



A frequency-optimised temperature record for the Holocene

Helen Essell, Paul J Krusic, Jan Esper, Sebastian Wagner, Pascale Braconnot, Johann Jungclaus, Francesco Muschitiello, Clive Oppenheimer, Ulf Büntgen

► To cite this version:

Helen Essell, Paul J Krusic, Jan Esper, Sebastian Wagner, Pascale Braconnot, et al.. A frequency-optimised temperature record for the Holocene. *Environmental Research Letters*, 2023, 18 (11), pp.114022. <10.1088/1748-9326/ad0065>. <hal-04295414>

HAL Id: hal-04295414

<https://hal.science/hal-04295414v1>

Submitted on 20 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

LETTER • OPEN ACCESS

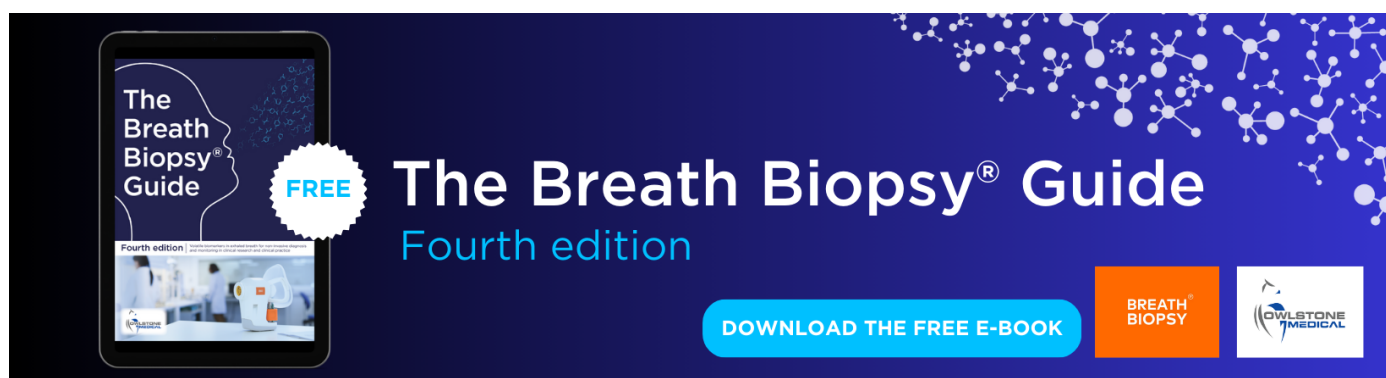
A frequency-optimised temperature record for the Holocene

To cite this article: Helen Essell *et al* 2023 *Environ. Res. Lett.* **18** 114022

View the [article online](#) for updates and enhancements.

You may also like

- [A phase space description of the Earth System in the Anthropocene](#)
O. Bertolami and F. Francisco
- [Estimation of potential and actual evapotranspiration of boreal forest ecosystems in the European part of Russia during the Holocene](#)
A Olchev and E Novenko
- [Green Sahara tipping points in transient climate model simulations of the Holocene](#)
Peter O Hopcroft and Paul J Valdes



The Breath Biopsy® Guide
Fourth edition

FREE

DOWNLOAD THE FREE E-BOOK

BREATH BIOPSY

OWLSTONE MEDICAL

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

A frequency-optimised temperature record for the Holocene

Helen Essell^{1,2} , Paul J Krusic^{2,3}, Jan Esper^{4,5}, Sebastian Wagner⁶, Pascale Braconnot⁷, Johann Jungclauss⁸,
Francesco Muschitiello^{2,9}, Clive Oppenheimer² and Ulf Büntgen^{2,5,10,11,*} ¹ Archaeology & Palaeoecology, School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN, United Kingdom² Department of Geography, University of Cambridge, Cambridge CB2 3EN, United Kingdom³ Department of Physical Geography, Stockholm University, 10691 Stockholm, Sweden⁴ Department of Geography, Johannes Gutenberg University, 55099 Mainz, Germany⁵ Global Change Research Institute (CzechGlobe), Czech Academy of Sciences, 603 00 Brno, Czech Republic⁶ Helmholtz-Zentrum Hereon, Institute of Coastal Systems—Analysis and Modelling, 21502 Geesthacht, Germany⁷ CNRS LSCE-Vallee, 91198 Gif-Sur-Yvette, France⁸ Max-Planck-Institute for Meteorology, 20146 Hamburg, Germany⁹ Centre for Climate Repair, DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, United Kingdom¹⁰ Department of Geography, Faculty of Science, Masaryk University, 611 37 Brno, Czech Republic¹¹ Swiss Federal Research Institute (WSL), 8903 Birmensdorf, Switzerland

* Author to whom any correspondence should be addressed.

E-mail: ulf.buentgen@geog.cam.ac.uk**Keywords:** climate reconstructions, global warming, Holocene climate, paleoclimate, proxy archives, temperature changesSupplementary material for this article is available [online](#)RECEIVED
31 July 2023REVISED
16 September 2023ACCEPTED FOR PUBLICATION
5 October 2023PUBLISHED
17 October 2023Original content from
this work may be used
under the terms of the
[Creative Commons
Attribution 4.0 licence](#).Any further distribution
of this work must
maintain attribution to
the author(s) and the title
of the work, journal
citation and DOI.

