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 ◦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.

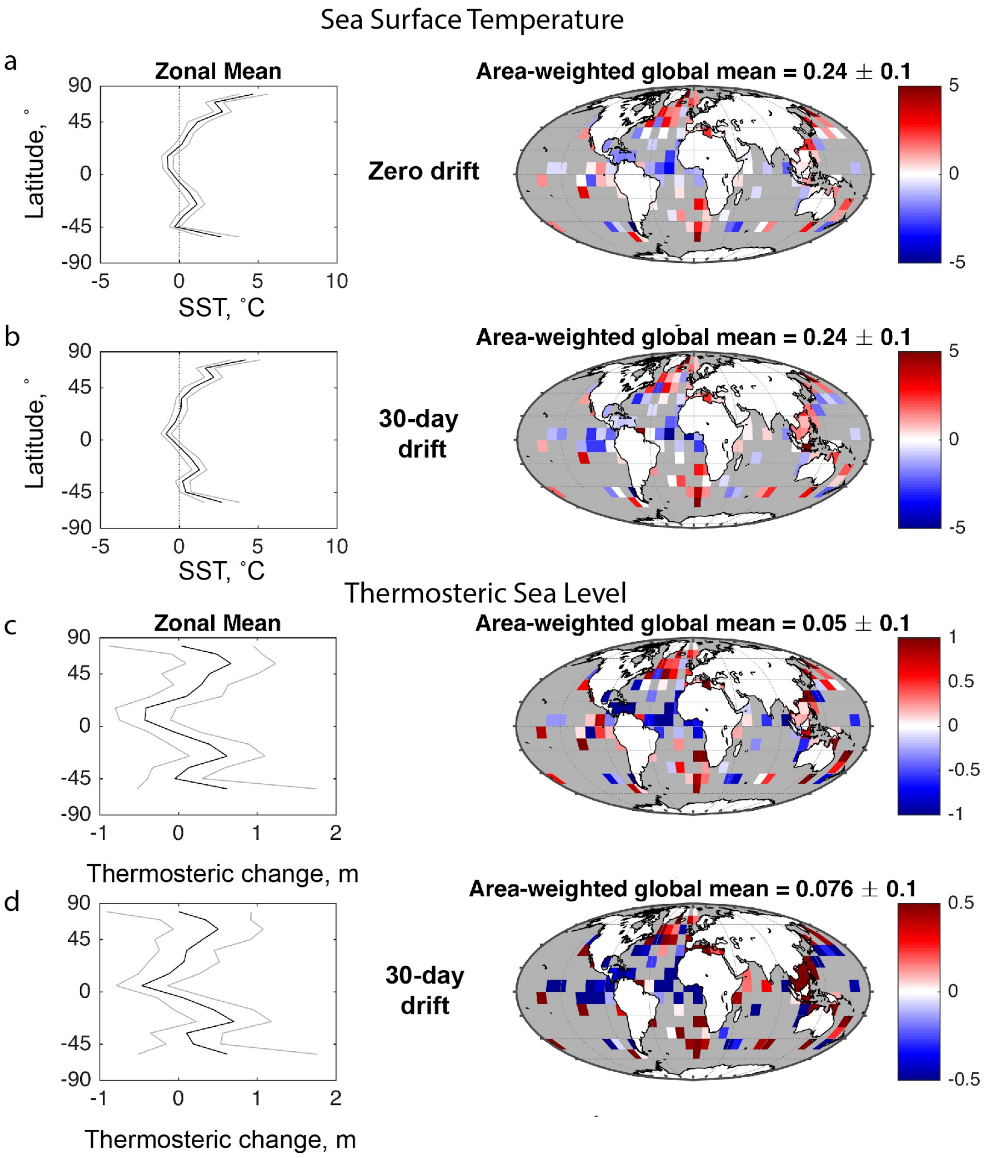


Figure 5: Global and zonal mean annual sea-surface temperature (SST) anomalies and thermosteric sea level change across the full Last Interglacial. Temperature anomalies reported as uncorrected (panels a and c respectively) and after applying 30-day (panels b and d respectively) temperature offsets arising 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).

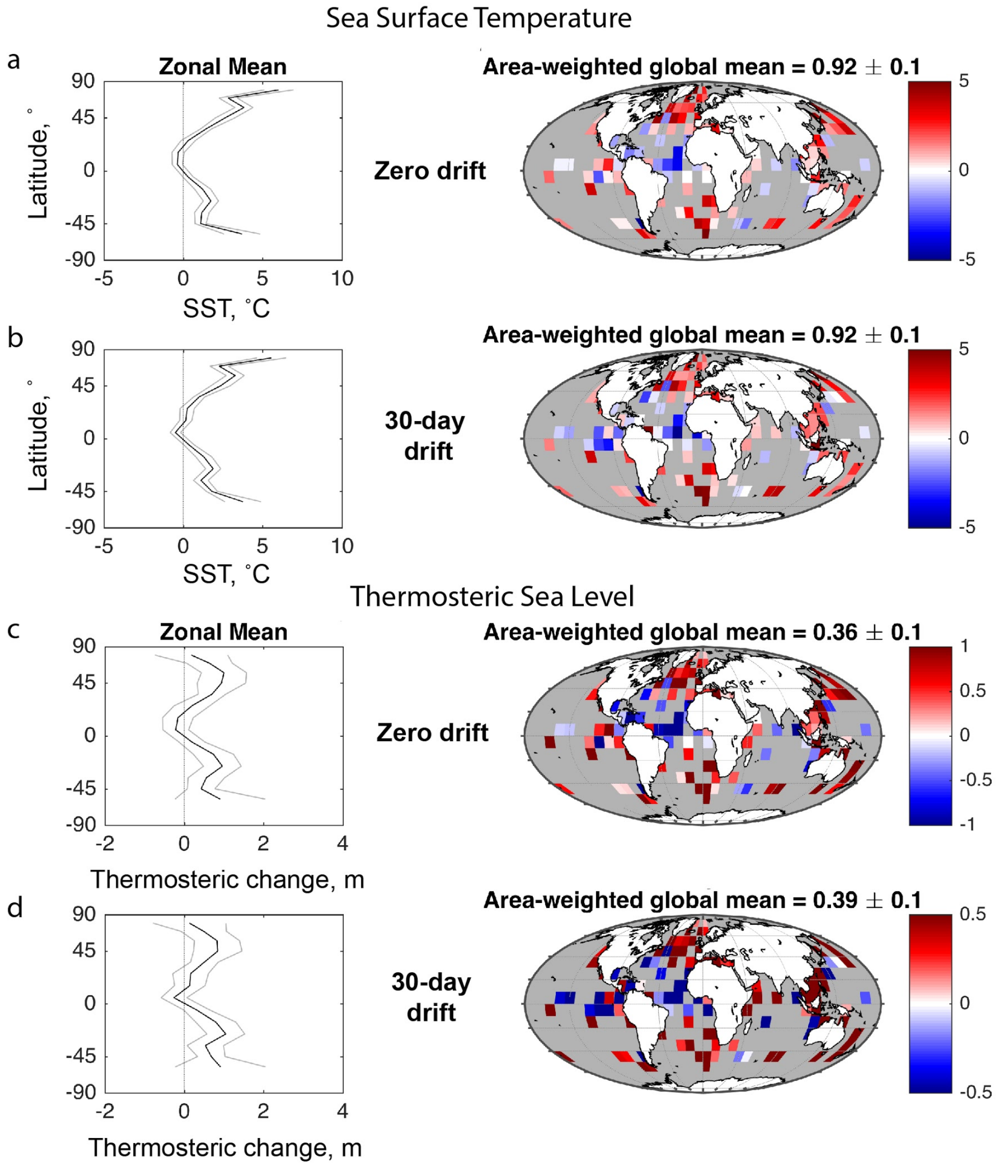


Figure 6: Global and zonal mean annual sea-surface temperature (SST) anomalies and thermosteric sea level change during the early Last Interglacial. Temperature anomalies reported as uncorrected (panels a and c respectively) and after applying 30-day (panels b and d respectively) temperature offsets 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.

Response to Reviewers Comments (essd-2019-249)

REVIEWER #1

Turney et al. 2020 present an updated version of the Turney and Jones 2010 data compilation. As such, there is nothing too exciting about it but the inclusion of many new records, the effort to quantify ocean drift for all sites, and the resulting thermal expansion contribution to sea level are useful contributions and merit publication. There are similar data compilations (especially Hoffman et al. 2017) already to be found in the literature, with the main additional contribution of this work is the inclusion of more records and the quantification of ocean drift. Still, it is useful to see slightly different approaches yielding generally similar results. The discussion of LIG sea surface temperatures is thus justifiably short, but the thermal expansion section could be fleshed out a bit more.

As Reviewer #SC1 highlights, there are several major innovations in this study. 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. As Reviewer #1 acknowledges, it is valuable that different approaches for reconstructing LIG temperatures show broadly consistent results, providing increased confidence in our understanding of the sensitivity of the Earth system to high temperatures.

Specific comments
Turney et al. 2020 note that there are issues with previous approaches with regards to the reference period for all reported data, and they go on to express their anomalies as relative to modern instrumental observations. This seems like a reasonable thing to do, but it is difficult to estimate the effect of this change in referencing on the final data. It would be helpful and I would recommend to try to quantify the difference that arises from different referencing approaches, i.e. modern instrumental, preindustrial, or 20th century. This would allow closer comparison of this compilation to the works of Hoffman et al. 2017 and Capron et al. 2014.

The use of different time periods to represent ‘present day’ has somewhat confused the literature. Whilst we appreciate the sentiment of the reviewer, there are major problems with using earlier periods (e.g. pre-industrial) to express relative temperature differences given the long known and continuing paucity of observations further back in time, particularly in remote locations e.g. Brohan et al., 2006. Such a study would need to fully quantify the uncertainties in the limited network of ‘observations’ prior to the satellite era, only increasing the uncertainties further, and would be a separate study in itself. As a result we are concerned this may further confuse the literature and are hesitant to undertake comparisons as suggested by the reviewer. We hope the Editor approves. Reference: Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B., Jones, P.D., 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. Journal of Geophysical Research 111, D12106.

As noted above, section 3.5 on thermal expansion could be substantially improved in my opinion. As already mentioned by Paolo Scussolini, the recent work of Shackleton et al. 2020 should be taken into account. Further, the methodology for computing the thermosteric contribution from sea surface data could be more detailed. It is stated that the top 700m of each grid cell is assumed to have changed according to the SST change. This seems like a fairly arbitrary depth that stems from the IPCC estimate for modern ocean warming (McKay et al. 2011). With the temperature anomaly estimates being very close to zero the volume used to calculate the thermisteric component is fairly irrelevant. Still, I would appreciate more justification or some sort of sensitivity of the final sea level numbers to the assumed ocean volume. Probably it's insignificant given the temperature dependence of the expansion coefficient, but would be interesting to see the thermosteric component if e.g. half the ocean volume warmed by the stated amount.

We thank the reviewer for their suggestion. We have expanded the discussion on the thermosteric sea level rise as Reviewer #SC1 suggested. And following on from the recommendation of this review we have included the analysis of the greater ocean depths (2000 m and 3500 m). We derived the following results:

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).

We thank the reviewer for the suggestion. We have now also expanded the discussion to include Shackleton et al. (2020) paper which was published after our submission.

Finally, I have some issues with Table 1. The column headings need clarification, e.g. which latitude band does <45◦S refer to? 23.5◦S to 45◦S, 0◦ to 45◦S or something else? Same for <50◦S. I'm not sure what the intention was with the order of the columns, but I would suggest going from the far north to the south and not switching back and forth between N and S. Furthermore, if Mean/uncorrected SST <45◦S is 0.2 and Mean/uncorrected SST <50◦S is 2.7, then the 45◦S to 50◦S latitude band must be very very warm (5+ degrees). Looking at Figure 4 or 5, this is not so. So something is off or I'm not understanding what is being shown in which case it should probably be described more clearly.

We must apologise. Looking at the table again, we realised it was confusing. The four columns in question refer to polewards of either 45˚ or 50˚ in both hemispheres. We have now made this explicit and reordered the columns as the reviewer has recommended.

Technical corrections

Line 19: I recommend spelling out +6-11m as it is done in the main text to avoid confusion.

Done.

Line 58: Buizert et al. did not measure LIG CO2 concentrations, I would suggest removing said citation.

This study did report CO2 concentrations from Taylor Glacier but we are happy to remove the citation.

Line 231: Should it say Figures 4 and 5? Line 250: delete ’enable’.
Done.

Line 292: The NEEM community paper is a pure data paper, I don’t see how that reference supports the preceding sentence.
Done.

Line 297: Buizert et al. also did not measure LIG sea level, hence that citation is inappropriate.
We apologise. This has been removed.

Line 410+: The bibliography also needs a bit of work. There are lots of links to nature.com supplementary information that should be removed and inconsistent usage of DOIs, some as full links, some as the number only.
We have edited the references to tidy them up. Sorry about this.

Response to Reviewers Comments (essd-2019-249)

REVIEWER #2

This dataset will potentially be valuable to other paleoclimate researchers and is well suited to be published in ESSD. However, I think the database would greatly benefit from more thorough presentation of the data in terms of their quality and their limitations (i.e. uncertainties therein and potential biases). For example, the data density (temporal resolution) for each record is not given or accounted for (n=? in each average SST value), the influence of outlier SST values on the LIG averages is not adequately addressed, and the spatial biases due to latitudinal/ longitudinal binning and/or lack of spatial resolution are not explored. The criteria for including records in the database need to be more rigorously and explicitly defined (were datasets rejected? how different is this compilation from the recent Hoffman 2017 compilation?).

Because we are not investigating centennial and millennial-scale variability, we were able to expand the number of records to that reported by Hoffman et al. The key criteria was that there was a minimum of three SST estimates across the LIG. In contrast, Hoffman et al. was focussed on time series data that required: 'The sample resolution ranges from centennial to <4000 years on their published age models, with a median resolution of 1100 years.' We are therefore able to report almost double the number of records to that presented by Hoffman et al. (189 vs 104 mean annual SSTs). Inevitably there are differences in the number of analyses undertaken through the different records which is dependent on the accumulation rate. In addition to the large database of temperature reconstructions, in response to the reviewer's suggestion, we now include the temporal density of the SST observations. For the error calculated for the regional and global SST anomalies, we incorporate the errors from the SST proxies (reported in the database), and the error associated with estimating regional and global SST from limited spatial coverage. To achieve this we propagated the SST errors for each measurement through each of the averaging steps (i.e. temporal to grid cell to zonal to area-weighted global) in our ocean-area-weighted average, as described by McKay et al. (2011). We used quoted error estimates for each study where reported. If not available, we applied proxy-specific error estimates. Although the impact of the spatial coverage was not explored in this study, it has been previously estimated in McKay et al., 2011. In that study, the error associated with the limited spatial range of the oceanographic proxies was estimated by calculating 1000 random 1-year global SST anomalies over the twentieth century, and comparing that to averages derived using only the paleoceanographic network available to that study. With that approach, they found no systematic biases associated with spatial network, and a 1 sigma uncertainty estimate of <0.1 degree. In this study, we've expanded the spatial network, and so it's reasonable to to consider ±0.1 degrees Celsius a reasonable, high-end estimate, making the contribution of spatial uncertainty modest in comparison to the other uncertainties in the study.

