

CLIMATOLOGY

The seasonal temperature conundrum for the Holocene

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Temperature is the key variable in the study of climate changes in the past and future. Most previous studies on past temperature reconstructions, however, have focused on the mean annual temperature (MAT). Here, focusing on the seasonal temperature reconstructions in the Northern Hemisphere extratropics during the Holocene period, we show that the change in seasonal cycle of temperature reconstructions is severely underestimated in comparison with the expectation from present observations. Our study highlights the current uncertainty in seasonal temperature reconstructions in the Holocene, with an implication that the MAT simulation in current climate models may not be much biased.

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INTRODUCTION

One of the most important climate variables in the study of past climate change is temperature. In particular, the past decade has seen greatly intensified interest in understanding of temperature evolution in the Holocene [about past 10 thousand years (ka)], which provides the background climate for our ongoing anthropogenic global warming. However, much of the effort has focused on the mean annual temperature (MAT). Notably, the so-called Holocene temperature conundrum still remains unresolved: It has the global MAT exhibited a cooling trend as indicated in most proxy reconstructions or a warming trend in response to increased concentrations of greenhouse gases and retreating ice sheets, as in most climate models (1–5). Relatively, much less attention has been paid to the temperature evolution of different seasons, which, nevertheless, have distinct effects on various aspects of climate change. Here, we study the seasonal temperatures in the Northern Hemisphere (NH) extratropics, with a focus on the Holocene period. In comparing the seasonal cycle in temperature reconstructions and that expected from present observations, we find that most available seasonal temperature reconstructions (4–8) severely underestimate the change in seasonal cycle amplitude in the Holocene. This highlights the current uncertainty in seasonal temperature reconstructions, with implications for the reconstructions of MAT.

RESULTS

Evolution of seasonal temperatures in reconstructions and climate models

We first reexamine the temperature reconstructions from the most recent comprehensive compilation of Kaufman *et al.* (6), focusing on the extratropical NH (20° to 50°N) where the seasonality is strong and most of the seasonal temperature proxies are located. We derive

the total change in temperatures as the area-averaged temperatures for summer, winter, and annual mean using all proxy reconstructions within the 20° to 50°N band during the Holocene (see the “Temperature data from reconstructions, present observations, and climate models” section and fig. S1B). One notable yet peculiar feature of the summer and winter temperatures is a similar evolution pattern, with a weak cooling trend (<1°C in the Holocene) averaged over the proxy stacks. This weak cooling trend of seasonal temperatures is also somewhat similar to that of the MAT after the mid-Holocene. These temperature changes represent the temperature change over land because the proxy sites are located over land area (figs. S2 and S3). To focus on the amplitude of seasonal cycle, we derive the net change in seasonal temperatures from the total change in seasonal temperatures by subtracting the MAT from the seasonal temperatures (Fig. 1B, thin lines). The net change in summer and winter temperatures, thus derived, again shows a similar evolution pattern, with an overall decreasing trend of magnitude less than 1°C, interrupted by a minimum before the mid-Holocene caused by the mid-Holocene peak of the MAT. The similarity of summer and winter temperature changes is in sharp contrast to the opposite changes of summer and winter insolation associated with the changing precession, decreasing in summer but increasing in winter (Fig. 1A), which is little affected by the annual mean insolation (fig. S1A). The similar and comparable changes in summer and winter temperatures imply a small amplitude change in the seasonal cycle. This can be seen more clearly in the small change in seasonal cycle amplitude (<0.6°C), which is derived from the difference between summer and winter temperatures (Fig. 2A, black).

The similar winter and summer temperatures and the resultant small amplitude change in seasonal cycle are in contrast to climate models. For example, in the Transient Climate Evolution (TRACE) simulation (9), the net change in seasonal temperature decreases in summer but increases in winter in the NH extratropics over both land and ocean (Fig. 1D), resembling the change in insolation. The difference between summer and winter temperature changes and, in turn, the amplitude of the seasonal cycle exhibit a large reduction of over 3°C in the Holocene averaged over land and proxy sites, almost five times greater than that in the reconstruction (Fig. 2A, brown dashed line). A comparably large change in seasonal temperature is also simulated in the latest Paleoclimate Modelling Intercomparison Project 4 (PMIP4) models in the mid-Holocene at 6 ka (diamonds in Figs. 1D and 2A) (10) and in a recent climate model with different vegetation coverage at 9, 6, and 3 ka (circles and stars in Fig. 2A)

