 11-yr mean period of the 20th century ( $T_m$ ) and compared it with all 11-yr periods of the pre-1900 interval. We calculated the last time that temperature was reached in the past, and the time interval between them. If  $T_m$  is already the warmest local temperature of the entire 755-2003 CE period, the corresponding duration is computed with respect to the beginning of the series. For each grid point, the ensemble distribution of durations was calculated for running centred 100-yr bins and the most populated bin of duration was selected. The corresponding durations are shown with colour shading in Fig. S12, and the size of the black dot is proportional to the degree of agreement across the ensemble members at the given grid point (i.e. the percentage of ensemble members in that bin).



**Figure S12:** Top: spatial distribution with the time interval (in years) between the last 11-yr mean period of the pre-1900 CE period with equal or higher temperatures than the warmest 11-yr mean period of the 20th century. The black dots denote the agreement across the ensemble, with the size proportional to percentage of members giving the same levels of precedence. Bottom: As in the top panel but for 51-yr mean periods.

## ***GCM simulations over the last 2000 years and model data comparison***

Atmosphere-ocean coupled general circulation model (AOGCM) simulations are compared to the European summer temperature reconstructions at the continental and grid point scale (Figs. 3 and 4 in the main text). AOGCMs show their highest skill at larger scales and present reduced reliability at the grid-point scale, as a consequence of factors such as simplified local orography and surface physics (e.g. von Storch 2004). Therefore, we discuss the grid point scale comparison (Fig. 4 in the main text) of AOGCM output and the climate reconstructions only on regional scales. Near surface temperatures at these spatial scales indicate a large spatial coherence (Jones et al. 1997; Büntgen et al. 2010; Ljungqvist et al. 2012) due to the influence of large-scale circulation and external forcings (Hegerl et al. 2011). A growing number of climate simulations from comprehensive state-of-the-art AOGCMs and Earth System Models (ESMs) extend well back into the first millennium CE. These models are driven with different estimates of external climate forcings (Fernández-Donado et al. 2013). We consider an ensemble of paleoclimate simulations including 37 experiments. 26 of these simulations were performed with eight different AOGCMs under diverse external forcing configurations (Table S14; Fernández-Donado et al. 2013). The remaining eleven simulations are part of the Paleo Model Intercomparison Project Phase III (PMIP3; Taylor 2009; Braconnot et al. 2012) and generally follow the PMIP3-protocol for estimates of external forcing factors (Schmidt et al. 2011, 2012). PMIP3 simulations are made available from the Earth System Grid (<http://cmip-pcmdi.llnl.gov/index.html>). The model ensemble used herein matches that used in Masson-Delmotte et al. (2013).

The model experiments used for comparison differ in model complexity, in the forcing reconstructions used and their implementation (see Table S14). Model resolution in the atmosphere ranges from R21 spectral resolution (Phipps et al. 2011) to a maximum grid resolution of  $1.25^{\circ}\text{lat} \times 0.9^{\circ}\text{lon}$ , similar to those used in the CMIP5 historical and future scenario simulations (e.g. Landrum et al. 2013). The most notable differences in the forcing configurations (Schmidt et al. 2011; Fernández-Donado et al. 2013) concern long-term variations in total solar irradiance (TSI). Most of the earlier TSI-reconstructions exhibit a TSI-change larger than 0.23 % from the Late Maunder Minimum (LMM) to present. The reassessment of the reconstructions by Lean et al. (2002) led to generally lower (about 0.05-0.1%) estimates (see Fernández-Donado et al. 2013). The PMIP3 simulations therefore adopt TSI-changes from the LMM to present on the order of 0.1 % (Schmidt et al. 2011, see also Schmidt et al. 2012). The coordinated convention for the forcing scenarios for the PMIP3 forcing ensemble allows flexible options for uncertain climate forcings for which multiple estimates are available. This results in differences in the setups between individual simulations. For example, the volcanic forcing data by Gao et al. (2008, 2012) incorporates larger changes than the data by Crowley and Unterman (2013). Some of the model-systems include an interactive carbon cycle but only the ECHAM5/MPIOM ensemble performs a prognostic calculation of atmospheric  $\text{CO}_2$ . The other simulations are driven by prescribed atmospheric concentrations from reconstructions. While the interactively calculated  $\text{CO}_2$  concentrations in ECHAM5/MPIOM show smaller variations than reconstructions on decadal to centennial time scales (Jungclauss et al., 2010), we consider this a minor distinction. Newer simulations apply land-use changes as additional forcing, which are missing in most of the pre-PMIP (except for EH5/MPIOM) simulations. Note that Ahn et al. (2011) published a new estimate of atmospheric  $\text{CO}_2$  concentrations over the last millennium that is not included in the PMIP3-protocol (Schmidt et al., 2011, 2012).