Furthermore, the uncertainties acquired by applying the ocean drift correction are not addressed, nor are other models explored or tested to demonstrate model sensitivity.

The full method of the ocean drift is provided by van Sebille et al. (2015). This approach tracks virtual particles in an eddy-resolving ocean model, the Japanese Ocean model For the Earth Simulator or OFES. In future work we would like to explore other models. In our previous work, however, we utilised the INALT01 model and found the ±1 s.d. of the INALT01, OFES and proxy distributions overlap. See figure below using two examples. We therefore consider the OFES to provide a robust estimate of possible drift in this early study.

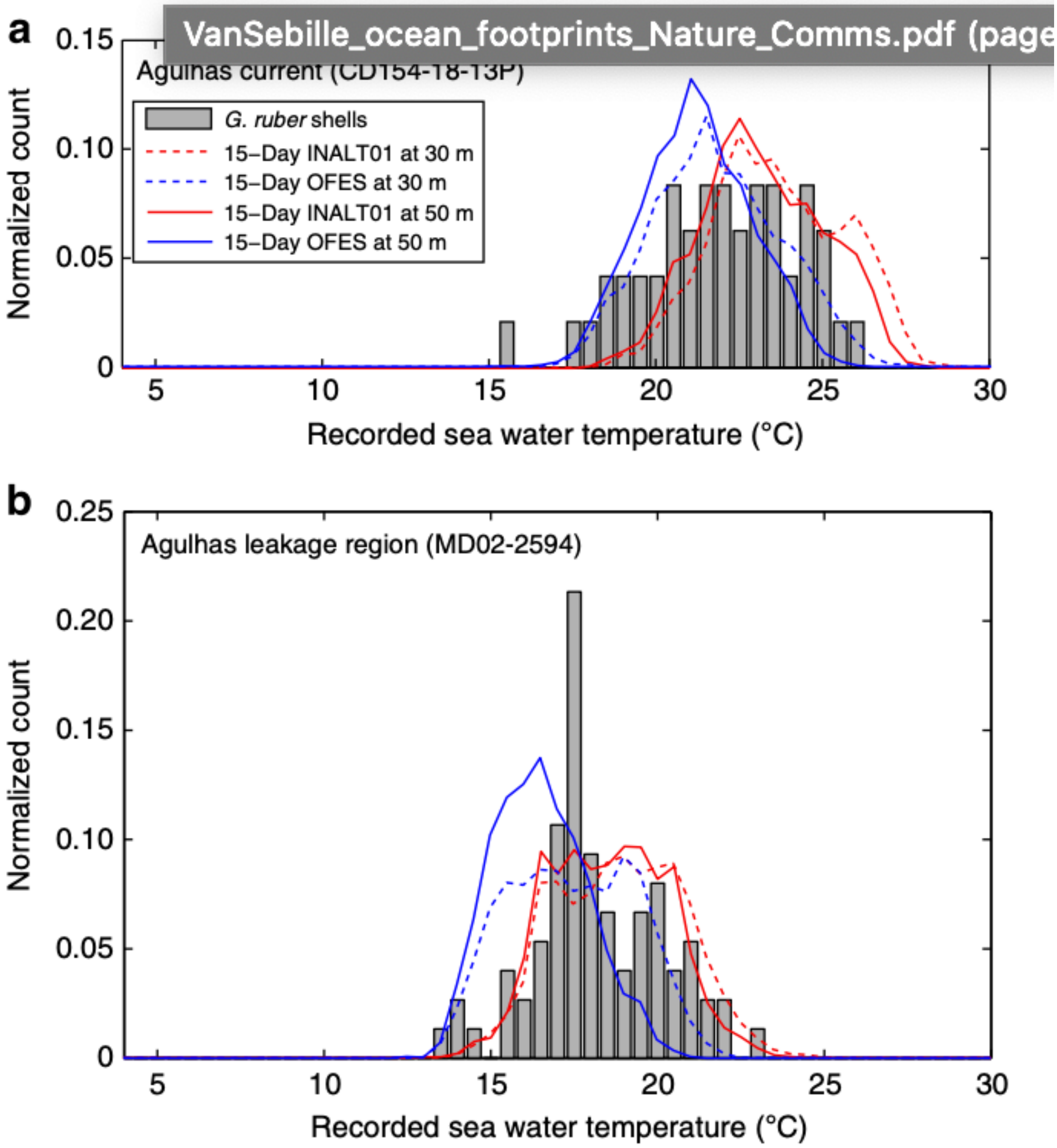


Figure from van Sebille et al. (2015): Distributions of temperature at two cores in the Agulhas region. The observed proxy temperatures (grey bars) at (a) the Agulhas Current core and (b) the Agulhas leakage core are compared with the temperature distributions for the virtual foraminifera experiments in the INALT01 model (red) and the OFES model (blue).

Reference: van Sebille, E., Scussolini, P., Durgadoo, J.V., Peeters, F.J.C., Biastoch, A., Weijer, W., Turney, C., Paris, C.B., Zahn, R., 2015. Ocean currents generate large footprints in marine palaeoclimate proxies. Nature Communications 6, 6521.

Additionally, the authors attempted to avoid complications arising from chronological alignment of proxy records by averaging over the entire LIG period; however, there is zero discussion of how the δ18O minimum was defined in each record, how well this minimum

was expressed in their 203 different sites, or to what degree errors were inherited due to local variations in benthic δ18O (even though the authors admit that such variations may temporally offset marine records by up to several millennia). In some cases, the SST records relied on proxies other than benthic δ18O to define the LIG time period, but it is nowhere explained what alternative proxies were used, how many records for which this was the case, or to what extent it might have influenced the results. The authors also do not address to what extent aligning the δ18O minima (because that is effectively what they are doing) warps the original age scales in the 203 records, except to show a very limited number of datasets (4) in Figure 2 – and there it is evident that the differences from the original age scales are substantial in some cases. Put another way, the authors need to address to what extent local variations in benthic δ18O might cause them to falsely identify the LIG time period and ultimately bias their LIG average temperature.
As the reviewer correctly identifies no one method provides an absolute age model for the last Interglacial. Even the use of d18O to define the LIG has an age uncertainty of 1-2 millennia. In some records where d18O was unavailable, other proxies used by the original authors have been used to identify the placement of the LIG; for instance, the CaCO3 content of the sediments as a measure of glacial-interglacial variability. However, it is important to note that we are not aiming to resolve centennial and millennial-scale variability through the interglacial and while we acknowledge that some individual SST estimates may not fall within the LIG or have been excluded (due to the uncertainties in the d18O for defining the interglacial) we consider the averaging of values across the full interglacial provides a robust value for each record and ultimately the regional and global reconstructions.

Finally, the manuscript would benefit from a comparison to other published LIG SST compilations (and estimates of thermosteric sea level rise) so that the reader either has some context for whether the new LIG reconstructions are reasonable, and/or why the new data are novel or represent an improvement on preexisting work. The authors also need to clarify what portion of the ocean volume their thermosteric sea level rise applies to (only surface 700 m?). It is confusing in the text as most of the authors' statements make it sound like whole ocean thermosteric sea level rise was calculated (I am still not 100 % certain).
We have now expanded the discussion of how we calculated the thermosteric sea level rise. As the reviewer correctly surmised we had originally determined this for the uppermost 700 m of the ocean. But we have now expanded the analysis to include the uppermost 2000 metres (approximately half the world's ocean) and 3500 metres. The 2000 metre depth warming provides comparable results to those reported by Shackleton et al (2020) and Hoffman et al (2017) which we have now discussed in the text.

If these comments can be sufficiently addressed, I see no reason not to publish this useful database.
We thank the reviewer for their support.

Specific comments (main text):
Line 109-110 – I cannot grasp how reliable this method was for selecting the LIG time period from the various proxy records based on what is presented in the manuscript. Were there any objective criteria for selecting δ18O minima? The authors must describe what they mean by "other complimentary proxy values," and state for how many records in the database this

applies. The authors also must state what they mean by “such a δ18O plateau is not obvious.” Were there objective criteria for electing to use alternative proxies rather than δ18O? The authors seem to think spatial variations in δ18O are not an important source of error in their approach, though they admit below that local variations can cause offsets of several millennia. Please provide more convincing arguments for this method and demonstrate to what extent these local δ18O variations are important for your analyses. We have addressed this issue in the main manuscript by explicitly recognising the uncertainties in the recognition of the d18O minima (and other proxies such as CaCO3) in each record, stating the uncertainty in this method and emphasizing the averaging of values across the full interglacial provides a robust value for each record and ultimately the regional and global reconstructions (see above).

Line 159-164 – The wording in this section is a bit too sleight of hand in my opinion. I disagree that the strategy is better than aligning records to a common temporal framework, or that it somehow circumvents the problem of generating time series data. While I agree that the authors do not interpret temporal trends (though they do distinguish the first 5 kyr from the rest of the LIG), by averaging over the selected periods with minimum δ18O the authors are in essence still aligning records to a common chronology because their analysis assumes the periods were coeval. I also disagree that this strategy is better than the example of aligning North Pacific data with EDC δD (which they state could be off by 1-2 millennia) because Figure 2 shows even larger temporal offsets of up to ~ 6 kyr (for example the end of the LIG in MD06-2986). The authors still need to present a convincing argument that aligning benthic δ18O is robust against the spatio-temporal variability between sediment cores, and then please state some estimate of the uncertainty and inherited SST error.
The age models reported in Figure 2 are from the original studies. We have not attempted to generate new age models. We are simply recognising the LIG in each record and then averaging the SST estimates over what we consider to be a common time period. The statement about the alignment of North Pacific data with the Antarctic EDC δD was to emphasise the challenges of identifying asynchronous changes between the hemispheres. Here we take a different approach to derive a first-order estimate of the temperature through the Last Interglacial, bypassing such issues.

Line 188-197 – Could you show some sensitivity analysis by running the model with different circulation? Just bracketing a plausible range would be enough to demonstrate the sensitivity. Also, I am very keen to see how the core top calibrations may change due to the ocean drift. I know the full analysis is beyond the scope of this paper, but perhaps selecting only a few core top measurements and examining how impacted they are by ocean drift would be useful for demonstrating the concept?

Unfortunately, recent work by EvS and colleagues (Nooteboom *et al*., 2020, *PlosOne*), has demonstrated that palaeoclimate modelling simulations 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 the Last Interglacial. In future work we would like to undertake a detailed study of the impact of drift on the calibration but such a study would be beyond the scope of this database. We hope by highlighting the potentially substantial impact of drift (particularly in some key locations) this may be a focus for future research for others in the community as well. 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.

Line 203 – How is the uncertainty determined? If most proxies have uncertainties of 1-2 ◦C, it seems like the uncertainty on the mean should be larger than 0.1 ◦C.
We have described this more fully in the revised manuscript.

Line 213 – So far I did not realize that you were just calculating the thermal expansion of the upper 700 m of the ocean. I highly recommend saying this in the text prior when stating your results (e.g. in the abstract and also in the introduction when discussing previous sea level work). Otherwise, the reader may think you mean thermosteric sea level due to whole ocean thermal expansion (deep-water and surface).
Done. We apologise for the confusion.

Line 296-305 – Please specify here that the authors mean thermal expansion of the top 700 m of the ocean (which I think is what they mean, though it needs to be clarified more explicitly in the text). The authors should compare their result to other estimates of the thermosteric component of LIG sea level in addition to the McKay result (Hoffman et al., 2017;Shackleton et al., 2020).

Done.

Line 303-305 – This statement is too strong without explicitly stating that the deep ocean was not considered. Readers will misinterpret it to mean whole ocean thermosteric. Or, if the deep ocean was considered (I am still unclear about whether the authors did this or not), it must be justified why SST estimates alone were used to estimate whole ocean thermosteric sea level rise and why the estimates were so low compared to other work (e.g. Shackleton 2020).

Done. We apologise for the confusion.

Figure 2 – Showing the alignment of only four marine cores is much too limited to give readers any sense for how much the 203 chronologies were distorted when the authors picked δ18O minima to delineate the LIG time period, over which they averaged the SST results. Figure 2 demonstrates that for none of the four cores shown did the LIG actually

occur during the period 129-116 kyr (on their respective age models), and in core MD06-2986 the LIG notably occurred during a span of only about 5 kyr. Can you say with confidence (or even better, demonstrate for readers) that the cores in Figure 2 represent the full range of chronological differences in the δ18O minima between all of the records? Additionally, please improve the figure resolution so that the text and traces are not blurry.

We apologise for the blurriness of the figure. We have now resolved this. The figure is for illustrative purposes and reports the chronologies for the original studies. We have not developed new chronologies for the records (as undertaken by Hoffman et al and Capron et al). Instead, we have used the d18O minima to define a common period to derive a mean temperature.

Figure 3 – This is confusing. It looks like only the modern data were run through the drift correction. I thought the correction was applied to each LIG average.

The drift correction was undertaken using a modern ocean configuration and the temperature offset applied to the average LIG estimate for each site.

Figure 4 – I recommend plotting a third panel showing the residual between the original SST and the drift-corrected SST.

We can provide this panel if the editor would like.

Table 1 – It strikes me as odd that the DJF and JJA global SST values are both negative, whereas the mean global SST value is positive. What delineated a DJF and JJA record from the other 189 records? How much overlap is there between the 92 + 99 seasonal records and the 189 annual records?

The seasonal estimates are provided in the database. Seasonal temperature estimates are challenging to provide with confidence given the seasonal biases of proxies which are likely latitudinally-dependent. As a result we consider the annual estimates to be more reliable.

Table 2 – Similar comment as above. Specific comments (regarding the Excel file):

Sheet 1 – The spatial delineations are confusing. Why do you average > 45◦ and then also > 50◦ with only 5◦ difference? Please justify.

These estimates are to provide a measure of changes in the polar latitudes. There are considerably more records polewards of 45˚ so we included both to provide a measure of the robustness of the zonal reconstructions. This is now given in the revised manuscript.

Column H - By “Jan-Dec” do you mean annual? Just say “annual” so as not to be confused with “DJF.”

Done. We apologise for the confusion.