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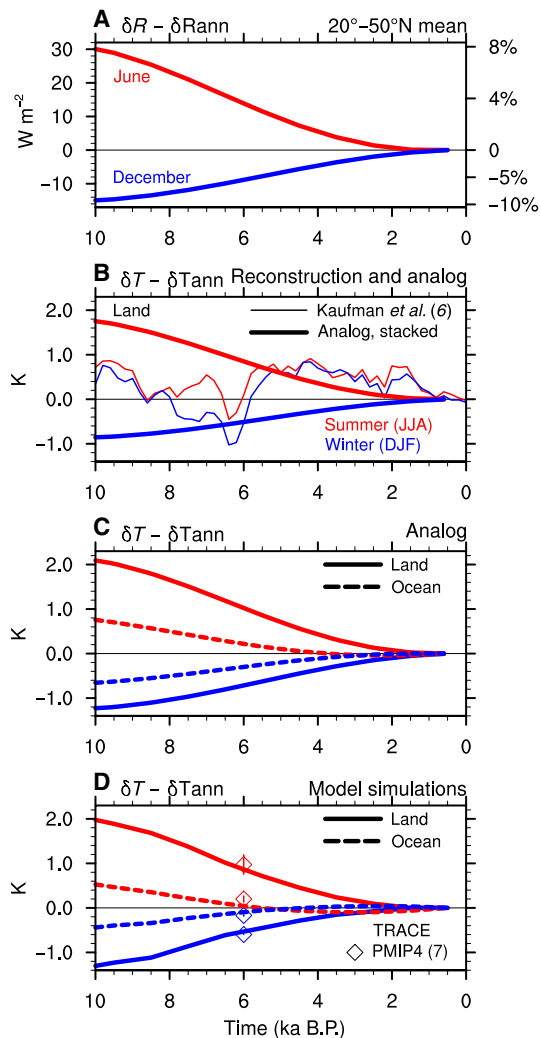


Fig. 1. Holocene seasonal temperatures. Evolution of summer (red) and winter (blue) (both minus annual mean) (A) solar radiation, (B) temperature in reconstructions (6) (thin solid) and our analog model (bold solid) averaged over the proxy stack sites, (C) temperature in the analog model averaged over land (solid) and ocean (dashed lines), and (D) temperature in TRACE model averaged over land (solid) and ocean (dashed lines) and in PMIP4 at 6 ka (diamonds, with the cross-model spread in vertical tick). All variables are area-weighted averages with $\cos(\text{latitude})$ in the 20° to 50°N band. JJA, June, July, and August; DJF, December, January, and February; B.P., before the present.

(11). Note that the last model simulates a global MAT warming or cooling in the mid-Holocene depending on the large or small area of prescribed vegetation (Fig. 2) (11). However, regardless of the vegetation change and MAT response, the change in seasonal cycle amplitude remains virtually the same (Fig. 2A).

The strong inconsistency in the response of seasonal temperatures between reconstructions and climate models may be seen at first as posing a model-data comparison conundrum similar to that for MAT. If the reconstruction is correct, then climate models are deficient in their seasonal cycle. For MAT, potential model deficiencies have been proposed, including the underestimation of the feedback from dust aerosol and vegetation (11, 12), although these deficiencies remain difficult to assess quantitatively

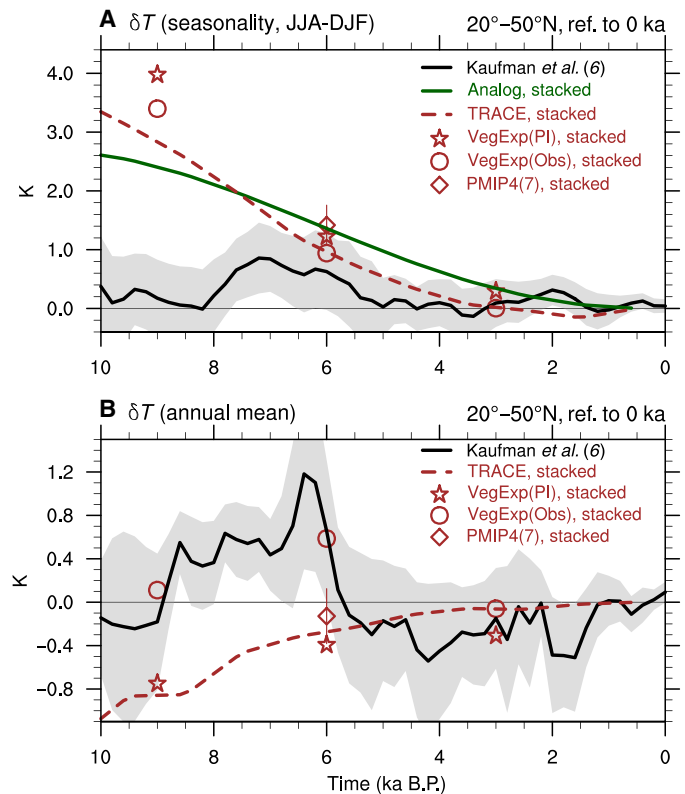


Fig. 2. Holocene evolution of seasonal cycle and annual mean temperature. (A) The amplitude of temperature seasonal cycle, derived from the difference between summer (June, July, and August) and winter (December, January, and February) temperatures in reconstructions (black) (6), the analog model (green), climate models (brown) of TRACE (dashed line), PMIP4 (diamonds at 6 ka), and the model simulations of Thompson *et al.* (11), with the vegetation prescribed as the present (star) and observation (circles at 9, 6, and 3 ka). (B) Same as (A) but for annual mean temperatures. All area-weighted average over the proxy stack sites in the 20° to 50°N band. Shadings in (A) and (B) represent the uncertainty of the reconstructions as derived from the 1σ ensemble spread.

from observations independent of these reconstructions. For the seasonal cycle responses, it is even more challenging to attribute the inconsistency to climate models because of the relatively much simpler physics for the response of seasonal cycle than MAT. To avoid a similar dilemma as for MAT on the potential deficiencies of climate models, it is desirable to compare the reconstruction with the expectation from current observations directly, independent of climate models.

