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Proxy record selection to refine Holocene temperature reconstruction in Europe

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ABSTRACT: Holocene climate reconstructions are characterized by rather smooth temperature trends owing to the low temporal resolution, dating uncertainty, and non-climatic noise of underlying proxy records. In this study, we apply methods to refine such reconstructions in Europe by calibrating a network of 126 low-resolution Holocene proxies against a continental-scale (smoothed) high-resolution temperature reconstruction over the past 2000 yr. This approach differentiates between 35 records that correlate with the shorter continental reconstruction, and 91 records that do not correlate or have other issues such as abrupt variance, temperature level, or temporal resolution changes. The separation into 'calibrating' and 'non-calibrating' proxies has limited statistical skill, however. This is because the smoothed record autocorrelations exceed r = 0.99 and constrain the degrees of freedom of any correlation-based analysis. The selection based on fit with a common target naturally increases covariance among the records, from an inter-series correlation (Rbar) of 0.00 for all 126 proxies, to Rbar = 0.33 for the 35 calibrating proxies over the Common Era (CE). Covariance in the latter group also reached Rbar = 0.30 during the period Before the Common Era (BCE), compared to Rbar = 0.04 among the non-calibrating proxies. This increase in covariance prior to the CE, while not statistically significant, indicates that the selection process based on fit with a much shorter, 2000 yr target may have improved the temperature reconstruction over the Holocene.

KEY WORDS: Paleoclimate · Proxy records · Climate archives · Lake sediments · Pollen · Climate change

1. INTRODUCTION

Proxy records from lake sediments, peat bogs, and speleothems form the backbone to reconstruct temperature variability over the Holocene (Wanner et al. 2015) and assess the skill of long-term climate model simulations (Braconnot et al. 2012). While developing such time series is highly laborious, several hundred pollen, chironomid, and stable isotope records have been made available by numerous groups over the past decades (e.g. van Zeist 1964, Heeb & Welten 1972, Binka et al. 1988, Allen et al. 1996, Bigler et al. 2006). The transfer of these data into estimates of temperature variability is typically based on elementary assumptions of space-for-time calibration and on different data modeling approaches, such as the modern analogue technique or weighted-averaging partial least-squares regressions (Chevalier et al. 2020). However, dissimilarities between single reconstructions, even within a limited spatial domain such as Europe, can be substantial, as illustrated by reconstructed Holocene temperature amplitudes from 2 nearby Norwegian lake pollen records that range from <1.5 to >5.8°C (see Liltlvatn [Lil] and Gun-

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narsfjorden [Gun] in our Fig. 1; Sundqvist et al. 2014). Other records are entirely free of long-term trends (but include inter-annual variability), such as the Torneträsk (Tor) tree-ring time series from northern Sweden (Grudd et al. 2002), or reveal long-term warming trends >9°C over the past 4 ka (4000 yr), such as recorded in the Laguna Salada de Chiprana (Lag) lake pollen data from northern Spain (Kaufman et al. 2020a). Records may contain abrupt changes in variance or temporal resolution (see Liivjarve [Lii] and Schwarzsee [Schwa] in Fig. 1) that are unique within the context of neighboring data (Koff 1990, Ilyashuk et al. 2011).

These caveats forced the paleoclimate community to opt for approaches that enable the integration of multiple proxy time series, characterized by vastly differing resolution, trend, and amplitude characteristics, into large-scale temperature reconstructions covering the Holocene (Wanner et al. 2008). A key component of these techniques is the binning and averaging of proxy data over relatively large temporal intervals of 100 to 1000 yr blocks (Kaufman et al. 2020a,b, Bova et al. 2021, Osman et al. 2021), which greatly mitigates outlier effects and further smooths resulting mean time series (Essell et al. 2023). Binning and averaging support the inclusion of effectively all available data within a region, regardless of the spread and covariance among time series. The approach has been highly successful as it enabled the documentation of substantially warmer conditions during the Holocene Optimum between 8–6 ka Before Present (BP; before 1950 in the Common Era [CE]) across the Northern Hemisphere and helped place current greenhouse gas-forced warming into a long-term context (IPCC 2021).

A downside of binning all data is the potential lack of climate information in single records or portions of records that not only decreases covariance within a proxy network but also mutes the variability of reconstructed temperatures in derived mean time series. Covariance assessments are fundamentally challenged, however, by the varying resolutions, trends, and amplitudes of proxy records (e.g. see Fig. 1). In an attempt to explore potential pathways to refine Holocene temperature reconstructions, we here smooth a larger number of proxy records from Europe (Seppä et al. 2009) and calibrate these time series against a continental-scale summer temperature reconstruction covering the CE (Luterbacher et al. 2016, hereinafter Lut16). We detail how such an approach can be used to differentiate between proxies that fit and do not fit the CE target and compare covariance between split groups. While we acknowledge that any such approach lacks statistical significance, it is argued that the inclusion of proxy records that do not cohere at all with a well-verified European temperature reconstruction over the past 2 ka may not improve our understanding of Holocene climate variability.

