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Supplementary information

Globally resolved surface temperatures since the Last Glacial Maximum

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Globally resolved surface temperatures since the Last Glacial Maximum

Matthew B. Osman[1*], Jessica E. Tierney[1], Jiang Zhu[2], Robert Tardif[3], Gregory J. Hakim[3], Jonathan King[1], Christopher J. Poulsen[4]

[1] *Department of Geosciences, The University of Arizona, Tucson, AZ 85721, USA*

[2] *Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO 80305, USA*

[3] *Department of Atmospheric Sciences, University of Washington, Seattle, WA 98195, USA*

[4] *Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI 48109, USA*

*To whom correspondence should be addressed: mattosman@arizona.edu.

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1. Timing of last deglacial and interglacial onset We quantify the onset timing of the last deglacial and current interglacial periods by considering GMST of the last 24 ka as a linearly contiguous three part sequence: a glacial period, a deglacial period, and an interglacial period. We incorporate the changepoint methodology of ref. [1] to isolate the two leading changepoints separating these three periods, accounting for time and temperature uncertainty through Monte Carlo randomization ($n = 10,000$). In each iteration, we produce a surrogate 24 ka GMST time series by 1) normal random sampling of temperature for each 200-yr interval, using the LMGR ensemble mean and standard deviation and 2) uniform random sampling an associated age for each 200-yr interval. For each resultant time- and temperature-perturbed global mean temperature time series, we then determine the location of the two changepoints; for each iteration, we assume that the leading changepoint denotes the deglaciation onset and that the second changepoint denotes the interglacial onset. Both routines, in addition to randomization of proxy age models used to generate the LGMR GMST time series, ensure conservative change-point constraints implying a deglaciation onset at 17.1 ka (18.5–16.1 ka 95% confidence interval), and an interglacial onset at 9.3 (10.9–8.4) ka (Fig. 2).

2. Empirical Orthogonal Function (EOF) analysis We assessed the drivers of global surface temperature change during the last 24 kyr using Empirical Orthogonal Function (EOF) analysis, extending prior LGM-to-present EOF analyses that focused solely on sparsely situated global temperature-proxy data [2–4]. The aim of EOF analysis is to decompose a spatiotemporal dataset into a set of spatial "modes" and associated "principal component" time series, each describing progressively less of the original LGMR variance and subject to the constraint of orthogonality. Our decomposition of LGMR followed standard practice (e.g., ref. [5]), wherein global grid points were first centered to mean zero and subsequently weighted by the cosine of the corresponding latitude. We focused on the first two modes of variability, EOF1 and EOF2 (and their associated principal component time series, PC1 and PC2), as only these were deemed to be both significantly distinct from background noise and physically meaningful. The significance of EOF1, in particular, was unequivocal: it explains 92% of the LGMR variance, and clearly encompasses the globally coherent LGM to present warming driven by deglaciation of the Northern Hemisphere ice sheets and rising greenhouse gases (Fig. 3c). The significance of EOF2 was less clear since it describes only $\sim$3.5% of the LGMR variance. However, analysis of the relative uncertainty range ascribed to this mode (95% confidence of $\sim$1.8–5.2%) via the "North rule of thumb" [5,6], as well as secondary testing using the "broken stick" method [7], each suggested this mode was distinct from successive modes (that each describe, in turn, $\leq$1% variance). Moreover, the bipolar spatial loading pattern of EOF2 is also physically consistent with expectations from prior work (see main text discussion; [2,3] and [4]).

3. Proxy-specific reconstructions We assessed the influence of each proxy type on our results by conducting proxy-specific reconstructions of LGM-to-present GMST using both our "proxy-only" (see Methods section "Proxy-only global mean temperature reconstruction") as well as data assimilation (see Methods section "Paleoclimate data assimilation") approaches. Due to the limited number of TEX_{86} records, our analysis is focused on $U_{37}^{K'}$, Mg/Ca, and $\delta^{18}O_c$. Overall, we find that GMSTs are, on average, mildly warmer in our proxy-only reconstructions than in our data assimilation results across all proxy types, a difference that is especially pronounced during the early Holocene (ca 9–6 ka) period (Extended Data Figure 6a). The proxy-only Mg/Ca reconstruction appears to be the least internally consistent of the six reconstructions (Extended Data Figure 6a) implying that it is the least reliable proxy type. Most likely, this reflects the multivariate sensitivity of this proxy. In particular, since our iCESM simulations do not include an interactive ocean carbon cycle, we make basic assumptions about surface water pH and bottom water saturation to forward model Mg/Ca. Bottom water saturation (Ω) in particular is the second-most important environmental influence on foraminiferal Mg/Ca after temperature [8], and must have changed dramatically across the deglacial transition. Unfortunately, we lack good constraints on Ω, so we must assume that it is constant through time. Despite these concerns, we do not have probable cause nor reason to consider Mg/Ca as inherently "incorrect," and it is clear from the proxy-specific experiments that data assimilation draws the Mg/Ca data closer to a solution that is consistent with $U_{37}^{K'}$ and $\delta^{18}O_c$ (Extended Data Figure 6a).