Abstract

Existing global mean surface temperature reconstructions for the Holocene lack high-frequency variability that is essential for contextualising recent trends and extremes in the Earth's climate system. Here, we isolate and recombine archive-specific climate signals to generate a frequency-optimised record of interannual to multi-millennial temperature changes for the past 12 000 years. Average temperatures before ~8000 years BP and after ~4000 years BP were 0.26 (± 2.84) °C and 0.07 (± 2.11) °C cooler than the long-term mean (0–12 000 years BP), while the Holocene Climate Optimum ~7000–4000 years BP was 0.40 (± 1.86) °C warmer. Biased towards Northern Hemisphere summer temperatures, our multi-proxy record captures the spectral properties of transient Earth system model simulations for the same spatial and season domain. The new frequency-optimised trajectory emphasises the importance and complex interplay of natural climate forcing factors throughout the Holocene, with an approximation of the full range of past temperature changes providing novel insights for policymakers addressing the risks of recent anthropogenic warming.

1. Introduction

The pace of recent anthropogenic climate change is regarded as 'unprecedented' in at least the past 2000 years [1], implying irreversible ecological and societal consequences [2–4]. A meaningful evaluation of ongoing changes in the Earth's climate system hinges on our understanding of past climate variations [5] and our capacity to disentangle the relative contributions of anthropogenic and natural climate forcing factors [6]. Both tasks are challenged by the limitations of instrumental observations, proxy reconstructions, and model simulations [7, 8]. Decreasing quality (e.g., dating precision, sample resolution and signal strength) and quantity (e.g., spatial and seasonal coverage) of proxy records

back in time reduce the fidelity of climate reconstructions, compromising efforts to contextualise current climate dynamics [9].

To date, four multi-proxy reconstructions have attempted to describe the course of global mean surface temperatures during the Holocene [10–13], whose onset defines the beginning of the present interglacial period ~11 700 years before 1950 CE [14]. Without seasonal adjustments, the existing records depict long-term warming out of the Late Glacial period until ~7000 years BP, followed by moderate pre-industrial cooling [10–13]. While all reconstructions lack information about interannual to centennial scale temperature variability that is characteristic of the Earth's climate system [15, 16], they are widely used to frame the intensity

and severity of anthropogenic climate change, thus influencing public and political discourse [1, 17]. However, incomplete frequency preservation back in time has problematic implications for contextualising recent annual and decadal extremes, as they reflect different aspects and amplitudes of the Earth's climate system to past longer-term means.

Here, we isolate and recombine archive-specific climate signals to generate a new multi-proxy record that approximates the interannual to multi-millennial behaviour of large-scale surface temperatures over the past 12 000 years. We then compare our findings with transient Earth system model simulations and discuss the relevance of our findings for policymakers.

2. Data and methods

Our frequency-optimised record utilises a subset of 814 temperature-sensitive proxy timeseries (figure S1; table S1; supplementary data 2) drawn from 1319 records in the Temperature 12k database [18]. Marine and terrestrial proxies from 679 sites were included to maximise the number of contributing archives. Preference was given to annual mean temperature estimates, and seasonal information was only included in absence of an annual mean from a given site, to remain comparable to previous studies. Proxy timeseries from lacustrine ($n = 367$), marine ($n = 317$), ice ($n = 28$), peat ($n = 76$), speleothem ($n = 13$), midden ($n = 10$), and wood ($n = 3$) sources were first differentiated and binned by averaging measurements within intervals corresponding to the associated archive's mean sampling resolution over the Holocene (table S1). This step moderates the impacts of dating uncertainty and places timeseries on a common timescale. In absence of a common reference period, we normalised each record against its own Holocene mean (Materials and Methods; figure S2). Statistical infilling procedures that would increase a record's length to facilitate a common reference period were deemed inappropriate as this step would likely introduce artificial signals that would distort the climate information we sought to identify and isolate. We demonstrate suitability of this normalisation approach by assessing the distribution of normalised temperature anomalies in each bin interval for each archive type (Materials and Methods; figure S2).

We employed a bootstrap procedure to generate archive-specific Holocene temperature histories from the seven different proxy archive types (figure S3). No spatial gridding was applied in this procedure as no archive type is globally distributed (figure S1(a)). We acknowledge this creates a spatial bias in our record towards the Northern Hemisphere from where most of the proxy archives derive [18]. We then used multi-taper spectral analysis to identify the predominant signals in each timeseries [19]. Consistent

with the greatest number of significant periodicities at the 95% confidence interval, interannual signals (<10 years) are best captured by tree-ring chronologies (wood), multi-decadal variability (10–150 years) by speleothems, multi-centennial variations (150–1000 years) by ice and midden archives, multi-millennial changes (1000–6000 years) by peat and marine archives, and ultra-long trends (>6000 years) by lacustrine archives (figure S4).

Bandpass filtering was employed to isolate proxy-specific information from the respective temperature histories [20], with an exception for the tree-ring proxies. From 7450–0 BP, the linearly detrended wood temperature history is taken to reflect interannual variability due to the bandwidth limits of the dendro-chronological records [21, 22]. To extend high-frequency signal of this record beyond 7450 years BP, we built a synthetic series reflecting the autoregressive properties of the tree-ring temperature history in the pre-industrial Common Era. Although different boundary conditions may have prevailed in the early Holocene influencing the high-frequency characteristics of climate fluctuations [23], model simulations used in this study suggest that high-frequency temperature variability during the early Holocene was comparable with the pre-industrial Common Era (Materials and Methods), justifying our approach to present, for the first time, temperature variability on interannual timescales over the past 12 000 years.