2. MATERIALS AND METHODS

The Temperature 12k Database (Kaufman et al. 2020a) was used to extract 354 temperature-sensitive proxy records from the Linked Paleo Data (LiPD) framework (McKay & Emile-Geay 2016) covering the area from 40°–70° N and 10° W–30° E in Europe (Fig. 1). Sixty-nine of these records were either too coarsely resolved (>300 yr on average), or did not include data older than 5 ka BP or younger than 400 yr BP, and were therefore excluded from the analysis. Since many of the remaining sites include highly similar and differently scaled duplicate records (to winter, summer, and annual temperatures), we further removed another 159 time series and only kept the data containing an assigned summer temperature signal. This step was conducted to maximize overlap with the spatially resolved Lut16 June–August temperature reconstruction that integrates 8 tree-ring chronologies from Sweden, Finland, Romania, Austria, Switzerland, France, and Spain, as well as historical documents from Central Europe. Due to the limited spatial correlation decay of summer temperatures, a European mean time series representing the area from 35–70° N and 10° W–40° E, derived from a nested composite-plus-scaling approach and extending back over the CE, was used for calibration.

The remaining 126 Holocene summer temperature proxies were smoothed using a 10-point LOESS filter (Savitzky & Golay 1964, Cleveland 1979) and calibrated against the Lut16 reconstruction. The latter was smoothed using a 20-point filter to mitigate autocorrelation differences resulting from the high, interannual resolution of the continental-scale CE temperature reconstruction. The filters were assessed to flag fits portraying deviations outside the variance range of the original measurements (Fig. S1, Text S1 in the Supplement at www.int-res.com/articles/suppl/c094p071_supp.pdf), and lag-1 autocorrelations were computed over the periods covered by each series. The smoothed proxies were scaled (Esper et al. 2005) against the smoothed Lut16 reconstruction to homogenize mean and variance over their common period. An additional adjustment was applied to 25 records characterized by >300 % variance increases between the Before Common Era (BCE) compared to the CE