Technical corrections:

Line 42 – “The timing and impacts. . . remain. . .” instead of “remains.”

Done.

Line 47 – Better references exist for “multi-millennial duration shifts in the Earth system took place in the past.” The ones used here appear to mostly be about Anthropocene/ future tipping points.

Done. We have replaced with more appropriate references.

Line 51 – Can you provide a reference for 129,000-116,000 years ago, if it is elsewhere defined? Otherwise state it is the authors’ definition.

Done. The reference is from Dutton et al. (2015, Science).

Line 56 – Global Mean Sea Level should not be capitalized.

Done.

Line 57 – There are better references for the observation of abrupt shifts in regional hydroclimate during the last interglacial than Thomas et al. 2015. Why not just cite cave record papers (Wang et al., 2008;Cheng et al., 2016), for example?

Done.

Line 58 – Buizert 2014 is not about CO2. Kohler 2017 is partly, but why not cite the original data? (Petit et al., 1999;Barnola et al., 1987) or (Bereiter et al., 2015) for the most recent compilation of CO2 ice core data.

This is correct but Buizert et al. do report CO2 measurements from Taylor Dome. However, we have included these other references.

Line 61 – Provide references for “considerable debate” about the contribution of sources to sea level rise.

Done.

Line 74 – Cite also (Hoffman et al., 2017).

Done.

Line 80 – Sea-Surface Temperature should not be capitalized.

Done.

Line 83 – Can you move the Mercer 1978 reference to somewhere in the middle of the sentence? At the end of the sentence it looks like it is a reference for the Paris Climate Agreement.

Done.

Lilne 117 – Does “maximum” refer to the average of the first 5kyr? I recommend changing the wording because “maximum” can be interpreted here that your means are upper limits.

This is a fair point and we have changed.

Line 121-123 – I don’t think Figure 3 should be referenced here, as it doesn’t really relate to what is said in the sentence.

Done.

Line 125-129 – Again the use of the word “maximum” could be misunderstood to mean you only used the highest values in the datasets, especially on line 126.

Done.

Response to Reviewers Comments (essd-2019-249)

REVIEWER #3 (JEREMY HOFFMAN)

Turney et al. have compiled the most comprehensive data base of sea-surface temperatures spanning the last interglaciation (LIG) to date. Their results support the conclusions of several recent studies in important ways, even given their (novel) attention to potentially confounding effects present within SST reconstructions from planktonic sources (their "ocean drift") that were largely unaddressed in previous LIG work.

Understandably there has been considerable attention to the LIG as it can serve to assess the sensitivity of important Earth systems (such as the cryosphere, which was considerably smaller than at present due to higher insolation and warmer global tem- peratures) to natural climate fluctuation in recent Earth history, potentially illuminating mechanisms currently unaccounted for or underestimated in present-day climate models.

Having a "living repository" of LIG datasets from the marine realm will do well to improve future (and ongoing) LIG model-data comparisons, as is highlighted by the authors. The accompanying article is appropriate to support the publication of this dataset. The dataset is highly useful, unique in its comprehensive nature, and functionally complete. This dataset is of extremely high quality.

We were very surprised to receive this review after the completion and closure of the review process but thank the reviewer for their opening comments.

However, Turney et al. add only marginally to the existing story about total LIG warming amplitude relative to recent climatology (their uncertainties on a global anomaly overlap with basically all previous work!) and, by their chosen study design, can't add anything to the discussions ongoing about rates, extents, and locations of warming or sea-level change at particular times within the LIG. These stories have recently been borne a bit more out of work in modeling (Clark et al., 2020, Nature - referenced below) and a new ice-core based SST reconstruction (Shackleton et al., 2020, Nature Geoscience).

We are sorry to read the reviewer's comments. There is considerable work still to be completed for understanding the impact of Last Interglacial warming on the Earth system. Here we report new innovations that complement previous work. This work includes 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 papers cited by the reviewer are important but were both published after our manuscript was submitted. In the revised manuscript we now discuss both of these studies. The paper by Clark et al provides an important analysis on the possible drivers of ice sheet melt but unfortunately restricts their model simulations of ocean temperatures to Termination 2. Here the model output suggests smaller temperatures than proxy data, highlighting the importance of extending the reconstruction further back in time. To help meet the need for future proxy-model comparisons, we have expanded on the submitted manuscript by generating late Marine Isotope Stage 6 SST estimates for records polewards of 40˚. These provide the first quantified estimates of the magnitude of the warming from the penultimate glaciation in key ocean sectors. We are now able to recognise warming patterns in different ocean sectors. The resulting figure is provided below.

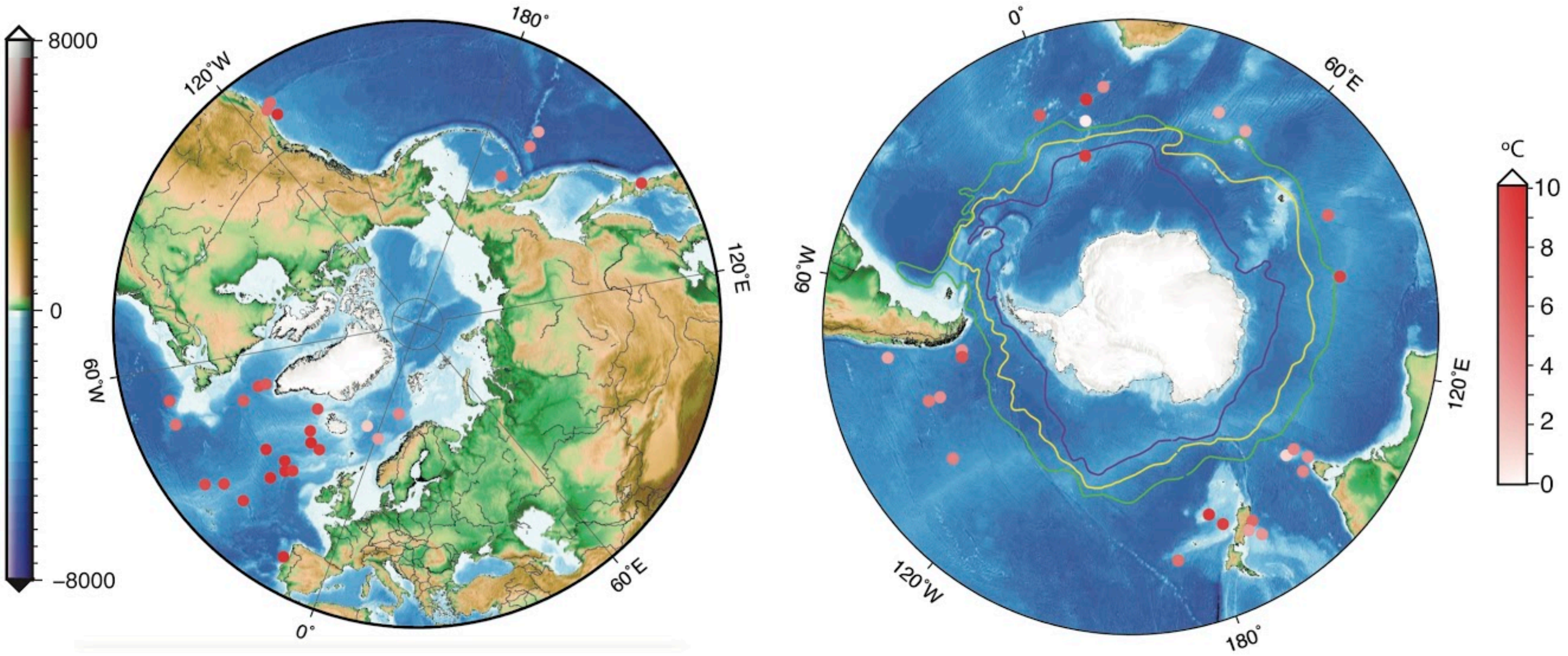

8000
0
−8000
180°
120°W
120°E
60°W
0°
60°E
0°
60°E
60°W
120°E
120°W
180°
°C
10
8
6
4
2
0

Figure showing the sea surface temperature increase from late Marine Isotope Stage 6 through to the maximum values reported in the early Last Interglacial. Most notably, where records are available, the greatest warming can be seen in the northeast Atlantic and south Atlantic, suggesting Greenland and the West Antarctic ice sheets would have been particularly vulnerable to warming in the early interglacial. We hope these new data may help with future coupled ocean-ice sheet modelling projects. The study by Shackleton et al. (2020) is described at length in the other rejoinders but will also be discussed (see other responses for more fuller consideration of our new analyses in respect to Shackleton et al.).

I am curious how the authors can work on an update to the manuscript that incorporates more discussion of the understanding of intra-LIG variability in sea level, temperature, and other variables, and as such, work to clearly justify just why the multi- millennial, LIG-long averages that they have generated help us to better understand those variables or model outputs. Are there modeling studies planned (lig127k PMIP?) that they can point to that would be targets for comparison with their new reconstruction? If the main SST magnitude conclusions aren't different from previous work, and the work can't resolve anything particularly new within the LIG time period, maybe the effort of the paper should simply focus on updating the maximum possible thermosteric component of LIG sea level and make that the centerpiece of the analysis?

The reviewer has correctly identified this is indeed the main objective of the study(!): to determine the contribution of ocean warming to thermosteric sea level rise. This was (and remains) the title of the manuscript: A global mean sea-surface temperature dataset for the Last Interglacial (129-116 kyr) and contribution of thermal expansion to sea-level change. We have now made explicit statements through the manuscript that we are not aiming to resolve millennial and centennial-scale variability given the considerable challenges of meaningfully resolving the timescale of many published records (as this reviewer has demonstrated).

Specific comments

Lines 188-197 – Are the ocean drift correction calculations estimated using the HadISST data used to calculate the anomalies from climatology as well? How are these "life trajectory" SST averages (which presumably have some sort of standard deviation or variance across space/time) then incorporated into the SST reconstruction uncertainty? Addressing this additional source of uncertainty in the SST estimates may further complicate the story that arises from the drift-corrected SSTs, but perhaps maybe only subtly. This might be worthwhile discussing or exploring in a couple of particular locations, especially those where the signals due to drift correction are large. I would suspect that as these areas have large SST gradients themselves that estimating an "average" SST across their lifetime/drift might generate some additional uncertainty in the estimated anomaly.

The temperature drift for the contemporary ocean is derived from the eddy-resolving ocean model, the Japanese Ocean model For the Earth Simulator or OFES. This temperature offset was then taken off the reconstructed SST values for each site. As the reviewer correctly identifies, there is more work to be undertaken investigating the impact of drift on the calibration of individual organisms into temperature, the role of differential lifespans and settling rates etc. but that is beyond the scope of this study. We hope our work will provide a future focus for reconstructing ocean temperatures incorporating the effects of drift.

Lines 63-68 – please add Clark, P.U., He, F., Golledge, N.R. et al. Oceanic forcing of penultimate deglacial and last interglacial sea-level rise. Nature 577, 660–664 (2020). https://doi.org/10.1038/s41586-020-1931-7 to references about ice sheet modeling during this time period, as well as amounts from particular reservoirs/sources of sea-level rise. Given these recent estimates of intra-LIG sea-level change (citations within), what does this "maximum" LIG thermosteric component tell us?

We have now expanded our discussion to include Clark et al. This was published after our study was submitted to the journal and is an important contribution to the field, exploring the impact of transient changes. We have made explicit that the maximum early LIG temperature provides an upper limit on the contribution of thermosteric sea level and that later in the interglacial, the contribution was negligible. This database implies a more substantial contribution from polar ice sheets than previously supposed, particularly later in the interglacial, something we hope will be of value to the community who wish to explore ice sheet contributions to high sea-level in the interglacial.

Discussion of the LIG-long averages and addressing the small specific considerations would, in my mind, improve the clarity of this largely incremental - however important! - addition to the body of LIG SST knowledge. I thank the authors for the opportunity to comment and look forward to reading an updated draft of the manuscript.

A global mean sea-surface temperature dataset for the Last Interglacial (129-116 kyr) and contribution of thermal expansion to sea-level change

Chris S.M. Turney[1,2*], Richard T. Jones[3]†, Nicholas P. McKay[4], Erik van Sebille[5,6], Zoë A. Thomas[1,2], Claus-Dieter Hillenbrand[7], Christopher J. Fogwill[1,8]
[1]Palaeontology, Geobiology and Earth Archives Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Australia
[2]ARC Centre of Excellence in Australian Biodiversity and Heritage, School of Biological, Earth and Environmental Sciences, University of New South Wales, Australia
[3]Department of Geography, Exeter University, Devon, EX4 4RJ, UK
[4]School of Earth and Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA
[5]Grantham Institute & Department of Physics, Imperial College London, London, UK
[6]Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, Netherlands
[7]British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[8]School of Geography, Geology and the Environment, Keele University, ST5 5BG, UK
[†]Deceased.

Correspondence to: Chris Turney (c.turney@unsw.edu.au)

Abstract. A valuable analogue for assessing Earth's sensitivity to warming is the Last Interglacial (LIG; 129-116 kyr), when global temperatures (0 to +2˚C) and mean sea level (+6 to 11 m) were higher than today. The direct contribution of warmer conditions to global sea level (thermosteric) are uncertain. We report here a global network of LIG sea surface temperatures (SST) obtained from various published temperature proxies (e.g. faunal/floral assemblages, Mg/Ca ratios of calcareous plankton, alkenone $U^{K'}_{37}$). We summarise the current limitations of SST reconstructions for the LIG and the spatial temperature features of a naturally warmer world. Because of local $\delta^{18}O$ seawater changes, uncertainty in the age models of marine cores, and differences in sampling resolution and/or sedimentation rates, the reconstructions are restricted to mean conditions. To avoid bias towards individual LIG SSTs based on only a single (and potentially erroneous) measurement or a single interpolated data point, here we report average values across the entire LIG. Each site reconstruction is given as an anomaly relative to 1981-2010, corrected for ocean drift and where available, seasonal estimates provided (189 annual, 99 December-February, and 92 June-August records). To investigate the sensitivity of the reconstruction to high temperatures, we also report maximum values during the first 5 ka of the LIG (129-124 kyr). We find mean global annual SST anomalies of 0.2 ± 0.1˚C averaged across the LIG and an early maximum peak of 0.9 ± 0.1˚C respectively. The global dataset provides a remarkably coherent pattern of higher SST increases at polar latitudes than in the tropics (polar amplification), with comparable estimates between different SST proxies. Polewards of 45˚ latitude, we observe annual SST anomalies averaged across the full LIG of >0.8 ± 0.3˚C in both hemispheres with an early maximum peak of >2.1 ± 0.3˚C. Using the reconstructed SSTs suggests a mean global 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). The data provide an important natural baseline for a warmer world, constraining the contributions of Greenland and Antarctic ice sheets to global sea level during a geographically widespread expression of high sea level, and can be used to test the next inter-comparison of models for projecting future climate change. The dataset described in this paper, including summary temperature and thermosteric sea-level reconstructions, are available at https://doi.pangaea.de/10.1594/PANGAEA.904381 (Turney et al., 2019).