4. Comparing Holocene global mean surface temperature (GMST) trends The proxy-specific reconstructions (Mg/Ca in particular) show cooling across the Holocene since about 8 ka (Extended Data Figure 6a), a feature that translates into the full proxy-only reconstruction (Fig. 4a). However, these trends are altered after assimilating the same proxy data with iCESM; the cooling trend in Mg/Ca is attenuated, and the stable Holocene temperature evolution implied by $\delta^{18}O_c$ becomes a warming trend when assimilated with iCESM. Several assessments were thus conducted to explore the source of differences between the Holocene GMST trend in the LGMR and the long-term cooling implied by our (and prior studies' [9–11]) proxy-only reconstruction(s). These tests focused on isolating the influence of proxies from particular latitudinal bands and assessing the influence of proxy seasonal biases. To determine whether proxies from certain latitudes had a large influence on the reconstructions, we systematically removed records situated in contiguous intervals of 15° latitude between 60°S to 60°N. Proxy-only GMST reconstructions show a strong sensitivity to the removal of records situated between 60°S to 45°S: when removed, GMST cools by ∼0.2–0.3°C across the Holocene, with a reduction of ∼50% during the early Holocene (Extended Data Figure 6b). The Southern Ocean zonal band represents $<5\%$ of the proxy database, but includes records that have a notably warm early Holocene [12,13]. While these records are a robust representation of Southern Ocean SST, since the proxy-only reconstruction method relies on zonal mean averages [10,14,15], these data become upweighted and thus have a stronger influence on the global mean than data from proxy-rich zonal bands. Data assimilation is not subject to this restriction and so the removal of Southern Ocean records does not result in Holocene GMST trends that are overtly anomalous (Extended Data Figure 6b). Rather, data assimilation shows the largest deviations—a positive excursion of ∼0.2-0.3°C across the Holocene—when northern mid-high latitude (45°N to 60°N) records are removed, possibly reflecting the omission of cold Northern Hemisphere SST anomalies related to the presence of the Laurentide and Eurasian ice sheets. The global propagation of such anomalies is not explicitly accounted for in the proxy-only approach, which may explain why the omission of high-latitude Northern Hemisphere sites has less of an influence on these reconstructions.

We tested the influence of seasonal bias on the proxy-only reconstructions by removing $\delta^{18}O_c$, $U_{37}^{K'}$ and Mg/Ca records that, according to our proxy forward models, are seasonally-biased in the present day (50 $\delta^{18}O_c$, 20 Mg/Ca, and 24 $U_{37}^{K'}$ records). The removal of these records did not result in noticeably different Holocene GMST trends (Extended Data Figure 6a), implying either a) that the proxy-only Holocene GMST cooling trends are not caused by seasonal bias, or b) that the assumption that seasonal bias remains static through time is insufficient. The latter possibility, in particular, should not be understated given the potential for large seasonal changes in SST in response to orbital forcing [16].

Our data assimilation method attempts to overcome the static seasonality limitation by allowing for dynamic seasonality changes based on the model priors, which are in turn used to forward model $\delta^{18}O_c$ and Mg/Ca [8,17]. To isolate the influence that accounting for dynamic seasonality has on our data assimilation solution, we created a suite of proxy-specific GMST reconstructions using both annual mean and fixed seasonality forward models. For $\delta^{18}O_c$ and Mg/Ca, this was done by using the "pooled-annual" and "pooled-seasonal" models, as well as running the species-specific models with seasonality fixed to either the LGM or preindustrial assumption. Unlike the "species-specific" forward models, which require monthly SSTs to estimate $\delta^{18}O_c$ and Mg/Ca on both a seasonal and per-species basis (c.f. Methods section "Paleoclimate Data Assimilation"), the pooled models predict $\delta^{18}O_c$ and Mg/Ca across all species, using either annual mean SST or seasonal average SST (static, based on modern seasonality) [8,17]. Use of these forward models thus tests the influence of the species-specific calibrations on the data assimilation results. By fixing the seasonality in the species-specific models, we can further isolate the impact that dynamic seasonality has on the LGMR. Use of the pooled-annual and pooled-seasonal forward models, as well as the fixed seasonality models, had virtually no impact on the $\delta^{18}O_c$-based GMST reconstructions (Extended Data Figure 6c). In contrast, Mg/Ca-based GMST was considerably warmer (+2°C ΔGMST) during the early Holocene when the pooled models were used (Extended Data Figure 6c). This suggests that accounting for species-specific differences is critical for the Mg/Ca proxy. However, the pooled results cannot explain early Holocene warmth in the proxy-only reconstructions, because these use the species-specific models. Furthermore, fixing the Mg/Ca seasonality at both preindustrial and LGM values had the effect of reducing early Holocene warmth (Extended Data Figure 6c), which suggests that the warmer early Holocene in the proxy-only Mg/Ca reconstruction is not (within the limits of our forward modeling assumptions) strictly due to seasonal bias. The pooled model results for Mg/Ca also demonstrate that the DA method can yield a Holocene cooling trend if the underlying proxy data suggest it, ruling out the possibility that the Holocene trend in LGMR is coming exclusively from the model prior (c.f. Extended Data Table 1).