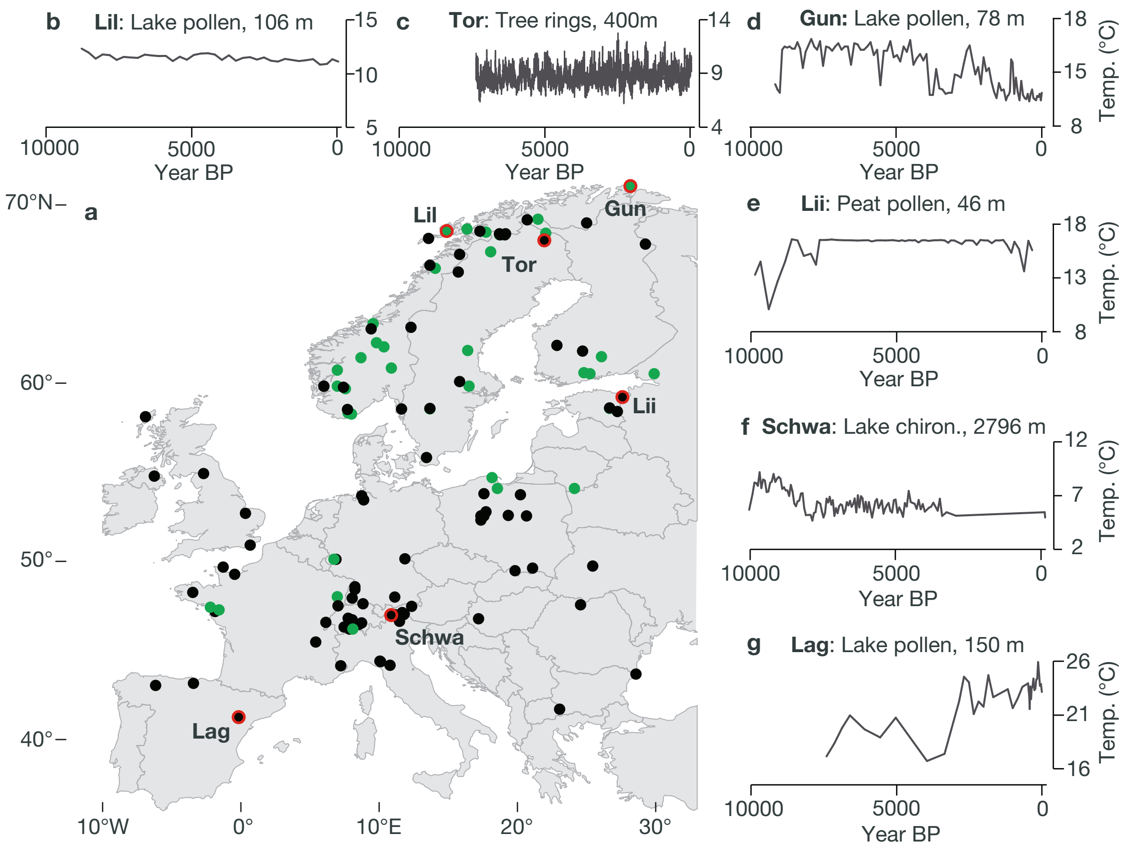

Fig. 1. Holocene proxy network. (a) 126 proxy locations across Europe differentiated by records included in the refined temperature reconstruction (green) and those not included (black). Red circles indicate example records highlighted in (b) Liltlvatn (Lil), (c) Torneträsk (Tor), (d) Gunnarsfjorden (Gun), (e) Liivjarve (Lii), (f) Schwarzsee (Schwa), and (g) Laguna Salada de Chiprana (Lag). BP: Before Present; chiron.: chironomids. Note the different *y*-axis values

periods, considering the average standard deviation (SD) of all other records, to mitigate effects of temperature outliers in reconstruction mean curves (Fig. 2a, Fig. S2).

Several calibration trials against Lut16 and separation into correlating and non-correlating groups were computed to evaluate the effects of proxy selection using a common target on the variability of derived mean time series. For the final reconstruction, the 126 proxies were partitioned into calibrating (Cal) and non-calibrating (Non-Cal) groups based on positive correlations with Lut16 and considering specific features including (1) lacking low-frequency variance, (2) poor LOESS filter fits, (3) missing recent warming trend, and (4) abrupt variance, level, or resolution changes (see Fig. S1 for examples). At least one of these exclusion criteria occurred in 20 of the proxy records correlating $r > 0.2$ with Lut16 and were therefore moved into the Non-Cal group. Covariance within the Cal and Non-Cal groups (as well as the 'All' group integrating all 126 records) was assessed over their full, CE, and BCE periods, and the temperature variability and trends among group mean time series compared.

3. RESULTS

While 52 of 126 European proxy records correlate positively at $r > 0.2$ with Lut16, 35 fall into the range from $r = -0.2$ to 0.2, and 39 records correlate negatively at $r < -0.2$ (Fig. 2b). Considering this basic scheme for data partitioning, notable effects of smoothing and averaging become visible (Fig. 3). Whereas the variability of the single LOESS filters is similar, ranging from SD of 0.18°C in the proxy records to 0.19°C in the Lut16 reconstruction, reconstructed temperature variances are attenuated in the proxy mean time series (red curves in Fig. 3; SD = 0.04–0.11°C). The reduction is particularly obvious in the mean of the non-correlating data, which is derived from 35 independent records (inter-series corre-