1 Introduction

The timing and impacts of past, and future, abrupt and extreme climate change remains highly uncertain. A key challenge is that historical records of change are too short (since CE 1850) and their amplitude too small relative to projections for the next century (IPCC, 2013;PAGES2k Consortium et al., 2017), raising concerns over our ability to successfully plan for future change. While a wealth of geological, chemical, and biological records (often referred to as 'natural archives' or 'palaeo') indicate that large-scale and often multi-millennial duration shifts in the Earth system took place in the past (Thomas, 2016;Steffen et al., 2018;Lenton et al., 2008;Thomas et al., 2020), there are limited global datasets of such events. A comprehensive database of environmental

Deleted: -+

Deleted: -

Deleted: Each reconstruction is averaged across the LIG (anomalies relative to 1981-2010), corrected for ocean drift and with varying seasonality (189 annual, 99 December-February, and 92 June-August records).

Deleted: average across the entire LIG.

Deleted: ,

Deleted: We report mean global

Deleted: of

Deleted: 2

Deleted: 1˚C and a

Deleted: 9 ± 0.2˚C respectively.

Deleted: 01

Deleted: 13

Deleted: .

Deleted:

Deleted:

Deleted:

conditions during periods of warmer-than-present-day is essential for constraining uncertainties surrounding projected future change, including sea level rise, extreme weather events and the climate-carbon cycle. In this regard, the Last Interglacial (LIG), an interval spanning approximately 129,000 to 116,000 years ago, is of great value (Dutton et al., 2015). Described as a 'super-interglacial' (Turney and Jones, 2010;Overpeck et al., 2005), the LIG was one of the warmest periods of the last 800 kyr, experiencing relatively higher polar temperatures compared to the global mean ('polar amplification') (Past Interglacials Working Group of PAGES, 2016;Hoffman et al., 2017;Turney and Jones, 2010;Capron et al., 2017), with the most geographically widespread expression of high global mean sea level in the recent geological record (GMSL, +6.6 to +11.4 m) (Dutton et al., 2015;Grant et al., 2014;Kopp et al., 2009;Rohling et al., 2017), abrupt shifts in regional hydroclimate (Wang et al., 2008;Thomas et al., 2015), and elevated atmospheric CO$_2$ concentrations (relative to the pre-industrial period) of ~290 ppm (Köhler et al., 2017;Schneider et al., 2013;Barnola et al., 1987;Petit et al., 1999), suggesting non-linear responses in the Earth system to forcing (Steffen et al., 2018;Thomas, 2016;Dakos et al., 2008;Thomas et al., 2020). Importantly, there remain considerable debate over the contribution of sources to the highstand in global sea level (Dutton et al., 2015;Rohling et al., 2019). Previous work has suggested ocean thermal expansion contributed some 0.4 m (McKay et al., 2011), while Greenland Ice Sheet melt is estimated at some 2 m (NEEM Community Members, 2013) and melting mountain glaciers ~0.6 m (Dutton et al., 2015), implying Antarctic mass loss >3.6 m (Fogwill et al., 2014;Turney et al., 2020;DeConto and Pollard, 2016;Dutton et al., 2015;Rohling et al., 2019). Constraining the different contributions to GMSL during the LIG requires a comprehensive ocean temperature database to precisely quantify the role of ocean thermal expansion, compare to climate model-generated temperature estimates, and use these temperature estimates to drive ice sheet models (Fogwill et al., 2014;Mercer, 1978;DeConto and Pollard, 2016;Sutter et al., 2016;Hoffman et al., 2017;Clark et al., 2020).

Quantified temperature reconstruction data for the LIG are often drawn from disparate publications and repositories (usually reported alongside other Late Pleistocene data). To obtain reliable temperature reconstructions, it has until recently proved necessary to determine a global estimate of the magnitude of warming using only a selected number of "high-quality" records; the resulting temperature reconstructions of LIG temperatures ranged from 0.1 to >2˚C warmer than present (CLIMAP, 1984;White, 1993;Hansen, 2005;Rohling et al., 2008;Turney and Jones, 2010). With the ever-increasing number of quantified temperature reconstructions of the LIG reported in individual publications, it is crucial that these datasets are brought together to derive a comprehensive reconstruction of global change during the LIG. A further consideration is that in contrast to terrestrial sequences, marine records typically provide a continuous record of LIG conditions (Turney and Jones, 2010;Turney and Jones, 2011), providing an opportunity to determine the sensitivity of GMSL to Sea-Surface Temperature (SST) conditions during the interglacial (including early maximum temperatures). Given the estimated warming of 2˚C (Turney and Jones, 2010), the LIG potentially provides insights into the drivers of sea level rise and the long-term impacts under a global temperature target set out in the 2016 Paris Climate Agreement (Schellnhuber et al., 2016).

Here we present version 1.0 of the Last Interglacial SST database (Turney et al., 2019). This database builds on the previously published 2010 data compilation of (Turney and Jones, 2010), and includes substantially more records. Importantly, the micro-organisms used to determine SSTs move along with the currents and encounter a range of temperatures during their life cycle (van Sebille et al., 2015;Doblin and van Sebille, 2016;von Gyldenfeldt et al., 2000). As a result, previous workers have suggested ocean drift of micro-organisms can have a major influence on reconstructed environmental change (van Sebille et al., 2015;Monroy et al., 2017;Kienast et al., 2016;Hellweger et al., 2016;Rembauville et al., 2016;Viebahn et al., 2016;Nooteboom et al.) and potentially explains the divergence between laboratory culture and core-top calibrations (Anand et al., 2003;Müller et al., 1998;Prahl et al., 2003;Sikes et al., 2005;Segev et al., 2016;Elderfield and Ganssen, 2000), and palaeoclimate estimates and model outputs (Otto-Bliesner et al., 2013;Bakker and Renssen, 2014;NEEM Community Members, 2013;Lunt et al., 2013), including the recently recognised historic (Anthropocene) change in modern plankton communities which has major implications for calibration studies (Jonkers et al., 2019). The influence of ocean currents has not been explored (or corrected for) in previous studies of the LIG (Hoffman et al., 2017;Capron et al., 2014;Turney and Jones, 2010) and is important for obtaining correct absolute SSTs. This descriptor describes the contents of the database, the criteria for inclusion, and quantifies the relation of each record with instrumental temperature, including the estimated impact of ocean current drift on individual sites and global averages. The current database includes a large number of metadata fields to facilitate the reuse of the data and identification of key records for future investigations into the LIG. Specific criteria were developed to gather all published proxy records that meet key objective and reproducible criteria. The database will be updated yearly as newly reported records are published.

Deleted: .

Deleted:

Field Code Changed

Deleted:

Deleted:

Deleted:

Deleted: Global Mean Sea Level

Deleted:

Deleted:

Deleted:

Deleted: , abrupt shifts in regional hydroclimate (Thomas et al., 2015)…

Deleted: Buizert et al., 2014;

Deleted: , suggesting non-linear responses in the Earth system to forcing (Thomas, 2016). Importantly, there remains considerable ... [1]

Deleted:

Deleted:

Deleted:

Deleted: ; Turney et al., in press

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted: (Schellnhuber et al., 2016; Mercer, 1978)

Deleted: This database builds on the previously published 2010 ... [2]

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

Deleted:

2 Methods

2.1 Global Compilation

We have compiled a global network of published quantified SSTs using faunal and floral assemblages, Mg/Ca and Sr/Ca ratios of calcareous organisms, and $U^{K'}_{37}$ estimates across the period of record interpreted as representing the LIG. In many instances, we used the period represented by low ^{18}O values in benthic foraminifera shells (the lightest isotopic values during 90-150 kyr representing minimum global ice volume), although in some sequences, $\delta^{18}O$ values were reported and we relied on other complimentary proxies; for instance, the $CaCO_3$ content of sediments as a measure of glacial-interglacial variability (Turney and Jones, 2010;Cortese et al., 2013) (Figures 1 and 2). Whilst the age control points defining the plateaus in $\delta^{18}O$ and other proxies are not absolutely dated with chronological uncertainties of one to two millennia (Martinson et al., 1987;Lisiecki and Raymo, 2005), it is important to note that we are not aiming to resolve centennial and millennial-scale variability through the interglacial. We acknowledge that some individual SST estimates may not fall within the LIG or have been excluded (due to these chronological uncertainties) but we consider the averaging of values across the full interglacial provides a robust value for each record and ultimately the regional and global reconstructions.

It is important to recognise that we have not attempted to generate a time series of sea surface temperatures through the LIG. Previous studies have highlighted that individual site $\delta^{18}O$ changes in benthic foraminifera (for instance, during deglaciation) may be offset by several millennia as a result of local deep-water temperature and $\delta^{18}O$ seawater variations) (Govin et al., 2015;Waelbroeck et al., 2008) (Figure 2). In an attempt to bypass some of these issues, other studies have attempted alignment of marine records to speleothem-dated, ice core reconstructions (Hoffman et al., 2017) but modelled age uncertainties can be on the order of millennia (e.g. Hoffman et al. Fig. S7) while the assumed synchroneity of extra-regional changes has challenges; for instance, more than half of reported Pacific marine cores (those from the Northern Hemisphere) were correlated to the Antarctic EPICA Dome C δD (Hoffman et al., 2017), with warming in the south known to lead the north by 1-2 millennia (Hayes et al., 2014;NEEM Community Members, 2013;Kim, 1998;Rohling et al., 2019). 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 (Govin et al., 2015). Given the relatively large chronological uncertainties associated with comparing global SST time series (Hoffman et al., 2017;Govin et al., 2015;Capron et al., 2017) we have therefore not attempted to generate a time-series of changes within the LIG but instead determine average temperatures as a robust estimate of mean climatic conditions. Whilst not offering precisely-dated geochronological frameworks, the global ice minima as represented by the $\delta^{18}O$ plateau and/or associated proxy measures of interglacial conditions are sufficiently well-defined in all marine records to accommodate local deep-water temperature and $\delta^{18}O$ variations, sampling resolution and/or sedimentation rates to identify the LIG, thereby maximising the number of records that have reported quantified SSTs across the interglacial (Cortese et al., 2013;Govin et al., 2015); a minimum of three SST values across the LIG in each record were required for inclusion in our dataset. This is not to downplay the significance of millennial-scale climate variability across the LIG (Galaasen et al., 2014;Rohling et al., 2002;Tzedakis et al., 2018;Jones et al., 2017) but our approach does provide some benefits. Whilst our approach sacrifices temporal control, it does minimise the uncertainty on zonal and global temperature averages.

To quantify the temperature difference between the LIG and present day, we do not compare the LIG estimates to the relatively poor observational coverage of earlier periods, including the nineteenth century (pre-industrial) (Hoffman et al., 2017) or the long-term annual means calculated from 1900-1997 (Capron et al., 2014), both of which have considerable uncertainties given the limited network of 'observations' prior to the satellite era (Brohan et al., 2006;Huang et al., 2020). Here instead we report SSTs expressed as anomalies relative to global 'modern' instrumental and satellite observations across the period 1981-2010 obtained from HadISST (Rayner et al., 2003). Each LIG temperature record is linked to at least one literature source, the citation of which includes author(s), year of publication and typical archiving information (e.g. journal, volume, issue, pages, publisher and place of publication). Where multiple temperature estimates have been published over time from the same site, we chose the most recent publication for inclusion in the database (so long as the data were not flagged as erroneous) (Figure 3). Note that alkenone proxies are interpreted as providing annual SST estimates.

Here we use the mean temperature estimates to constrain the role of thermal expansion in global sea level rise across the LIG and provide boundary conditions for future modelling studies investigating the impact of warming on polar ice sheets. To determine the greatest possible contribution of warming to ocean thermal expansion and ice sheet melt, we used the published age models to identify the maximum annual SST within the first 5 kyr of the LIG (i.e. 129-124 kyr). For the purposes of this sensitivity analysis, the maximum temperatures were assumed to be synchronous globally, a scenario we recognise as unlikely but does provide an upper limit for warming in

Deleted: such a

Deleted: plateau is not obvious

Deleted: proxy values interpreted

Formatted: English (UK)

Deleted: representing

Formatted: English (UK)

Deleted: conditions

Deleted:

Moved (insertion) [1]

Moved (insertion) [2]

Deleted: (Figures 1 and 2).

Moved down [3]: Note that alkenone proxies are interpreted as providing annual SST estimates.

Deleted:

Deleted: . Here instead we report 189 maximum and mean annual SST estimates averaged across the LIG and

Formatted: English (AUS)

Moved (insertion) [3]

Formatted: English (AUS)

Moved (insertion) [4]

the 'early' LIG. To provide an upper estimate on the magnitude of warming in polar waters over the deglaciation, we also report here the difference between late Marine Isotope Stage 6 mean SSTs (~140-135 kyr) and the maximum early LIG SSTs for ocean cores in the mid to high-latitudes. To calculate the anomaly relative to present day, we utilise SSTs from the nearest 0.5˚ latitude x 0.5˚ longitude averaged across the period 1981-2010 (Rayner et al., 2003). For the uncertainties calculated for the regional and global SST anomalies, we incorporate the uncertainties from the proxies (reported in the database), and the uncertainties associated with estimating regional and global temperatures from limited spatial coverage. To achieve this we propagated the SST uncertainties for each measurement through each of the averaging steps (i.e. temporal to grid cell to zonal to area-weighted global) in our ocean-area-weighted average (McKay et al., 2011). We used quoted uncertainty estimates for each study where reported; if not available, we applied proxy-specific uncertainty estimates. Although the impact of the spatial coverage was not explored in this study, it has been previously estimated using the same approach (McKay et al., 2011). In that study, the uncertainty associated with the limited spatial range of the oceanographic proxies was estimated by calculating 1000 random one-year global SST anomalies over the twentieth century, and compared to averages derived using only the palaeoceanographic network. No systematic biases were identified with a 1σ uncertainty estimated to be <0.1˚C. In this study, we have expanded the spatial network, and consider ±0.1˚C to be a reasonable, high-end estimate.

