Concerns of assuming linearity in the reconstruction of thermal maxima

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Seasonal biases in proxy records are an outstanding issue in deciphering past climate evolution, and may contribute to the current discrepancy between models and proxy reconstructions during the Holocene, which is most pronounced in the northern extratropics[1–3]. Bova et al.[4] reported a method of transforming seasonal into mean annual temperatures (the SAT method) at low and mid-latitudes, and concluded that the thermal maxima during the Holocene and last interglacial (LIG) were mainly an artefact of a seasonal proxy response. We provide evidence that, in addition to this geographic mismatch, key assumptions of the SAT method are violated, and more importantly, that the method by construction removes thermal maxima. Thus, the main findings of Bova et al.[4] probably reflect peculiarities of the SAT method instead of shedding light on the so-called Holocene conundrum.

The SAT method considers a record to be seasonally biased if it is better correlated with insolation during a particular time of year than the mean annual insolation. It then converts this record into mean annual temperatures using the difference between the seasonal and mean annual insolation curves. Bova et al.[4] calibrate temperature–insolation relationships during the LIG, when changes in insolation were large but other forcings (greenhouse gases and ice sheets) were small, and use these relationships to correct Holocene temperatures for inferred seasonal biases at selected sites between 40° N and 40° S. Importantly, however, the SAT method has the underlying assumptions that any local seasonal temperature variation can be approximated as the sum of two components: (1) a linear (potentially time-lagged) response to seasonal insolation forcing (that is, climate is equally sensitive to insolation throughout the year), and (2) other temperature variations (for example, resulting from greenhouse gas forcing or internal changes such as the Atlantic Meridional Overturning Circulation[5] or vegetation feedbacks[6]) that are independent from any seasonal insolation forcing and evenly distributed throughout the year in the calibration period (that is, the LIG) as well as in the application period (that is, the Holocene). We highlight two potentially fatal flaws.

First, these assumptions largely pre-determine the outcome. The question of the LIG and Holocene temperature evolution is essentially a question of how linearly climate responds to insolation. Although a proxy record may correlate with insolation during a particular season because it can only monitor temperature during that season (that is, the proxy is seasonally biased), it is also possible that the shape of the mean annual temperature evolution is actually dominated by a particular season that has a larger response to insolation forcing (that is, the proxy faithfully records the annual mean, but the annual mean itself is dominated by a seasonal response as the other seasons are less sensitive). As the SAT method assumes linearity, it discounts the latter possibility, and thus unsurprisingly concludes that the former explains the Holocene conundrum.

For example, consider the extreme case that summer insolation changes ($\Delta\mathrm{Insolation}_{\mathrm{summer}}$) dominate the mean annual temperature changes ($\Delta T_{\mathrm{annual}}$)

$$\Delta T_{\mathrm{annual}} = \alpha \times \Delta\mathrm{Insolation}_{\mathrm{summer}}$$

where α is the temperature sensitivity to insolation. The SAT method would 'correct' for the correlation with summer insolation by regressing $\Delta T_{\mathrm{annual}}$ onto the difference between $\Delta\mathrm{Insolation}_{\mathrm{summer}}$ and $\Delta\mathrm{Insolation}_{\mathrm{annual}}$, which as a first approximation (because $\Delta\mathrm{insolation}_{\mathrm{annual}} << \Delta\mathrm{Insolation}_{\mathrm{summer}}$) removes the $\alpha \times \Delta\mathrm{Insolation}_{\mathrm{summer}}$ term, leaving $\Delta T_{\mathrm{SAT}} \approx 0$, which is clearly wrong.

Second, there are several well-founded reasons to question the assumptions of Bova et al.[4] in the first place. Contrary to assumption 1, the climate response to insolation is generally nonlinear. As visible in instrumental data, the modern seasonal insolation–temperature relationship is nonlinear around most of the world owing to seasonal feedbacks that modulate sensitivity (for example, varying mixed layer depth, winter sea ice and summer monsoons), which also include the mid-latitudes and tropics (all coloured areas in Fig. 3 of ref. [7])[7].

As orbital cycles modulate the seasonal cycle, these nonlinearities acting on the seasonal cycle are also relevant on orbital timescales, as supported by climate model simulations (Fig. 5 in ref. [7] and refs. [8,9]). In fact, astronomical theories for Pleistocene climate change invariably call on seasonally dependent feedbacks such as summer insolation intensity as driver of snow ablation to produce glacial cycles[10,11].