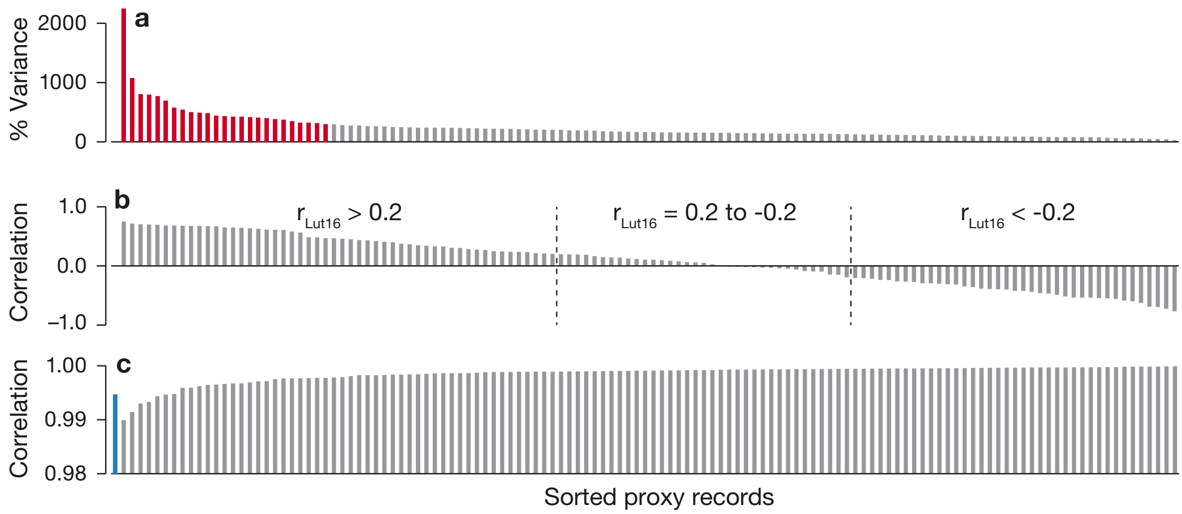

Fig. 2. Proxy time series statistics. (a) Variance difference of 126 European proxy records between Before Common Era (BCE) and Common Era (CE) periods. Red: records with >300% variance difference. (b) Correlation scores of the records against Luterbacher et al. (2016) (Lut16). (c) Lag-1 autocorrelation of proxy records (grey) and the Lut16 reconstruction (blue)

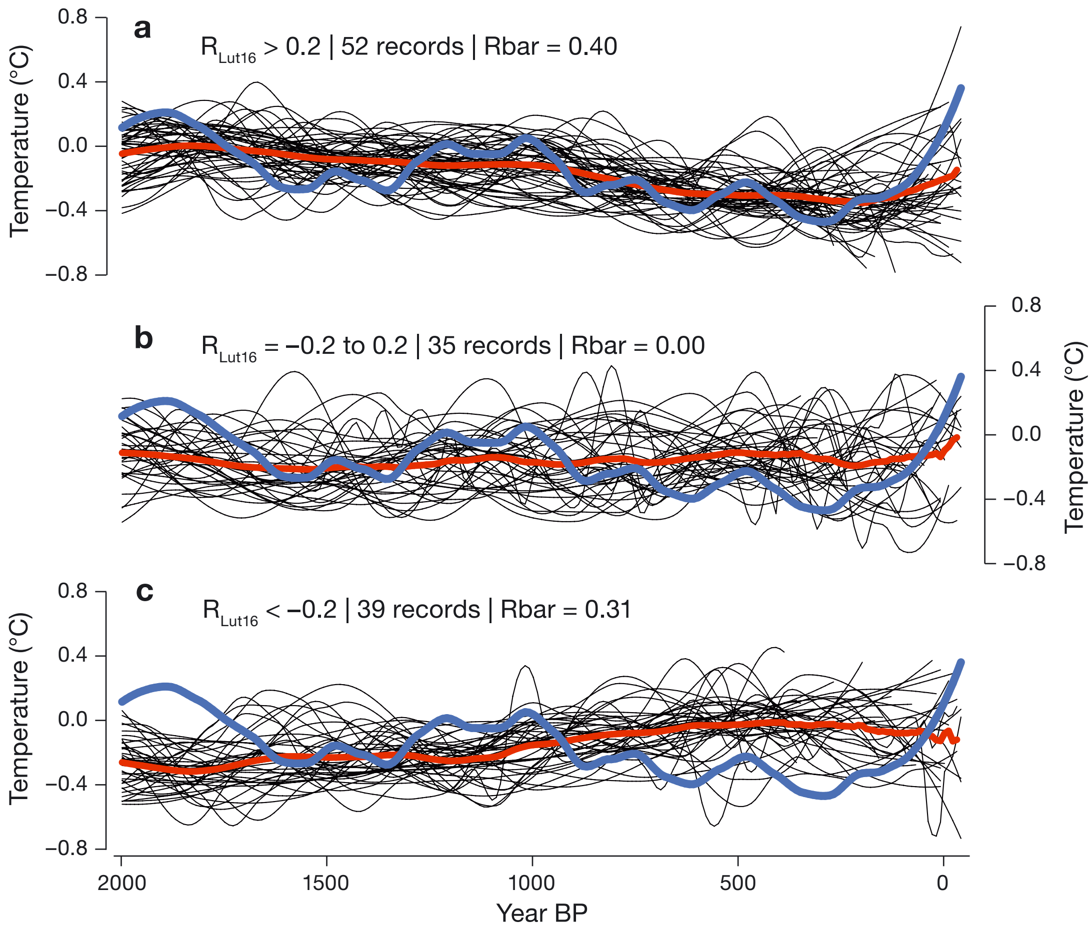

Fig. 3. Smoothed proxy records (black) and their means (red) shown together with the Luterbacher et al. (2016) (Lut16) temperature reconstruction (blue). (a) 52 records each correlating r > 0.2 against Lut16; (b) 35 records correlating between r = −0.2 and 0.2; and (c) 39 records correlating r < −0.2. Rbar is the mean inter-series correlation calculated over the past 2 ka. All temperatures expressed as anomalies with respect to the 1961–1990 climatology from the Lut16 reconstruction. BP: Before Present

