Response to Reviewers Comments (essd-2019-249)

REVIEWER #SC1 (PAOLO SCUSSOLINI)

This is a welcome work that tackles a key question that is presently still insufficiently resolved: understanding global and regional temperatures during a key instance of past warm climate. It is ideal that independent groups of researchers address the same problem with different approaches and producing comparable results, something that also addresses the hotly discussed issue of reproducibility in the sciences at large. This study parallels a number of previous efforts, and most closely the recent work of Hoffman et al (2017). The main differences with that study are, in subjective order of importance: ocean drift correction is applied; SSTs are integrated across the whole LIG; a larger sample of SST proxy records; much larger sampling of seasonal SSTs.

We thank the reviewer for their kind words and recognition of the value of this study. As Reviewer #SC1 highlights, this study provides a contribution to an important topic: the sensitivity of the Earth system to relatively high temperatures during past interglacials. In contrast to other studies, this study makes several contributions including a study into the potential role of ocean drift in reconstructing Last Interglacial temperatures, the development of a robust reconstruction of mean temperatures, the largest yet published network of quantified sea surface temperatures, and an analysis of published seasonal SSTs.

The accounting of the oceanographic footprint of the proxy records seems to me the clearest novelty introduced in this work. This is very timely, and the importance of the drift is clear as seen in the biases in Fig. 1, although I expected this to also impact the global SST estimate. The authors provide some sensitivity test on the choice of the lifespan parameter of the virtual particles, but I find this aspect somewhat incomplete, as it focused only on parameters appropriate for foraminifera. In a sensitivity test, only lifespans longer than the 30-day value adopted in the database are tested, while shorter lifespans seem plausible for coccolith-based reconstructions, which make up much of the database; the sinking speed of 200 m/day and the 30 m depth for the lifecycle may not be adequate to simulate the situation with coccoliths and other organisms smaller than foraminifera, and with phytoplankton that is confined to the photic zone. I am not expert in these organisms, but it should have been relatively easy to apply dif- ferent parameters to the main type of organisms relevant to the database (that is, if the literature suggests that these are substantially different from those used), and at least test the effect of taking unique values for the whole database when a differentiation could have been possible. Also, while this probably exceeds the scopes of this study, would it be possible to mention why a simulation of OFES with LIG boundary conditions is not contemplated, e.g., initiated with data from the coarser grid of an ocean model from a PMIP4 GCM? Maybe an idea for future work.

We thank the reviewer for their comments regarding the lifespan of different organisms. For sure, there will almost certainly be an effect from different lifespans (and sinking rates) but that is a considerable expansion in the scope of the study from this initial investigation. Our intention in this work was to explore whether the amount of drift using contemporary ocean dynamics was sufficient to cause a substantial difference in regional and global temperature estimates. In this study we find that some sectors record relatively large anomalously warm

signals, up to 3.5˚C, for example in the tropical East Pacific, the North Atlantic and South China Sea. Future work will investigate the impact of drift on different taxa for temperature reconstruction. This work would ideally also use an eddy-resolved Last Interglacial model simulation to quantify the lateral advection of sinking particles. Unfortunately, recent work by EvS and colleagues (Nooteboom *et al*., 2020, *PlosOne*), has demonstrated that palaeoclimate modelling simulations generally have insufficient spatial resolution to capture mesoscale features that are critical for modelling particle drift. We hope future modelling outputs will enable this work to be undertaken. As a result, in the revised manuscript, we have acknowledged that the drift is estimated by contemporary ocean circulation which we consider to be a reasonable first-order approximation of Last Interglacial conditions.
Reference: Nooteboom, P.D., Delandmeter, P., van Sebille, E., Bijl, P.K., Dijkstra, H.A., von der Heydt, A.S., 2020. Resolution dependency of sinking Lagrangian particles in ocean general circulation models. *PLoS ONE* 15, e0238650.

The integration of SSTs across the whole period has both advantages and pitfalls: on the one hand it makes results independent from the delicate set of choices that necessarily come with assessing age models and aligning them within and across basins on a coherent chronology; on the other hand it dismisses the millennial scale variability that is critical to understand notable climatic variability within the LIG. The authors recognize this, but I suggest that a more convincing explanation could be provided of the choice of working from the hypothesis (as in Turney and Jones 2010) of global synchronicity of peak SSTs: why is it superior to other solutions that make some use of the each record's explicit age models, what are the implications of the assumption for the results?