For assumption 2, the response to mean annual forcing is not necessarily expressed equally throughout the year. For instance, there have been pronounced differences in seasonal temperature trends over the instrumental era[12], despite the year-round nature of anthropogenic forcing. Even in the case that the SAT method would detect the true season of the proxy bias, it cannot correct a seasonal expression of a signal that is independent from the insolation signal. Finally, as the SAT method maximizes the correlation of the proxy time series to any seasonal insolation curve, it tends to overfit and spuriously interpret true annual mean variations as seasonal biases and thus dampen them. Although Bova et al.[4] aimed to minimize this artefact in choosing the LIG, as we show below, this still precludes the possibility of reconstructing thermal maxima with the SAT method.

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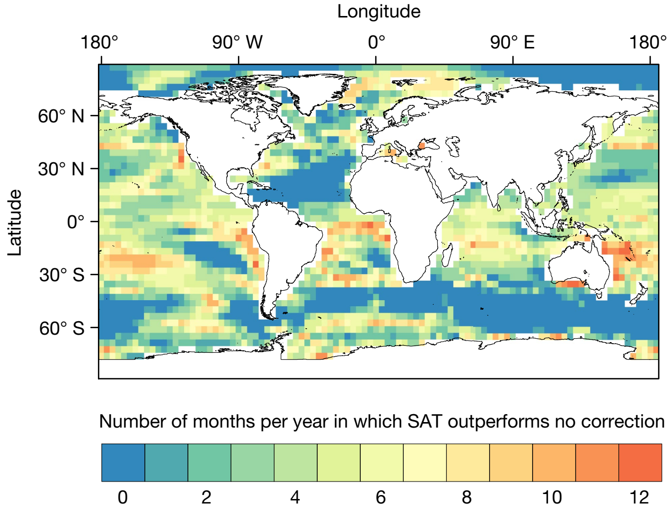

Fig. 1 | SAT method lacks skill in reconstructing simulated Holocene annual temperature. For all 12 possible proxy seasonality months, the SAT method is applied to the LIG simulation[13] to estimate the seasonality and the insolation sensitivity needed for the seasonal to annual conversion. On the basis of these values, the Holocene time series are corrected and compared with the true annual mean temperature. The colours indicate the number of proxy months in which applying the SAT method leads to an improvement of the correlation to the mean annual temperature compared with the uncorrected time series. A good correction method should work regardless of the unknown proxy seasonality, thus for all 12 months; by contrast, the SAT method fails this test and only works at some specific locations. The basemap comes from the deprecated clim.pact R package[16].

Given that the assumptions of Bova et al.[4] are probably violated to some extent, the question is whether the SAT method is still useful to reconstruct annual mean temperatures. As shown for a single location in Bova et al.[4] (their Fig. 1), climate models offer the possibility to test the method, even if such a model test is partly circular in evaluating a data–model discrepancy. We thus applied the SAT method across the entire ocean domain in the accelerated LIG and Holocene simulations[13] used in Bova et al.[4].

To begin, we test the ability of the SAT method to detect seasonal biases. For this, we apply the SAT method to the LIG modelled annual mean temperatures that are by construction not seasonally biased. Interestingly, for 79% of the global grid boxes (and 79% in the 40° S–40° N domain used in Bova et al.[4]), the SAT method incorrectly indicates a seasonal bias because the annual mean temperatures have a stronger correlation with one of the monthly insolation curves than the annual mean insolation. The falsely inferred seasonal biases also include spring, summer and autumn (37% of the detections in the 40° S–40° N domain are in March–October), similar to detected seasonal biases in Bova et al.[4].

As a second experiment, we test the ability of the SAT method to correct for seasonal proxy biases. Mimicking seasonal proxy records, we picked LIG temperatures from a single month, and then corrected them to mean annual temperatures in the LIG and Holocene, repeating this procedure for all 12 possible proxy-response months. We define the correction to be skilful if the corrected time series is better correlated with the 'true' Holocene mean annual temperature time series than the uncorrected monthly time series. Ideally, the SAT method should improve the temperature reconstruction regardless of the month the proxy is biased to. However, this is not the case (Fig. 1); the method works for all possible proxy-response months in less than 1% of grid boxes, fewer than half the months in 74% of grid boxes and 0 months in 26% of cases. Restricting the domain of analysis to 40° S–40° N leads to similar results (less than 1% for all months, 67% for less than 6 months and 14% for 0 months). Likewise, for 34 of the 44 sites carefully selected by Bova et al.[4], the method is skilful in fewer than six possible proxy-recording months. Similar results (no skill in at least 4 out of 8 months at 30 out of 44 sites) are obtained when excluding certain months (November–February), which might be prone to a misdetection owing to the correlation of annual and seasonal insolation.