lation [Rbar] = 0.00) and effectively displays a horizontal straight line cutting through the Lut16 reconstruction. The 39 negatively correlating records display a higher Rbar of 0.31, but their mean curve opposes all of the well-documented paleoclimatic periods in Europe, including warmth during Roman times (Esper et al. 2012), cold Late Antique Little Ice Age (Büntgen et al. 2016), Medieval Warm Period (Esper & Frank 2009), Little Ice Age (Wanner et al. 2022), and recent greenhouse gas-driven warming (Esper et al. 2024a). These key characteristics of CE climate variability are also not well-depicted in the 52 fitting proxies (Fig. 3a; Rbar = 0.40), even though their mean correlates at r = 0.72 with Lut16. This proxy mean displays a prolonged cooling trend until 300 yr BP followed by an obvious but restricted warming trend. Effects of variance attenuation caused by averaging proxy networks of limited covariance need to be considered when interpreting Holocene temperature reconstructions. The sources of variance muting include lacking climatic signals in some of the Holocene proxy records but are also fundamentally linked to dating uncertainties and resolution changes inherent to the archives (Esper et al. 2024b).

Proxy records correlating negatively or not at all with the continental-scale Lut16 reconstruction may well contain climatically meaningful information prior to the CE calibration period. However, if we consider the commonly applied principle of uniformitarianism used to verify high-resolution proxies against much shorter instrumental data (Cook & Kairiukstis 1990), it appears conclusive that the correlating records are the more skillful predictors of Holocene temperature variability. This being said, it is paramount to recall that none of the correlations between smoothed proxy records and smoothed Lut16 target is statistically significant. Lacking significance results from very high serial correlations caused by time series smoothing and expressed by lag-1 autocorrelations exceeding 0.99 (Fig. 2c), constraining the degrees of freedom to <5.

Building on the approach of calibrating long Holocene proxy records against a shorter CE target, and additionally considering exceptional variance, level, and resolution changes, 35 pollen and chironomid time series are used to calculate a refined Holocene temperature reconstruction for Europe (Table 1). As with the strictly correlation-based separation, the Cal proxy mean traces the Lut16 reconstruction, though at a substantially muted variability particularly during the first millennium CE (Fig. 4a). The Non-Cal proxy mean, on the other hand, does not show any climatically meaningful CE variability, perhaps except for the most recent temperature uptick, but reveals warmer conditions during the well-documented Little Ice Age centered in the second millennium CE. The Non-Cal proxies correlate on average at r = 0.08 with the Lut16 target, whereas the Cal proxies reach r = 0.47 (Table 2).

Partitioning the European network into Cal and Non-Cal proxies reveals substantial temperature trend and covariance differences over the past 9 ka. Cal paleotemperatures are up to 0.4°C warmer during the Holocene Optimum between 7.2 and 6 ka BP, whereas the Non-Cal reconstruction hardly deviates from the late 20th century mean (Fig. 4b). The Non-Cal reconstruction also shows less temperature variability compared to the mean derived from all 126 proxies, demonstrating that the combination of calibrating and non-calibrating records naturally places the grand mean in between the split-data reconstructions. Differences in reconstructed temperature amplitude are in line with changing covariances ranging from Rbar = 0.05 in the Non-Cal, to 0.13 in the All, and 0.48 in the Cal data over the past 9 ka (Table 2). Importantly, the Cal Rbar values are not only increased during the CE calibration period (0.33 compared to 0.00 in All), but are also elevated during BCE (0.34 compared to 0.04 in Non-Cal), indicating that the selection against a continental-scale CE temperature target likely improved the reconstruction over the Holocene.

While the differences between mean temperatures appear distinct, the spread among proxy records and size of reconstruction uncertainties, even if calculated using conservative interquartile ranges, are too large to claim significance (Figs. S3 & S4). However, the refined Cal reconstruction indicates relatively rapid warming until ~7.2 ka BP, reaching maximum temperatures ~6 ka BP (Fig. 5). The warm mid-Holocene is punctuated by a distinct cold period from 5.5 to 5.0 ka BP that might have been much more prominent than depicted, when considering the variance-muting effects from dating uncertainties and resolution changes as reflected during the CE calibration period by comparison with Lut16 (blue curve in Fig. 5). The refined Cal reconstruction indicates persistent cooling from 4.5 to 3 ka BP, and steady temperatures from 3.3 to 2.6 ka BP. The contributing proxy sites are weighted towards northern Europe with no additions from the UK, Spain, and eastern Europe (except 1 site from Lithuania; green dots in Fig. 1). It appears unlikely, however, that this bias is related to synoptic weather patterns, as low-frequency temperature trends are homogeneous at large spatial scales (Davis et al. 2003).