Seasonal temperature in the analog model

Because the seasonal cycle of temperature is driven by that of insolation, a greater insolation seasonal cycle is expected physically to generate a greater temperature seasonal cycle, with everything else remaining the same. This motivates us to develop the simplest model to predict the amplitude of temperature seasonal cycle from the local insolation using present observations. The model is simply a linear regression model of the seasonal cycle between temperature and insolation at each location, taking into account the 1 to 2 months of lag of the temperature response (see the “The analog model for the temperature seasonal cycle” section and figs. S4 and S5). This

model does particularly well over the NH extratropical land region in comparison with present observations, with explained variance over 95% (fig. S4C). The good fit of this seasonal model to the present observations is partly attributed to the relatively simpler physical processes of the seasonal cycle compared to those of MAT. The seasonal cycle of insolation is about 200 W m^{-2} in the extratropics (fig. S4D), much greater than any other seasonal forcing agents and feedback effects. Furthermore, the seasonal timescale is short, such that the seasonal cycle is little affected by subsurface oceanic circulations. As a result, the seasonal cycle of temperature is dominated by the local response to insolation with a magnitude of over 10°C (fig. S4D). In contrast, the MAT response to present climate change depends critically not only on several competing forcing agents and feedbacks of comparable impact of less than 1°C but also on ocean circulations, none of which is easy to calibrate in a simple model. Our statistical model is, in some sense, similar in complexity to a local energy balance model that predicts only the amplitude of the seasonal cycle or the net changes in summer and winter temperatures relative to the annual mean. To distinguish from climate models, which are based on known physics, however, our model will be called the modern analog model, as it only uses the present observations as an analog to predict the seasonal cycle of other times under different insolation.

From the local energy balance perspective, one major factor that affects the seasonal cycle amplitude of surface temperature is the condition of the surface layer. This can be seen in the NH extratropics along the same latitude; the regression coefficient ranges from about $0.8 \text{ K (} 10 \text{ W m}^{-2}\text{)}^{-1}$ over land to less than $0.3 \text{ K (} 10 \text{ W m}^{-2}\text{)}^{-1}$ over ocean (figs. S4A and S5J), with a greater sensitivity over land caused by its smaller heat capacity and reduced latent heat fluxes (13). A typical amplitude of insolation seasonal cycle of, say, 240 W m^{-2} in the extratropics would, therefore, force a seasonal cycle of about 20 K over land and 7 K over ocean (fig. S5, D to F).

We now use the analog model to predict the net change in extratropical summer and winter temperatures (relative to their annual mean) in the Holocene, through which seasonal insolation varies with a large amplitude of 30 W m^{-2} (Fig. 1A and fig. S6). Averaged over all the proxy sites (6), the analog model predicts a decreasing summer temperature and an increasing winter temperature, similar to the insolation (Fig. 1B, heavy solid lines). This linear response is expected because the analog model is essentially a linear regression model. Quantitatively, the amplitude of the temperature seasonal cycle in the analog model decreases by over 2.5 K (Fig. 2A), which can also be estimated using a regression coefficient over land of $0.8 \text{ K (} 10 \text{ W m}^{-2}\text{)}^{-1}$ multiplied by an insolation change of 30 W m^{-2} . The change in seasonal cycle amplitude in the Holocene predicted by the analog model is, therefore, five times that of reconstructions, with the largest difference predominantly in the early to mid-Holocene (Fig. 2A).

DISCUSSION

Potential uncertainty in models

If the reconstruction is correct, then the analog model overestimates the seasonal response by 500%. We find it difficult to reconcile with the relatively simple physics of the seasonal cycle response implied by the analog model. The analog model is consistent with our current understanding of the seasonal cycle, as seen in the agreement between the present seasonal cycles in these climate models across the proxy

sites, all of which are consistent with observations (fig. S7D). Furthermore, over the continental scale, the analog model also produces the Holocene change in seasonal cycle or seasonal temperatures, highly consistent with current climate models, as seen in the averages over the proxy sites (Fig. 2A) and the average over land and ocean, separately (Fig. 1, C and D). The agreement at the continental scale is accompanied by some spreads across some individual sites, suggesting different responses in some localized regions, potentially associated with the changing atmospheric circulation and land surface feedbacks in climate models, but these spreads are averaged out over the continental scale (see the “Comparison of the analog model and climate models” section and fig. S7, A to C). Sensitivity experiments with individual forcing in TRACE further suggest that the change in seasonal cycle in the Holocene is, as expected, caused predominantly by that of the orbital forcing (fig. S8).

