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Differing pre-industrial cooling trends between tree-rings and lower-resolution temperature proxies

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Abstract. The 692 proxy records of the new PAGES 2k compilation offer an unprecedented opportunity to study regional to global temperature trends associated with orbitally-driven changes in solar irradiance over the past two millennia. Here, we analyse the significance of long-term trends from 1-1800 CE in the PAGES 2k compilation's tree-ring, ice core, marine and lake sediment records and find, unlike ice-cores, glacier dynamics, marine and lake sediments, no suggestion of a pre-industrial cooling trend in the tree-ring records. To understand why the tree-ring proxies lack a significant pre-industrial cooling, we divide the dendro data by location (high NH latitudes vs. mid latitudes), seasonal response (annual vs. summer), detrending method, and temperature sensitivity (high vs. low). We conclude the ability to detect any pre-industrial, millennial-long cooling in the tree-ring proxies does not increase with latitude, seasonal sensitivity, or detrending method. Consequently, caution is advised when using multi-proxy approaches to reconstruct long-term temperature changes.

1 Introduction

Apart from documentary archives (Pfister et al., 1999), our perception of climate variability prior to the systematic collection of instrumental measurements in the mid nineteenth century relies on climate sensitive proxy data (Frank et al., 2010). Paleotemperature information can be extracted from natural archives such as ice cores (Steig et al., 2013), speleothems

(Martín-Chivelet et al., 2011), tree-rings (Esper et al., 2014), lake and marine sediments (Nieto-Moreno et al., 2013), and glacier fluctuations (Solomina et al., 2016), among others (Jones et al., 2009; Wanner et al., 2008). Today, a number of multiproxy (Christiansen and Ljungqvist, 2011; Hegerl et al., 2007; Jones et al., 1998; Ljungqvist et al., 2012; Mann et al., 2008; Shi et al., 2013), and solely tree-ring based reconstructions (Briffa, 2000; D'Arrigo et al., 2006; Esper et al., 2002; Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016) of Northern Hemisphere (NH) and global temperatures have been established. These reconstructions provide an opportunity to study pre-instrumental, naturally forced climate variability at annual to millennial timescales (Christiansen and Ljungqvist, 2017), and are essential for placing Anthropogenic warming in a long-term context. Proxy data themselves provide valuable climate information needed to test and verify paleoclimate model simulations (Braconnot et al., 2012; Fernández-Donado et al., 2013; Hartl-Meier et al., 2017).

The PAGES 2k database represents a unique community effort organized by PAGES (http://pastglobalchanges.org), to amass the world's largest collection of proxy records covering the Common Era (CE) (PAGES 2k Consortium, 2017). The PAGES 2k database 2.0.0 contains 692 temperature-sensitive proxy records from trees (415), ice cores (49), lake (42) and marine sediments (58), corals (96), documentary evidence (15), sclerosponges (8), speleothemes (4), boreholes (3), bivalves (1) and a hybrid tree/borehole (1), and represents 648 locations from all continents and major oceans (Fig. 1). Unlike previously published multiproxy compilations (Mann et al., 2008; PAGES 2k Consortium, 2013), the PAGES 2k database includes substantially more evidence from sources other than tree-rings and many more records that cover the first millennium, thereby expanding the spatial and temporal coverage over oceanic and polar regions (PAGES 2k Consortium, 2017). The number, spatial distribution, and diversity of the PAGES 2k dataset provides an unprecedented opportunity to analyse regional to large-scale temperature patterns over the Common Era. The PAGES 2k Consortium (2017) produced a collection of global mean composites from each of the major proxy types in its dataset. The average summer temperature of all marine sediments, lake sediments, and glacial ice cores (Fig. 2a) exhibit strong negative trends that are consistent with the gradual pre-1800 cooling reported previously by other major syntheses of Holocene proxies (cited previously). By contrast, the global composite derived from just the tree-ring records (Fig. 2b) shows the rapid post-1800 increase was preceded by an essentially flat trend from 1-1800 CE. A pre-industrial cooling can be attributed to gradual changes in orbital forcing, shown to be an important driver of Holocene long-term climate oscillations (Milanković, 1941; Wanner et al., 2015). Changes in solar insolation (Huybers and Curry, 2006) are caused by variations in the Earth's tilt (obliquity), orbit (eccentricity) and rotation axis (precession). Over the Common Era, precession triggers a shift of the Perihelion (the closest point between sun and Earth) from December to January (Berger, 1978; Berger and Loutre, 1991). The collective effects of eccentricity, precession and obliquity cause a decrease of incoming solar radiation of ~9 W/m^2 at 90°N, 5.5 W/m^2 at 60°N, and 3.4 W/m^2 at 30°N in June-August over the NH, and a corresponding warm season increase of ~3.8 W/m^2 at 90°S, 4.1 W/m^2 at 60°S, and 5 W/m^2 at 30°S in December-February over the Southern Hemisphere (Laskar et al., 2004) (Fig. 3). These long-term changes in orbital forcing, from a theoretical perspective, affect regional temperatures differentially (Masson-Delmotte et al., 2013).