The reviewer is absolutely correct that it is a delicate balance resolving the numerous chronological uncertainties of individual sedimentary records with robust millennial-scale reconstructions possible in some records. Most studies rely on some form of alignment that link sequences to one or more reference records with robust chronological frameworks. As Hoffman *et al.* (2017) demonstrated, the age uncertainties remain considerable for the Last Interglacial (up to several millennia during the LIG e.g. their Fig S7). Here, the authors aligned marine records to speleothem-dated, ice core reconstructions, assuming synchronous climate changes in the records. This approach is not without its problems, however. More than half of reported Pacific marine cores (from the Northern Hemisphere) were correlated to the Antarctic EPICA Dome C dD record (page 3 of our manuscript) even though this study highlighted that the south leads the warming of the north by 1-2 millennia. The development of accurate and precise age estimates for the LIG is urgently needed to resolve the timing of global climate change but will require a considerable future international effort. We have provided a more detailed explanation of our approach on pages 3 and 4 of the manuscript. We stress we do not wish to underplay the importance of resolving millennial-scale variability in the climate evolution of the LIG but this is not the focus of this study. Here we are using the mean temperature estimates to constrain the role of thermal expansion in global sea level rise across the LIG, and also provide boundary conditions for future modelling studies investigating the impact of warming on polar ice sheets. Whilst we may sacrifice temporal control, our study does help minimise the uncertainty on zonal and global temperature averages.

Last, it is important that the results are discussed in the light of the new results on mean LIG ocean temperature based on Antarctic noble gas, in the paper by Shackleton et al. just out in January (2020; doi: 10.1038/s41561-019-0498-0). It is encouraging that the global average anomaly from the present is indistinguishable in the two studies, although one has to consider that the Shackleton et al estimate refers to the temperature of the whole ocean and not to its surface as here. What is the relationship between these two metrics at these timescales? This should be a fine opportunity to pick up the discussion on this in Shackleton et al, and see what else can be learned from the new global compilation, especially from the fact that, unlike from Hoffman et al., mean ocean temperatures don't seem here to much exceed global (or hemispheric?) SSTs. Also, it seems very important to understand how come the thermosteric implications for global sea levels are so much lower than obtained by both Shackleton et al and Hoffman et al? The latter use a relationship of 0.42-0.64 m $^{\circ}C^{-1}$ to infer a thermosteric contribution of 0.08-0.51 m. it is not clear how the authors obtained their thermosteric estimates.

We thank the reviewer for highlighting the importance of the Shackleton *et al*. paper. This was published after our submission to the journal and is now part of the discussion in our revised manuscript. As the reviewer states, the new work by Shackleton and colleagues uses noble gas measurements from Antarctic ice cores (Taylor Glacier and EPICA Dome C). The isotopic ratios in atmospheric trace gas (nitrogen, xenon and krypton) are sensitive to the mean ocean temperature via their solubility in seawater. These results suggest an early LIG peak in ocean heat content contributed 0.7±0.3 m, subsequently declining to no appreciable contribution after 127 kyr. In contrast, Hoffman et al., reported a range of 0.08 to 0.51 m for peak (early) LIG warmth centred on 125 kyr (although this is after 127 kyr reported by Shackleton et al. this is almost certainly the same event but represents the age uncertainties in the marine records). Here we have not attempted to resolve the relative timing of peak warmth but have determined the maximum temperature within the first 5 kyr of the Last Interglacial to provide an upper estimate of the contribution from thermal expansion. In the revised manuscript we have provided more detail on how we calculated the thermosteric sea level rise. In our previous submitted version of the manuscript, we followed the procedure reported by McKay et al (2011). To provide a maximum estimate of thermosteric sea level rise, we assumed our average SST warming was representative of the uppermost 700 m in the water column. Using the Thermodynamic Equation of Seawater 2010 (TEOS-10) we calculated the change in the specific volume of the upper 700 m of the ocean while holding the salinity constant, and neglecting changes in ocean area. We determined the change in the specific volume of the top 700 m of each a 10° latitude × 10° grid cell while holding the salinity constant. As the reviewer hints, it is possible that sustained warming ocean occurred below 700 m. We have therefore repeated the above analysis down to an average ocean depth of 2000 m (approximately the upper half of the ocean) and 3500 m (the whole ocean). The results for the early LIG are as follows:

700 m depth of warming: GMSL of 0.12 ± 0.10 m (uncorrected) and 0.13 ± 0.10 m (drift corrected).

2000 m depth of warming: GMSL of 0.36 ± 0.10 m (uncorrected) and 0.39 ± 0.10 m (drift corrected).

3500 m depth of warming: GMSL of 0.67 ± 0.10 m (uncorrected) and 0.72 ± 0.10 m (drift corrected).