One potential cause of the smaller reduction in seasonal cycle during the Holocene in reconstructions could be an increased vegetation cover and, in turn, reduced surface albedo, increased soil moisture, and increased heat capacity (11). This vegetation impact, however, seems too weak to account for the large difference between reconstructions and the analog model. First, a 0.6°C reduction in the temperature seasonal cycle averaged over the proxy sites, all of which are over land, is comparable or even smaller than that over the ocean in the analog model (Fig. 1C, dashed lines) and climate models (Fig. 1D, dashed lines). This seems physically impossible because the heat capacity of oceanic surface mixed layer, usually about 30 to 50 m in the extratropics, is much higher than that of the wettest possible land surface at the continental scale. On the contrary, it seems more reasonable to assume the seasonal cycle response over the ocean as a lower bound for the reconstructions over land proxy sites. Second, in climate model simulations by Thompson *et al.* (11) that have prescribed a high-end reconstruction of the Holocene vegetation, the vegetation impact on the reduction in seasonal cycle can be detected, especially at some specific locations, as seen in the response across sites (see the “Vegetation impact in climate models” section and fig. S7, A to C). However, averaged across sites on the continental scale, the net impact on seasonal temperature is less than 0.5°C , which is then easily overwhelmed by the strong seasonal response to insolation forcing in the early and mid-Holocene.

Potential uncertainty in reconstructions

If the analog model is correct, then the change in temperature seasonal cycle is underestimated by over 70% in reconstructions. This underestimation is likely caused primarily by the winter temperature reconstruction. The reconstructed summer temperatures in different types of proxies exhibit a similar cooling trend of over 1 K over the Holocene (fig. S3A), which is consistent in sign with, and also of comparable amplitude to, that of either the analog model (Fig. 1, B and C, and fig. S1, B and C) or current climate models (Fig. 1D and fig. S1D), whether the MAT is taken from the reconstruction or climate model. However, the reconstructed winter temperature, only from pollen (fig. S3B), still shows a cooling trend of about 0.4 K over the Holocene. This is in the opposite sign to the warming trend as implied by either the analog model or climate models. This seems to suggest that the largest uncertainty of the current seasonal temperature reconstructions is derived from the pollen reconstructions of winter temperature. The uncertainty of the temperature reconstructions may also depend on the methods and proxy types. For example, in a carefully designed procedure based on pollen-induced plant

functional type score (7), the amplitude of the reconstructed temperature seasonal cycle change over the NH landmass can be up to $\sim 1.5^{\circ}\text{C}$ in the early Holocene, although it is still smaller than those in the analog and climate models. The uncertainty in proxy type will be discussed later.

Seasonal temperature and MAT

The change in seasonal cycle may also have implications for the reconstructed MAT. Given a modest trend of MAT in the Holocene, a smaller trend in the seasonal cycle amplitude will lead to the temperatures of all seasons evolving in a similar trend as the MAT, while a greater trend in the seasonal cycle amplitude will lead to opposite temperature trends between winter and summer seasons. The small trend of seasonal cycle amplitude in reconstruction (Fig. 2A) has led to a similar cooling trend in summer, winter, and annual temperatures (fig. S1B). In contrast, for example, in TRACE simulation, the large temperature seasonal cycle over land (Fig. 1D and fig. S1D) leads to the opposite trends of cooling in summer and warming in winter and annual mean (figs. S1D and S9D). However, in the same TRACE model, the small trend of seasonal cycle over ocean leads to the same warming trend in summer, winter, and annual mean temperatures (fig. S1D, dashed lines).

The evolution patterns of seasonal and annual mean temperatures are shown more clearly after normalization in Fig. 3 (with the corresponding original temperature in fig. S9). In the reconstruction, the normalized temperatures show a similar cooling trend for summer, winter, and annual mean (Fig. 3A, heavy lines), consistent with the impression before normalization (figs. S1B and S9A). In contrast, the normalized temperature over land in TRACE model shows a summer cooling trend, opposite to the winter/annual warming trend (Fig. 3D, heavy lines). The effect of seasonal cycle amplitude can be seen more explicitly in two hypothesized scenarios: a small and a large change in seasonal cycle amplitude of 30 and

100%, respectively, of that in the analog model. When the small seasonal cycle change is added to the MAT of the reconstruction, both seasonal temperatures exhibit a cooling trend as the MAT (Fig. 3B), reminiscent of the reconstruction temperatures (Fig. 3A). When this small seasonal cycle change is added to the MAT of TRACE model, both seasonal temperatures show a warming trend (Fig. 3E), somewhat similar to the TRACE temperatures over ocean (fig. S1D, dashed lines). In contrast, when the large seasonal cycle change is superimposed on the MAT of the reconstruction and TRACE over land, the summer temperature always exhibits a cooling trend, while the winter temperature is changed to a warming trend. The MAT trend is similar to the cooling summer trend in reconstruction but not the warming winter trend in TRACE (Fig. 3, C and F). Thus, if the amplitude of seasonal cycle change predicted by the analog model is correct, given the modest MAT trend of less than 1 K, regardless of whether there was cooling as in the reconstruction or warming as in climate models, then the trends of summer and winter temperatures should be opposite in the Holocene.