Our final record was produced by combining signals from different frequency domains that were isolated by bandpass filtering (figures 1 and 2). For variability on multi-centennial and multi-millennial timescales that are best represented by multiple archive types, we weighted the contribution of each band-passed signal by the number of contributing records. Confidence intervals are deliberately permissive to account for non-climate variability preserved in proxy archives, methodological uncertainties, and year-to-year uncertainty associated with annually resolved climate records [24], and thus are reported as the sum of 95% confidence intervals of the archive-specific temperature histories. For the tree-ring data for which we cannot calculate confidence intervals beyond 7450 years BP, we report two standard deviations from the mean of the simulated interannual variability (Materials and Methods), and as such uncertainty estimates of our final trajectory widen prior to 7450 years BP due to the experimental nature of the interannual signal in this period. See Materials and Methods for further information on the production of our frequency-optimised record.

For model comparison, we selected outputs from three state-of-the-art transient Earth system models: CCSM3-TraCE-21k [25], MPI-ESM1.2 slo0050 [26, 27], and IPSL-TR6AV-Sr02 [28, 29]. All simulations are driven by greenhouse gas concentrations and orbital forcing. The MPI-ESM1.2

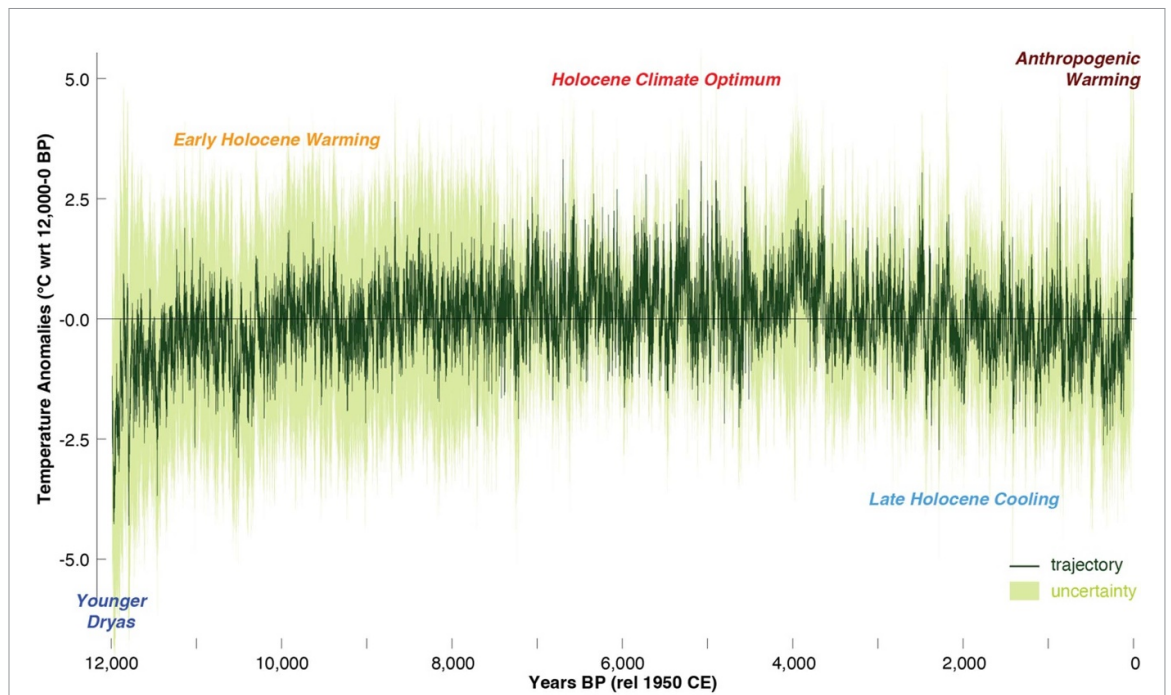


Figure 1. Frequency-optimised record of interannual to multi-millennial temperature changes for the period 12 000–0 years BP reported as anomalies with respect to the Holocene mean ($^{\circ}\text{C}$). The light green shading represents uncertainty based on the sum of 95% confidence intervals of the archive-specific temperature histories from which our record is derived, along with two standard deviations from the mean of the simulated interannual variability when confidence intervals were absent.