Thus, our reconstructed SSTs suggest a mean thermosteric sea level rise of 0.08 ± 0.1 m and a maximum of 0.39 ± 0.1 m respectively (assuming warming penetrated to 2000 m depth). These estimates provide upper limits on thermosteric sea level rise. Our results are consistent with the absolute amount and timing of the contribution reported by Shackleton et al. (2020) and Hoffman et al. (2017). We have included these new results in our revised manuscript, highlighting the results from 2000 m water depth as the more likely scenario. The revised figures 5 (mean annual across the full Last Interglacial) and 6 (maximum temperatures during the early Last Interglacial) are provided below.

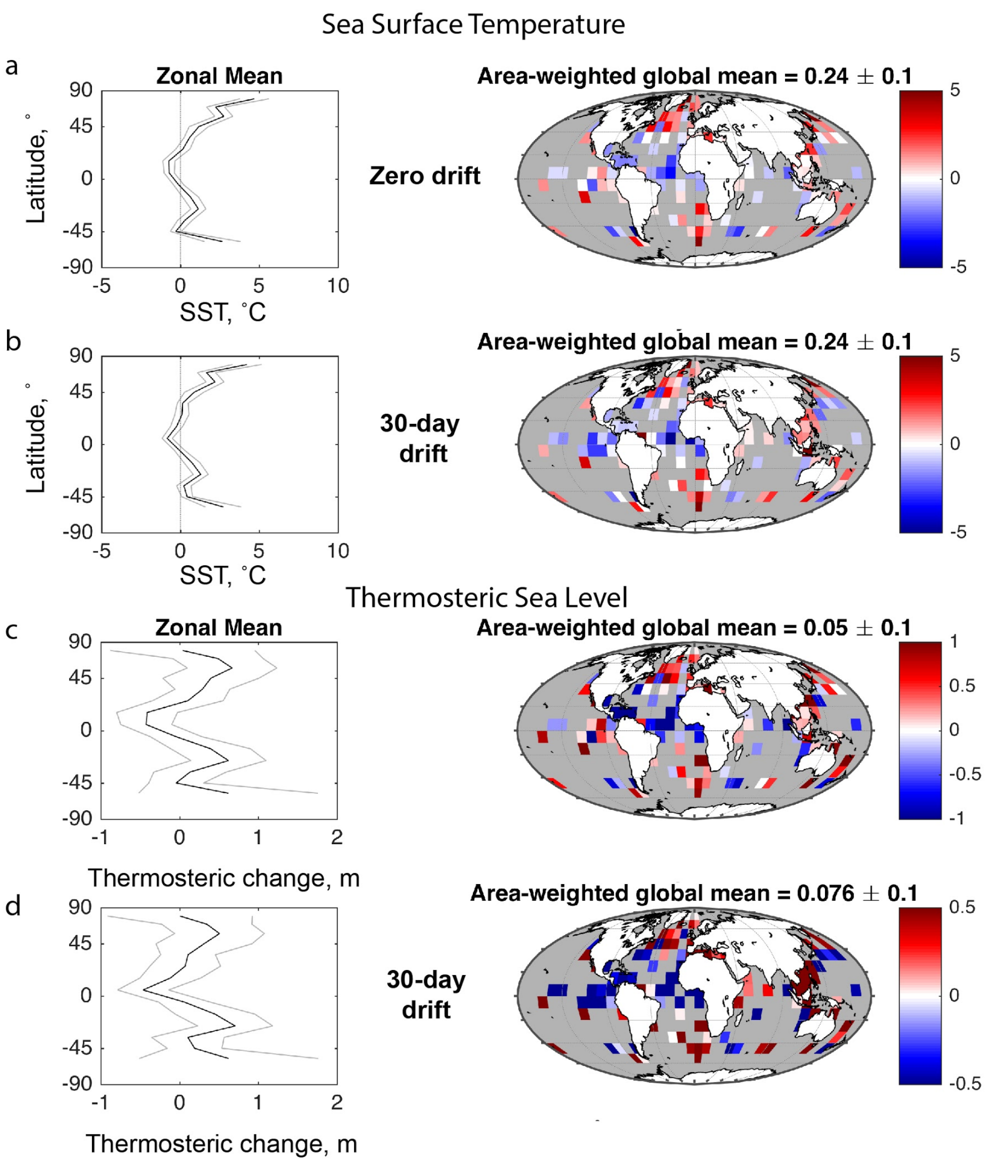

Figure 5: Global and zonal mean annual sea-surface temperature (SST) anomalies and thermosteric sea level change across the full Last Interglacial. Temperature anomalies reported as uncorrected (panels a and c respectively) and after applying 30-day (panels b and d respectively) temperature offsets arising from ocean current drift. Uncertainty for zonal average reconstructions given at 1sd. Here ocean warming is assumed to have penetrated to 2000 m depth, on average. Temperature estimates relative to the modern period (CE 1981-2010).