The branched glycerol dialkyl glycerol tetraether temperatures

Our discussions above suggest potential uncertainties in the seasonal temperature reconstructions compiled in Kaufman *et al.* (6), in comparison with the expectation from the present-day observations. As another sign of data uncertainty, we show our originally developed branched glycerol dialkyl glycerol tetraether (brGDGT)-based reconstruction of summer and annual temperatures. Recently, applying a deep learning method to a global network of bacterial brGDGT observations, Zheng *et al.* (14) reconstructed the Holocene summer temperature over 14 sites in the NH extratropics. Here, we further extend the brGDGT-DLNN (deep learning neural network) temperature reconstruction to MAT over 33 sites globally, with 25 sites in the 20° to 50°N band (see the “The brGDGT temperature

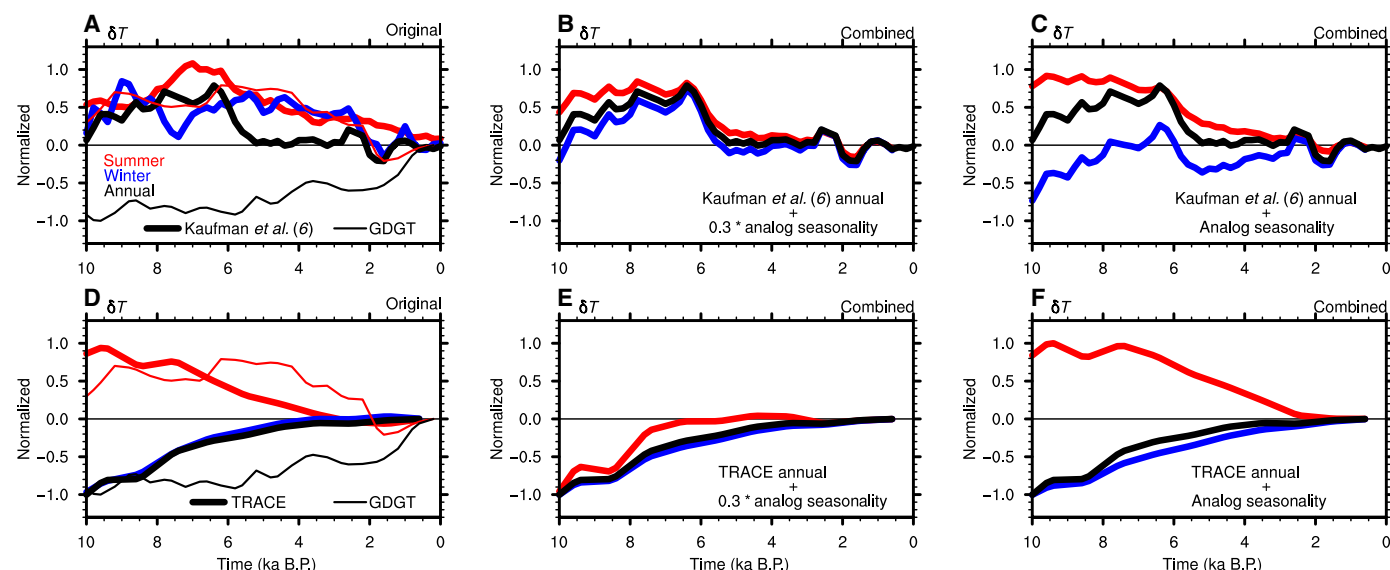


Fig. 3. Normalized seasonal and annual mean temperature evolutions over Holocene. (A) Summer, winter, and annual mean temperature anomalies of Kaufman *et al.*'s reconstructions (6) (heavy solid) area-averaged on the proxy sites in the 20° to 50°N band. Each temperature anomaly is relative to 0 ka and is normalized by its SD. (B) Same as (A) but the seasonal temperatures are reconstructed with 30% of the amplitude of the analog model superimposed on the annual mean. (C) Same as (B) except for using 100% of the amplitude of the seasonal cycle. (A) also shows our normalized brGDGT-DLNN temperature anomalies for the summer and annual mean (thin lines). (D to F) The same as (A) to (C), respectively, but for TRACE simulation stacked at the proxy sites of Kaufman *et al.* (6).