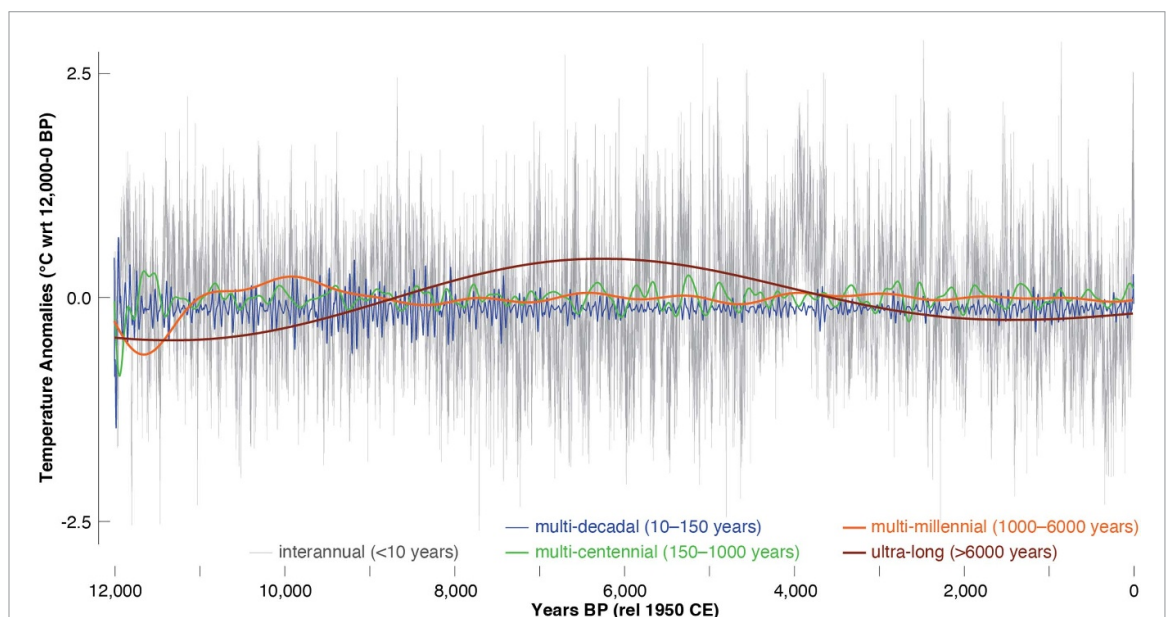


Figure 2. Experimentally derived proxy signals combined to produce our frequency-optimised Holocene temperature record given their demonstrated suitability in preserving variability in their five respective frequency bands. Signals were isolated by bandpass filtering, except for the interannual signal before 7450 years BP that is synthetically derived from the autoregressive properties of the wood temperature history in the pre-industrial Common Era. Units are reported as anomalies with respect to the Holocene (12 000–0 years BP) mean ($^{\circ}\text{C}$).

simulation further accounts for volcanic, solar, and land-cover forcing, while the CCSM3-TraCE-21k simulation also includes ice sheet and meltwater forcing mechanisms. Proxy-model comparison focuses on Northern Hemisphere summer temperatures due to a bias in the underlying proxy timeseries towards warm-season sensitive proxies from Europe and North America (figure S1). However, we also

compared our frequency-optimised record separately against simulated global annual and Northern Hemisphere annual temperatures (figures S6 and S7) to assess spectral properties across different seasonal and spatial domains (Materials and Methods). Comparisons were evaluated by computing Morlet wavelets [30] and performing multi-taper spectral analysis [19].

3. Results

Our frequency-optimised Holocene temperature history reveals a long-term trend of rising temperatures through the early and mid Holocene until ~4000 years BP when cooling sets in until the recent anthropogenic warming (figure 1). The early Holocene is the coldest period of the record, with temperatures up to ~8000 years BP averaging $0.26 (\pm 2.84)^\circ\text{C}$ cooler than the long-term mean (12 000–0 years BP). Gradual warming during this time led into a relatively warm Holocene Climate Optimum from ~7000 to 4000 years BP (figure 1), with temperatures averaging $0.40 (\pm 1.86)^\circ\text{C}$ warmer than the Holocene mean. Late Holocene temperatures after ~4000 years BP average $0.07 (\pm 2.11)^\circ\text{C}$ cooler than the long-term mean. This pre-industrial cooling trend culminates in the Little Ice Age in the early-19th century CE, after which recent warming commenced. Temperatures from 1850 to 1950 CE average $0.25 (\pm 2.46)^\circ\text{C}$ above the Holocene mean, and significantly differ from the magnitude of past natural variability ($p < 0.05$ in t -test).

We consider a complex interplay of diverse natural climate forcing factors responsible for the observed Holocene temperature changes (figure 2). Abrupt warming that brought an end to the Younger Dryas can be attributed to a combination of multi-decadal and multi-centennial forcing prior to ~11 500 years BP (figure 2). Multi-millennial forcing until ~10 000 years BP and ultra-long forcing until ~7000 years BP can be regarded as the main cause for gradually increasing temperatures during the early Holocene. The Holocene Climate Optimum correlates with a maximum in ultra-long forcing factors, while late Holocene cooling relates to its subsequent decline. Multi-decadal and multi-centennial variability from ~4000 years BP together explain short lived anomalies and warming since ~1850 CE.

Prevalent in our record is interannual variability throughout the Holocene (figures 1 and 2). The coldest extremes of the record occur at the end of the Younger Dryas; all but six of the fifty coldest years in our record occur during the early Holocene. Additionally, the coldest 10 year, 25 year, 50 year and 100 year intervals centre around 11 795 years BP, 11 971 years BP, 11 974 years BP and 11 945 years BP, respectively, which roughly coincides with the termination of the last glacial period (figure 1). The frequency and intensity of cold extremes appears diminished since ~1850 CE (figure 2). The warmest 10 year, 25 year, 50 year and 100 year intervals centre on 4896 years BP, 4895 years BP, 3939 years BP and 3914 years BP, respectively, all falling into the Holocene Climate Optimum.