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The lack of a long-term negative trend in the average global tree-ring record stands in stark contrast to the cooling detected in the well-replicated maximum latewood density (MXD) record from northern Scandinavia (Esper et al., 2012). Esper et al. (2012) argues that, unlike long MXD records, tree-ring width (TRW) records are incapable of capturing orbital trends. If this is the case, then including TRW records in past global temperature assessments might result in an underestimate of pre-instrumental warmth, e.g. during Medieval and Roman Times (Esper et al., 2004; Frank et al., 2010; Wang et al., 2014). Combining proxies that systematically vary in their low-frequency trends seemingly contributes to the development of temperature reconstructions of differing temperature amplitudes over the pre-industrial era (Christiansen and Ljungqvist, 2012; Christiansen and Ljungqvist, 2011; D'Arrigo et al., 2006; Jones et al., 1998; Juckes et al., 2007; Ljungqvist et al., 2012; Mann et al., 1999; Mann et al., 2008; Schneider et al., 2015; Wilson et al., 2016). Here, we analyse the PAGES 2k collection of temperature-sensitive proxy records to understand why the mean tree-ring record lacks a pre-industrial millennial-scale cooling trend that is otherwise preserved in ice core, lake and marine sediment data. We hypothesize that the absence of this long-term negative trend in tree-ring chronologies may be a consequence of the climate sensitivity of the trees used, their detrending, and spatial distribution of the datasets. To test these potential explanations, here we explore the effect of three significant attributes of just the tree-ring component that may have bearing on the long-term temperature trend reported in the PAGES 2k initiative.

(1) Based on the spatial and seasonally varying effect of orbital forcing over the Common Era, we expect a millennial-scale cooling trend prior to the industrial period, particularly in summer-sensitive, high northern latitude proxies, compared to annually-sensitive proxies (Esper et al., 2012; Kaufman et al., 2009). Therefore, the absence of a distinct pre-industrial cooling in the PAGES 2k tree-ring network could be a by-product of the spatial distribution of tree-ring proxies in the network. If the network were not biased by northern, mid-latitude tree-ring sites it should capture the millennial-length cooling trend in summer, as we expect proxy records from high northern latitudes to contain a stronger summer cooling trend than their mid-latitude counterparts.

(2) All tree-ring parameters, with the possible exception of $\delta^{18}O$ (Esper et al., 2015; Helama et al., 2015; Young et al., 2011), include age-related, non-climatic signals that need to be removed prior to chronology development and reconstruction (Bräker, 1981; Cook, 1990; Douglass, 1919; Fritts, 1976). The selection of a suitable tree-ring detrending method is one of the fundamental challenges in the field of dendroclimatology (Briffa et al., 1992; Cook et al., 1995; Esper et al., 2004; Melvin et al., 2013). However, tree-ring detrending methods vary in their approach to model tree growth and if applied indiscriminately can remove long-term cooling trends related to orbital forcing, either intentionally or inadvertently, interpreted as biological noise (Cook et al., 1995; Esper et al., 2004). Given that the PAGES 2k database contains no information regarding the detrending method used to produce the tree-ring chronologies in its collection, we assume all were produced using different detrending methods, and that those methods are applied to differently structured tree-ring datasets

(i.e. the temporal distributions of short and long tree-ring measurements series, indicative of young and old trees, over the past 2k years are not the same). If this is the case, such disparities will affect the database chronologies' low frequency variance, causing the tree-ring mean to lack millennial scale trends (Briffa et al., 2013; Büntgen et al., 2017; Linderholm et al., 2014).

(3) The inclusion of chronologies having a mixed climate sensitivity (Seim et al., 2012) and their potential introduction of non-temperature related noise (Baltensweiler et al., 2008) might weaken a reconstruction. The establishment of large-scale (continental or hemispheric) temperature reconstructions relies on the assumption that all proxy records used to produce the reconstruction have a substantial temperature signal, and that the signal is temporally stable over the entire record length (Esper et al., 2016). We assume the inclusion of tree-ring chronologies with a mixed sensitivity, including other climate parameters besides temperature (Baltensweiler et al., 2008; Seim et al., 2012), weakens a reconstruction, and that reconstructions composed of weakly calibrating chronologies contain less or no orbitally forced trends.

Here we first describe the varying ability of the proxies used in the PAGES 2k network to preserve orbitally forced, millennial-scale, temperature trends. Then we evaluate and discuss how a more critical proxy selection could improve our understanding of past climate variability over the Common Era.

2 Data and methods

2.1 Data preparation

The PAGES 2k database (Fig. 1) was accessed via the website of the NCEI-Paleo/World Data Service for Paleoclimatology (https://www.ncdc.noaa.gov/paleo/study/21171). All 692 records were normalized over their individual record lengths by subtracting the time series mean (μ) from each single proxy value, then dividing the difference by the series' standard deviation (σ). Normalization is a necessary step to eliminate differences in measuring scale, as the database includes a variety of measured parameters, including $\delta^{18}O$ (Horiuchi et al., 2008), TRW (Luckman and Wilson, 2005), MXD (Klippel et al., 2018), blue intensity (Björklund et al., 2014), varve thickness (Moore et al., 2001) or Sr/Ca (Rosenheim, 2005). We realize that the choice of normalization period, from which we calculate μ and σ, has an influence on the expression of low-frequency trends as seen in the tree-ring data (Fig. 4). Using μ and σ of all the tree-ring chronologies' common period (1758-1972) leads to a slightly different millennial-scale trend compared to the PAGES 2k procedure of using the individual records' total lengths. Large trend discrepancies arise from using μ and σ of even shorter periods (e.g., 1800-50, 1850-1900 and 1900-50; Fig. 4). A $\mu_{sub\ period}$ and $\sigma_{sub\ period}$ smaller, or a $\mu_{sub\ period}$ and $\sigma_{sub\ period}$ larger, than the entire time series μ and σ produces records with increased or decreased temperature levels and trends, respectively (Fig. S2). By normalizing all the proxies in the same manner, we minimize the influence of the normalization method on the preservation of low-frequency trends in tree-rings.