reconstruction with deep learning” section and fig. S10). These brGDGT-DLNN temperatures provide a set of summer and annual mean temperatures independent of the Kaufman dataset. Our brGDGT-DLNN summer temperature exhibits a cooling trend (fig. S11, red), similar to all other types of reconstructions in Kaufman *et al.* (6) (fig. S3A) and climate models. The brGDGT-DLNN MAT, however, exhibits a warming trend (fig. S11, black), opposite to those in the Kaufman data but the same as in climate models (Fig. 2B and figs. S1, B and D, and S3C). These qualitative trend behavior can be seen more clearly after normalization (Fig. 3, A and D, thin lines). The magnitude of the trends of the brGDGT-DLNN temperatures for both the summer and annual mean is large, although the uncertainty of the net change in summer minus annual mean temperatures still appears to be within the range of the prediction of the analog model (fig. S11). The larger amplitude of the brGDGT-DLNN seasonal temperature change may be partly attributed to its representation of surface soil temperature instead of surface air temperature (15). Other factors, such as microbial communities, can also affect the sensitivity of brGDGT compounds to temperature (16). The warming trend in our brGDGT-DLNN MAT reconstructions is opposite to the brGDGT MAT reconstructions derived using the traditional linear regression method (see Supplementary Text and fig. S12), suggesting different MAT trends for the same brGDGT proxy but using different methods. Some potential causes of the different MAT trends between our brGDGT-DLNN reconstruction and other reconstructions, including those of Kaufman temperatures, are speculated (see the “Vegetation impact in climate models” section) (14), although a full understanding remains to be explored in the future. Regardless of the cause, however, the difference between our brGDGT-DLNN temperatures and other temperatures adds to additional uncertainty in the Holocene temperature reconstruction.

Summary

Holocene temperature change is studied after a decomposition into the two components of seasonal cycle and MAT. This decomposition sheds light on the temperature evolution physically because the two components are controlled by very different physical processes. Most previous seasonal temperature reconstructions over NH extratropical land suggest a reduction in the seasonal cycle of only $\sim 0.6^\circ\text{C}$ over the Holocene (6), much smaller than the $\sim 2.5^\circ\text{C}$ reduction as expected from current observations, posing a conundrum for Holocene seasonal temperature. Unlike the conundrum for the global MAT (2), this seasonal conundrum is independent of physical climate models because our analog model is constructed from the present observations (albeit consistent with current climate models on the continental scale posterior), reflecting the nature of energy balance involved in the seasonal cycle response on the continental scale (17). Furthermore, the relatively simpler physics of the seasonal cycle response compared to MAT implies that the seasonal conundrum is less likely to be caused by the uncertainty in climate models than the MAT conundrum or, equivalently, the reconstruction of seasonal temperature is more likely biased than MAT. Given the largely consistent summer temperatures across all proxies and models, the uncertainty in seasonal temperatures is more likely caused by the winter temperature reconstruction from pollen. This seasonal temperature conundrum has direct implications to the MAT conundrum: A small change in seasonal cycle as in reconstructions would favor a cooling trend in

summer, winter, and annual mean temperatures, as in most previous reconstructions, while a large change in seasonal cycle as in our analog model will lead to the opposite summer and winter temperature changes, as in current climate models. If the MAT reconstructions are biased seasonally, then the MATs may not be very inconsistent between reconstructions and climate models. Hence, excessive modifications of feedback processes in current climate models in, for example, vegetation and dust emission (11, 12), may not be necessary. Overall, given the possible temperature changes in the past and future not only in the annual mean but also in the seasonal cycle (18), our study calls for a new approach in the future for studying the temperature response in both the seasonal cycle and the annual mean temperature.

MATERIALS AND METHODS

Temperature data from reconstructions, present observations, and climate models

A total of 509 records of multiproxy temperature reconstructions in the extratropical NH (20° to 50°N) were extracted from the Temperature12k database (<https://github.com/nickmckay/Temperature12k>) (6), including 206 annual, 164 summer, and 139 winter temperature records (fig. S2). All of the records were converted to anomalies using the mean of the latest 1 ka, linearly interpolated to 200-year bins, and then averaged to generate the zonal composites of annual and seasonal temperatures. Zonal compositing procedures followed Marcott *et al.* (1) and Marsicek *et al.* (19) using a two-step average, namely, a 2° -by- 2° grid mean, followed by a 10° latitude area-weighted mean. The area-weighted procedure can reduce the potential latitude bias induced by the nonuniformity of record distribution (1). The observations used to construct the modern analog model are the climatological surface air temperature at 2 m and solar insolation at the top of the atmosphere in NCEP-DOE Reanalysis 2 averaged between 1991 and 2020 (20).

Three sets of monthly model output from climate model simulations are used here: (i) TRACE simulation and its four solo-forced experiments involving orbital insolation/greenhouse gases/meltwater pulse/ice sheet (for further details, see www.cgd.ucar.edu/ccr/TraCE), (ii) mid-Holocene experiments in seven PMIP4 models (10), and (iii) Holocene time slice simulations at 9, 6, and 3 ka of the Community Earth System Model with the vegetation prescribed as documented in pollen records and simulated under preindustrial climate conditions (11), which are used to assess the impact of vegetation on the changes in annual and seasonal mean temperature over the Holocene. All deviations are calculated relative to the corresponding preindustrial control experiment.