This suggests that even in the mostly linear model world, the nonlinear part of the insolation response is strong enough to challenge the SAT approach at most sites. The lack of skill in half of the possible proxy-recording months implies that in reality, where the proxy-recording months are unknown, applying no correction will generally lead to better reconstructions.

The nonlinear response in the model simulations also leads the SAT method to often detect the incorrect proxy season. Across the globe, even in this extreme case of perfect noise-free seasonal data, the correct season (defined here as two to zero months before the prescribed month to allow for a delay between insolation and temperature owing to heat capacity) is identified in 42% of cases, better than the 25% one would expect by chance (3 out of 12) but still relatively low.

Finally, we tested whether the SAT method would be able to reconstruct a trend or broad thermal maximum such as suggested by the uncorrected proxy records (Fig. 4a in Bova et al.[4]). Although Bova et al. discounted the possibility that such a trend in annual mean

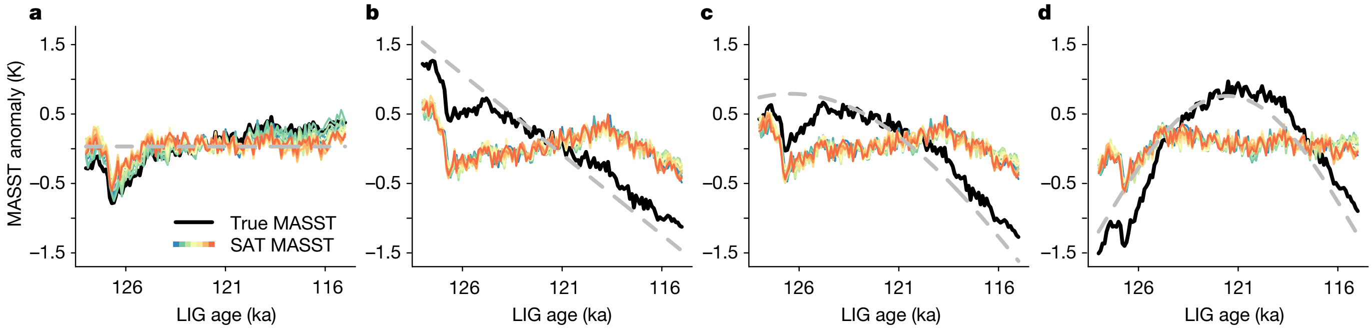

Fig. 2 | SAT method mutes thermal maxima. a–d, To test the ability of the SAT method in reconstructing annual mean thermal maxima, we create artificial thermal maxima by modifying the LIG model output[13] and then compare the true (black) and SAT-reconstructed (colours) 40° S–40° N mean annual sea surface temperature (MASST). For this, we add a range of trends on every grid box and month of the LIG simulation (grey dashed, no change (**a**), linear trend (**b**), section of sine wave with a decreasing trend (**c**), section of sine wave with a maximum around 121 ka (**d**)), resulting in a range of idealized LIG temperature evolutions (compare Fig. 4a in Bova et al.[4]). We then mimic seasonal proxy records by picking single months for every grid box and apply the SAT method, yielding 12 reconstructions of the MASST (coloured lines). Regardless of the true prescribed annual mean temperature evolution (black), the SAT method reconstructs a flat LIG temperature evolution (coloured lines). All time series are expressed as anomalies relative to the full time period.

temperatures could have occurred during the LIG because sea level and greenhouse gases were stable, it might, for example, be caused by hemispheric changes in ice sheets[14] and freshwater flux[15] or monsoon-controlled atmospheric dust loading[6]. We imposed a range of temperature trends on the LIG climate model results (added equally on each month and thus also on the annual mean) and reconstructed the annual mean temperature using the SAT method. The SAT method spuriously assigns the trend to some seasonal insolation ('overfits') and largely removes the trend, always resulting in a flat LIG temperature curve regardless of the 'true' annual mean climate (Fig. 2). Owing to the similarity of the insolation in the LIG and Holocene, the spurious removal of thermal maxima also extends to the Holocene time period. The lack of thermal maxima during the LIG and Holocene suggested by Bova et al.[4] is therefore probably an artefact of the SAT method itself. In other words, Bova et al. precluded the possibility of a thermal maximum during the LIG by assuming that the LIG was solely a linear response to insolation, and violations of this assumption will also bias the Holocene reconstruction.