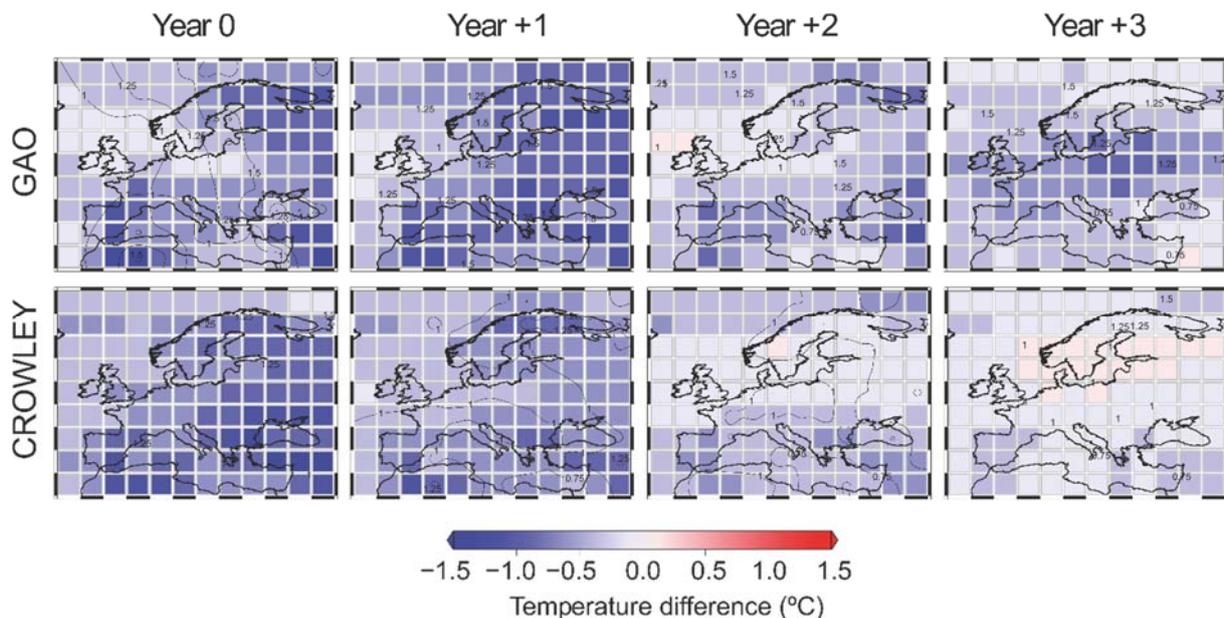
**Table S14:** Models and experiments considered for the analysis (column 1); horizontal and vertical resolution of atmospheric and ocean model components (columns 2 and 3); set of external forcings considered in the experiment configuration (column 4); number of simulations and length (column 5) and original reference describing the experiments (column 6). Legend for external forcing configuration: (W) solar forcing using stronger changes in amplitude (i.e. larger than 0.23 TSI change since LMM to present); (N) solar forcing using weaker changes in amplitude (i.e. lower than 0.1 % TSI change since LMM to present); (V) volcanic activity; (G) greenhouse gases; (A) anthropogenic aerosols; (L) land use changes; and (O) orbital variations.