The long-term trend of our frequency-optimised temperature history for the Holocene is not only comparable with those of existing multi-proxy reconstructions prior to any seasonal adjustments [10–13] (figures 3 and 4), but also with those simulated by transient Earth system models when using mean Northern Hemisphere summer temperatures (see section 4 for details).

4. Discussion

Our study reveals a complex interplay of different climate forcing factors and emphasises the importance of multi-proxy compilations in providing a more complete understanding of Holocene climate dynamics on interannual to multimillennial timescales. Relatively cool phases at the end of the Younger Dryas and ~10 000 years BP were likely driven by the presence and later collapse of Northern Hemisphere ice masses [31]. The Holocene Climate Optimum and subsequent long-term cooling are best explained by summer insolation changes around 65°N [32, 33]. Pronounced decadal to multi-centennial variability since ~4000 years BP likely reflects diminished ice sheet forcing together with prevalent volcanism [15, 34, 35].

In presenting a similar long-term trend to simulated Northern Hemisphere summer, as opposed to global annual mean temperatures (figures 3(c), 4 and S6), we regard our frequency-optimised record, as well as existing multi-proxy reconstructions prior to seasonal adjustment, to predominantly reflect a Northern Hemisphere summer signal. Although we use a global network of proxy records, 455 of the 814 of these are located between 40° and 70°N in a circumpolar belt across Eurasia and North America, and most of the biogeochemical archives are active in, or sensitive to warm season conditions [18]. This not only produces spatial and seasonal biases, but also explains why our frequency-optimised record mainly reflects Northern Hemisphere summer temperatures (figures 3(c) and 4). Such understanding feeds into the debate about a ‘Holocene temperature conundrum’, a discrepancy between proxy-based pre-industrial cooling after the Holocene Climate Optimum and transient model simulations that indicate a relatively warm late Holocene during which temperatures steadily increase [32, 33, 36]. This trend offset has been suggested to reflect several factors: spatial variation in the modes of temperature variability [26, 37], seasonal biases of biotic proxy archives [32], greater spatial co-variance in models compared to proxies [38], and uncertainties in model parametrisations [39–42]. Our results, however, suggest that the ‘conundrum’ simply from misinterpreta-

