Response to Zhang & Chen – Non-trivial role of internal climate feedback on interglacial temperature evolution

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The accompanying Comment[1] questions various aspects of the Seasonal to Annual mean Transformation (SAT) method proposed in our original study[2], suggesting the final results are predetermined by its underlying assumptions[1]. The primary critique raised relates to the assumed dominance of external insolation over internal feedbacks in shaping the evolution of interglacial temperatures, at least in the low to mid-latitudes. While the issue as it relates to feedbacks arising from slow components of the climate system needs to be further explored, the role of feedbacks from fast processes, such as sea ice, should not affect our conclusions qualitatively. The consistency of our trends with fully coupled model simulations supports the suggested evolution of mean annual temperatures throughout the Holocene.

The SAT Method offers a possible solution to the apparent discrepancy between proxy records showing long term cooling[3,4] and models, which show long-term warming across the Holocene known as the 'Holocene temperature conundrum'[5,6]. Importantly, it also offers a solution to the observed discrepancies between proxy archives; alkenone and *G. ruber*-Mg/Ca SST reconstructions exhibit a systematic divergence in Holocene SST trends with the former often indicating warming and the latter cooling across the Holocene, even at adjacent core locations[7,8]. It is therefore *not possible* for both alkenone and *G. ruber*-Mg/Ca SST reconstructions to record mean annual SSTs at a majority of low to mid-latitude locations. Nevertheless, they are largely considered to be mean annual records when integrated into global reconstructions[3,4], likely because there has been no systematic approach for assessing proxy seasonal biases. We remind the readers of this issue, as it must be addressed in any proposed solution to the Holocene Conundrum. Model deficiencies, as suggested in the accompanying Comment[1], therefore may contribute to the conundrum, but they are not a sufficient explanation.

The fact that the corrected records, generated by the SAT method, are consistent with the trends suggested by state-of-the-art climate models, supports our argument that seasonal biases in proxy data are a major reason for the disparity with models. Although seasonal biases have been discussed previously, due to the low eccentricity of Earth's orbit and the resulting low seasonal contrast in insolation, it is difficult if not impossible to detect proxy seasonal biases in the modern ocean, especially in the low latitudes, due to the low signal-to-noise ratio. As illustration, despite (1) a majority of sediment trap studies indicating a greater flux of *G. ruber* and alkenone biomarkers in boreal summer and fall, including sites in the western tropical Pacific[9,10], eastern tropical Pacific[11,12], northwest Pacific[13], and south of the subtropical front on the Chatham Rise[14] (note an austral summer bias was observed north of the front), (2) an often observed "warm-bias" in SST estimates[15,16], and (3) discrepancies between the two SST proxies seen in many sites that can only be explained if their carriers have different seasonal biases[8], measurements of *G. ruber* shell Mg/Ca and the alkenone unsaturation index are interpreted, and calibrated as reflecting mean annual surface conditions. A mean annual interpretation is usually justified because the correlation with both mean annual SST and boreal summer SSTs is statistically indistinguishable[8,9,15]. Thus, seasonal biases in marine SST proxies cannot directly be addressed in calibration studies, leading us to "calibrate" the SAT method using records from the last interglaciation (LIG), when seasonality was at its maximum.

Notably, this "calibration" method enables SAT to be applied widely, overcoming the limitations of modern field studies. However, we caution that the SAT method cannot be applied blindly. For an effective application of SAT, two key assumptions that underpin the method must be upheld:

> (1) The SST responds approximately linearly to local insolation, or to insolation that is highly correlated with the local insolation.
>
> (2) Multi-millennial trends in LIG SST at the location are forced dominantly by orbitally driven changes in local insolation or to insolation that is highly correlated with the local insolation.

If either of these assumptions are violated, SAT will not work and should not be applied.

We openly acknowledge that these assumptions will not be satisfied in all locations. For example, there may be locations where feedback processes responding to remote climate forcing uncorrelated to the site local insolation overwhelm the response to changes in local insolation, leading to changes uncorrelated with local insolation. In our compilation, we were therefore selective of the records included, limiting the records included to low- to mid-latitude regions where SST is most likely to respond linearly to the local insolation. Even within this region, we were critical of the records utilized, excluding sites in proximity to oceanographic fronts where SST can be strongly affected by nonlinear dynamics as seen, for example, in a previous reconstruction[4].