The database comprises six worksheets of data comprising maximum annual temperatures during the early LIG (defined here as the maximum temperature reported within the first five millennium of the LIG; 129-125 kyr), mean annual temperature, the Marine Isotope Stage 6/5 SST difference, December to February temperature (DJF; Northern Hemisphere winter and Southern Hemisphere summer), June to August temperature (JJA; Northern Hemisphere summer and Southern Hemisphere winter), and summary statistics (see Supplementary Information):

- The early maximum and mean annual SST dataset comprises 189 marine sediment and coral records from latitudes spanning from 55.55˚S (radiolaria assemblage transfer function reconstruction obtained from site V18-68) (CLIMAP, 1984) to 72.18˚N (planktonic foraminifera assemblage modern analogue technique from site V27-60) (Vogelsang et al., 2001)
- The mean December-February SST dataset comprises 99 marine sediment records from latitudes spanning from 61.24˚S (diatoms transfer function reconstruction obtained from site PS58/271-1) (Esper and Gersonde, 2014) to 72.18˚N (planktonic foraminifera assemblage modern analogue technique from site V27-60) (Vogelsang et al., 2001).
- The mean June-August SST dataset comprises 92 marine sediment records from latitudes spanning from 54.55˚S (radiolaria assemblage transfer function reconstruction obtained from site V18-68)(CLIMAP, 1984) to 72.18˚N (planktonic foraminifera assemblage modern analogue technique from site V27-60) (Vogelsang et al., 2001).

In total, the Last Interglacial SST database comprises a total of 203 unique sites described in 100 publications.

2.2 Ocean Drift

Crucially, modern calibration relationships are an average developed using a selected number of locations that will not necessarily capture the range of "signal drift". This drift is caused by the fact that planktic SST recorders can be transported over considerable distances in the water column before being deposited, which particularly applies to all those sites that lie under strong boundary currents or near major ocean fronts (van Sebille et al., 2015). Unfortunately, Ocean General Circulation Models (OGCMs) typically have insufficient spatial resolution to capture mesoscale features that are critical for modelling the lateral drift of particles (Nooteboom et al., 2020). To investigate the impact of drift on SST reconstructions, we therefore used contemporary ocean circulation as a first-order approximation for the LIG. Whilst we acknowledge that there was likely a weakening of the Atlantic Meridional Overturning Circulation (AMOC) during the early LIG (Shackleton et al., 2020;Turney et al., 2020;Thomas et al., 2020;Jones et al., 2017), subsequent recovery after 127 kyr appears to have established a global circulation comparable to present day as suggested by recent ocean $\delta^{13}C$ modelling results across the mid-interglacial (Bengtson et al., 2020). We performed an experiment with virtual particles in an eddy-resolving ocean model (the Japanese Ocean model For the Earth Simulator or OFES) (Masumoto et al., 2004), which has a 1/10° horizontal resolution and near-global coverage between 75°S and 75°N (van Sebille et al., 2012). Utilising the 3D velocity field of the model, we used the Parcels code (oceanparcels.org) (Lange and van Sebille, 2017) to compute the trajectories of more than 170,000 virtual planktic particles that end up at each of the sites by tracking them backwards in time, first simulating the sinking to these sites at 200 m/day and subsequently the advection at 30 m depth for a lifespan of 30 days; coral SSTs were not corrected for drift. Given the lifespan of most organisms that have been used to generate a temperature signal (Jonkers et al., 2015;Bijma et al., 1990), we consider a 30-day drift provides a reasonable estimate of the

Moved (insertion) [5]

Deleted: four

Deleted: representing

Deleted: mean

Deleted: and

Moved up [1]: It is important to recognise that we have not attempted to generate a time series of sea surface temperatures through the LIG. Previous studies have highlighted that individual site $\delta^{18}O$ changes in benthic foraminifera (for instance, during deglaciation) may be offset by several millennia as a result of local deep-water temperature and $\delta^{18}O$ seawater variations)

Moved up [2]: (Figure 2). In an attempt to bypass some of these issues, other studies have attempted alignment of marine records to speleothem-dated, ice core reconstructions (Hoffman et al., 2017) but

Deleted: the assumed synchroneity of extra-regional changes has challenges; for instance, the correlation of more than half of reported Pacific marine cores from the Northern Hemisphere to the Antarctic EPICA Dome C δD (Hoffman et al., 2017), with warming in the latter known to lead the north by 1-2 millennia (Hayes et al., 2014; NEEM Community Members, 2013; Kim, 1998; Rohling et al., 2019). Whilst not offering precisely-dated geochronological frameworks, the global ice minima as represented by the $\delta^{18}O$ plateau and/or associated proxy measures of interglacial conditions are sufficiently well-defined in all marine records to accommodate local deep-water temperature and $\delta^{18}O$ variations, sampling resolution and/or sedimentation rates to identify the LIG, thereby maximising the number of records that have reported quantified SSTs across the interglacial (Cortese et al., 2013; Govin et al., 2015); a minimum of three SST values across the LIG in each record were required for inclusion in our dataset. Given the relatively large chronological uncertainties associated with comparing global SST time series (Hoffman et al., 2017; Govin et al., 2015; Capron et al., 2017) we have therefore not attempted to generate a time-series of changes within the LIG but instead determine average temperatures across the LIG as a robust estimate of mean climatic conditions and constrain the role of thermal expansion in global sea level rise during this period. Whilst this approach sacrifices temporal control, it does reduce the uncertainty on zonal and global temperature averages. To determine the greatest possible contribution of warming to ocean thermal expansion, we also used the published age models to identify the maximum annual SST within the first 5 kyr of the LIG (i.e.

Moved up [4]: 129-124 kyr). For the purposes of this sensitivity analysis, the maximum temperatures were assumed to be synchronous globally, a scenario we recognise as unlikely but does provide an upper limit for warming in the 'early' LIG.

Moved up [5]: To calculate the anomaly relative to present day, we utilise SSTs from the nearest 0.5˚ latitude x 0.5˚ longitude averaged across the period 1981-2010 (Rayner et al., 2003).

Deleted: (Govin et al., 2015; Waelbroeck et al., 2008)

Deleted: ¶
¶

Deleted: To investigate the impact of drift on SST reconstructions for the LIG, we

Formatted: English (UK)

Deleted:) (Lange and van Sebille, 2017)

Deleted:

drift distance. Previous work has demonstrated comparable uncertainties between different models (van Sebille et al., 2015), providing confidence in the use of the OFES for the purposes of this study.

Formatted: English (UK)

During the 30-day lifespans, we recorded the temperatures along the trajectories and compared those to the local temperature at 30 m water depth at the site where the particles would end up on the ocean floor. This resulted in daily temperature anomalies along the trajectories, which were averaged through the lifespan and over the 840 virtual particles that ended up at each site, and then subtracted from the reported LIG estimates (Figure 1 and Database). With the recent recognition that core-top calibrations may be incorrect given historic changes in marine communities (Jonkers et al., 2019), it should be noted that SST proxy calibrations based on regional core-top calibrations may give an incorrect absolute value that will not be comparable to other regional reconstructions, an aspect that will form the focus of future work.

Deleted: Whilst there is evidence that Atlantic Meridional Oceanic Circulation (AMOC) was relatively strong during the LIG (Evans et al., 2007; Böhm et al., 2015), we take a conservative approach and assume a contemporary ocean circulation to correct for ocean drift.

2.3 Hemispheric and Global Calculations

Global mean SST anomalies were calculated by averaging anomalies in a 10° latitude × 10° longitude grid, then averaging globally after weighting for the area of ocean in each grid cell (Figure 5). The uncertainty calculated for global SST anomalies incorporates uncertainties in the SST proxies as reported in the original studies, which typically ranges from 1 to 2°C, and is then propagated through subsequent steps in the analysis. Additional uncertainty associated with estimating global anomalies from limited spatial coverage, and the potential impacts of age uncertainty or averaging non-synchronous data are not considered here. Consequently, the derived estimates do not capture all of uncertainty in global and zonal SST anomalies, however, the zonal consistency of the results suggest that the signal is large enough to overcome these unquantified sources of uncertainty. Furthermore, whilst some regions may exhibit substantial differences arising from drift (Figure 4), taken globally the mean annual temperature estimates are comparable (Figure 5). The new LIG SST dataset allows us to report the estimated thermosteric contribution for LIG sea levels using the method reported by (McKay et al., 2011). We use the above temperature changes to calculate the thermosteric contribution to LIG sea levels by using the Thermodynamic Equation of Seawater 2010 (TEOS-10). To provide an estimate of thermosteric sea level rise, we explored a range of scenarios where warming penetrated different ocean depths: 700 m, 2000 m (approximately the upper half of the ocean) and 3500 m (the whole ocean). We determined the change in the specific volume of the warmed water column of each a 10° latitude × 10° grid cell while holding the salinity constant and neglecting changes in ocean area. Here absolute temperature is considered, as specific volume is more sensitive to temperature changes at warmer temperatures.

Deleted:) to calculate

Deleted: top 700 m

Deleted: , following McKay et al. (2011).

Formatted: English (UK)

3 Results and Discussions

3.1 Quality Control

The Last Interglacial SST database is derived from published articles that have already been peer-reviewed. To generate the database, we undertook a comprehensive check to remove duplicate records, erroneous location information and other errors. In addition to ensuring consistency of data processing and any recalculations (for instance, sea-surface temperature anomalies relative to the period CE 1981-2010), we also checked uncertain metadata reported for individual sites, and directly communicated with selected article authors and/or other experts as part of the record-validation process.

3.2 Ocean Circulation

A challenge for the Last Interglacial is determining what influence (if any) ocean circulation had on the temperatures experienced (and reconstructed) by organisms that are used to generate SST reconstructions. Addressing this issue is an important objective of the current study but we found the magnitude of temperature offset (bias) is limited to only a few key locations (Fig. 1), with similar final reconstructions for individual sites, latitudinally-averaged and globally average temperatures (Figures 4 and 5, and Table 1). This provides an important check of our temperature recalculations. As a sensitivity test, we therefore explored virtual planktic particles that 'live' for 30 days to investigate whether a prolonged period of drift made a discernible difference (data not reported here). Only a few species have been suggested as living for a longer period of time. For instance, in laboratory experiments the planktic foraminifer *Neogloboquadrina pachyderma* sinistral has been shown to survive up to 230 days (Spindler, 1996) but this species may be an exception due to its ability to survive in sea ice (Dieckmann et al., 1991).

Deleted: 3

Using 30-days' drift to simulate the travelling time/lifespans of virtual planktic particles in the upper part of the water column, we quantified the inherited temperature signal of flora/fauna at each site in the database. The virtual microorganisms with a 30-day 'lifespan' travelled from a few tens to a few hundreds of kilometres. The temperature offsets are almost all positive in the tropical East Pacific, the North Atlantic and South China Sea, meaning that the planktic particles originated from warmer climates and hence record a higher temperature estimate than local conditions would suggest; with the opposite effect observed in the western tropical Pacific and Southern Ocean (Figure 1). The offset can be substantial – with values ranging from -6.9˚C for site MD98-2162 at 4.7˚S in the tropical West Pacific (Visser et al., 2003) and up to 3.5˚C in site RC13-110 on the Equator (Pisias and Mix, 1997) – with the largest changes associated with boundary currents and major ocean fronts. Intriguingly, these values are comparable to the difference previously reported for Mg/Ca foraminifera core-top calibration with those obtained from laboratory-cultured Mg/Ca calibrations (Elderfield and Ganssen, 2000;Hönisch et al., 2013). Both the uncorrected and 30-day drift temperatures are provided in the database. These temperature reconstructions led to statistically indistinguishable global temperature (and thermosteric sea level change; Figure 5). Users of the database are therefore able to use either the authors' original sea-surface temperature determinations or our drift-corrected estimates, as required.

3.3 Proxy and Seasonal Effects

To evaluate potential biases in our analysis, we further subsampled our database by proxy type (Figure 4). The large network of sites and proxies do not appear to demonstrate any significant offset in annual reconstructions (at least within the uncertainty of the reconstructions), although there is a tendency for alkenone temperatures to be at the upper end of the range, implying there may be a seasonal bias, as reported previously (Hoffman et al., 2017). Importantly, we also compiled seasonal quantified temperature estimates that have been reported as the seasonal warmest or coolest months in the year (taken here to represent June-August and December-February depending on the hemisphere being considered). Our result suggests that any bias, if real, is smaller than the uncertainties at the global or zonal level reported here. Intriguingly, the warmest month estimates for the high latitudes in both hemispheres have more muted warming than the mean annual estimates while the low to mid latitudes exhibit considerably cooler estimates (Table 1). In contrast to the alkenone estimates for the annual estimates, the more muted response of foraminifera, radiolaria and diatoms for the seasonal reconstructions implies they are influenced by a larger part of the seasonal cycle. We therefore consider that seasonal reconstructions should be treated as conservative estimates of temperature for the LIG.

3.4 Average and Early Temperatures during the Last Interglacial

We find global average annual temperatures across the full duration of the LIG were only marginally warmer than present day. We derive a global mean annual temperature anomaly of 0.2 ± 0.1˚C, the same value obtained after correcting for drift (Table 1). These values, however, mask considerable zonal differences, with significantly cooler mean annual uncorrected temperatures (i.e. not corrected for drift) within 23.5˚ of the equator (-0.3 ± 0.2˚C) and amplified warming polewards (Figure 5). Ideally, we would have a dense network of records in the mid- to high-latitudes for investigating the impact of warming surrounding polar ice sheets but unfortunately the number of sites and their spatial distribution do appear to have an impact on the reconstructed values. Comparison of the SST anomalies poleward of 45˚ and 50˚ latitude (Table 1) shows substantial differences, most notably in the Southern Hemisphere where a large increase in zonally averaged SST occurs alongside a decrease in the number of records polewards of 50˚S (Table 1). For instance, the drift-corrected SSTs for the LIG are 0.8 ± 0.3˚C (n=13) and 2.7 ± 1.1˚C (n=3) polewards of 45˚S and 50˚S respectively. It should also be noted that whilst the Northern Hemisphere polar estimates are similar for both latitudinal ranges, the majority of sites are in the North Atlantic, with limited representation in the Pacific Ocean. We therefore recommend that when considering mid- to high-latitude zonal SST averages, the values derived from records polewards of 45˚ are more likely robust but acknowledge these may be conservative estimates (with considerably larger warming further to the south). We therefore estimate uncorrected 'polar' warming in the Northern Hemisphere to be 2.0 ± 0.4˚C, and in the Southern Hemisphere, 0.2 ± 0.3˚C (Table 1). Correcting for drift decreased the northern estimate to 1.5 ± 0.4˚C and increased in the south to a mean annual SST to 0.8 ± 0.3 ˚C.