Table 1. Proxy record characteristics. Resolution (in yr) is derived from dividing the period between the first and last year Before Present (BP) by the number of data points in each record. Correlation refers to the fit with Luterbacher et al. (2016) over the Common Era (CE). Rbar is the mean correlation with all other records

Name	Latitude	Longitude	Elevation (m)	First year BP	Last year BP	Resolution	Correlation	Rbar
Lake sediment								
Pollen								
Arapisto	60.58° N	24.80° E	133	8889	0	108	0.61	0.63
Dalene	58.25° N	8.00° E	40	8940	−57	180	0.61	0.36
Flarken	58.55° N	13.67° E	108	8982	−50	99	0.70	0.62
Flotajønn	59.67° N	7.55° E	890	9021	−44	211	0.63	0.54
Gammelheimvatnet	68.47° N	17.75° E	290	8968	−42	122	0.20	0.58
Gloppsjon	59.83° N	16.53° E	198	8972	0	123	0.67	0.62
Godziszewskie lake	54.09° N	18.55° E	71	9521	212	108	0.48	0.25
Gondo Alpjen	46.21° N	8.11° E	1724	6577	151	153	0.42	0.49
Gunnarsfjorden	71.04° N	28.17° E	78	9124	−40	88	0.65	0.57
Haugtjern	60.83° N	10.88° E	338	8959	−23	134	0.29	0.56
Kinnshaugen	62.02° N	10.37° E	591	8829	−23	184	0.21	0.46
Klotjarnen	61.82° N	16.40° E	235	8942	−48	86	0.47	0.62
Laihalampi	61.48° N	26.07° E	137	8995	49	73	0.17	0.57
Liltlvatn	68.52° N	14.87° E	106	8780	−45	232	0.43	0.43
Meerfelder Maar	50.10° N	6.75° E	337	10990	163	27	0.47	0.47
Myrvatn	68.65° N	16.38° E	200	8894	−42	186	0.35	0.37
Raigastvere	58.58° N	26.65° E	53	8923	0	99	0.61	0.61
Reiarsdalvatnet	58.32° N	7.78° E	245	8931	−72	107	0.45	0.43
Svanåvatnet	66.44° N	14.05° E	243	8750	−18	107	0.41	0.59
Svartvatnet-Norway	63.35° N	9.55° E	183	8938	−37	180	0.33	0.59
Tibetanus	68.33° N	18.70° E	560	10238	39	227	0.65	0.49
Trettetjørn	60.72° N	7.00° E	810	8527	−52	162	0.11	0.55
Tsuolbmajavri	68.41° N	22.05° E	526	8967	−45	67	0.63	0.50
Chironomid								
Brurskardstjorni	61.42° N	8.67° E	1309	10900	−27	179	0.70	0.59
Hirvijaervi	60.51° N	25.23° E	104	11500	0	261	0.30	0.48
Holebudalen	59.83° N	6.98° E	1144	10948	−10	166	0.67	0.61
Medvedevskoe	60.53° N	29.90° E	102	12018	0	353	0.25	0.39
Ratasjoen	62.27° N	9.83° E	1169	11621	−49	154	0.27	0.35
Sjuuodjijaure	67.37° N	18.07° E	826	9317	36	182	0.68	0.34
Toskaljavri	69.20° N	21.47° E	704	9500	0	100	0.68	0.51
Njakajaure	68.33° N	18.78° E	409	8855	111	213	0.31	0.41
Peat Pollen								
Bebrukas lake	54.09° N	24.12° E	149	10890	286	259	0.68	0.44
Darzlubie forest	54.70° N	18.17° E	40	10887	72	142	0.75	0.14
Saint Thomas	47.27° N	1.75° W	1	6947	152	67	0.14	0.49
Saint Viaud Contin	47.27° N	2.02° W	2	7364	−18	105	0.46	0.56