Our tests underline that the method may work for some selected sites (that in our experiments do not coincide with the sites chosen by Bova et al.[4]), but there is no way of knowing this without relying on climate model simulations that we ultimately want to test. Therefore, in practice, there is no protocol to verify whether the SAT method is successful in correcting the proxy records. Finally, even if such 'linear' sites could be identified in the lower latitudes as Bova et al.[4] contend, it is unlikely that these sites would resolve the origin of the global Holocene conundrum, as the largest model–proxy mismatch is in the higher latitudes[1–3].

The Holocene conundrum remains an important problem in unravelling proxy–model disagreements and the linearity and feedbacks of the climate system. Indeed, the possibility that the climate system does not always behave linearly is one of the major motivations to explore the palaeoclimate record and better constrain models; otherwise, climate change could be easily predicted from forcings and the need for proxy-based temperature reconstructions would be lessened. Although the approach by Bova et al.[4] is novel, their method is based on doubtful assumptions and when applied is largely not skilful.

Code availability

The R code for the performed analysis is deposited at https://doi.org/10.5281/zenodo.6564932.

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Additional information

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Reply to: Concerns of assuming linearity in the reconstruction of thermal maxima

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The seasonal-to-annual mean transformation (SAT) proposed by Bova et al.[1], offers a possible solution to the apparent discrepancy between proxy records showing long-term cooling[2,3], and models, which show long-term warming across the Holocene known as the 'Holocene temperature conundrum'[4,5]. Model–data inconsistencies and conflicting proxy records are particularly prominent in the mid- to low latitudes, and have been variably attributed to seasonal biases in proxy temperature reconstructions[6–9], model deficiencies[10,11] or both. Bova et al.[1] have suggested that proxy seasonal biases are the primary source of the conundrum. Although it is widely acknowledged that seasonal biases complicate palaeoclimate data interpretations, Laepple et al.[12] question whether SAT is a robust solution to this problem, challenging the validity of the foundational assumptions of SAT and thereby arguing that the consistency with model results is fortuitous.

The clear impact of seasonality on marine proxies of surface temperature, which compose 30% (ref. [2]) and 80% (ref. [3]), respectively, of the proxy records included in prior global stacks, has been discussed previously[8,9,13–15]. These authors show a systematic divergence in Holocene sea surface temperature (SST) trends between alkenone and *Globigerinoides ruber* magnesium (Mg)/calcium (Ca) proxy reconstructions. In regions, such as the eastern equatorial Pacific, for example, alkenone and *G. ruber* Mg/Ca SST estimates measured on adjacent sediment cores show opposite Holocene SST trends, making it impossible for both proxies to reflect mean annual sea surface conditions. We therefore assert that any proposed resolution of the Holocene temperature conundrum must also come to terms with this second conundrum—the observed discrepancies among the proxy records themselves. Notably, the SAT method proposed and implemented in our recent Article resolves both.

The divergent Holocene SST trends were explored previously through model–data comparison studies, which showed that accounting for proxy seasonality improved, but did not resolve, model–data discrepancies during the Holocene[13–15]. However, these tests were conducted using model simulations forced only by orbital forcing, and did not account for the Holocene variations in greenhouse gas (GHG) and ice forcing, which cannot be ignored. This led us to 'calibrate' the SAT method using records from the last interglacial (LIG), when GHG and ice-sheet forcing were stable, while seasonality was at its maximum.

A key strength of the SAT method is that it provides a systematic, physically based way to assess seasonal bias and calculate the mean annual SST (MASST) from seasonal SSTs in individual records. However, the SAT method cannot be applied indiscriminately. For an effective application of SAT, two foundational assumptions must be satisfied: (1) SST responds linearly to changes in the local insolation (or to insolation that is highly correlated with the local insolation) and (2)the response to insolation is dominant in the absence of other forcing 'external' to the coupled ocean–atmosphere system (that is, GHGs and land ice), as is arguably the case during the LIG.