The maximum temperatures of the early LIG were up to 0.9 ± 0.1˚C warmer than 1981-2010, regardless of whether the values were corrected for drift (Table 1 and Figure 6). Similar to the mean SSTs of the LIG, there appears to have been considerable zonal differences in the uncorrected values: 0.1±0.2˚C within 23.5˚ of the equator, 3.2 ± 0.4˚C polewards of 45˚N, and 1.5 ± 1.1˚C polewards of 45˚S. After correcting for drift, the estimated SST in the north changed to 2.8 ± 0.4˚C and in the south, to 2.1 ± 1.1˚C. The latter estimate from the Southern Hemisphere is ~2˚C (relative to 1981-2010), potentially providing an important constraint for future Antarctic ice-sheet model simulations for the LIG. These data support previous work which have reported substantial polar temperature amplification during the LIG (Overpeck et al., 2006;Mercer, 1978;Mercer and Emiliani, 1970). The global temperature pattern closely follows insolation changes across this period, during which the Earth's greater eccentricity led to reduced radiation over the equator and more intense high latitude spring-summer insolation (Figure 2) (Overpeck et al., 2006;Hoffman et al., 2017). Comparison to Marine

Deleted:

Deleted: enable

Deleted: at least

Deleted: of 50˚N (2.8 ± 0.4˚C) and 50˚S (2.7 ± 1.1˚C) (Table 1); correcting for drift only influenced the estimate the northern estimate, reducing the mean annual SST to 2.3 ± 0.4˚C (from 2.8˚C). South of 50˚S we find the lower bounds of the mean annual warming to be 0.5˚C (at the 2σ range limit).

Deleted: 8

Deleted: 50˚N

Deleted: 3.7

Deleted: 50˚S. Only the northern polar estimate was significantly impacted by

Deleted: reducing

Deleted: to 3.2 ± 0.4˚C. We find south of 50˚S

Deleted: low range end of early maximum warming to be 1.5˚C (at

Deleted: 2σ range limit

Field Code Changed

Deleted:

Deleted:

Field Code Changed

Deleted:

Deleted: .

Isotope Stage 6 SSTs appears to show the greatest warming in the northeast Atlantic and south Atlantic (Figure 7), suggesting Greenland and the West Antarctic ice sheets would have been particularly vulnerable to warming in the early interglacial (Clark et al., 2020;Turney et al., 2020;Dutton et al., 2015;Mercer, 1978) though we cannot resolve the relative timing of mass loss in this analysis (Rohling et al., 2019;Hayes et al., 2014). Recent work suggests the earliest warming took place in the Atlantic (and Indian) Ocean sectors of the Southern Ocean (Chadwick et al., 2020), consistent with our findings. However, our observed polar warming is larger than some climate model simulations, implying the latter are failing to capture one or more key feedbacks (e.g. carbon and ice-sheet feedbacks) in the climate system (Bakker et al., 2013;Otto-Bliesner et al., 2013;Thomas et al., 2020;Clark et al., 2020).

Deleted: NEEM Community Members,

Field Code Changed

3.5 Thermal Expansion Contribution to Last Interglacial Sea Level

The LIG is characterised by higher GMSL than present day (+6.6 to +11.4 m) (Grant et al., 2014;Dutton et al., 2015;Turney and Jones, 2010;Rohling et al., 2017;Rohling et al., 2019). Here we quantified the contribution of the relatively high temperatures on global sea levels through ocean thermal expansion for warming down to 2000 m ocean depth (Table 2). We find that through the LIG, the average SSTs contribution to thermosteric sea level was negligible, approximately 0.05 ± 0.10 m uncorrected for drift and 0.08 ± 0.10 m corrected for drift, consistent with a recent reconstruction of near-modern global ocean heat content and negligible thermosteric sea level rise (Shackleton et al., 2020). But for the early LIG (129-124 kyr), we obtained a maximum possible contribution of thermal expansion to GMSL of 0.36 ± 0.10 m (uncorrected) and 0.39 ± 0.10 m (drift corrected). The quantified estimates are comparable to a previously reported value of 0.4 ± 0.3 m (McKay et al., 2011) which used the same methodology as here but a smaller network of SST records. However, we should recognise that the depth of ocean warming is uncertain, and could even have extended deeper than 2000 m. If we assume warming penetrated the full ocean depth (down to 3500 m), we obtained a maximum early LIG thermosteric sea level rise of 0.67 ± 0.10 m (uncorrected) and 0.72 ± 0.10 m (drift corrected) (Table 2). The recently reported early LIG (~129 ka) peak in global ocean heat content reconstructed from isotopic ratios in atmospheric trace gases has determined a maximum thermal expansion of 0.7±0.3 m (Shackleton et al., 2020). Consistent with these estimates, a recent modelling-proxy estimate proposed a range of 0.08 to 0.51 m for peak LIG warmth centred on 125 kyr (Hoffman et al., 2017) (although this is later than the peak in global ocean heat content, this is effectively the same event but represents the age uncertainties in the marine records). Together, these studies suggest ocean warming likely penetrated to a depth of between 2000 and 3500 m, and that up to ~0.7 m of thermosteric sea level rise occurred during the early interglacial peak in temperatures. Importantly, the sustained high global sea levels across the LIG and the limited role of warming on thermal expansion implies a greater contribution from ice sheets, mountain glaciers, permafrost and hydrological change. With the greatest warming relative to Marine Isotope Stage 6 in Atlantic basin (Figure 7), our results are consistent with previous studies suggesting substantial mass loss from Greenland and the West Antarctic Ice Sheet early in the Last Interglacial (Clark et al., 2020;Turney et al., 2020;Dutton et al., 2015;Mercer, 1978;Hayes et al., 2014;Rohling et al., 2019).

Deleted:

Deleted:

Deleted: Buizert et al., 2014;

Deleted: (Table 2). We find that through the LIG, the average SSTs contributed approximately 0.00 ± 0.10 m (uncorrected for drift) and up to 0.01 ± 0.10 m (corrected for drift). For

Deleted: 12

Deleted: 13

Deleted: Our

Deleted: considerably less than the

Deleted: upper limit

Deleted: Over the LIG, the contribution of thermal expansion to global sea level can be effectively considered negligible, implying a greater contribution from ice sheets, mountain glaciers, permafrost and hydrological change.

Formatted: English (AUS)

4 Data Availability

The Last Interglacial SST database is provided as an Excel workbook in Supplementary Information and on the PANGAEA Data Publisher at https://doi.pangaea.de/10.1594/PANGAEA.904381 (Turney et al., 2019); the data is also available on the NCEI-Paleo/World Data Service for Paleoclimatology at https://www.ncdc.noaa.gov/paleo/study/26851. This release comprises a single Excel file, tab delimited. We welcome contributions from authors of additional or clarifying information. These will be incorporated into any subsequent iteration of the database. When using data in this compilation, the original data collector(s) as well as the data compiler(s) will be credited. Given the typically large uncertainties in the absolute dating of each individual record, no attempt has been made to develop individual time series, and only mean values across the Last Interglacial have been compiled. For simplicity we record the 1σ (68%) confidence interval in the site temperature reconstructions. The inclusion of key metadata allows users to interrogate individual records for their own appropriate screening criteria.

Deleted: enables

5 Conclusions

During the Last Interglacial (LIG; 129-116 kyr), global temperatures were up to 2˚C warmer than present day with marked polar amplification and global sea levels between 6.6 and 11.4 m higher than present day, offering a powerful opportunity to obtain key insights into the drivers of future change (a so-called 'process analogue'). The contributions of different sources to the LIG sea level highstand remain highly uncertain, however. As a result of

Deleted: remains

relatively warmer surface temperatures, ocean thermal expansion has previously been estimated to have contributed 0.4 ± 0.3 m. To more precisely constrain this contribution to global mean sea level we report a new comprehensive database of quantified SSTs estimates derived from faunal and floral assemblages, Mg/Ca and Sr/Ca ratios of calcareous organisms, and $U^{K'}_{37}$ estimates from records spanning 55.55˚S to 72.18˚N. Here we report maximum annual SSTs during the early interglacial (129-124 kyr) and mean annual SSTs through the LIG (129-116 kyr; n=189 sites) alongside mean December-February (99 records) and June-August (92 records) SST values. Temperatures are reported as anomalies relative to the period CE 1981-2010. To estimate the temperature footprint arising from ocean circulation we also report SST anomalies corrected for 30-day drift, to simulate the travelling time/lifespans of virtual planktic particles in the upper part of the water column. Our reconstruction suggests an early LIG maximum global mean annual SST of 0.9 ± 0.1˚C and an average warming across the LIG of 0.2 ± 0.1˚C. However, these values are strongly driven by polar warming of several degrees, with little to no warming in the tropics. We find the influence of warming on ocean thermal expansion to have had a limited influence on global mean sea levels across the full LIG, but with a likely range of between 0.39±0.1 m and 0.72±0.10 m during the early interglacial. Our findings therefore imply a relatively greater contribution from ice sheets, mountain glaciers, permafrost and hydrological change to LIG global sea level, likely driven by polar amplification of temperatures. An improved network of high-resolution, well-dated and quantified LIG climate reconstructions (particularly in data-sparse locations) will enable precise integration of ice sheet, marine and terrestrial records to better understand Earth system responses to high-latitude warming. The Southern Ocean and North Pacific are regions where major knowledge gaps currently exist.

Deleted: have calculated

Deleted:) are reported (

Deleted: negligible

Deleted: ,

Deleted: an upper maximum contribution

Deleted: 13 ±

Deleted: .

Deleted: of

Deleted: during the LIG

Deleted: We hope this database may provide a springboard for future studies that can bring

Deleted: bear new geochronological methods (e.g. tephra)

Deleted: constrain the age models of individual sequences to sub-millennial uncertainty, something

Deleted: not possible for most reported marine sequences.

Supplement. The supplementary figures and version 1.0 of the database (Excel file) can be accessed via the *Earth System Science Data* discussion page of this manuscript.

Author contributions. RTJ and CSMT conceived the research; CT, NPM, EvS, and ZT designed the methods and performed the analysis; CT wrote the paper with substantial input from all authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. It is with great sadness that our close friend and colleague Richard T. Jones was not alive to see the publication of this study. Without Richard this work would not have been possible. He is terribly missed. CSMT and CJF were supported by their Australian Research Council (ARC) fellowships (FL100100195 and FT120100004). We would also like to acknowledge the important role of the International Ocean Discovery Program (IODP), the Australian and New Zealand International Ocean Discovery Consortium (ANZIC), and the previous scientific ocean drilling programs, the results from which underpin this study and without whom this analysis would not have been possible. We are grateful to the four reviewers and editor for helping improve the first draft of this manuscript.

Deleted: sorely

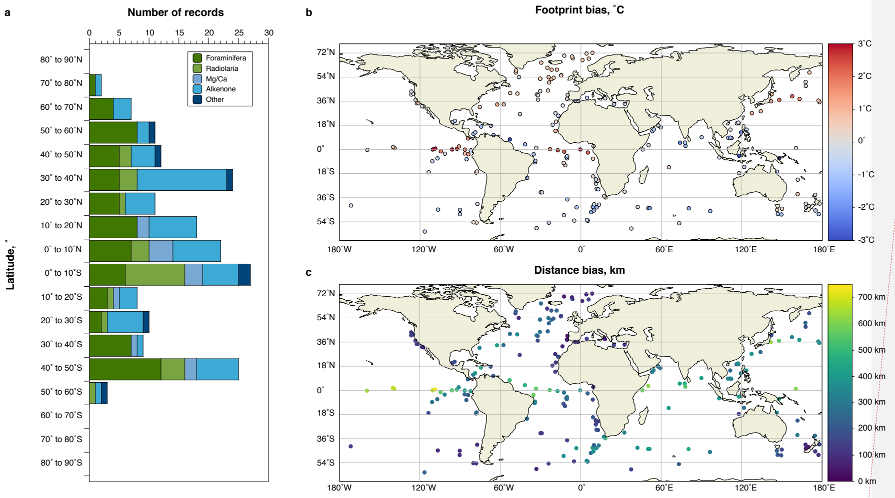


Figure 1: Last Interglacial proxy-based annual sea surface temperature dataset and modelled inherited signal. Histogram showing the number of Last Interglacial records of annual sea surface temperature binned by 10° latitude (panel a) with virtual microfossil temperature offsets defined as the difference between along-trajectory recorded temperatures and local temperatures (panel b) and distance (panel c) travelled in the Japanese Ocean model For the Earth Simulator (OFES; run between CE 1981 and 2010) determined for 30-day 'lifespans'(van Sebille et al., 2015).

Deleted: Section Break (Next Page) ... [3]

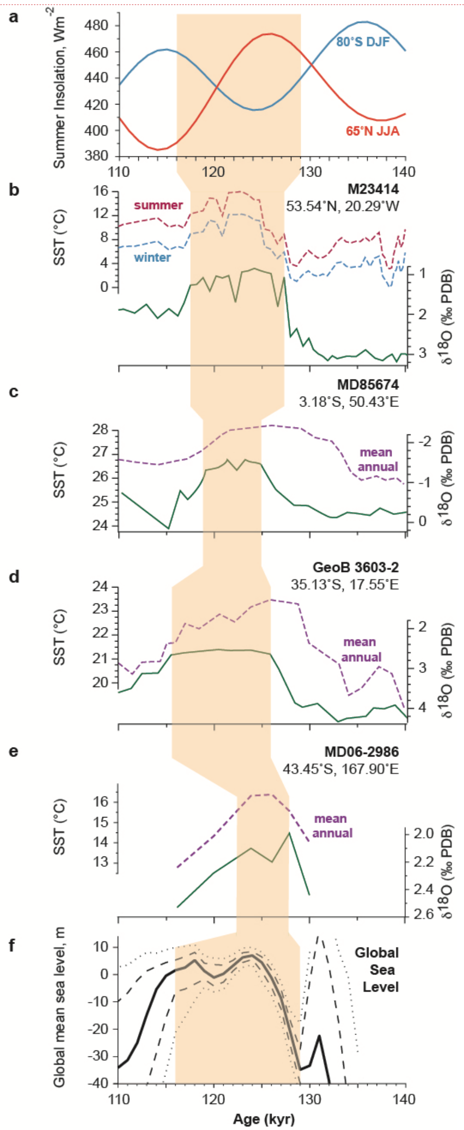
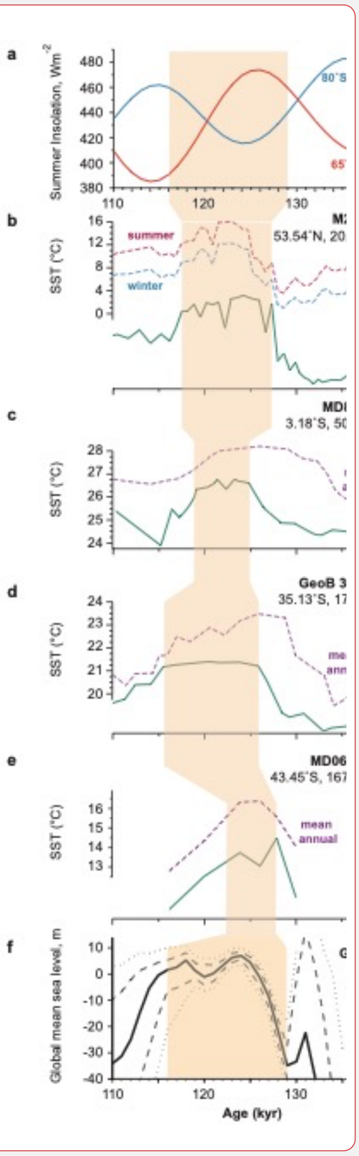


Figure 2: Relationships between δ^{18}O plateau and sea surface temperatures and environmental changes across the Last Interglacial. (a) Insolation changes calculated from ref. (Laskar et al., 2004). Sea surface temperatures (dashed purple lines) across the Last Interglacial (light orange shading) compared to the benthic foraminifera δ^{18}O (solid green lines) for selected sites in different ocean basins: (b) M23414 (North Atlantic) (Kandiano et al., 2004), (c) MD85674 (equatorial Indian Ocean) (Bard et al., 1997), (d) GeoB 3603-2 (southern Indian Ocean) (Schneider et al., 1999), and (e) MD06-2986 (southern Pacific Ocean) (Cortese et al., 2013). (f) The probabilistic reconstructed global sea level curve is reported by (Kopp et al., 2009); heavy lines mark median projections, dashed lines the 16th and 84th percentiles, and dotted lines the 2.5th and 97.5th percentiles.