The analog model for the temperature seasonal cycle

The analog model is constructed simply as a linear regression between the seasonal cycles of monthly temperature and insolation of the NCEP-DOE Reanalysis 2 (20). At a given location (x and y), we regress the seasonal cycle of monthly temperatures against the local insolation in present observations as

$$T(n + \tau_m) - \bar{T} = a[R(n) - \bar{R}] + \varepsilon, \quad n = 1, \dots, 12, \quad (1)$$

Here, $T(n)$ and $R(n)$ are, respectively, the temperature and local insolation of calendar month n ; τ_m is the lag of maximum correlation; $\bar{T}$ and $\bar{R}$ are, respectively, the annual mean temperature and

insolation; and a is the regression coefficient. The regression coefficient, the lag, and the explained variances are shown in the global map in fig. S4 (A to C), respectively. Despite the large change in insolation with latitudes, the regression coefficients do not change substantially with latitudes in the NH extratropics over land or ocean (figs. S4A and S5) but do increase by about three times from over ocean to over land [~ 0.2 to $0.8 \text{ K} (10 \text{ W m}^{-2})^{-1}$].

The regression (Eq. 1) is then used to predict the seasonal cycle of temperature (i.e., the deviation from the annual mean) of the past at the same location, with the summer (winter) temperature taken as the mean of the three warmest (coldest) months. It should be emphasized that the analog model is derived from observations statistically and is, therefore, independent of any climate model. The analog model only predicts the seasonal cycle but not the annual mean temperature. In essence, this model is the simplest model to predict the change in seasonal cycle from insolation. The model is called the analog model here because it uses the present-day seasonal cycle as the analog, in a sense similar to those of some past temperature reconstructions. Physically, this analog model assumes that the seasonal cycle is determined predominantly by local processes, without marked change in the local physical condition of the surface layer and the nonlocal advection impact. This assumption is supported by the reasonable agreement between the analog model and various climate models (Figs. 1, C and D, and 2A; and fig. S7).

Comparison of the analog model and climate models

The analog model compares well with climate models in the seasonal temperature responses in the Holocene averaged over a large area of continental scale (Figs. 1, C and D, and 2A). The responses can also be compared for their spatial changes across proxy sites (fig. S7). Under strong seasonal insolation forcing in the early (9 ka) and mid-Holocene (6 ka) (fig. S7, A and B), the spatial variation of seasonal cycle in the analog model is strongly correlated with that in all climate models (significant at 95% level). Across individual sites, there is a substantial spread between the analog model and climate models, as seen in the scatters away from the diagonal line, suggesting that seasonal cycle responses in some localized regions differ between climate models and the analog model. These scatters, however, are averaged out over the continental scale, such that the mean responses over the proxy sites are still in good agreement [heavy markers are close to the diagonal line in fig. S7 (A and B), as well as in Figs. 1, C and D, and 2A]. These scatters at individual sites are likely caused by several reasons. Physically, the analog model implicitly assumes no change under the local surface condition (including vegetation cover, heat capacity, and albedo), remote temperature advection, and, in turn, their impact on local seasonal cycle. However, in response to external climate forcing, atmospheric circulation and the associated heat transport as well as local surface conditions, are changed. Statistically, at each point, the analog model only has 11 degrees of freedom (12 months, with the annual mean removed), such that the regression coefficient may be affected by some sampling errors. Averaging over a large area tends to reduce these random effects associated with heat redistribution, surface change, and sampling error.

Vegetation impact in climate models

Vegetation impact on seasonal cycle can be detected across proxy sites by comparing the seasonal cycle responses in the vegetation

Holocene simulations between the experiment with preindustrial vegetation [VegExp(PI)] and that with high-end proxy-reconstructed vegetation [VegExp(Obs)] (fig. S7) (11). With a small increase in seasonal insolation forcing at 3 ka (fig. S7C), the seasonal cycle is increased at most sites in VegExp(PI), such that the mean change is an increase of 0.4 K, but increased and decreased at about half the sites in VegExp(Obs) with the mean change of about 0 K (green stars versus blue circles). Therefore, the expanded vegetation leads to a decrease in seasonal cycle amplitude of about -0.4 K on average over the continent, although the seasonal cycle can be reduced up to over -1 K locally in isolated regions, especially over the boreal forest region where the increased vegetation cover and, in turn, the albedo effect are the greatest.