All proxy records having a negative correlation with instrumental temperature were inverted (multiplied by -1) to ensure that high proxy values represent warm temperatures and low proxy value cold temperatures. To account for the varying temporal resolution among the proxies, from sub-annual to multi-decadal, all normalized records are averaged and set to the same resolution consisting of 50-year bins (e.g. 1901-1950; 1951-2000; Fig. 4). The Southern Hemisphere was excluded from this analysis due to having too few samples (111 records in total, with 13 tree-ring records) and the suggestion of ambiguous links between the hemispheres on orbital timescales (Kawamura et al., 2007; Laepple et al., 2011; Petit et al., 1999).

2.2 Hypothesis testing

Based on the Milankovitch cycles (Milanković, 1941) we expect latitudinally and seasonally varying temperature trends, with the strongest cooling to be found in summer-sensitive proxies from high latitude, and the least cooling to be found in the annual temperature sensitive proxies from lower latitudes (Berger and Loutre, 1991; Laskar et al., 2004). To assess the long-term trends preserved in an individual tree-ring record, the statistical significance of the slope of least-squares linear regressions through each proxy record (at 50-year resolution) was evaluated, and the fraction of records that exhibit a significant or insignificant cooling trend over the pre-industrial period (1-1800 CE), and a warming trend over the industrial (post 1800 CE) period were recorded. Those records with significant warming and cooling trends were further analysed with respect to proxy type (archive), latitude, and temperature sensitive seasonality. Assuming the longer proxy records more likely exhibit a significant long-term cooling trend, the minimum considerable length for a tree-ring proxy was set to 800 years (PAGES 2k Consortium, 2013).

Of the original 415 tree-ring datasets a subset of 70 tree-ring collections, each at least 800 years-long, was drawn from the International Tree-ring Databank (ITRDB), or kindly provided by the original authors, and used to test the influence of three different tree-ring detrending methods on removing non-climatic age trends from the raw measurements (Cook et al., 2017). The tree-ring detrending methods applied are the calculation of residuals from individually fit (i) cubic smoothing splines with a 50% frequency-response cutoff at 100 years (SPL; Cook, 1985), (ii) negative exponential functions (NEG), and (iii) from regional growth curves (RCS; Esper et al., 2003). The individual series detrending methods (i & ii) emphasize annual to centennial trends in the resulting index chronologies (Cook and Peters, 1981) by removing long-term trends that exceed the lengths of sampled trees. By contrast, RCS (iii) (Briffa et al., 1992) attempts to preserve low-frequency climate variability through its address of the so called "segment length curse" (Briffa and Melvin, 2011; Cook et al., 1995). However, RCS is best applied to large datasets with a homogenous age-structure through time to guarantee a proper representation of the population growth curve used to detrend the data (Esper et al., 2003), and most tree-ring measurements in the 2k database do not satisfy this criterion. Prior to detrending, a data adaptive power transformation was applied to all measurements to mitigate the heteroscedastic nature of the tree-ring series (Cook and Peters, 1997), and chronologies calculated using the bi-weight robust means of tree-ring indices in each calendar year. In addition, the average correlation coefficient among the individual series (rbar; Wigley et al., 1984) was used to stabilize the variance of the chronologies (Frank et al., 2007). The resulting chronologies produced from each of the three methodologies i, ii, and iii were then z-transformed and averaged over 50-year bins to produce three unique composite chronologies. The 50-year binned composites were compared with the PAGES 2k subset composite that includes the same 70 records to investigate the influence of tree-ring standardization on millennial scale temperature trends.

The nature of the climate signal encoded in each tree-ring record was assessed by Pearson correlation coefficients between all 415 z-transformed tree-ring chronologies, and both the 1° and 5° gridded CRU TS 4.01 (Harris et al., 2014) monthly June-September temperatures from 1950-1980. The relatively short interval of 31 years was selected for computing correlations in response to the sparse station data availability, especially in Asia, and the decline in the quality of interpolated observational temperature data prior to 1950 (Cook et al., 2012, Krusic et al., 2015). For each re-standardized and z-transformed chronology, the highest monthly maximum correlation coefficient was extracted and plotted with respect to the trees' location as provided in the metadata table (PAGES 2k Consortium, 2017). The use of extended calibration periods (prior to 1950 and post 1980), and annual temperatures, yielded no meaningful differences in the calibration results. The stability of the growth-climate relationship was assessed by first smoothing the tree-ring and corresponding CRU temperatures using 10-year splines, to emphasize decadal and, using these splines to high-pass filter the data to accentuate inter-annual variances. The tree-ring records were ranked according to the strength of their maximum monthly temperature response between June and September, and averaged into 50-year binned composites to evaluate the importance of changing signal strength on any preserved millennial-scale trend.