Deleted:

Deleted: Kopp et al. (2009)

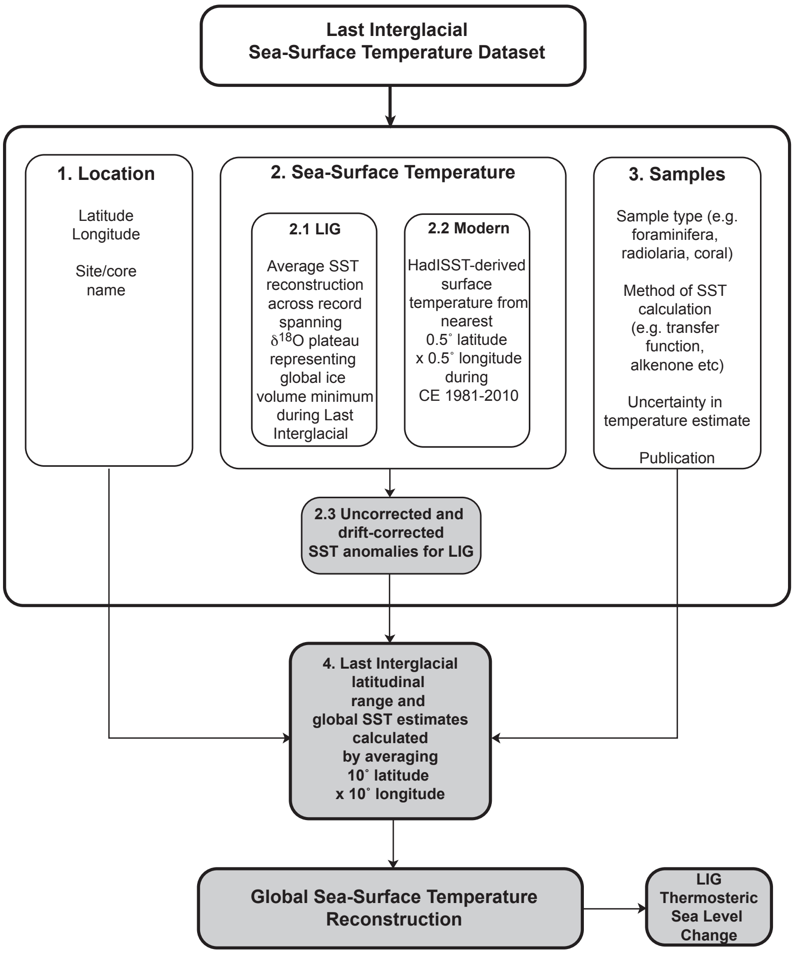
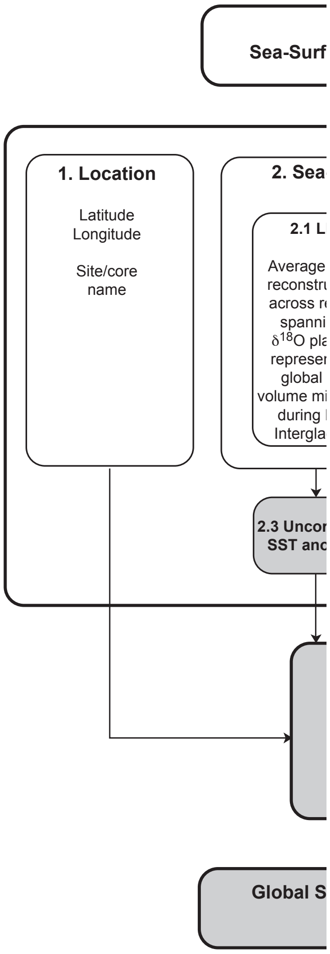


Figure 3: Simplified scheme for the generation of the Last Interglacial sea-surface temperature database providing an overview of the data collection and processing. The numbered boxes set out the stages required to generate a global database of surface temperatures from marine records: 1. Location; 2. Last Interglacial and modern SSTs (including drift calculation); and 3. Metadata including method of temperature reconstruction and associated uncertainty. Grey boxes indicate additional processing of data from the original publications, generating new outputs (which are provided in the database).



Deleted:

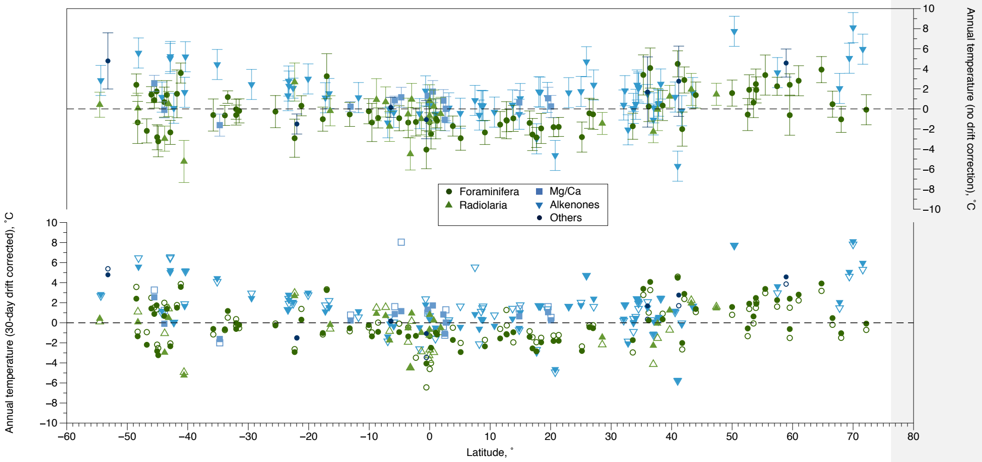


Figure 4: Quality-control plot of latitudinal distribution of proxy mean annual Last Interglacial sea-surface temperature anomalies. Estimates given relative to the modern period (1981-2010) (Rayner et al., 2003) with no drift correction (upper panel) and 30-days drift (lower panel). Lower panel shows drift-corrected SSTs as open symbols with the uncorrected SSTs given as filled symbols. Uncertainties on upper panel given at 1σ.

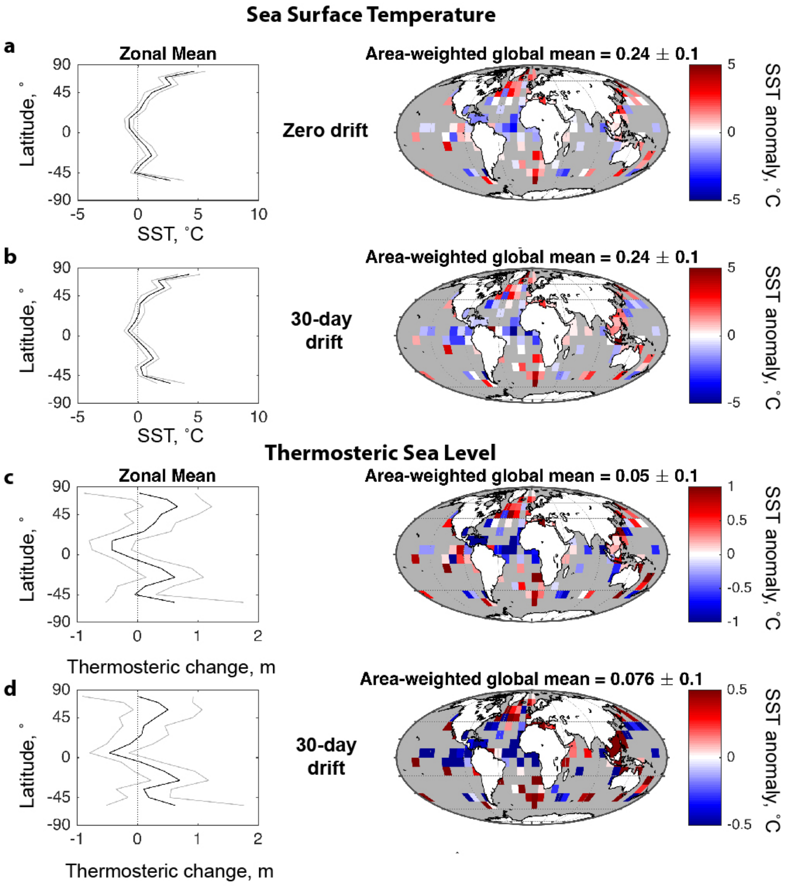
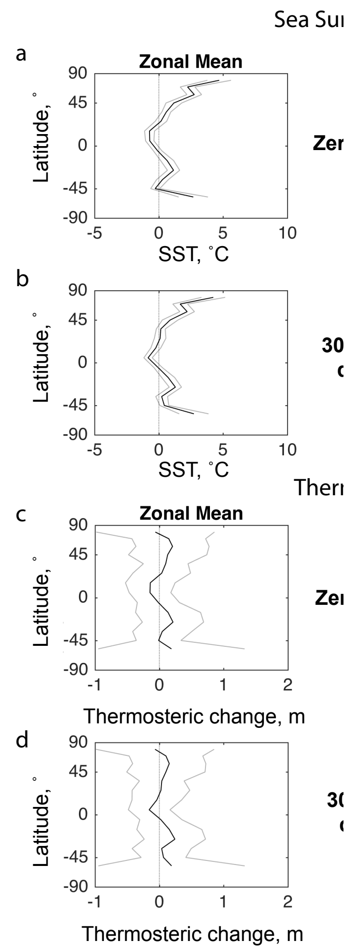


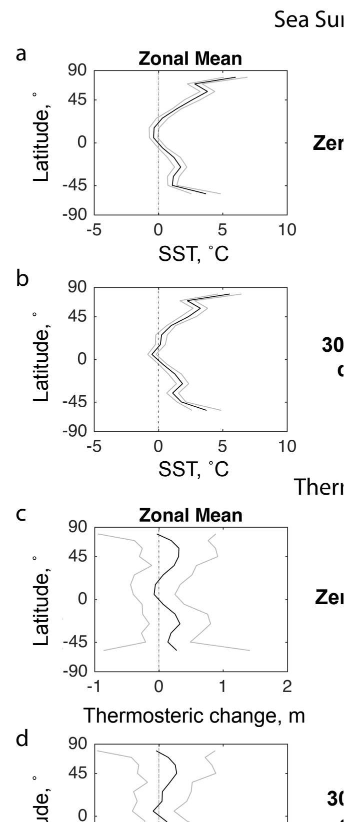
Figure 5: Global and zonal mean annual sea-surface temperature (SST) anomalies and thermosteric sea level change across the full Last Interglacial. Temperature anomalies reported as uncorrected (panels a and c respectively) and after applying 30-day (panels b and d respectively) temperature offsets arising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



Deleted:

Deleted: Last Interglacial …ea-surface temperature (SST) anomalies and thermosteric sea level change. ... [4]

Formatted: English (UK)



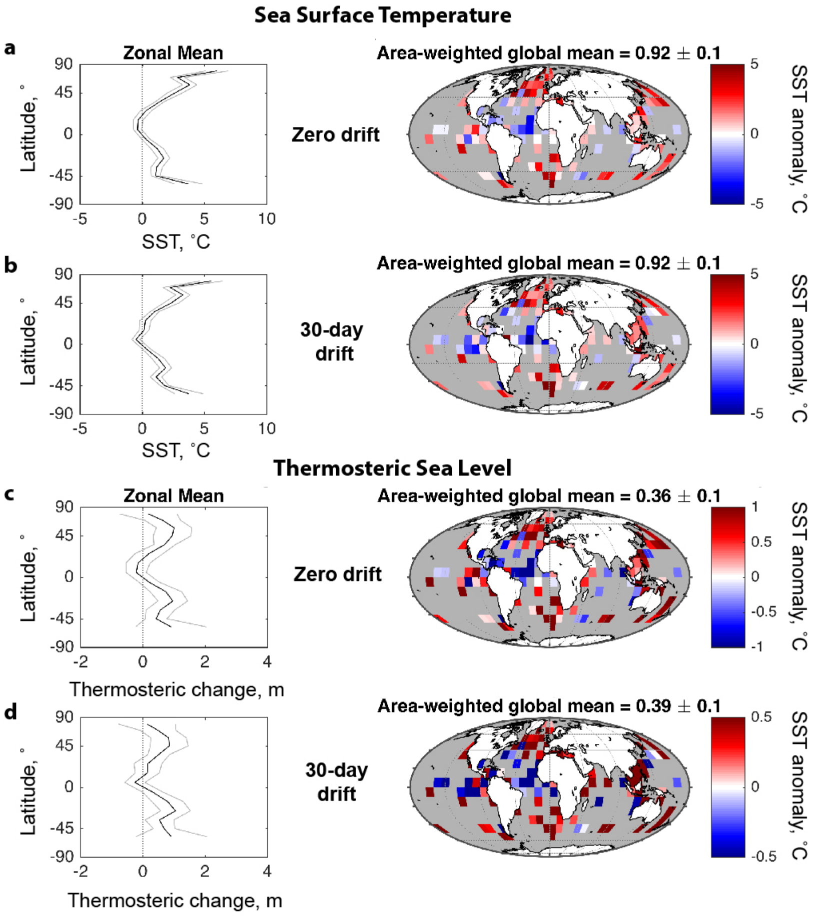


Figure 6: Global and zonal mean annual sea-surface temperature (SST) anomalies and thermosteric sea level change during the early Last Interglacial. Temperature anomalies reported as uncorrected (panels a and c respectively) and after applying 30-day (panels b and d respectively) temperature offsets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

Deleted: LIG.

