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OPINION PIECE

Rethinking the Holocene temperature conundrum

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ABSTRACT: Recent scholarship argues for more research to resolve the 'Holocene temperature conundrum', an apparent discrepancy between decreasing proxy-reconstructed and increasing model-simulated long-term temperature trends during the late Holocene. Here, we argue that the observed proxy—model offset likely results from inappropriate comparisons of different seasonal and spatial signals in the reconstructed and simulated palaeo-data. Since proxy archives have been used to reconstruct global annual mean temperatures, they have been compared against model simulations of the same seasonal and spatial domains. However, we suggest that most of the proxy-based large-scale reconstructions are biased towards Northern Hemisphere summer temperatures, and as such model comparisons have predominantly focused on the wrong target data. Further to advancing our understanding of long-term temperature trends, we recommend prioritising the refinement of proxy networks and climate reconstructions to preserve the full spectrum of naturally forced, interannual to multi-millennial variations needed to contextualise recent anthropogenic changes against past Holocene ranges.

KEY WORDS: Holocene climates · Temperature reconstructions · Proxy archives · Model simulations · Orbital forcing · Paleoclimate research

Motivated by recent scientific debate about the 'Holocene temperature conundrum' that triggered a range of conceptual and methodological advancements at the vibrant proxy—model interface of palaeoclimate research (Z. Liu et al. 2014, Marcott & Shakun 2015, Y. Liu et al. 2018, Bader et al. 2020, Wanner 2021, Cartapanis et al. 2022, Thompson et al. 2022, Zhang et al. 2022a,b), this study rebuts the assumption that natural proxy records and their combined large-scale networks predominantly reflect global annual mean temperatures (Kaufman & Broadman 2023). Instead, we suggest that most of these records are biased towards mid- to northern latitude warm season average temperatures rather than global annual mean conditions. Moreover, we argue that the observed proxy—model offset simply results from misleading assessments of different seasonal and spatial signals in the reconstructed and simulated palaeo-data. Hence, the 'conundrum' would not have emerged if the same reconstructed and simulated domains were considered for comparisons.

The first proxy-based, large-scale temperature reconstruction for the past 11 300 yr was published 10 yr ago (Marcott et al. 2013). This pioneering study showed

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warming out of the Younger Dryas, a distinct long-term cooling trend from around 6000 yr ago until the end of the Little Ice Age in the early 19th century, and recent anthropogenic warming afterwards. Preceded and followed by generally cooler climates, the existence of a Holocene thermal maximum around 8000–6000 yr ago was then corroborated by 3 additional multi-proxy compilations prior to any seasonal adjustments (Kaufman et al. 2020a, Bova et al. 2021, Osman et al. 2021) (Fig. 1a). Since these proxy-based reconstructions have been interpreted as global annual mean temperatures, their comparisons against independent Earth system model simulations focused on the same spatial (i.e. global) and seasonal (i.e. annual) domains (Fig. 1b). The 'Holocene temperature conundrum' emerged subsequently and is best described as a mismatch in the long-term behaviour of proxy-reconstructed and model-simulated temperatures, with proxies showing cooling and models showing warming during the pre-industrial late Holocene (Liu et al. 2014).

A closer look at the complex behaviour of individual proxy archives that are included in large-scale temperature reconstructions, however, indicates seasonal and spatial biases towards summer and the Northern Hemisphere extra-tropics, respectively. This imbalance is particularly visible in the Temperature 12k (Temp12k) database (Kaufman et al. 2020a,b), where 899 of 1319 proxy records from 470 terrestrial and 209 marine sites are distributed within a circumpolar belt between 40° and 70° N.

By consistently reproducing late Holocene cooling (Davis et al. 2003, Marsicek et al. 2018, Herzschuh et al. 2022), pollen data from extratropical sites in the Northern Hemisphere support a seasonal bias in existing large-scale surface temperature reconstructions, because they predominantly reflect conditions of the growing season (Seppä et al. 2004, Rehfeld et al. 2016, Marsicek et al. 2018, Wirths et al. preprint doi.org/10.5194/egusphere-2023-86). Agreement between the long-term trends of North Atlantic pollen