3 Results

3.1 Latitude and season

In total, 66.3% of the tree-ring, 93.8% of the glacier ice, 75.0% of the marine and 79.3% of the lake sediment records, longer than 800 years, reveal a millennial-scale cooling over the period 1-1800 CE (Fig. 5a). Substantial proxy differences appear when comparing the fraction of records with a significant overall cooling trend ($p < 0.05$): 68.8% of the glacier ice, 54.5% of the marine and 37.9% of the lake sediment records, but only 11.2% of the tree-ring records. Separating the data by latitude reveals that the fraction of significantly cooling tree-ring records decreases from 25.0% at 60-90°N to 8.7% at 30-60°N, which, though the percentages are fairly small, supports the theory that the signature of orbital forcing in tree-rings has a meridionally declining spatial signature. In contrast, the cooling trends in glacier ice, marine and lake sediment records reach their maximum in the mid-latitudes, from 30-60°N, which contradicts this explanation. The overall number of summer temperature sensitive proxy records showing long-term cooling is similar to the number of annual temperature sensitive proxies showing long-term cooling, suggesting that the orbitally forced reduction in summer insolation over the past 2k has

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no substantial effect on the expression of long-term trends. Over the industrial period 1800-2000 CE (Fig. 5b), glacier ice, marine and lake sediments, and the tree-ring records particularly, consistently show a temperature increase.

3.2 Tree-ring detrending

We applied three different detrending methods with varying ability to preserve low-frequency information on a subset of 70 of the 415 datasets in the PAGES 2k database. Together, these 70 collections include 7572 series. The single best replicated collection is the Torneträsk (Sweden) TRW dataset containing 650 measurement series and the least replicated is a dataset from southern China containing just 10 measurement series. This huge range of underlying data points to potential weaknesses in our application of RCS, which specifically requires high sample replication (Briffa et al., 1992, Esper et al., 2003). Comparisons between of the SPL, NEG, RCS, and the PAGES 2k subset composites reveals how there is substantially more low-frequency variability present in the RCS composite chronology (Fig. 6). Extended cool periods are seen in the intervals from 300-750 CE, 1450-1500 CE and 1600-1800 CE, and prolonged warm periods between 850-1200 CE and 1800-2000 CE. As expected (Cook et al., 1995), the SPL composite lacks any long-term cool or warm periods. In the NEG and PAGES 2k subset composite, pre-industrial temperature variations are restricted to multi-decadal scales, indicating cool conditions from 250-300 CE and 1450-1500 CE, warm conditions from 550-600 CE, and a more persistent warming from 1850 CE to present. Comparison of the RCS detrended composite against the PAGES 2k tree-ring composite reveals substantial differences in long-term trends in the first millennium. This demonstrable difference is a consequence of the pronounced cooling from 300-750 CE, a feature lacking in the both the PAGES 2k subset (Fig. 6) as well as entire PAGES 2k tree-ring composite (Fig. 2), but conserved in the RCS mean chronology. From 300-750 CE, the average standard deviation in the RCS composite is -0.32, which compares to -0.03 in the PAGES 2k subset. Good agreement exists in the second millennium, as the magnitude, timing and strength of warm and cool intervals largely overlap. The best fit over the entire Common Era exists among the NEG and PAGES 2k subset composites, suggesting the PAGES 2k database includes a sizable amount of NEG detrended records. However, even with the application of RCS, which is arguably the current best method for conserving low-frequency trends in tree-rings, the pre-industrial cooling trend in the PAGES 2k tree-ring dataset differs significantly from those found in glacier ice, marine and lake sediment records (Fig. 2 and Fig. 6).

3.3 Climate signal strength

Pearson correlation analyses between the tree-ring proxy records and their respective local temperature grids reveals considerable inter-continental differences in the proxy's response to maximum monthly June-September temperature (Fig. 7a). The median correlation coefficients differ substantially by region, reaching $r = 0.6$ in the Arctic, $r = 0.21$ in Asia, $r = 0.54$ in Europe and $r = 0.38$ in North America. In the Arctic 87.5%, Asia 21.1%, Europe 75.0% and North America 61.33% of the maximum monthly June-September correlation coefficients are significant ($p < 0.05$), indicating a more stable growth-climate relationships in the Arctic and Europe, compared to Asia and North America. However, these differences might be an artefact of different sampling strategies. In the first case (Arctic and Europe), only 16 and 8 highly temperature sensitive records are considered, but the second case (Asia and North America) has 228 and 150 records. The differences among the continents, as demonstrated by the distributions of their June-September correlation coefficients, remains fairly stable in the different frequency domains, as well as for the records longer than 800 years (Fig. 7b). To account for seasonal responses beyond June-September, and potential influences of the calibration period, the analysis was repeated for all months, varying warm season means, and extended the calibration periods (1950 to the end dates of the individual chronologies). Consequently, no substantial changes were recorded (not shown). Despite significant differences in high-to-low-frequency temperature signals we find that none of the composites, integrating the good, medium and poorly calibrating records, contain a significant millennial-scale cooling (Fig. 7c-d). This result suggests climate signal strength has no influence on the expression of low-frequency trends.