Model	Atmosphere	Ocean	Forcings	Simulations	Reference
	Resolution/vertical levels			(No runs/length)	
CCSM3	T31/18	3.6X2.8/25	WVG	1000-2100 CE (4) 1500-2100	Hofer et al (2010)
CNRM	T42/31	2X2/31	WVGAL	(1) 1001-1999 CE	Swingedouw et al. (2010)
CSIRO	R21/18	2.8X1.6/21	NGO NVGO	(3)1-2000 CE (3)501-2000 CE	Phipps et al. (2013)
CSM1.4	T31/18	3.6X1.8/25	WVGA	(1) 850-1999 CE	Ammann et al. (2007)
ECHAM5-MPIOM	T31/19	3X3/40	NVGALO WVGALO	E1 (5) 800-2000 CE E2 (3) 800-2000 CE	Jungclaus et al. (2010)
ECHO-G	T30/19	2.8X2.8/20	WVG WGO	(2)1000-1990 CE (1) 8000 - 0 BP	González-Rouco et al. (2006); Wagner et al. (2007)
HadCM	3.75X2.5/19	1.25X1.25/20	WVGALO	(1) 1492-1999 CE	Tett et al. (2007)
IPSL	3.75x2.5/19	2x2/31	WGAO	(1) 1001-2000 CE	Servonnat et al. (2010)
PMIP3/CMIP5					
BCC	T42L26	tripolar, 1 lon x (1-1/3) lat, L40	Schmidt et al. (2011, 2012)	(1) 850-1850 CE	Wu (2012)
CCSM4	1.25x1.25L26	1.1 lon x 0.27-0.54 lat L60	Schmidt et al. (2011, 2012)	(1) 850-1850 CE	Landrum et al. (2013)
CSIRO	R21	2.8x1.6 L21	Schmidt et al. (2011, 2012)	(1) 851- 1850 CE	Phipps et al. (2013)
FGOALS	72x40L26	360x170L30	WVG	(1) 1000-1999 CE	Zhou et al. (2011)
GISS	2.5x2/L40	1x1.25xL32	Schmidt et al. (2011, 2012)	(3) 850-1850 CE	Schmidt et al. (2014) <a href="http://data.giss.nasa.gov/modelE/ar5/">http://data.giss.nasa.gov/modelE/ar5/</a>
HadCM3	3.75X2.5/19	1.25x1.25L20	Schmidt et al. (2011, 2012)	(1) 800- 2000 CE	Schurer et al. (2013)
IPSL-CM5A-LR			Schmidt et al. (2011, 2012)	(1) 850-2005 CE	Khodri et al. (2015, in prep)
MIROC	T42L80	256x192 L44	Schmidt et al. (2011, 2012)	850-1849 CE	Sueyoshi et al. (2013)
MPI-ESM	T63L47	GR15L40	Schmidt et al. (2011, 2012)	850-2005 CE	Jungclaus et al. (2014)