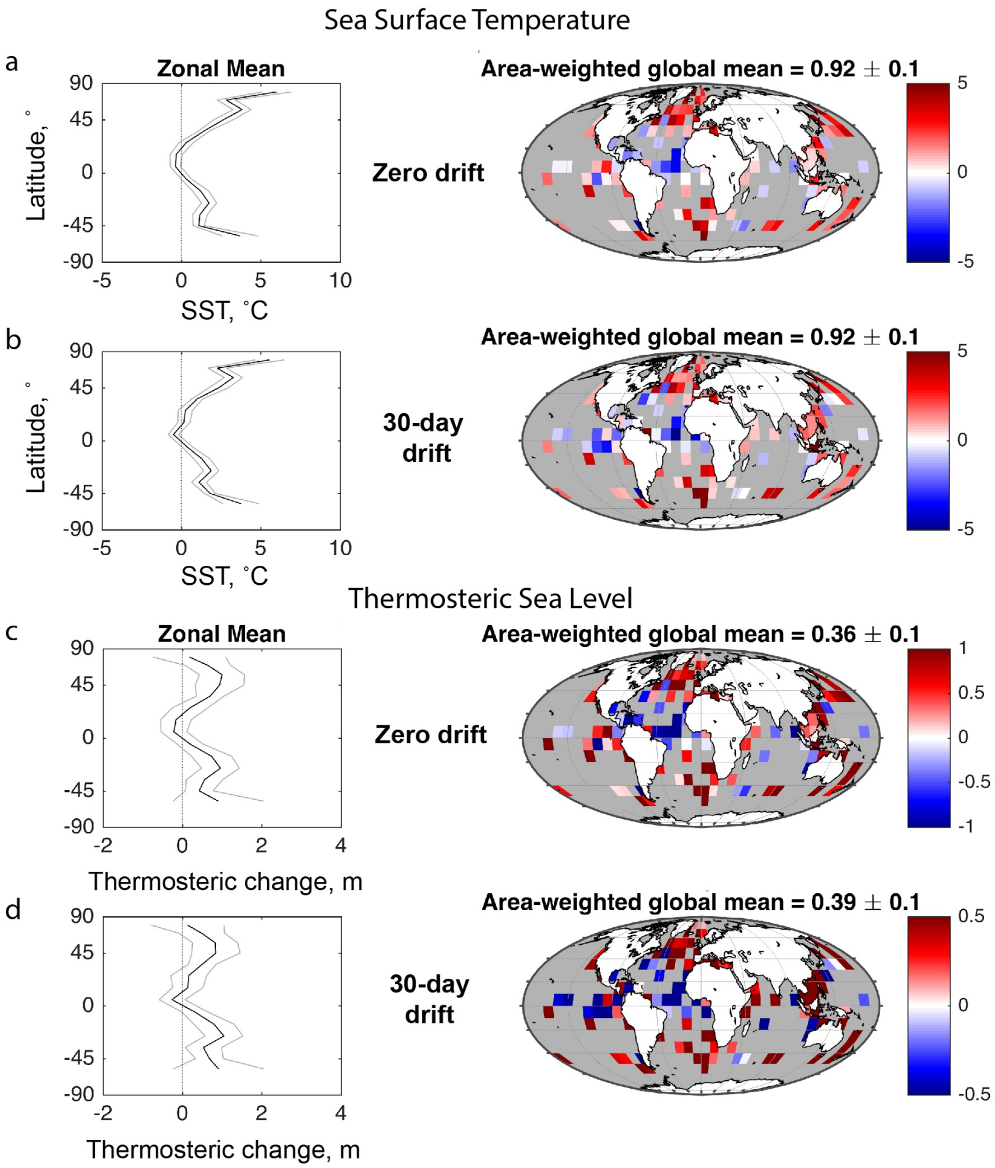

Figure 6: Global and zonal mean annual sea-surface temperature (SST) anomalies and thermosteric sea level change during the early Last Interglacial. Temperature anomalies reported as uncorrected (panels a and c respectively) and after applying 30-day (panels b and d respectively) temperature offsets arising from ocean current drift. Uncertainty for zonal average reconstructions given at 1sd. Here ocean warming is assumed to have penetrated to 2000 m depth, on average. Temperature estimates relative to the modern period (CE 1981-2010).

Our analysis allows us to identify the geographic contributions of thermal expansion to sea level. These figures show the zonal contributions of the maximum thermostatic sea level contribution were greatest at high latitudes, and were negligible (or possibly even negative) in the tropics, an observation not previously made in the literature. We have now made an explicit statement that there was an early peak contribution from thermal expansion during the early interglacial (something that was missing from the previous submission), further highlighting the important contribution polar ice melt must have made to account for the known substantial sea level height throughout the LIG.