4. DISCUSSION

Estimates of Holocene temperature amplitude, i.e. the deviation of Holocene Optimum from CE temperatures, range broadly from <0.5 to >3.5°C for Northern Hemisphere mid-to-high latitudes (Marcott et al. 2013, Marsicek et al. 2018, Kaufman et al. 2020b), complicating the attribution of long-term temperature trends to climate forcings (Büntgen 2022, Cartapanis et al. 2022, Laepple et al. 2023, Essell et al. 2024). This uncertainty largely results from applying different methods to highly similar proxy networks regardless of the records' covariance and fit with a common target. Considering these characteristics in a spatially limited domain such as Europe, our results indicate that the high-end variability estimates are probably more meaningful, as the integration of proxies that do not cohere with a continental-scale temperature reconstruction during CE likely add noise during BCE and thereby mute Holocene climate variance. While the approach implemented here, involving proxy smoothing and forfeiting degrees of freedom, cannot inform about the exact amplitude of Holocene temperature variability, it reveals the effects of removing

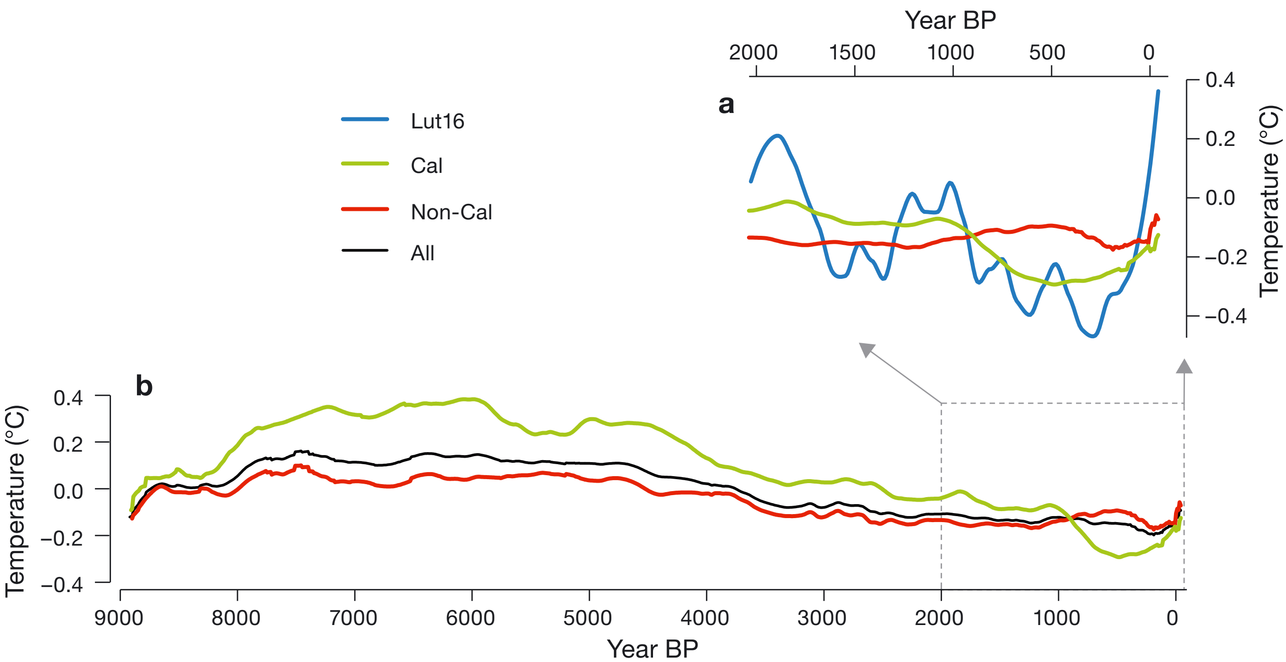

Fig. 4. Calibration against Luterbacher et al. (2016) (Lut16) and 3 Holocene temperature reconstructions. (a) Arithmetic mean curves of the calibrating (Cal) and non-calibrating (Non-Cal) proxy records plotted together with the Lut16 reconstruction. (b) Mean curves of the Cal, Non-Cal, and all proxy records over the past 9 ka. All temperatures expressed as anomalies with respect to the 1961–1990 climatology from the Lut16 reconstruction. BP: Before Present

Table 2. Proxy calibration and covariance. First row shows the mean correlations of all 126 proxies (All), 35 calibrating proxies (Cal), and 91 non-calibrating proxies (Non-Cal) against Luterbacher et al. (2016) (Lut16). Rbar is the inter-series correlation among proxy records calculated over the Common Era (CE), Before Common Era (BCE), and full Holocene periods

	Period	All	Cal	Non-Cal
Lut16	CE	0.07	0.47	0.08
Rbar	CE	0.00	0.33	0.02
	BCE	0.10	0.34	0.04
	Holocene	0.13	0.48	0.05

data with no notable climate signal during CE. The increased covariance of the remaining, calibrating data, beyond the past 2 ka, supports this conclusion on muted Holocene temperature variability.