We acknowledge that these assumptions will not be satisfied sufficiently at all times nor in all locations. First, SAT requires an approximately linear relationship to be satisfied only within interglacial periods, and thus does not dispute the role of seasonally dependent feedbacks in driving state changes in the climate system, as outlined by Milankovitch theory. However, there may be locations where seasonal feedbacks modulate the sensitivity of SST to insolation across the year[16], even during interglacials. For example, SAT should not be applied to sites in proximity to oceanographic fronts where SST can be strongly affected by nonlinear dynamics, as seen in the western Atlantic[6,17]. In fact, the inclusion of such records in a previous compilation[3] is the primary source of the apparent Holocene global cooling trend. Thus, the 'conundrum', in the high northern latitudes is largely solved simply by removing these datasets, as shown in a recent paper[6]. In our compilation, we were therefore selective of the records included, limiting the records included to low- to mid-latitude regions where the SST response to insolation is the most likely to respond quasi-linearly to the local insolation, and indeed, where the conundrum remains most prominent.

Nevertheless, Laepple et al.[12] question whether these assumptions are satisfied sufficiently anywhere in the global oceans. Strong nonlinearities are observed in the modern seasonal insolation–temperature relationship at some locations in the global oceans (at least three locations as shown by Laepple and Lohmann[16]: notably Northern Hemisphere mid-latitude and high-latitude southern sites because of the strong nonlinearity associated with the winter mixed layer and sea ice). However, it is not obvious, nor is it proven, that these same nonlinear relationships apply on orbital timescales, or that they apply everywhere in the global oceans. Laepple and Lohmann[16] provide a first test of this hypothesis in one model by applying the modern seasonal insolation–temperature relationship to orbital trends across the Holocene, either estimated using a linear or a polynomial relationship. The amplitudes of the calculated trends using the polynomial relationship are larger, but neither the polynomial nor the linear relationship reproduces the tropical ocean response robustly, at least as simulated by the atmosphere–ocean general circulation model (see Fig. 5 in Laepple and Lohmann[16]). An additional test noted in Laepple et al. refers to an experiment in an intermediate-complexity model with many assumptions[18], and is thus unlikely to be informative on this issue. Accordingly, the assertion that nonlinear responses dominate the global surface ocean temperature

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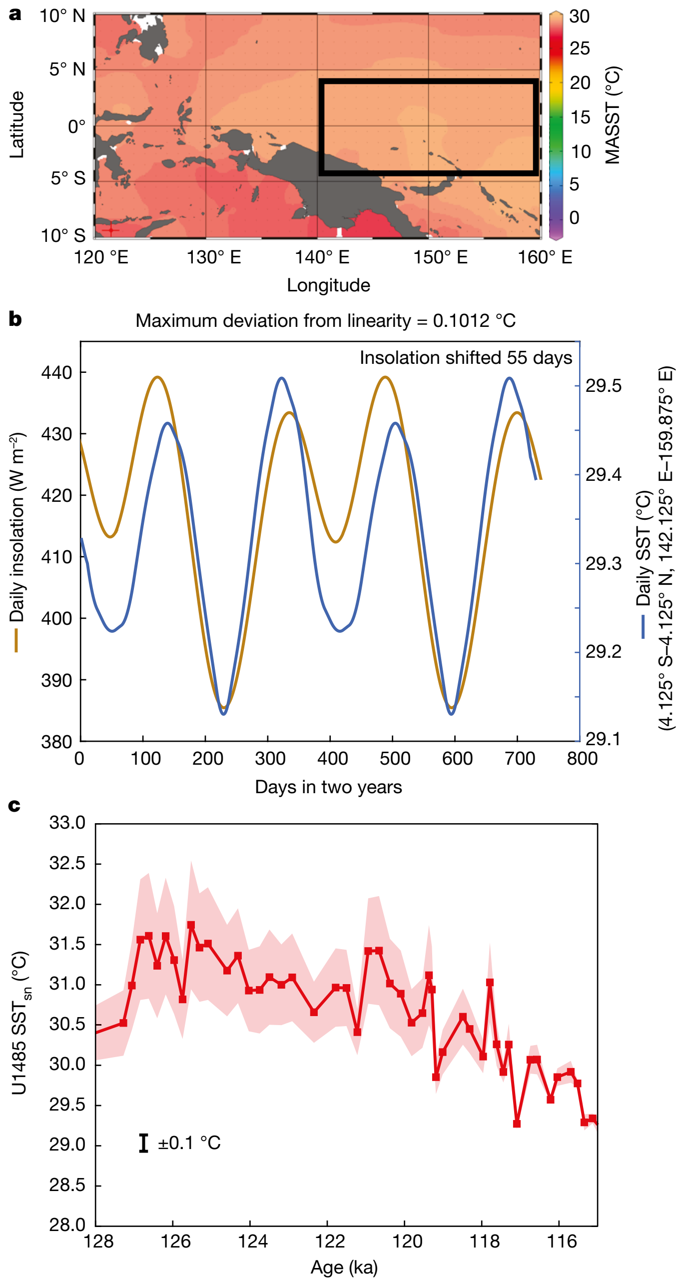