4 Discussion

4.1 Orbital signatures in regional and large-scale records

The signature of orbital forcing has been described in regional studies from the Arctic and Antarctica (Esper et al., 2012; Kaufman et al., 2009; Kawamura et al., 2007), as well as in one Holocene climate reconstruction based on a multiproxy collection from the northern high- and mid-latitudes; the latter attributing a distinct value to the orbital cooling effect of 0.5°C since the Holocene Thermal Maximum (Marcott et al., 2013). However, in the case of Marcott et al. (2013), it has been shown that NH cooling is only apparent in high-latitude North Atlantic proxies, and that the trend would not exist without them (Marsicek et al., 2018). Previous studies have also reported that it is difficult to reconcile the negative orbital forcing trends preserved in proxy data with simulated temperatures which show a strong warming of about 0.5°C over the Holocene (Liu et al., 2014, Laepple et al., 2011). Our results demonstrate that millennial-scale trends in NH proxy records are inconsistent between proxies. From a theoretical perspective, independent of the proxy type, we would expect a stronger cooling trend in summer temperature proxies and an increase in the strength of the trend from the mid to the high latitudes (e.g., Esper et al. 2012; Kaufman et al. 2009). The absence of a clear meridional and seasonal pattern demonstrates the importance of internal climate variability (Deser et al., 2010; Schneider and Kinter, 1994) and other external forcing factors (Sigl et al., 2015; Vieira et al., 2011) on proxy records. We conclude that although tree-rings are systematically limited in their low-frequency amplitude, they deviate from forcing expectations in the same way as all other proxies. We conclude that the reduced low-frequency variability in tree-ring data cannot be explained by an overrepresentation of the mid-latitudes in the global mean composite.

Despite the insignificant pre-industrial temperature changes in 86.5% of the tree-ring records, compared to other proxies, the post 1800 CE warming trend in tree-rings is significant (25.8% versus 11.9%). Consequently, large scale multiproxy climate reconstructions that include long tree-ring records (> 800 years), or solely tree-ring based reconstructions developed from the

PAGES 2k database, will likely show a stronger post-1800 warming than multiproxy reconstructions that deliberately exclude (long) tree-ring records (Fig. 2 and Fig. 6). The selection of the proxy type has major implications on the reconstructed warmest interval over the Common Era. Using marine data, the warmest period is 151-200 CE and the pre-industrial Era is dominated by a strong cooling trend, suggesting the magnitude of the current warming is not outstanding. By contrast, in lake sediments, ice cores, and tree-ring data, the most recent period is exceptionally warm (Fig. 2). This finding highlights the importance of tree-ring data in any effort to determine whether twentieth-century temperatures are unprecedented in both their magnitude and rate of warming during the past two millennia (Büntgen et al., 2011; Foley et al., 2013).

4.2 The impact of detrending on temperature trends

The degree of similarity between the NEG tree-ring chronology produced here and the corresponding PAGES 2k version suggests that the current PAGES 2k tree-ring collection is not the most ideal for studying millennial scale trends. This is in large part due to the limitations of individual series detrending (Cook et al., 1995). Even with the application of RCS (Briffa et al., 1992; Esper et al., 2003), currently the most widely accepted method to preserve low-frequency variance in tree-ring chronology development, detection of a millennial-scale cooling trend is still elusive. These findings clearly demonstrate that the limited low-frequency variance in tree-ring chronologies is not solely an artefact of inappropriate detrending, previously identified as main explanation for the observed lack of long-term oscillations in large scale temperature reconstructions (Esper et al., 2002; Mann et al., 1999). Our reassessment of tree-ring chronologies also highlights the importance of the detrending methodology in reconstructing centennial scale temperature variability, as evidenced by the performance of the RCS chronology. In the RCS chronology we are able to clearly identify the Late Antique Little Ice Age (LALIA) (Büntgen et al., 2016), a cool period from 300-750 CE that is absent in the PAGES 2k version, albeit with slightly greater uncertainty about the mean. The Büntgen et al. (2016) analysis and the dataset used in this study only share four tree-ring records in common, thus our analysis provides independent confirmation of the existence of LALIA and cooler conditions during the Migration period (Büntgen et al., 2011). In contrast, the PAGES 2k tree-ring time series suggest an alternation of warmer and cooler decades, but no persistent cooling at large spatial scales, during LALIA.

4.3 Temperature sensitivity and the link to long-term trends

Temperature sensitivity was key criterion for the inclusion of data into the PAGES 2k database (PAGES 2k Consortium, 2017) and was assessed by the PAGES community through comparison with gridded HadCRUT 4.2 temperatures (Morice et al., 2012). However, this analysis has shown the PAGES 2k database includes many tree-ring records that have a weak relationship with local temperature at high-to-low frequencies. The monthly maximum correlation coefficients between 1x1°

CRU TS 4.01, June-September temperature data falls below 0.2 in 126 cases. The lowest correlation coefficient is -0.25 (unfiltered data). Such week temperature sensitivities amongst the tree-rings is likely related to confounding non-climatic (Johnson et al., 2010; Konter et al., 2015) or hydroclimatic (Ljungqvist et al., 2016) growth controls, or to the circumstance that some records are by nature less sensitive to summer temperature than others (St. George, 2014). Further contributions to the range of climate signal strength found in the tree-ring proxies are related to the fact that MXD are more sensitive to temperature than TRW records (Büntgen et al., 2009). At the same time, some records might be more temperature sensitive than they appear due to their calibration against noisy or inappropriate temperature targets (Böhm et al., 2009; Cook et al., 2012). The re-calibration against instrumental temperatures showed that temperature sensitivity and absolute climate signal strength are of limited importance for the preservation of millennium scale cooling trends in tree-ring records. Even the best calibrated records ($r > 0.6$; 1950-1980) convey a different low-frequency signature compared to the glacier ice, marine, and lake sediment records. This observation is relevant to the current debate in paleoclimatology on developing basic strategies for compiling proxy datasets to represent past natural temperature variability; is it best to include (a) a large number of proxy records, including those possessively a relatively weak temperature signal, or (b) a small number of only the very best calibrated proxies (Christiansen and Ljungqvist, 2017).