This small -0.4 K reduction on seasonal cycle due to vegetation expansion is, however, overwhelmed by the larger increase response to insolation change in the mid- and early Holocene (fig. S7, A and B). Now, the reduction in seasonal cycle between VegExp(Obs) and VegExp(PI) is less than -0.4 K on average, such that seasonal cycle is enhanced almost everywhere even with expanded vegetation in VegExp(Obs). Note that this vegetation impact on seasonal cycle of about 0.4 K is one order smaller than that of the insolation impact in the early Holocene (fig. S7A), although it can be comparable with the MAT change in the Holocene (Fig. 2B). Therefore, the vegetation impact seems unlikely to explain the small seasonal response in reconstructions, although it may contribute substantially to the change in MAT.

The TRACE experiments and PMIP4 experiments, although not specifically designed to address the vegetation impact, seem also consistent with the analysis above. In TRACE, vegetation cover decreases from the early to late Holocene due to the coupling with a dynamic vegetation model (21). The seasonal cycle is reduced over about half of the sites at 3 ka with little mean change, similar to VegExp(Obs), but is enhanced in almost all sites in the early and mid-Holocene (black pluses in fig. S7, A to C). The PMIP4 experiments mostly adopt the present vegetation cover without the dynamic vegetation model. At 6 ka, they show strong increase in seasonal cycle, in good agreement with the analog model (red stars in fig. S7B), with the increase in seasonal cycle more than that in TRACE (black plus in fig. S7B).

The brGDGT temperature reconstruction with deep learning

The mean annual and summer brGDGT temperature reconstructions in this study are all based on a DLNN, following the brGDGT-MAP (mean annual precipitation) model as outlined by Zheng *et al.* (22). The summer brGDGT-DLNN temperatures consist of those from 14 sites in the 20° to 50°N band (14). The details of these summer temperature reconstructions have been described in detail in Zheng *et al.* (14) and, therefore, will not be described here.

The mean annual brGDGT-DLNN temperatures have 25 sites in the 20° to 50°N band. The MAT reconstruction has not been published and, therefore, will be described here briefly in Materials and Methods, with more details in the Supplementary Text. The MAT relies on lower data requirement than that for summer temperature, the latter of which requires samples separated by 5-methyl and 6-methyl brGDGT isomers. Thus, we further improved the precision of three widely used brGDGT-based temperature proxies: cyclization of branched tetraether (CBT), methylation of branched tetraether (MBT') (23), both for surface soils and lacustrine samples, and MBT'_{5ME} (24), for lacustrine samples (see Supplementary Text; fig.

S13, models IA, IB, and IIB; and table S2). In addition, we established four original optimal models both in surface soil and lacustrine samples, one based on all 15 compounds of brGDGT and the other based on the nine 5-methyl brGDGT isomers (see Supplementary Text; fig. S13, optimized models and models IIIA, IIIB, IVA, and IVB; and table S2). The four optimal models reduce the long-standing weakness of brGDGTs' elevated uncertainty in low-temperature environments ($<5^{\circ}\text{C}$). These seven models enable us to reconstruct the Holocene temperatures for more variety of profiles of different data quality. More details about these models can be found in Supplementary Text. The three improved models (IA, IB, and IIB) are applied for low-quality data, while the four optimal models (IIIA, IIIB, IVA, and IVB) are applied to profiles of high quality.

To reconstruct the global Holocene MAT, we first compiled 33 well-dated sedimentary profiles (loess, lakes, and peats; fig. S10) in Africa, Asia, and Europe. We also add the data of a new Dajiuhu (lake) site (Dajiuhu_GDGT_analysis.xlsx in <https://zenodo.org/records/15012871> and more details in text S3). Considering the various data conditions and modern MAT values in each profile, we input different combinations of brGDGT indices, percentages of 15 compounds, or percentages of nine 5-methyl brGDGT into one of the four DLNN models (see details of the DLNN models and profiles in Supplementary Text). More specifically, for the high-quality profiles that contain 15 compounds of brGDGT in their original studies, we use the four optimal DLNN models (IIIA, IIIB, IVA, and IVB; tables S2 and S3). For low-quality profiles that do not separate the 5-methyl and 6-methyl brGDGT or those profiles that only provide CBT, MBT', and MBT'_{5ME} in their original studies, we use the three improved models (IA, IB, and IIB; tables S2 and S3). In addition, the MAT reconstructions of four profiles in Africa, used TEX₈₆ (the tetraether index of tetraethers consisting of 86 carbon atoms), are based on GDGT (isoprenoid GDGT and brGDGT) because we are unable to obtain the original brGDGT datasets in these four profiles. The MATs for these four profiles are reconstructed using the same method as in the original study, which is called the "traditional" method in table S3. Taking into account the stability of the DLNN, we run the results of each profile 20 times, then take the average as the final outcome, and obtained the outputs by averaging the mean temperatures of these 33 regions every 100 years and smoothing the curve through the five-point average method (fig. S14). Last, we merged the temperature curves of all profiles with 1-SE uncertainty shaded (fig. S11).

Supplementary Materials

This PDF file includes:

Supplementary Text
Figs. S1 to S15
Tables S1 to S3
References

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