Fig. 1 | Impact of nonlinearities on Western Pacific Warm Pool SSTs. a, Mean annual SST in the Western Pacific Warm Pool showing the domain used to assess modern insolation–SST relationship (4.125° S to 4.125° N and 142.125° E to 159.875° E). The basemap is the World Ocean Atlas 2013 dataset[25], showing annual SST at 1.00° resolution and plotted in Ocean Data View. **b**, Daily insolation[21] versus the long-term average seasonal SST[19,20] averaged across the domain indicated in **a** using daily SST data from 2,414 locations spanning the period from 1971 to 2000 ($n = 881{,}110$). SST data are from the National Oceanic and Atmospheric Administration daily optimum interpolation SST dataset. Daily insolation is shifted 55 days forwards in time to account for the time delay in the SST response. The maximum deviation from linearity in the SST response to insolation across this region is 0.1 °C. It is noted that this deviation arises owing to both variations in the magnitude of the SST response to the insolation forcing and variations in the time lag. **c**, Unadjusted SST reconstructed from IODP site U1485 from the Western Pacific Warm Pool during the LIG or SAT calibration period. It is noted that the maximum deviation from linearity in the modern insolation–temperature relationship is negligible (±0.1 °C) relative to the long-term trend in SST during the LIG at this site (about 2.25 °C).

response to insolation at orbital timescales remains a hypothesis, and one, that like ours, needs further testing.

Given that there is some uncertainty, we acknowledge that there is more confidence in the successful application of SAT at locations where the modern seasonal insolation–temperature relationship is approximately linear. Here we assess linearity as the maximum deviation from the linearity of modern SST[19,20] from the daily insolation[21], with some time lag (estimating by maximizing the correlation coefficient) relative to the magnitude of SST change during the SAT calibration interval or LIG period. We illustrate this proposed approach for Integrated Ocean Drilling Program (IODP) site U1485 in the western Pacific. Here we find that in examining the seasonal SST (long-term average from 1971 to 2000) response to daily insolation, the maximum deviation in warm pool SST is ±0.1012 °C (Fig. 1a,b). Although future versions of SAT should explicitly account for this uncertainty, at most of the sites included in the Bova et al.[1] study, the observed deviation is small relative to the change in SST across the LIG, less than about 20%. An exception is ODP site 1240, where we identify strong nonlinear behaviour, with a maximum deviation from linearity of 1.4 °C and a reconstructed change in LIG SSTs of about 1.5 °C. The strong nonlinearity observed in the modern seasonal SSTs at the site should disqualify the record from inclusion in the compilation, although its removal does not fundamentally impact the conclusions of our original study.

Lastly, Laepple et al.[12] outline an additional requirement for the successful implementation of SAT: that temperature variations arising from other 'external' forcings to the climate system (that is, not insolation) are evenly distributed throughout the year and independent from the seasonal insolation. We do not include this requirement because neither GHGs nor ice volume show substantial change across the LIG. Nevertheless, we acknowledge that the impacts of these forcings are probably not evenly distributed throughout the year. Atmospheric carbon dioxide, for example, is substantially impacted by insolation via the seasonal cycle in photosynthetic activity by plants. In addition, GHG forcing takes place in the infrared part of the spectrum and thus its magnitude depends on many properties of the climate system, including clouds and the vertical profile of water vapour. However, the insolation-dependent component of the GHG forcing would be accounted for in the transformation because it is correlated to the insolation and thus covered under assumption 1, and variations independent from the insolation forcing are probably small relative to the SST changes arising from the seasonal insolation.

The fidelity of the transformation using a linear relationship between SST and insolation is evaluated by applying our method in a state-of-the-art climate model (see 'Linear insolation–temperature relationships' in Methods of ref. [1]). The good agreement between estimates based on the SAT method and from the complex climate model is, on its own, an important outcome of the paper, suggesting that when averaged across our chosen sites our simple linear model estimates the long-term SST response to solar forcing in the tropical and subtropical regions equally well as the nonlinear dependencies in the climate model. Our results are further supported by a reanalysis using palaeoclimate-data-assimilation techniques, which shows a remarkably similar Holocene temperature evolution and no evidence for a Holocene thermal maximum, despite following a completely different methodological approach[22]. Thus, we show that SST in the climate model, which is forced by fully nonlinear dynamics in the coupled ocean–atmosphere system and includes sea ice and other fast feedback processes, can be approximated with a linear transformation to climate forcing on multi-millennial timescales in the region studied.