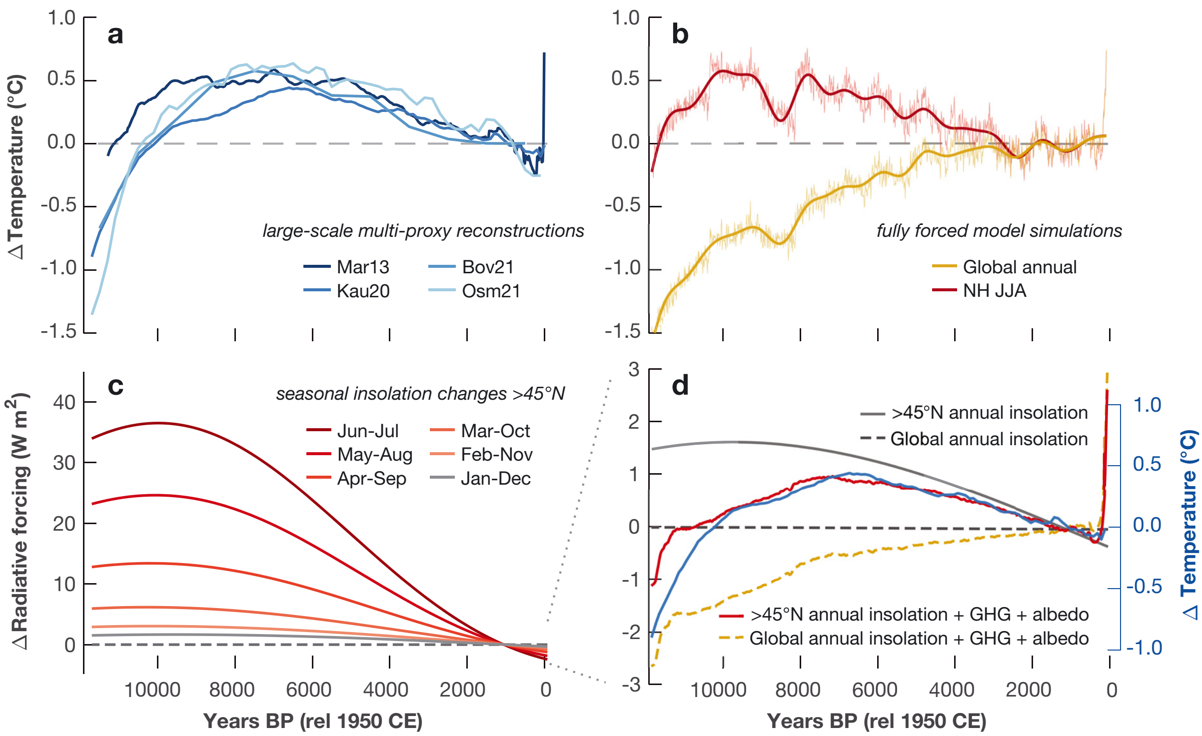

Fig. 1. Simplified presentation of climate and forcing behaviour during the Holocene (without the prevailing uncertainties). (a) Seasonally unadjusted multi-proxy temperature reconstructions for the Holocene (Mar13: Marcott et al. 2013; Kau20: Kaufman et al. 2020a,b; Bov21: Bova et al. 2021; Osm21: Osman et al. 2021). (b) Decadal and millennial-smoothed global annual and Northern Hemisphere summer (NH JJA) mean temperatures simulated by the fully forced CCSM3-TraCE-21k transient Earth system model (Liu et al. 2009). (c) Seasonal differences in Holocene-long insolation changes at the top of the atmosphere above 45° N. (d) Comparison of Holocene-long, annual mean insolation changes estimated for the northern latitudes above 45° N (solid grey line). Temperature estimates from the summation of annual mean insolation changes estimated for the northern latitudes above 45° N (red line) and global mean (dashed yellow line) with greenhouse gases (Köhler et al. 2017) and global albedo changes (Marcott et al. 2013), together with the Temp12K-based temperature reconstruction (Kaufman et al. 2020a) (blue line). All time series (a–d) are expressed as anomalies relative to the preindustrial last 2 millennia (0–1850 CE), and the solid grey lines in (c) and (d) are the same

records and reconstructed temperatures suggests a summer bias in these studies (Marcott et al. 2013, Kaufman et al. 2020a, Bova et al. 2012 Osman et al. 2021), which is also supported by water isotopes from West Antarctica that exhibit long-term summer cooling during the late Holocene (Jones et al. 2023). A seasonal and spatial bias in proxy temperature reconstructions is further supported by a recent multi-proxy temperature history for the Holocene derived from a global network of Temp12k proxy timeseries (Essell et al. 2023). This record presents a similar long-term trend to simulated Northern Hemisphere summer rather than global annual temperatures, which is attributable to spatial and seasonal biases of the underlying proxy archives.