## ***European summer temperature response after strong tropical volcanic eruptions***

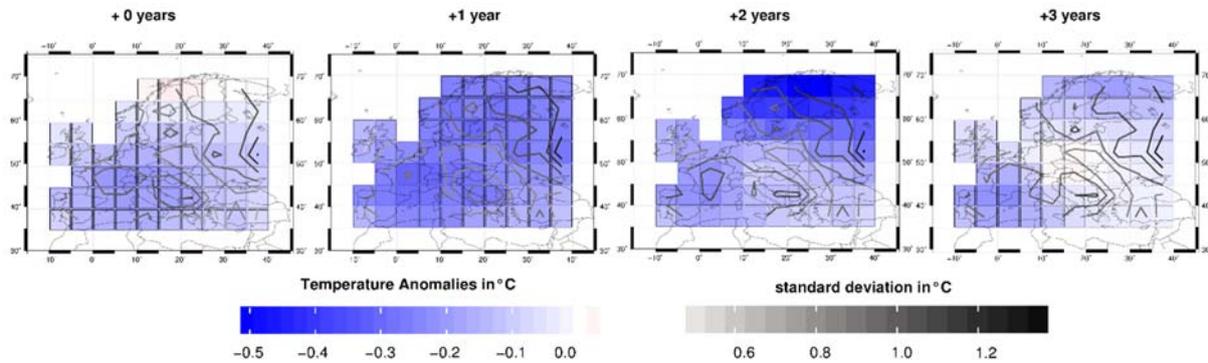
The European summer temperature response to the volcanic events is analyzed for the PMIP3 model simulations through SEA (Fig. S13). Compared to the Crowley and Untermann (2012) series, the temperature response to the volcanic activity is stronger in the simulations driven by Gao et al. (2008) forcing (PAGES2k-PMIP3 group, 2015). Therefore, the temperature responses are separated according to the volcanic forcing presented in Table S14. Simulations driven by the Gao et al. (2008) forcing correspond to BCC and CCSM4, while CSIRO, HadCM3, MIROC, MPI and GISS ensemble use the Crowley and Untermann (2012) forcing (Table S14). For each volcanic forcing, the 12 strongest volcanic events are selected, following the same approach as in PAGES2k-PMIP3 group (2015). The temperature response of each simulation to each volcano is obtained as the spatial summer temperature difference between a given year and the average of the five years previous to the eruption (similar to the SEA of the reconstructions; Fig. S14). The simulated temperature response is analyzed from the year of the eruption to the third year after the event. The standard deviation obtained from all the individual summer anomaly maps is shown as contours.

Figure S13 shows an overall European summer cooling as response to the volcanic events, larger for the year of the eruption and the year after. Simulations driven by the Gao et al. (2008) volcanic forcing show a stronger cooling compared to the Crowley and Untermann (2012) subgroup, in agreement with the results of PAGES2k-PMIP3 group (2015).