Overall, our sensitivity tests suggest that the differences between the LGMR GMST evolution and those based on proxy-only methods do not have a singular origin; however, the way in which individual proxy records are weighted—by latitude for proxy-only reconstructions vs. based on covariance structures for the LGMR—appears to be the most important factor. It remains possible that seasonal bias contributes, but within the constraints of our forward models, it does not seem to be the primary factor. Although future testing with different model priors is needed, our experiments also demonstrate that the LGMR Holocene evolution is not a precondition of the model prior, which includes warm early Holocene simulations (Extended Data Table 1) and can allow for a cooling trend if the underlying proxies suggest it (Extended Data Figure 6c).

5. Contextualizing the rate and magnitude of modern warming In order to compare the magnitude of industrial-era warming (from the HadCRUT5 product [18]) to global temperature changes estimated by LGMR, we first adjusted the LGMR and HadCRUT5 GMST anomalies to a common, overlapping frame of reference. This was accomplished by re-centering GMST estimates from the Last Millennium Reanalysis (LMR) v2.1 [19] as anomalies relative to 1000–1850 CE, and then adjusting LGMR and HadCRUT5 to this LMR frame of reference during their respective overlapping periods: 1000–1950 CE for LGMR and 1850–2000 CE for HadCRUT5. Next, in order to directly compare decadal-mean HadCRUT5 GMST values to LGMR GMST values, we adjusted the latter for decadal-to-centennial variance attenuation. This was done by individually scaling the LGMR GMST ensemble variance by the GMST decadal-to-centennial mean variance ratio from iCESM at each reconstruction time interval using our evolving prior approach (see Fig. 2). This adjustment produces pseudo decadal-mean GMST values for all LGMR time intervals, rendering comparison to HadCRUT5 decadal-mean GMST more direct and conservative. Comparison between the decadal-adjusted LGMR and HadCRUT5 indicates that decadal mean GMST exceeded the range ($>99^{th}$ percentile) of Holocene values by the turn of the 21st century (2000–2009; Fig. 2). During the most recent decade (2010–2019), GMST exceeded maximum Holocene values by a more considerable margin: $>$0.5°C, corresponding to $+$1.5°C above mean Holocene GMST.

To compare the centennial-scale rate of temperature change in LGMR to HadCRUT5, we randomly sampled GMST (n = 10,000) from the decadal-adjusted LGMR for each time interval across the deglaciation (ca. 17.1–9.3 ka; see "Timing of last deglacial and interglacial onset", above), which contains the largest and most rapid changes in GMST during the last 24 kyr (Fig. 2). These randomly sampled values of GMST were then used to estimate rates of change across adjoining time intervals, allowing us to develop a broad distribution of possible deglacial warming rates. We emphasize that this approach is largely unaffected by our assimilation of randomly sampled proxy age models, which induces centennial-scale smoothing in the LGMR ensemble mean but does not truncate the inter-centennial variance across individual ensemble members (nor, by association, the range of centennial-scale deglacial GMST warming rates). We verified this by computing LGMR deglacial warming rates without proxy age uncertainty modeling (not shown). In addition, as a secondary test we also compared rates of modern warming to the monthly-resolved TraCE-21k simulation [20,21]. For this test, we applied a scaling of $\sim$1.6$\times$ to TraCE-21k ΔGMST prior to computing rates of centennial-scale GMST warming (analyzed decade-wise across the deglaciation), thus maintaining consistency with the greater deglacial warming shown by LGMR while also providing a more conservative comparison to modern warming. Collectively, our analysis shows that by the early 20th to 21st century (1910–2009 CE), the rate of warming (0.84°C century^{-1}) exceeded the 99th percentile of composited warming rates for all time intervals of the deglaciation for both LGMR and TraCE-21k. In the ensuing (most recent) decade the rate of centennial-scale GMST change has risen by an additional $\sim$16% (0.98°C century^{-1} for the period 1920–2019 CE), underscoring the unusual nature of 21st century warming (Fig. 5b).

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