Nevertheless, in the accompanying Comment, Zhang and Chen[1] question whether these assumptions can be reasonably upheld even in the selected locations. While they agree that land ice and GHGs likely had a limited impact, the authors assert that changes in polar sea ice may have had a nontrivial impact on SSTs at the locations studied, thereby violating assumption 2, and invalidating the use of SAT. Sea ice, which is the focus of the comment, is one possible mechanism that could induce a nonlinear response to local insolation forcing. Furthermore, its impact can extend from high to low latitudes via atmospheric and oceanic transports. Feedbacks involving vegetation and clouds have also been suggested.

We do not dispute the possible and, in fact, likely influence of sea-ice variations and other internal feedbacks on tropical and mid-latitude SSTs, but it is not yet clear that their impact is sufficient to alter the SST response such that it would be uncorrelated with local insolation, and thereby invalidate the SAT method. Sea-ice feedback is a fast feedback, similar to say, cloud feedbacks at high latitudes. Therefore, unless its response to high latitude insolation or other climate forcing significantly differs in phase from tropical insolation, it will not affect the tropical SST evolution. Reconstructions of LIG sea-ice extent variations[17,18] and the impacts of sea ice on low and mid-latitude SSTs[19] appear to follow the same phase to the insolation forcing as the seasonally unadjusted proxy SSTs in most reconstructions, and will therefore impact the amplitude of the overall response to the external forcing (JJA insolation) but not the phase. As discussed previously (Supplemental Methods), the SAT method is insensitive to the amplitude of variations, and therefore, the calculated MASSTs would not be compromised by sea ice feedbacks.

Nevertheless, even if the sea-ice feedback has an effect, it is far from clear if its remote impact is strong enough to overwhelm the local insolation effect quantitatively. Moreover, 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 seen to be far too weak to substantially change the global mean trends[5,19]. In fact, despite continued increases in complexity, the sign and magnitude of the mid- to late Holocene global mean temperature evolution has changed very little[5,6]. In fact, the latest mid-Holocene simulations (PMIP4-CMIP6), including all known feedback processes, suggest even greater Holocene warming than previous versions[6], thereby doubling down on the 'Holocene temperature conundrum'.

The key takeaway here is that the efficacy of the SAT method is not hindered by sea ice feedback, or any other fast feedback process, so long as their impacts either (1) do not alter the phase of the identified apparent seasonality of the SST record or are (2) small relative to those imparted by the local insolation forcing. The same is not true of slow feedback processes, such as ice sheets and GHGs (associated with global carbon cycle), which have much longer timescales. Therefore, they can be effectively considered as forcing "external" to the coupled ocean-atmosphere system, causing the phase of the response to deviate from that of the seasonal insolation. As neither land ice nor GHGs vary substantially across the LIG, the only relevant external forcing to consider during this period is insolation.

Although Zhang and Chen[1] do not explicitly question the models, they note that using an accelerated simulation may underestimate polar warming as a consequence of not fully representing the nonlinear feedbacks associated with millennial-scale climate variability during termination 2. We note that in a 100x simulation there is ample opportunity for the near surface to respond to the forcing. This assertion is supported by the fact that the 100x simulation gives the same results as the non-accelerated TRACE results for the Holocene. Furthermore, even if early interglacial warmth was underestimated in the accelerated simulation this would impact only the amplitude of the cooling observed in SST records, not the phase.

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, i.e., proxy-proxy discrepancies. In our opinion, these results provide strong support for the hypothesis that the SST response to local insolation and/or insolation that is highly correlated with the local insolation is dominant, at least over much of the low to mid-latitudes. Nevertheless, this hypothesis requires further testing and we encourage continued investigation.

Several lines of evidence including the benthic $\delta^{18}O$ stack[20], deep and intermediate ocean cooling, ice core noble gas records of mean ocean temperature[21,22], as well as direct proxy records of subsurface temperatures from the Pacific[23] suggest cooling across the last and current interglacials apparently at odds with our compilation. However, we remind the readers that our compilation is restricted to the low to mid-latitudes (40°N-40°S), and does not reflect changes in the high latitudes. Deep and intermediate waters, which make up more than 90% of the volume of the oceans, form at the high latitudes at the coldest season of the year, and thus, arguably the evolution of deep ocean temperature may be biased toward the high latitude winter temperature rather than reflecting annually averaged global mean temperatures at the surface at orbital time scales. In fact, if less heat is being sequestered in the deep ocean, more heat will remain at the surface, potentially amplifying surface warming trends across past interglacial periods as suggested by the SAT and model results.

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