# Response to Laepple et al. – SAT method precludes the reconstruction of interglacial 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. While it is widely acknowledged that seasonal biases complicate paleoclimate data interpretations, the accompanying Comment[12] questions whether SAT is a robust solution to this problem, challenging the validity of SAT's foundational assumptions 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[2] and 80%[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 SST trends between alkenone and *G. ruber*-Mg/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.

**SAT Foundational Principles revisited**

The divergent Holocene SST trends were explored previously via 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 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 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) sea surface temperature 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 (i.e. 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 was 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 non-linearities are observed in the modern seasonal insolation-temperature relationship at some locations in the global oceans (at least 3 locations as shown by Laepple and Lohmann[16]: notably NH mid-latitude and high latitude southern sites because of the strongly 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 amplitude 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 AGCM (see Fig. 5 in Laepple and Lohmann[16]). An additional test noted in the Comment 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 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 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 last interglacial period. We illustrate this proposed approach for IODP site U1485 in the western Pacific. Here we find that in examining the seasonal SST (long-term average from 1971-2000) response to daily insolation, the maximum deviation in warm pool SST is ± 0.1012°C (Fig 1A,B). While 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 behavior, with a maximum deviation from linearity of 1.4°C and a reconstructed change in LIG SSTs of ~1.5°C. The strong nonlinearity observed in the modern seasonal SSTs at the site should disqualify the record from inclusion in the compilation, though its removal does not fundamentally impact the conclusions of our original study.

Lastly, the accompanying Comment outlines an additional requirement for the successful implementation of SAT: that temperature variations arising from other “external” forcing to the climate system (i.e. 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 exhibit substantial change across the LIG. Nevertheless, we acknowledge that the impacts of these forcings are likely not evenly distributed throughout the year. Atmospheric $CO_2$, 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 vapor. 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 likely small relative to SST changes arising from the seasonal insolation.

**Evaluating SAT**

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 Methods, linear-insolation-temperature relationships). 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 non-linear dependencies in the climate model. Our results are further supported by a new reanalysis using paleoclimate data assimilation techniques, which shows a remarkably similar Holocene temperature evolution and no evidence for a HTM, despite following a completely different methodological approach[22]. Thus, we show that SST in the climate model, which is forced by fully non-linear 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 the Commenting authors. Although these tests highlight some important limitations of SAT as well as possible avenues for improvement, the results indicate no obvious “fatal flaws”.

*Test #1: False seasonal bias detection*

In test #1, Laepple et al.[12] apply the SAT method to LIG modeled 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 modeled mean annual SST 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 analyzed 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 modeled LIG mean annual SSTs, 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 insignificant, at most a few tenths of a degree, and thus the mean annual SST evolution remained unchanged. Why? Because LIG mean annual SSTs 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 the Commenting authors for bringing this issue to our attention. Nevertheless, while 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 article.

*Test #2: Assessing SAT’s skill*

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 due 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 significantly. This means that for many months out of the year (roughly November thru 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.

*Test #3: Questioning SAT's Foundational Assumptions*

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 "the response to insolation is dominant in the absence of forcing "external" to the coupled ocean-atmosphere system, such as land ice and GHGs". Since 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, though still constrained to respond linearly to seasonal insolation, are not constrained to respond solely to insolation.

Although we do not agree with the Commenting authors 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 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]. Further, temperature here is highly correlated with the global mean, though the magnitude of tropical warming is somewhat larger than the global mean as observed in the PMIP climate models (Fig.2), because the global mean warming is reduced by the cooling at high latitude.

## Final Thoughts

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 non-linear dependencies, thereby resolving the Holocene Temperature Conundrum. Furthermore, seasonal biases detected using SAT can resolve the second conundrum, i.e. 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 non-linear 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 (PMIP4-CMIP6), now including GHG forcing and feedback processes, suggest even greater Holocene warming than in previous versions[5] (Figure 2).

Figure Legends

Figure 1. **Impact of nonlinearities on WPWP SSTs.** (a) Mean annual SST in the WPWP (WOA 13)[25] showing the domain utilized to assess modern insolation-SST relationship (4.125°S to 4.125°N and 142.125°E to 159.875°E) (b) Daily insolation[21] versus the long-term average seasonal SST[19,20] averaged across the domain indicated in panel a. SST data from the NOAA daily optimum interpolation sea surface temperature dataset. Daily insolation is shifted 55 days forward 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. Note that this deviation arises due to both variations in the magnitude of the SST response to the insolation forcing as well as variations in the time lag. (c) unadjusted SST reconstructed from IODP Site U1485 from the WPWP during the LIG or SAT calibration period. Note 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 (~2.25°C).

**Figure 2. PMIP global vs tropical (40S-40N) mean annual temperature (area-weighted) change from 6ka to 0ka for PMIP2 (13 models), PMIP3 (15 models) and PMIP4 (15 models).** The change is calculated as the difference of 0ka - 6ka experiments. The 0ka experiments are forced by preindustrial orbital and GHG. The 6ka experiments are forced by orbital forcing only in PMIP2 and 3, and additionally by the lower GHG as observed in PMIP4. Note 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 & 3, the global mean MAT is centered around 0 with both warming and cooling, but when GHG forcing is included (i.e. PMIP4) then all experiments are warming, both in the global mean and in the tropics. Finally, note that the magnitude of tropical warming is stronger than the global mean in nearly all experiments, because of the insolation associated with reduced obliquity.

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**Competing Interests:**

The authors declare no competing interests.

**Data Availability:**

The datasets utilized 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 is available on GitHub (https://github.com/sambova/SAT).

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**Author Contributions**

S.B, Y.R., Z.L., M. Y., A.J., S.G. and C.Z. contributed to conception of the presented ideas. S.B. wrote the first manuscript draft. All authors provided review and editing. Three authors, not on the original paper were added to the author list. C.Z. provided additional analysis of model results. A.B. provided critical feedback and discussion. W.Z. provided the analysis of the PMIP global vs tropical mean annual temperature shown in Fig. 2.