Additional model tests of the SAT method were conducted by Laepple et al. Although these tests highlight some important limitations of SAT as well as possible avenues for improvement, the results indicate no obvious 'fatal flaws'.

In test 1, Laepple et al.[12] apply the SAT method to LIG modelled annual mean temperatures across the entire ocean domain and find that in nearly 80% of the global grid boxes SAT incorrectly assigns a seasonal bias. On the surface, this result appears highly problematic, but in practice the false bias detection has little impact and can be readily fixed in a future update.

First, the false seasonal bias detections arise because the modelled MASST increase across the LIG, especially in the mid- to low latitudes, is very small, which leads to a low signal-to-noise ratio. Thus, the monthly insolation curve that has the 'strongest correlation' is in many cases random, an assertion that is supported by a very low correlation coefficient. In the future, these false seasonal bias identifications can be avoided by implementing a threshold correlation value into the SAT algorithm, and we will do so in a future version.

Given that this fix was not in place, however, when we analysed the datasets included in the Bova et al.[1] study, the question remains as to whether a false seasonal bias detection could have impacted the previously published results. We tested this possibility by applying SAT to modelled LIG MASSTs, following Laepple et al.[12], at a handful of the sites included in the Bova et al.[1] compilation. We found that despite incorrectly identifying a seasonal bias at many of the sites, the correction applied was small, at most a few tenths of a degree, and thus the MASST evolution remained unchanged. This is because LIG MASSTs change very little, and when regressed against the identified seasonal insolation, the slope or SST sensitivity to the seasonal insolation is also small.

We appreciate Laepple et al. for bringing this issue to our attention. Nevertheless, although it should be addressed in the future by the addition of a threshold correlation value, in practice, the issue has little impact on the final results published in the original paper.

In the second test, the authors test the ability of SAT to perform in all months of the year in all ocean grid boxes. We agree it would be ideal for SAT to work for any record, regardless of its seasonal bias and location. However, this is not yet possible owing to an important statistical constraint for a successful application of the SAT method: the independence of the annual and seasonal insolation curves during the LIG. If the mean annual insolation is highly positively correlated with the seasonal insolation, SAT will be subject to large errors, because the filtering of the seasonal signal will also filter the annual signal substantially. This means that for many months out of the year (roughly November to February for the tropical region) seasonal detection will not be possible and the SAT method will not produce robust results. This statistical constraint, however, has little impact in practice given that July, August and September seasonal biases are identified for 36 out of the 44 records included in the Bova et al.[1] compilation.

The third test assesses whether the SAT method, prevents 'by construction' a trend or thermal maximum. However, this test, by construction, violates the foundational principles of the SAT method by artificially changing the evolution of MASST without changing the forcings. Nevertheless, the point of the third test is clearly to draw attention and additional scrutiny to the second foundational assumption of SAT, that the response to insolation is dominant in the absence of forcings 'external' to the coupled ocean–atmosphere system, such as land ice and GHGs. As SAT assumes that the LIG SSTs are forced solely by insolation, and to respond linearly, LIG MASSTs will inherently track the annual mean insolation. However, the Holocene MASSTs are not constrained or predetermined to follow the annual mean insolation, and, in fact, they do not. It is important to remember that the seasonal bias and SST sensitivity to monthly insolation in SAT are determined during the LIG, when GHG and ice volume were stable and seasonality was at a maximum, and then applied to the Holocene. Thus, Holocene SSTs, although still constrained to respond linearly to seasonal insolation, are not constrained to respond solely to insolation.

Although we do not agree with Laepple et al. that their tests reveal any fatal flaws in the SAT method, we recognize that SAT is not the ultimate method for filtering seasonal bias. We use it because seasonal biases in various SST proxies are not fully understood mechanistically. Ideally, the seasonal bias would be understood mechanistically and one could then filter the seasonal bias cleanly and directly from the proxy. This is possible for some proxies, such as borehole temperature, which is biased towards summer air temperature because snow cover tends to insulate the borehole from overlying air in winter[23]. It is hoped that such a direct method with a clear mechanism will be developed in the future. Until then, a next-generation approach for the SAT method should leverage model information to improve the relationship between SST and the local insolation forcing as well as to expand the spatial domain over which SAT can be applied. Importantly, however, model–data inconsistencies and conflicting proxy records are most prominent where we already have data, in the mid- to low latitudes[4,6]. Furthermore, temperature here is highly correlated with the global mean, although the magnitude of tropical warming is larger than the global mean as observed in the Paleoclimate Modelling Intercomparison Project (PMIP) climate models (Fig. 2), because the global mean warming is reduced by the cooling at high latitude.