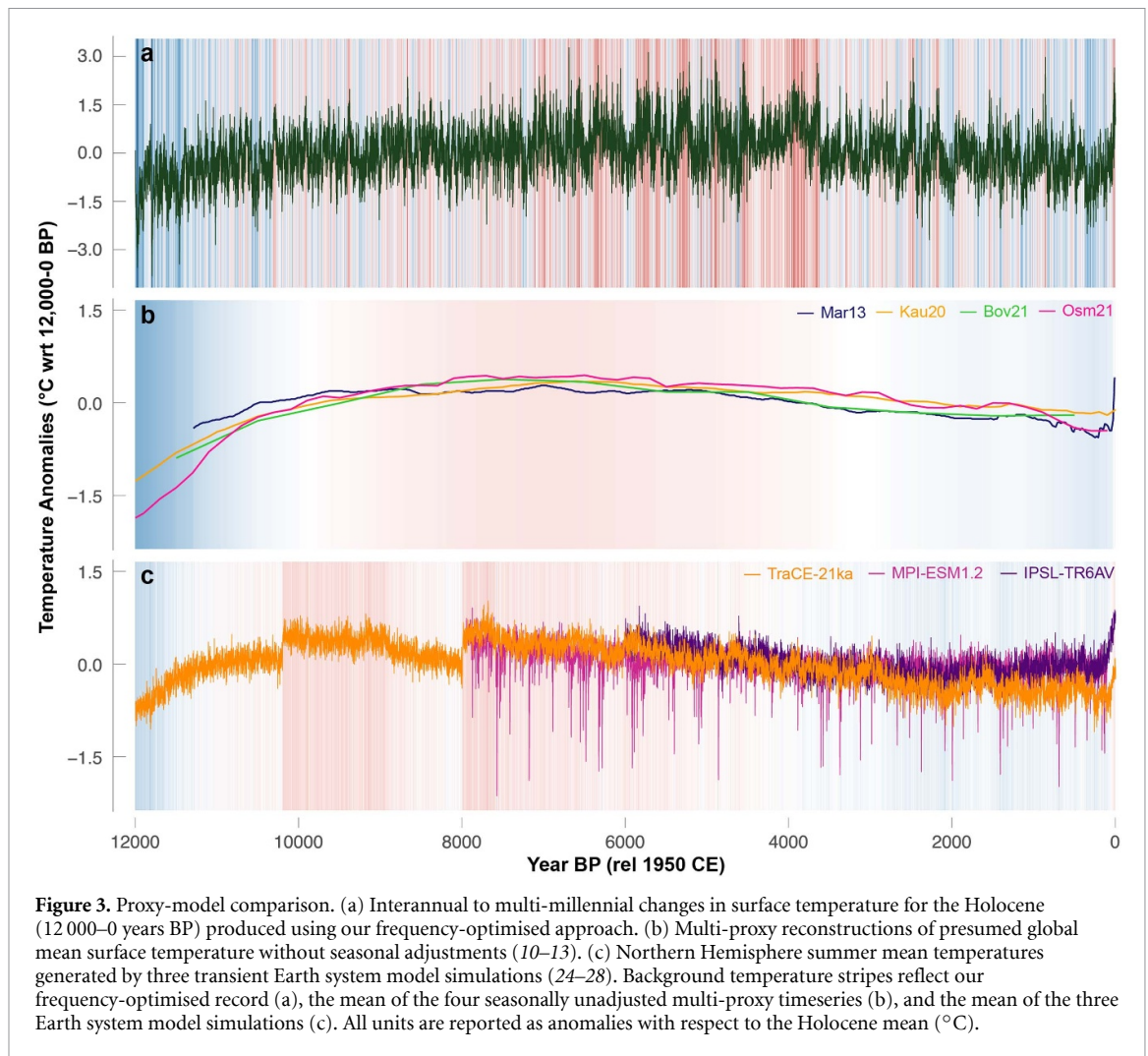


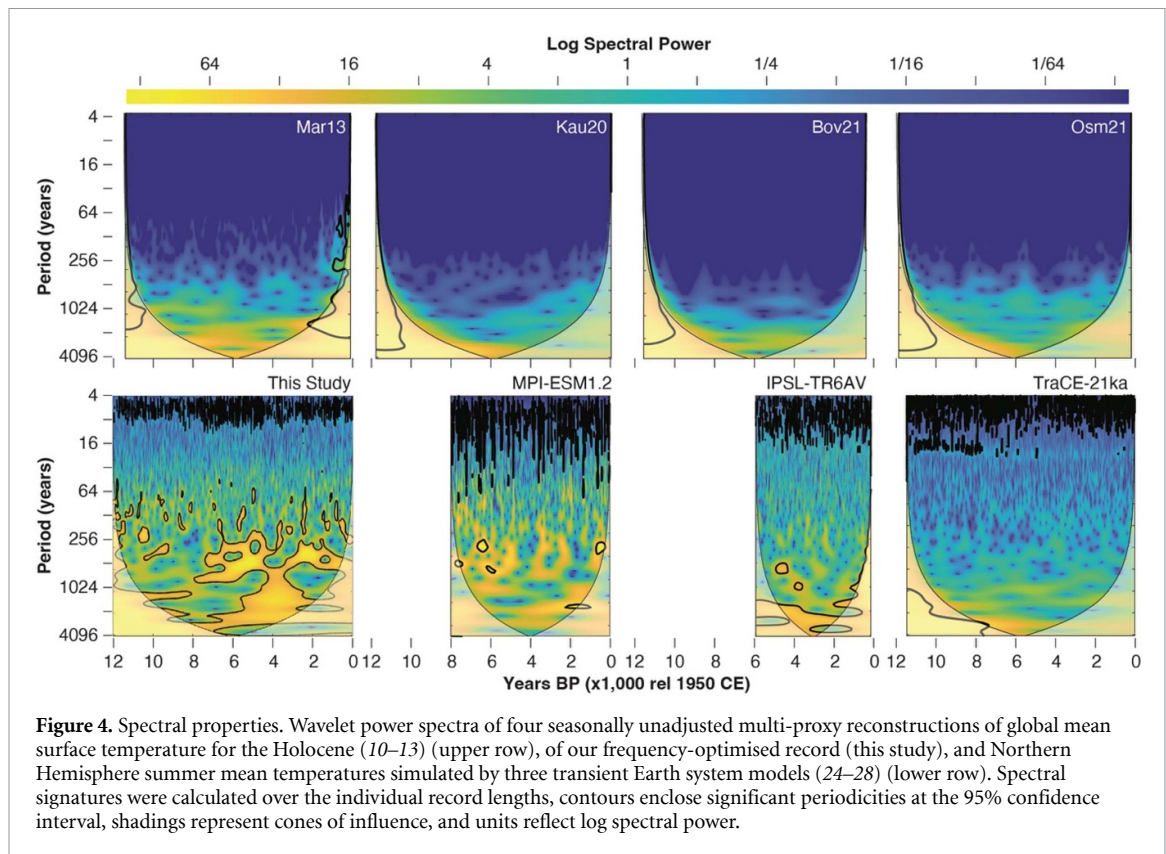
Figure 3. Proxy-model comparison. (a) Interannual to multi-millennial changes in surface temperature for the Holocene (12 000–0 years BP) produced using our frequency-optimised approach. (b) Multi-proxy reconstructions of presumed global mean surface temperature without seasonal adjustments (10–13). (c) Northern Hemisphere summer mean temperatures generated by three transient Earth system model simulations (24–28). Background temperature stripes reflect our frequency-optimised record (a), the mean of the four seasonally unadjusted multi-proxy timeseries (b), and the mean of the three Earth system model simulations (c). All units are reported as anomalies with respect to the Holocene mean (°C).

tion of the seasonal and spatial domains multi-proxy reconstructions predominantly reproduce. Hence, if the existing Holocene records would have been interpreted as a reflection of northern latitude warm season temperatures, model simulations used for comparison would have been selected to represent the same season and region, and the ‘Holocene temperature conundrum’ would not have emerged.