5 Conclusion

The community-sourced database of 692 different temperature-sensitive proxy records in the PAGES 2k initiative provides unprecedented opportunities to study long-term temperature trends at regional to global scales. The synthesis of glacier ice, marine and lake sediment records that span the Common Era reveals a persistent, millennial-scale cooling over the pre-industrial period that is missing in the tree-ring data. This analysis has shown that the observed discrepancies in long-term trends do not arise from the latitudinal and seasonally varying imprints of orbital forcing or the limited temperature sensitivity of tree-ring records. Despite application of the most suitable tree-ring detrending, one that can potentially support the preservation of low-frequency signals at millennial scale temperature trends, substantial long-term trend differences between proxies remain. On centennial scales, due to inappropriate detrending, some of the tree-ring records in the PAGES 2k database are limited in their low-frequency variance. However, when a more low-frequency conserving tree-ring detrending method is applied to the subset of suitable records new corroborating evidence for the existence of the LALIA appears. This lack of low-frequency variance needs to be considered when combining proxies in large scale temperature reconstructions to avoid the underrepresentation of late Holocene cooling trends prior to post-industrial warming in hemispheric and global mean temperature reconstructions.

Data availability.

The PAGES 2k database was accessed via the website of NCEI-Paleo/World Data Service for Paleoclimatology (https://www.ncdc.noaa.gov/paleo/study/21171).

Author contributions.

JE and SSG were the leaders of the project. PK and UB contributed to the planning and structuring of the analysis and publication. LK performed the analysis and wrote the manuscript with contributions from all co-authors.

Competing interests.

The authors declare that they have no conflict of interest.

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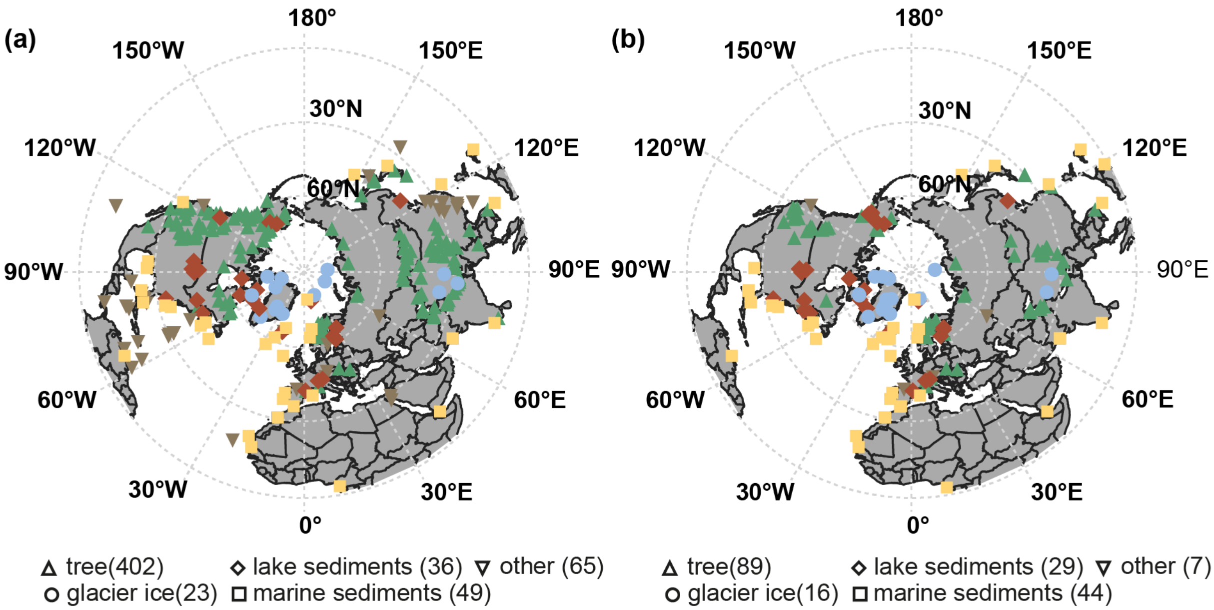

Fig. 1. (a) Map showing the spatial distribution of Northern Hemisphere proxy records from the PAGES 2k 2.0.0 database including primary tree-ring (green), glacier ice (blue), marine (orange) and lake (red) sediment records as well as a smaller number of records from bivalves, boreholes, corals, documents, hybrids, sclerosponges, and speleothems (brown). **(b)** same as (a) but only records longer than 800 years.