It is fundamentally different, however, if large temperature amplitudes are blown into the Holocene, (1) because all available data are scaled in a way that adds variability to binned and averaged mean time series, or (2) a selection of co-varying and climatically less noisy records is conducted before deriving mean temperatures over a larger spatial domain. The latter approach also increases the chance to add meaning-

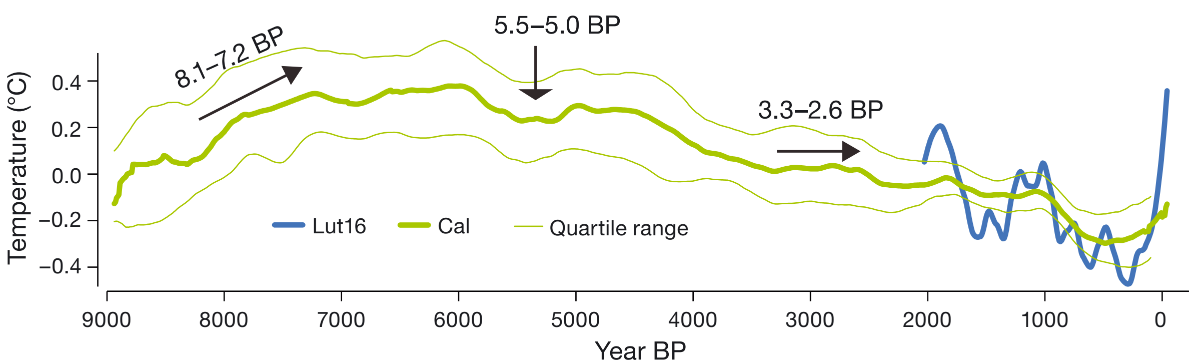

Fig. 5. Refined temperature reconstruction and quartiles. Holocene temperature reconstruction (green, with the 25–75% interquartile range) derived from 35 proxy records reasonably fitting the Common Era Luterbacher et al. (2016) (Lut16) reconstruction. Periods of increasing temperatures from 8.1–7.2 ka Before Present (BP), cooler temperatures from 5.5–5.0 ka BP, and invariable temperatures from 3.3–2.6 ka BP highlighted with arrows. All temperatures expressed as anomalies with respect to the 1961–1990 climatology from the Lut16 reconstruction

ful higher-frequency, centennial-scale variability to otherwise smooth Holocene temperature estimates, as is here revealed by a temperature drop between 5.5 and 5.0 ka BP in Europe. This feature and other distinctions, such as the rapid warming from 8.1–7.2 ka BP, are still likely muted in our reconstruction, however, as is emphasized by the mismatch in variability between the Holocene and CE Lut16 time series (Figs. 4a & 5). An overall increased variability and stronger long-term cooling trend towards the present, as concluded here for Europe, are arguments for a greater importance of orbital forcing for Northern Hemisphere mid-to-high latitude Holocene climate.

Conducting this study in Europe appeared advisable, as (1) the continent has been a focal point of proxy record production, (2) low-frequency temperature trends can be assumed to cohere north of 40° N, and (3) one of the most skillful temperature reconstructions covering the CE has been established. Considering this ideal setup, it appears remarkable that more than half of the Holocene proxies with sufficient resolution and time coverage do not correlate with the Lut16 target reconstruction over the past 2 ka. While this conclusion is restricted by limited degrees of freedom and deviating LOESS filters, readers may have expected a higher percentage of proxies, commonly used in binning approaches, to covary with well-established CE climate swings alternating between Roman, Medieval, and recent greenhouse gas-driven warmth. Proxy records that do not cohere with these major features of European paleoclimate, or even show opposing trends over the past 2 ka, are unlikely to add meaningful variability to Holocene temperature estimates.

This being said, it remains unclear whether the selection of records based on fit with a much shorter target truly improved Holocene temperature estimates, as the low and varying resolution of proxies and ultimately the lack of statistical skill hinders verification of this approach. An alternative solution would be the development of higher-resolution proxies covering the Holocene, which is under way but requires time and support by funding agencies. The necessary differentiation and selection of proxies could meanwhile further be improved by adding expert knowledge from a larger consortium of proxy developers to the process, which would again be a worthwhile subject for third-party funding. To this point, our limited understanding of the absolute temperature amplitude and higher-frequency variability of Holocene paleoclimate remain key challenges complicating the placement of current, greenhouse gas-driven dynamics into long-term context.

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