The high-frequency variability of our record contributes to a more complete picture of Holocene climatology than previous reconstructions achieved [10–13]. Our findings may therefore inform scientific debate about the relative contributions of natural and anthropogenic climate forcing factors as recent extremes can be placed in the context of the full range of past natural changes, rather than being compared to smoothed long-term means. Such discourse underpins the concept of a natural baseline temperature used to set warming thresholds for policy interventions [1]. Our frequency-optimised approach also stresses the sensitivity of the Earth’s pre-industrial climate system to natural forcing factors that operate on interannual and decadal

timescales. Since cold extremes are less prevalent after ~1850 CE, we conclude that sustained anthropogenic greenhouse gas emissions will continue to mask the occurrence of interannual cooling events, thereby intensifying the frequency and magnitude of warm anomalies, superimposed on an ‘unprecedented’ recent warming trend [1]. This reinforces the need for interventions to limit further global warming if its associated risks are to be curtailed [2–4].

Furthermore, we remain critical of the interpretation of the smooth trajectories of existing Holocene temperature reconstructions [10–13], which have influenced policy debate. For instance, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1], and its ‘Summary for Policy Makers’ and ‘Technical Summary’ compared recent annual extremes against past centennial averages [1]. Such unequal comparison has the potential to mislead portrayal of the threat of global warming as low- and high-frequency records reflect different aspects and amplitudes of the Earth’s climate system (figure 2).



5. Conclusion

The importance of existing multi-proxy reconstructions in broadening our understanding of past climate dynamics is undeniable. We maintain, however, that the full range of naturally forced high- to low-frequency variability should be presented in temperature reconstructions used to contextualise recent, and in turn future, climate changes. In achieving this, attention must be paid to the spectral properties of individual climate archives when evaluating recent anthropogenic climate change in the context of the Holocene record.

Data availability statements

All data used in this study are freely available or provided in the online supplementary material of this article.

Acknowledgments

U B and J E were supported by the Czech Science Foundation Grant HYDRO8 (23-08049S), and the ERC Advanced Grant MONOSTAR (AdG 882727). Much of the scientific discussion was stimulated by the Cooperation Group ‘Volcanoes, Climate and History (VCH) at ZiF, Bielefeld, Germany ([www.uni-bielefeld.de/\(en\)/ZiF/KG/2021Volcanoes/](http://www.uni-bielefeld.de/(en)/ZiF/KG/2021Volcanoes/)).

Author contributions

U B conceived the study. H E, P J K and F M processed data and performed the analyses. S W, J J and P B provided Earth system model simulations. H E and U B wrote the paper with input from P J K, C O and J E. All authors contributed to discussion and revision.

Conflict of interest

The authors declare no competing interests.

ORCID iDs

Helen Essell <https://orcid.org/0009-0008-7366-9975>

Ulf Büntgen <https://orcid.org/0000-0002-3821-0818>

References

- [1] IPCC 2021 *Climate Change 2021: The Physical Science* (Cambridge University Press)
- [2] Rockström J *et al* 2009 A safe operating space for humanity *Nature* **461** 472–5
- [3] Lenton T M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber H J 2019 Climate tipping points—too risky to bet against *Nature* **575** 592–5
- [4] Brovkin V *et al* 2021 Past abrupt changes, tipping points and cascading impacts in the Earth system *Nat. Geosci.* **14** 550–8
- [5] Büntgen U *et al* 2022 Recognising bias in Common Era temperature reconstructions *Dendrochronologia* **74** 125982