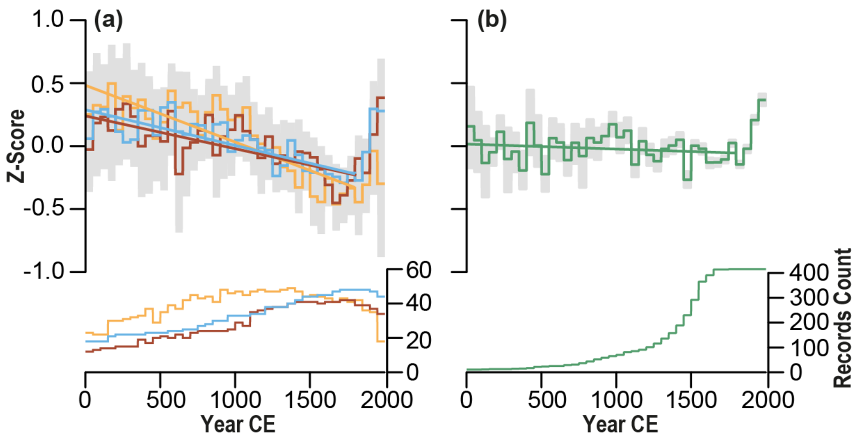

Fig. 2. Compilation of temperature-sensitive proxy records from the PAGES 2k initiative. **(a)** 50-year binned composites from 58 marine sediment (orange), 42 lake sediment (red) and 49 glacier ice (blue) records expressed in standard deviation units. Straight lines highlight the pre-industrial temperature trends (1-1800 CE) and lower panels show the corresponding temporal distribution of the records. Grey shadings indicate 95% bootstrap confidence intervals with 500 replicates. **(b)** same as in (a) for 415 tree-ring records.

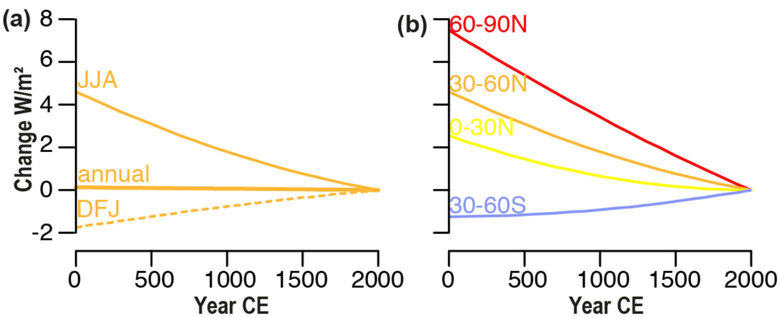

Fig. 3. (a) June-August, December-February, and annual insolation changes at 30-60°N relative to 2000 CE and **(b)** June-August insolation changes at different latitudinal bands (Laskar et al., 2004).

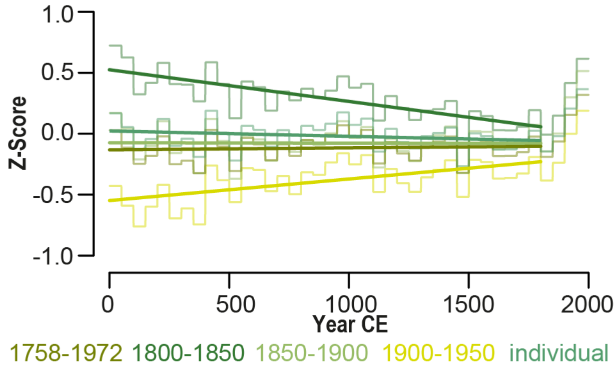

Fig. 4. Effect of tree-ring normalization on low-frequency temperature trends. Composite tree-ring records from 415 records normalized using the means and standard deviations over different time spans.

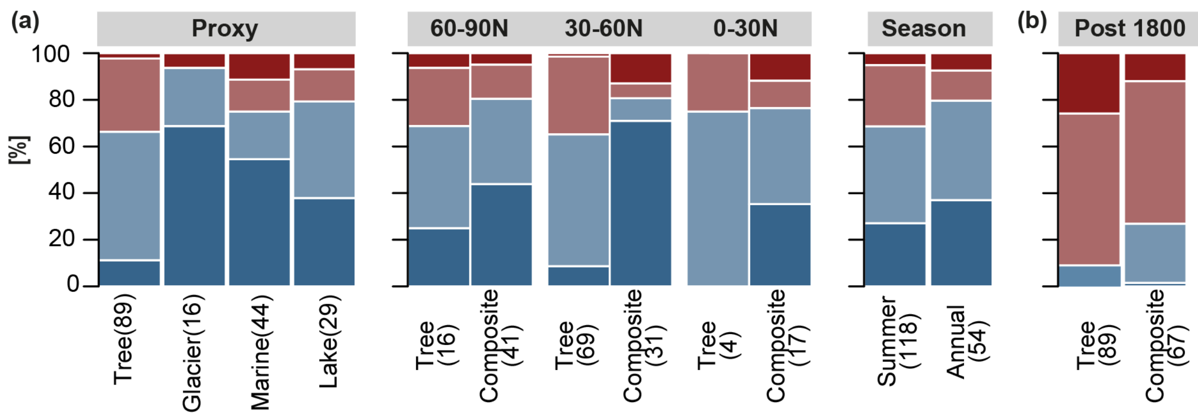

Fig. 5. Effects of orbital forcing on low-frequency temperature trends. Summary of NH long-term temperature trends from tree-ring, glacier ice, marine and lake sediment records longer than 800 years. The fraction of 50-year binned records that exhibit a significant negative (dark blue) and non-significant cooling (blueish) trend or significant (red) and non-significant (reddish) warming trend at $p < 0.05$ over **(a)** the pre-industrial (1-1800 CE) and **(b)** industrial (post 1800 CE) period derived from the statistical significance of the slope of least-squares linear regressions through each individual 50-year binned proxy record. Pre-industrial summaries are split by proxy, latitude, and seasonality. The category composite includes glacier, marine and lake sediments, and brackets indicate the number of records per category.