Conceptually similar issues have been observed in multi-proxy temperature reconstructions (Anchukaitis & Smerdon 2022) and pseudo-proxy experiments for the Common Era (Jaume-Santero et al. 2020). Mechanistic (Guiot et al. 2009, Hughes et al. 2010) and pseudo-mechanistic models (Evans et al. 2013) that estimate how environmental processes are recorded in biological and sedimentary archives have demonstrated that North Atlantic proxy records best match so-called global annual temperature fields (Jaume-Santero et al. 2020), demonstrating a bias in the spatial domains that these reconstructions reproduce.

In light of the available evidence outlined above, and considering the wide uncertainty ranges of both proxy reconstructions and model simulations (not shown), we argue that if the existing Holocene records (Marcott et al. 2013, Kaufman et al. 2020a, Bova et al. 2021, Osman et al. 2021) would have given more weight to northern latitude warm season temperatures, model simulations used for comparison would have been selected to represent the same seasonal and spatial output, and the 'Holocene temperature conundrum' would not have emerged, conceptually and empirically (as visually synthesised in Fig. 1).

Although several deficiencies in both proxy compilation (Liu et al. 2014, Bader et al. 2020, Wanner 2021, Cartapanis et al. 2022) and model parameterisation (Marcott & Shakun 2015, Liu et al. 2018, Thompson et al. 2022, Zhang et al. 2022a) have been discussed with regards to the conundrum, we consider the varying radiative effects of orbital forcing to be the key driver for distinctly differing long-term climate trends over much of the Holocene (Laskar et al. 2004). Long-term insolation changes due to the Earth's axial precession diverge considerably between summer and winter, and between hemispheres (Kaufman & Broadman 2023). Orbitally forced climate model simulations infer Northern Hemisphere summer cooling during the late Holocene (Fig. 1b). The same models, however, diverge around 4000 yr ago when simulating global annual mean temperatures, and suggest Holocene-long warming. Identified as a breakpoint in Holocene climate more than half a century ago (Porter & Denton 1967), this period was termed 'Neoglacial' and associated with several cold spells afterwards. Long-term Northern Hemisphere cooling following the Holocene thermal maximum was possibly amplified by ocean–atmosphere and other slow-operating feedback mechanisms (Lorenz & Lohmann 2004). Multi-millennial summer cooling after circa 4000 yr and before industrialisation has also been confirmed independently by the available multi-proxy reconstructions (Erb et al. 2022) (Fig. 1a).

To illustrate these effects, we compare seasonal differences in Holocene-long insolation changes above 45° N (Fig. 1c). Representing less than 15% of the global land surface, this area alone contains about 60% of the Temp12k proxy records (Kaufman et al. 2020b). Mid-summertime June–July insolation anomalies in this region exceed all other radiative forcing agents by over an order of magnitude. Spring and autumn anomalies exhibit the same overall trend, while the winter trend is near negligible. Although seasonal climate feedbacks nonlinearly regulate the insolation–temperature relationship across high latitudes between summer and winter (Liu et al. 2009), even small misinterpretations in seasonality by just a few weeks to months can have large implications for proxy–model comparisons and their subsequent interpretations (i.e. the 'conundrum'). Further to the summer bias comes a northern latitude bias (Fig. 1d). The effect of annual insolation changes for the northern latitudes above 45° N, summed with the effects of global greenhouse gases and albedo changes (Köhler et al. 2017, Osman et al. 2021) resemble reconstructed Holocene temperature histories without any seasonal adjustment (Kaufman et al. 2020a) (Fig. 1d), which suggests that the spatial bias alone is strong enough to invoke the conundrum.

While we agree that large-scale multi-proxy reconstructions have improved our perception of Holocene climate variations, their constrained seasonal and spatial signals must be acknowledged. Instead of calling for more research to resolve the 'conundrum' (Kaufman & Broadman 2023), we recommend refining proxy networks and reconstruction techniques to preserve the full spectrum of naturally forced interannual to multi-millennial scale temperature variability that is needed to adequately contextualise recent anthropogenically forced changes against past Holocene ranges (Essell et al. 2023).

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