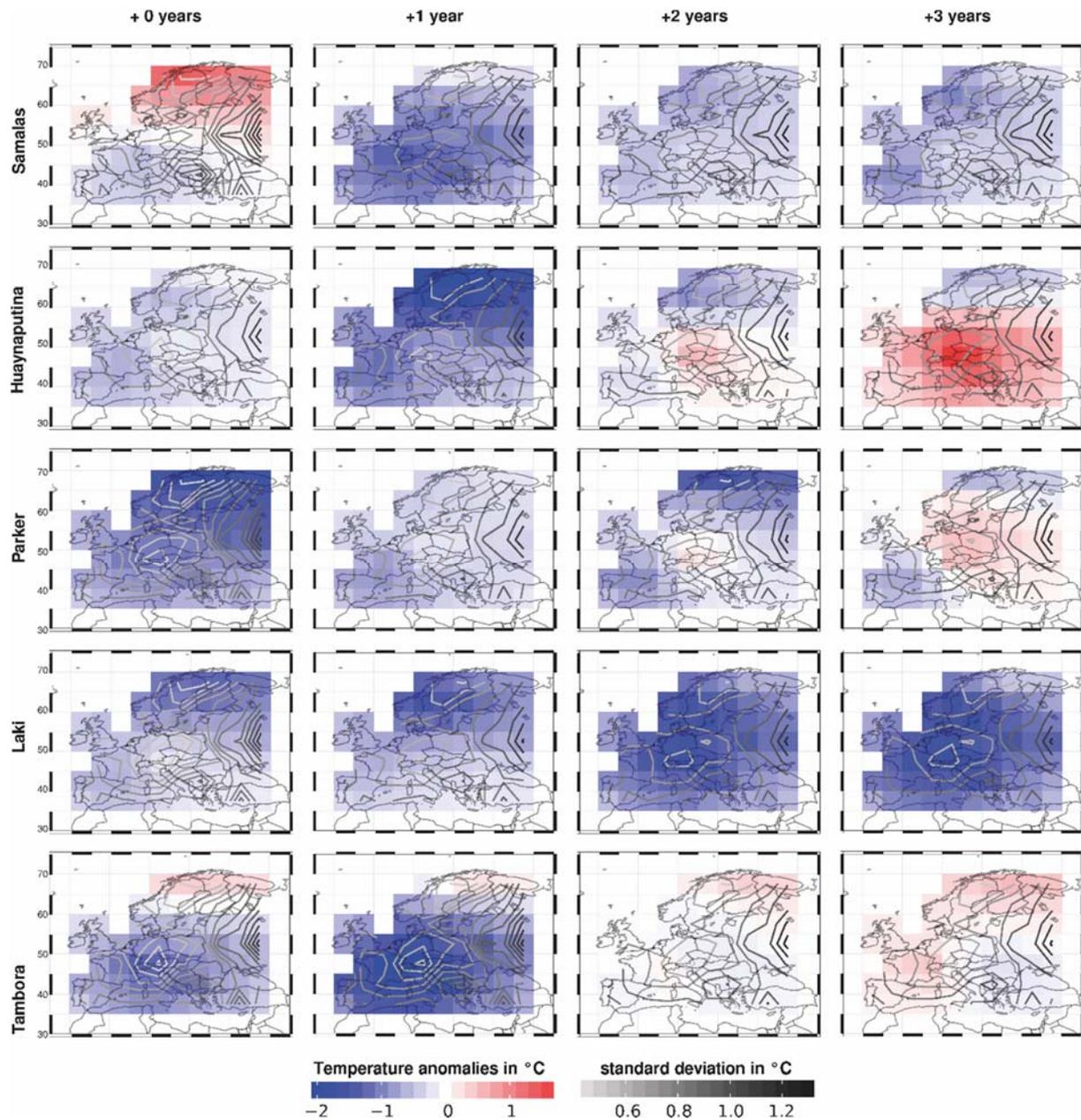
**Figure S13:** Superposed spatial composites of the summer temperature responses over the European region from PMIP3 simulations for their 12 strongest volcanic events over the past millennium. The temperature responses are shown from the year of the event to the third year after the eruption. Anomalies are presented with respect to the average of the five years previous to each eruption. Each map shows the average temperature difference (colours) from all the simulations driven by (top) Gao et al. (2008) and Crowley and Untermann (2012) (bottom) volcanic forcing. The standard deviations among all these temperature differences are also presented in the maps (contour lines).

Figure S14 shows the European summer temperature response to the volcanic events through SEA for the BHM reconstructions. The SEA is performed for the 13 strongest tropical volcanic eruptions ( $\geq$ VEI 5) published in Esper et al. (2013). The selected eruptions all occurred during the time period covered by the gridded BHM reconstruction.



**Figure S14:** Superposed Epoch Analysis (SEA) of European summer temperature for the 13 strongest tropical volcanic eruptions ( $\geq$ VEI 5) published in Esper et al. (2013). The temperature responses ( $^{\circ}$ C) are shown from the year of the event (left panel) to the third year after the eruption (right panel) with respect to the average of the five years preceding each eruption. Each map shows the average temperature difference (colours) from all ensemble members. The standard deviations among them are shown with contour lines

Figure S15 presents the European summer temperature response from the BHM reconstructions for a selection of strong tropical volcanic eruptions (Samalas 1257, Huaynaputina 1600, Parker 1641, Laki 1783/1784 and Tambora 1815). The responses (ensemble mean) are shown with respect to average temperatures over the five years preceding the eruption.



**Figure S15:** Summer temperature response ( $^{\circ}\text{C}$ ) for a selection of strong volcanic eruptions (Samalas 1257, Huaynaputina 1600, Parker 1641, Laki 1783/1784 and Tambora 1815). The responses (ensemble mean) are shown with respect to average temperatures over the five years preceding the eruption. The standard deviations are calculated from the ensemble members and show an estimate of the uncertainty of the reconstructed response. Columns are the year of the eruption and the three following years

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