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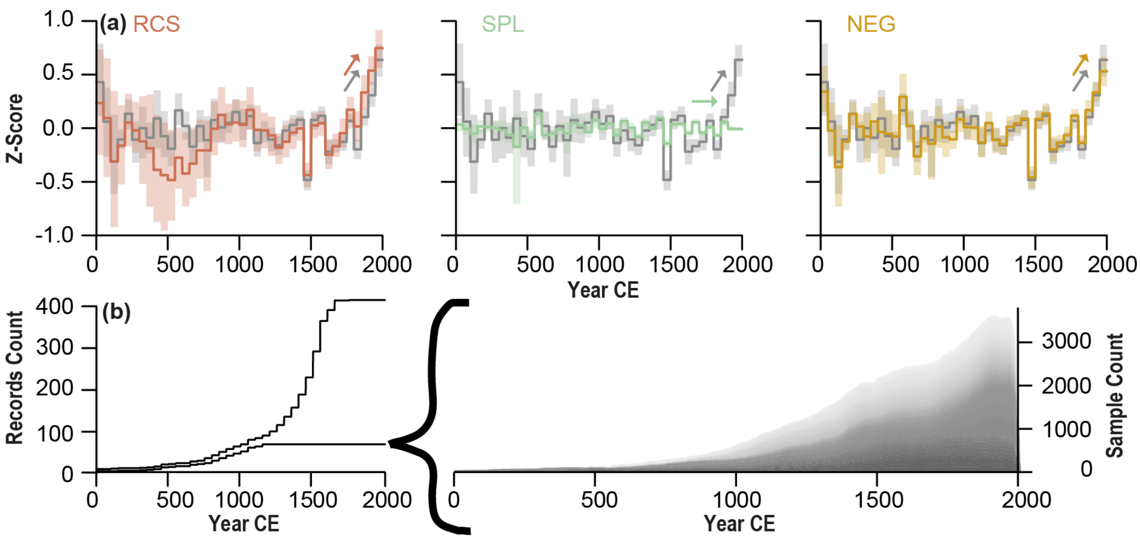

Fig. 6. Effects of tree-ring detrending on low frequency temperature trends. **(a)** 50-year binned composites from 70 RCS (red), 100-year SPL (green) and NEG (gold) standardized datasets. The PAGES 2k composite (dark grey) includes the corresponding chronology versions that are provided in the 2.0.0 database. Shadings indicate 95% bootstrap confidence intervals with 500 replicates, and the arrows indicate the direction of the post-1800 temperature trend. **(b)** Temporal distribution of the samples included in the whole database (415) relative to the detrended subset (70) and distribution of individual samples from records included in the subset (grey shadings).

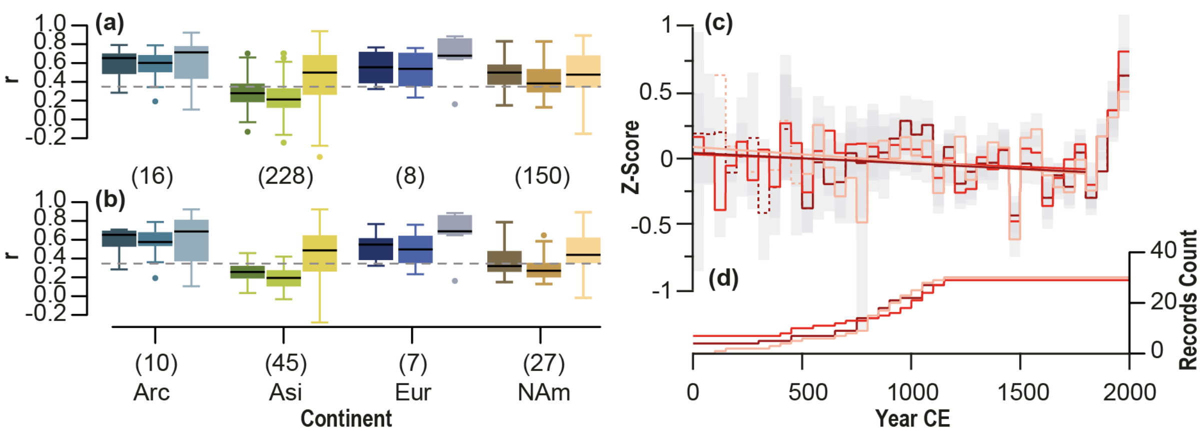

Fig. 7. Effects of tree-ring calibration on low-frequency temperature trends. **(a)** Maximum correlation coefficients between NH individual site-level tree-ring records and 1x1° CRU TS 4.01 June-September monthly temperature data over the period 1950-1980, divided by region, using 10-year high-pass filtered data (left box), original data (central box), 10-year smoothed data (right box). Dashed line indicates the $p < 0.05$ threshold. **(b)** Same as (a) using only records longer than 800 years, and corresponding **(c)** 50-year binned composites divided by climate signal strength including records with the lowest (n= 30; rose), medium (n= 31; red) and highest (n= 30; dark red) climate sensitivity. Light grey shadings indicate 95% bootstrap confidence intervals with 500 replicates and **(d)** temporal distribution of the records.