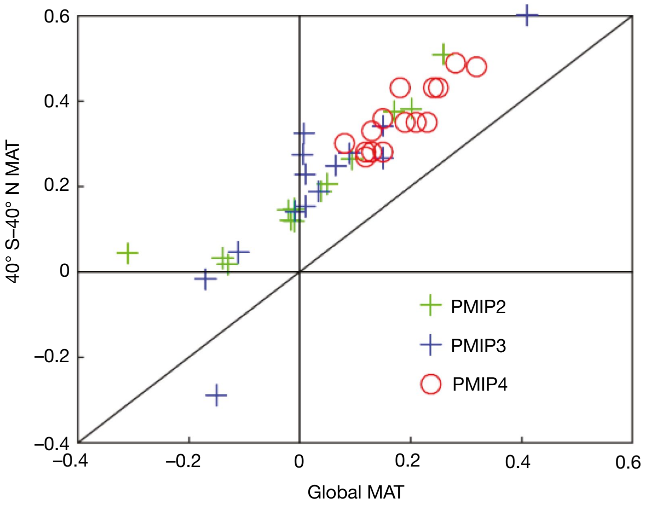

Fig. 2 | PMIP global versus tropical (40° S–40° N) mean annual temperature (area weighted) change from 6 ka to 0 ka for PMIP2 (13 models), PMIP3 (15 models) and PMIP4 (15 models). The change is calculated as the difference between 0-ka and 6-ka experiments. The 0-ka experiments are forced by preindustrial orbital forcing and GHGs. The 6-ka experiments are forced by only orbital forcing in PMIP2 and PMIP3, and additionally by the lower GHGs as observed in PMIP4. It is noted that the cross-model spread of tropical temperature is highly correlated with the global mean temperature such that the warming occurs in both the tropics and global mean in most models. A second point is that when responding to orbital forcing alone, as in PMIP2 and PMIP3, the global mean annual temperature (MAT) is centred around 0 with both warming and cooling, but when GHG forcing is included (PMIP4) then all experiments are warming, both in the global mean and in the tropics. Finally, it is noted that the magnitude of tropical warming is stronger than the global mean in nearly all experiments, because of the insolation associated with reduced obliquity.

Given the complexity of the feedbacks and the transport processes, the net effects of all the feedbacks and local insolation are difficult to assess. Our model test of SAT is a first attempt in this direction. We show that a simple linear response of SST to local insolation produces SST estimates consistent with climate models that include feedbacks and nonlinear dependencies, thereby resolving the Holocene temperature conundrum. Furthermore, seasonal biases detected using SAT can resolve the second conundrum, that is, proxy–proxy discrepancies. In our opinion, these results provide strong support for the hypothesis that local insolation is dominant, at least over much of the low to mid-latitudes and for the seasonal response. Nonetheless, we emphasize again that this method will only perform well in places where the underlying assumptions discussed above are met.

Finally, the possibility remains that both the SAT method and the climate model simulations have major flaws. Sea ice in the Arctic is one possible mechanism that could induce a nonlinear response to local insolation forcing, thereby violating the assumptions underlying SAT and invalidating its use. Furthermore, its impact can extend from high to low latitudes via atmospheric and oceanic transports. Vegetation and clouds have also been suggested. With the exception of vegetation, these feedbacks, to the best of our knowledge, have been included in all current generation climate models. As far as the global mean is concerned, these feedbacks have apparently been far too weak to substantially change the global mean trends[4,24]. Moreover, despite continued increases in complexity, the sign and magnitude of the mid- to late Holocene global mean temperature evolution has changed very little[4,5]. In fact, the latest mid-Holocene simulations (PMIP phase 4 (PMIP4)–Coupled Model Intercomparison Project phase 6), now including GHG forcing and feedback processes, suggest even greater Holocene warming than in previous versions[5] (Fig. 2).

Data availability

The datasets used in this study are available in the NOAA Database, World Data Service for Paleoclimatology at https://www.ncdc.noaa.gov/paleo/study/31752.

Code availability

A MATLAB code that implements the SAT method and the analysis presented in Fig. 1 is available on GitHub at https://github.com/sambova/SAT.

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Competing interests The authors declare no competing interests.

Additional information
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