- [6] Gillett N P *et al* 2021 Constraining human contributions to observed warming since the pre-industrial period *Nat. Clim. Change* **11** 207–12
- [7] Esper J, Wilson R J S, Frank D C, Moberg A, Wanner H and Luterbacher J 2005 Climate: past ranges and future changes *Quat. Sci. Rev.* **24** 2164–6
- [8] McClelland H L O, Halevy I, Wolf-Gladrow D A, Evans D and Bradley A S 2021 Statistical uncertainty in paleoclimate proxy reconstructions *Geophys. Res. Lett.* **48** e2021GL092773
- [9] Esper J and Büntgen U 2021 The future of paleoclimate *Clim. Res.* **83** 57–59
- [10] Marcott S A, Shakun J D, Clark P U and Mix A C 2013 A reconstruction of regional and global temperature for the past 11,300 years *Science* **339** 1198–201
- [11] Kaufman D, McKay N, Routson C, Erb M, Dätwyler C, Sommer P S, Heiri O and Davis B 2020 Holocene global mean surface temperature, a multi-method reconstruction approach *Sci. Data* **7** 201
- [12] Bova S, Rosenthal Y, Liu Z, Godad S P and Yan M 2021 Seasonal origin of the thermal maxima at the Holocene and the last interglacial *Nature* **589** 548–53
- [13] Osman M B, Tierney J E, Zhu J, Tardif R, Hakim G J, King J and Poulsen C J 2021 Globally resolved surface temperatures since the Last Glacial Maximum *Nature* **599** 239–44
- [14] Walker M J C *et al* 2008 The global stratotype section and point (GSSP) for the base of the Holocene series/epoch (Quaternary system/period) in the NGRIP ice core *Episodes* **31** 264–7
- [15] Sigl M, Toohey M, McConnell J R, Cole-Dai J and Severi M 2022 Volcanic stratospheric sulfur injections and aerosol optical depth during the Holocene (past 11 500 years) from a bipolar ice-core array *Earth Syst. Sci. Data* **14** 3167–96
- [16] Steinhilber F *et al* 2012 9,400 years of cosmic radiation and solar activity from ice cores and tree rings *Proc. Natl Acad. Sci. USA* **109** 5967–71
- [17] Marcott S A and Shakun J D 2021 A complete palaeoclimate picture emerges *Nature* **599** 208–9
- [18] Kaufman D *et al* 2020 A global database of Holocene paleotemperature records *Sci. Data* **7** 1–34
- [19] Rahim K 2014 Applications of multitaper spectral analysis to nonstationary data *PhD Theses* Queen's University, Kingston, Ontario, Canada
- [20] Meyers S R 2014 Astrochron: an R package for astrochronology (available at: <https://cran.r-project.org/package=astrochron>)
- [21] Cook E R, Briffa K R, Meko D M, Graybill D A and Funkhouser G 1995 The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies *Holocene* **5** 229–37
- [22] Esper J *et al* 2012 Orbital forcing of tree-ring data *Nat. Clim. Change* **2** 862–6
- [23] Debret M, Sebag D, Crosta X, Massei N, Petit J-R, Chapron E and Bout-Roumazeilles V 2009 Evidence from wavelet analysis for a mid-Holocene transition in global climate forcing *Quat. Sci. Rev.* **28** 2675–88
- [24] Meyers S R, Sageman B B and Pagani M 2008 Resolving Milankovitch: consideration of signal and noise *Am. J. Sci.* **308** 770–86
- [25] Liu Z *et al* 2009 Transient simulation of last deglaciation with a new mechanism for Bølling-Allerød warming *Science* **325** 310–4
- [26] Bader J, Jungclauss J, Krivova N, Lorenz S, Maycock A, Raddatz T, Schmidt H, Toohey M, Wu C J and Claussen M 2020 Global temperature modes shed light on the Holocene temperature conundrum *Nat. Commun.* **11** 4726
- [27] Dallmeyer A, Claussen M, Lorenz S J, Sigl M, Toohey M and Herzschuh U 2021 Holocene vegetation transitions and their climatic drivers in MPI-ESM1.2 *Clim. Past* **17** 2481–513
- [28] Braconnot P, Zhu D, Marti O and Servonnat J 2019 Strengths and challenges for transient mid- to late Holocene simulations with dynamical vegetation *Clim. Past* **15** 997–1024
- [29] Braconnot P, Crétat J, Marti O, Balkanski Y, Caubel A, Cozic A, Foujols M-A and Sanogo S 2019 Impact of multiscale variability on last 6,000 years Indian and West African monsoon rain *Geophys. Res. Lett.* **46** 14021–9
- [30] Grinsted A 2021 Cross wavelet and wavelet coherence (available at: <https://github.com/Grinsted/wavelet-coherence>)
- [31] Zhang Y, Renssen H and Seppä H 2016 Effects of melting ice sheets and orbital forcing on the early Holocene warming in the extratropical Northern Hemisphere *Clim. Past* **12** 1119–35
- [32] Liu Z, Zhu J, Rosenthal Y, Zhang X, Otto-Bliesner B L, Timmermann A, Smith R S, Lohmann G, Zheng W and Timm O E 2014 The Holocene temperature conundrum *Proc. Natl Acad. Sci. USA* **111** E3501–5
- [33] Wanner H 2021 Late-Holocene: cooler or warmer? *Holocene* **31** 1501–6
- [34] PAGES 2k Consortium 2020 Consistent multi-decadal variability in global temperature reconstructions and simulations over the Common Era *Nat. Geosci.* **12** 643–9
- [35] Büntgen U *et al* 2020 Prominent role of volcanism in Common Era climate variability and human history *Dendrochronologia* **64** 125757
- [36] Kaufman D S and Broadman E 2023 Revisiting the Holocene global temperature conundrum *Nature* **614** 425–35
- [37] Cartapanis O, Jonkers L, Moffa-Sanchez P, Jaccard S L and de Vernal A 2022 Complex spatio-temporal structure of the Holocene thermal maximum *Nat. Commun.* **13** 5662
- [38] Hartl-Meier C T M, Büntgen U, Smerdon J E, Zorita E, Krusic P J, Ljungqvist F C, Schneider L and Esper J 2017 Temperature covariance in tree ring reconstructions and model simulations over the past millennium *Geophys. Res. Lett.* **44** 9458–69
- [39] Braconnot P, Harrison S P, Kageyama M, Bartlein P J, Masson-Delmotte V, Abe-Ouchi A, Otto-Bliesner B and Zhao Y 2012 Evaluation of climate models using palaeoclimatic data *Nat. Clim. Change* **2** 417–24
- [40] Liu Y, Zhang M, Liu Z, Xia Y, Huang Y, Peng Y and Zhu J 2018 A possible role of dust in resolving the Holocene temperature conundrum *Sci. Rep.* **8** 4434
- [41] Thompson A, Zhu J, Poulsen C J, Tierney J E and Skinner C B 2022 Northern Hemisphere vegetation change drives a Holocene thermal maximum *Sci. Adv.* **8** 15
- [42] Zhang W, Wu H, Geng J and Cheng J 2022 Model-data divergence in global seasonal temperature response to astronomical insolation during the Holocene *Sci. Bull.* **67** 25–28