Formatted: English (UK)

Deleted: Section Break (Next Page)

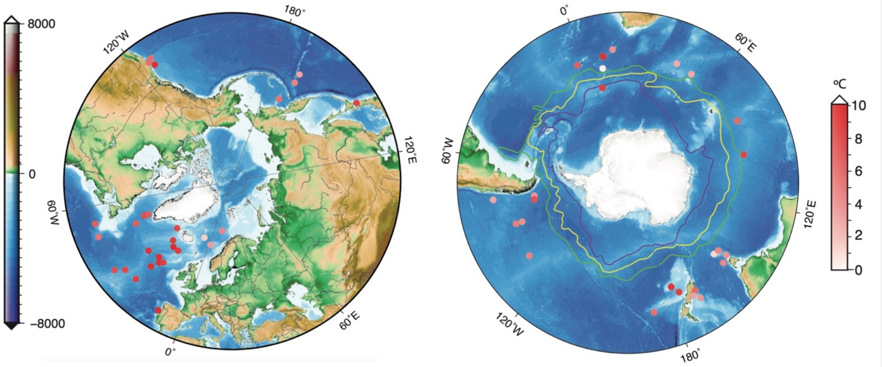


Figure 7: Mid- to high-latitude sea surface temperature (SST) difference between late Marine Isotope Stage 6 and maximum values of the early Last Interglacial (Stage 5).

	Global SST (°C)	Tropical SST (23.5°N to 23.5°S)	SST Polewards of 45°N	SST Polewards of 50°N	SST Polewards of 45° S	SST Polewards of 50°S
Maximum Early LIG (n)	(189)	(87)	(22)	(20)	(13)	(3)
Uncorrected	0.9	0.1	3.2	3.8	1.5	3.7
30-day drift	0.9	0.1	2.8	3.2	2.1	3.7
1σ	0.1	0.2	0.4	0.4	0.3	1.1
Mean (n)	(189)	(87)	(22)	(20)	(13)	(3)
Uncorrected	0.2	-0.3	2.0	2.8	0.2	2.7
30-day drift	0.2	-0.3	1.5	2.3	0.8	2.7
1σ	0.1	0.2	0.4	0.4	0.3	1.1
DJF (n)	(99)	(35)	(16)	(15)	(14)	(9)
Uncorrected	-0.6	-0.7	-0.1	0.0	-0.3	0.8
30-day drift	-0.7	-0.9	-0.5	-0.7	0.3	1.0
1σ	0.2	0.3	0.4	0.5	0.3	0.3
JJA (n)	(92)	(35)	(20)	(19)	(4)	(1)
Uncorrected	-0.4	-1.1	1.3	1.3	-1.9	0.1
30-day drift	-0.5	-1.2	0.9	0.7	-1.2	-0.2
1σ	0.2	0.3	0.4	0.4	0.4	1.1

Table 1: Annual and seasonal temperature estimates for the Last Interglacial. DJF: December to February; JJA: June to August. Temperature anomalies relative to the period CE 1981-2010. Maximum early temperature is defined as the maximum annual temperature recorded during the estimated first five millennia of the Last Interglacial.

Inserted Cells ... [5]
Inserted Cells ... [6]
Deleted: SST¶ ... [7]
Deleted Cells ... [8]
Deleted: >
Deleted: <
Deleted: <
Deleted: =189
Formatted ... [9]
Formatted ... [10]
Formatted ... [11]
Formatted ... [12]
Formatted ... [13]
Inserted Cells ... [14]
Deleted: 1.5
Deleted Cells ... [15]
Inserted Cells ... [16]
Inserted Cells ... [17]
Deleted: 2.1
Deleted: 3
Deleted: 4
Deleted: =189
Inserted Cells ... [18]
Deleted: 0.2
Deleted Cells ... [19]
Inserted Cells ... [20]
Inserted Cells ... [21]
Deleted: 0.8
Deleted: 0.3
Inserted Cells ... [22]
Deleted:
Deleted: =99
Inserted Cells ... [24]
Deleted: 0.0
Deleted Cells ... [25]
Inserted Cells ... [23]
Deleted: 0.3
Deleted Cells ... [26]
Inserted Cells ... [27]
Deleted: 0.3
Inserted Cells ... [28]
Deleted:
Deleted: =92
Deleted:
Deleted:
Inserted Cells ... [30]
Deleted: 0.1
Deleted Cells ... [31]
Inserted Cells ... [29]
Deleted: .3
Deleted: 0.7
Deleted Cells ... [32]
Deleted: LIG

	Global sea level (m)		
	700 m depth	2000 m depth	3500 m depth
Maximum Early LIG (n=189)			
Uncorrected	0.12	0.36	0.67
30-day drift	0.13	0.39	0.72
1σ	0.10	0.10	0.10
Mean (n=189)			
Uncorrected	0.00	0.05	0.10
30-day drift	0.01	0.08	0.15
1σ	0.10	0.10	0.10

Table 2: Annual temperature contributions to sea level during the Last Interglacial for different warming depths.

Deleted:

Deleted Cells

Formatted Table

Deleted: ¶

Formatted Table

Inserted Cells

Inserted Cells

Deleted: DJF (n=99) ... [33]

Formatted: English (US)

Deleted: ¶

Deleted: and seasonal

Deleted: . DJF: December to February; JJA: June to August.

References

Anand, P., Elderfield, H., and Conte, M. H.: Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series, Paleoceanography, 18, 10.1029/2002pa000846, 2003.

Bakker, P., Stone, E. J., Charbit, S., Gröger, M., Krebs-Kanzow, U., Ritz, S. P., Varma, V., Khon, S., Lunt, D. J., Mikolajewicz, U., Prange, M., Renssen, H., Schneider, B., and Schulz, M.: Last interglacial temperature evolution – a model inter-comparison, Clim Past, 9, 605-619, 10.5194/cp-9-605-2013, 2013.

Bakker, P., and Renssen, H.: Last interglacial model-data mismatch of thermal maximum temperatures partially explained, Clim Past, 10, 1633-1644, 10.5194/cp-10-1633-2014, 2014.

Bard, E., Rostek, F., and Sonzogni, C.: Interhemispheric synchrony of the last deglaciation inferred from alkenone palaeothermometry, Nature, 385, 707-710, 1997.

Barnola, J. M., Raynaud, D., Korotkevich, Y. S., and Lorius, C.: Vostok ice core provides 160,000 year record of atmospheric CO_2, Nature, 329, 408-413, 1987.

Bengtson, S. A., Menviel, L. C., Meissner, K. J., Missiaen, L., Peterson, C. D., Lisiecki, L. E., and Joos, F.: Lower oceanic $\delta^{13}C$ during the Last Interglacial compared to the Holocene, Clim. Past Discuss., 2020, 1-27, 10.5194/cp-2020-73, 2020.

Bijma, J., Erez, J., and Hemleben, C.: Lunar and semi-lunar reproductive cycles in some spinose planktonic foraminifers, Journal of Foraminiferal Research, 20, 117-127, 1990.

Brohan, P., Kennedy, J. J., Harris, I., Tett, S. F. B., and Jones, P. D.: Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850, Journal of Geophysical Research, 111, D12106, 10.1029/2005JD006548, 2006.

Capron, E., Govin, A., Stone, E. J., Masson-Delmotte, V., Mulitza, S., Otto-Bliesner, B., Rasmussen, T. L., Sime, L. C., Waelbroeck, C., and Wolff, E. W.: Temporal and spatial structure of multi-millennial temperature changes at high latitudes during the Last Interglacial, Quatern Sci Rev, 103, 116-133, 10.1016/j.quascirev.2014.08.018, 2014.

Capron, E., Govin, A., Feng, R., Otto-Bliesner, B. L., and Wolff, E. W.: Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last Interglacial simulations in the high-latitude regions, Quatern Sci Rev, 168, 137-150, 2017.

Chadwick, M., Allen, C. S., Sime, L. C., and Hillenbrand, C. D.: Analysing the timing of peak warming and minimum winter sea-ice extent in the Southern Ocean during MIS 5e, Quaternary Science Reviews, 229, 106134, 10.1016/j.quascirev.2019.106134, 2020.

Clark, P. U., He, F., Golledge, N. R., Mitrovica, J. X., Dutton, A., Hoffman, J. S., and Dendy, S.: Oceanic forcing of penultimate deglacial and last interglacial sea-level rise, Nature, 577, 660-664, 10.1038/s41586-020-1931-7, 2020.

CLIMAP: The Last Interglacial ocean, Quatern Res, 21, 123-224, 1984.

Cortese, G., Dunbar, G. B., Carter, L., Scott, G., Bostock, H., Bowen, M., Crundwell, M., Hayward, B. W., Howard, W., Martínez, J. I., Moy, A., Neil, H., Sabaa, A., and Sturm, A.: Southwest Pacific Ocean response to a warmer world: Insights from Marine Isotope Stage 5e, Paleoceanography, 28, 585-598, 10.1002/palo.20052, 2013.

Dakos, V., Scheffer, M., van Nes, E. H., Brovkin, V., Petoukhov, V., and Held, H.: Slowing down as an early warning signal for abrupt climate change, Proceedings of the National Academy of Sciences, 105, 14308-14312, 2008.

DeConto, R. M., and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, Nature, 531, 591-597, 10.1038/nature17145, 2016.

Dieckmann, G., Spindler, M., Lange, M. A., Ackley, S. F., and Eicken, H.: Antarctic sea ice: a habitat for the foraminifer *Neogloboquadrina pachyderma*, Journal of Foraminiferal Research, 21, 182-189, 1991.

Doblin, M. A., and van Sebille, E.: Drift in ocean currents impacts intergenerational microbial exposure to temperature, PNAS, 113, 5700-5705, 10.1073/pnas.1521093113, 2016.

Dutton, A., Carlson, A., Long, A., Milne, G., Clark, P., DeConto, R., Horton, B., Rahmstorf, S., and Raymo, M.: Sea-level rise due to polar ice-sheet mass loss during past warm periods, Science, 349, 153, 2015.

Elderfield, H., and Ganssen, G.: Past temperature and δ18O of surface ocean waters inferred from foraminiferal Mg/Ca ratios, Nature, 405, 442-445, 10.1038/35013033, 2000.

Esper, O., and Gersonde, R.: Quaternary surface water temperature estimations: New diatom transfer functions for the Southern Ocean, Palaeogeography, Palaeoclimatology, Palaeoecology, 414, 1-19, 2014.

Deleted: Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M. B., and Deininger, M.: Strong and deep Atlantic meridional overturning circulation during the last glacial cycle, Nature, 517, 73-76, 10.1038/nature14059¶
http://www.nature.com/nature/journal/v517/n7532/abs/nature14059.html#supplementary-information, 2015.¶
Buizert, C., Baggenstos, D., Jiang, W., Purtschert, R., Petrenko, V. V., Lu, Z.-T., Müller, P., Kuhl, T., Lee, J., and Severinghaus, J. P.: Radiometric ^{81}Kr dating identifies 120,000-year-old ice at Taylor Glacier, Antarctica, PNAS, 111, 6876-6881, 2014.¶

Deleted: http://dx.doi.org/10.1016/j.quascirev.2014.08.018,

Deleted: ¶
http://www.nature.com/nature/journal/v531/n7596/abs/nature17145.html#supplementary-information,

Fogwill, C. J., Turney, C. S. M., Meissner, K. J., Golledge, N. R., Spence, P., Roberts, J. L., England, M. H., Jones, R. T., and Carter, L.: Testing the sensitivity of the East Antarctic Ice Sheet to Southern Ocean dynamics: past changes and future implications, J Quatern Sci, 29, 91-98, 10.1002/jqs.2683, 2014.

Galaasen, E. V., Ninnemann, U. S., Irvalı, N., Kleiven, H. F., Rosenthal, Y., Kissel, C., and Hodell, D. A.: Rapid reductions in North Atlantic Deep Water during the peak of the Last Interglacial period, Science, 343, 1129-1132, 10.1126/science.1248667, 2014.

Govin, A., Capron, E., Tzedakis, P. C., Verheyden, S., Ghaleb, B., Hillaire-Marcel, C., St-Onge, G., Stoner, J. S., Bassinot, F., Bazin, L., Blunier, T., Combourieu-Nebout, N., El Ouahabi, A., Genty, D., Gersonde, R., Jimenez-Amat, P., Landais, A., Martrat, B., Masson-Delmotte, V., Parrenin, F., Seidenkrantz, M. S., Veres, D., Waelbroeck, C., and Zahn, R.: Sequence of events from the onset to the demise of the Last Interglacial: Evaluating strengths and limitations of chronologies used in climatic archives, Quatern Sci Rev, 129, 1-36, 10.1016/j.quascirev.2015.09.018, 2015.

Grant, K. M., Rohling, E. J., Ramsey, C. B., Cheng, H., Edwards, R. L., Florindo, F., Heslop, D., Marra, F., Roberts, A. P., Tamisiea, M. E., and Williams, F.: Sea-level variability over five glacial cycles, Nature Comms, 5, 5076, 10.1038/ncomms6076, 2014.

Hansen, J. E.: A slippery slope: How much global warming constitutes 'dangerous anthropogenic interference'?, Climatic Change, 68, 269-279, 2005.

Hayes, C. T., Martínez-García, A., Hasenfratz, A. P., Jaccard, S. L., Hodell, D. A., Sigman, D. M., Haug, G. H., and Anderson, R. F.: A stagnation event in the deep South Atlantic during the last interglacial period, Science, 346, 1514-1517, 10.1126/science.1256620, 2014.

Hellweger, F. L., van Sebille, E., Calfee, B. C., Chandler, J. W., Zinser, E. R., Swan, B. K., and Fredrick, N. D.: The Role of Ocean Currents in the Temperature Selection of Plankton: Insights from an Individual-Based Model, PLOS ONE, 11, e0167010, 10.1371/journal.pone.0167010, 2016.

Hoffman, J. S., Clark, P. U., Parnell, A. C., and He, F.: Regional and global sea-surface temperatures during the last interglaciation, Science, 355, 276-279, 10.1126/science.aai8464, 2017.

Huang, B., Menne, M. J., Boyer, T., Freeman, E., Gleason, B. E., Lawrimore, J. H., Liu, C., Rennie, J. J., Schreck, C. J., III, Sun, F., Vose, R., Williams, C. N., Yin, X., and Zhang, H.-M.: Uncertainty Estimates for Sea Surface Temperature and Land Surface Air Temperature in NOAAGlobalTemp Version 5, Journal of Climate, 33, 1351-1379, 10.1175/jcli-d-19-0395.1, 2020.

Hönisch, B., Allen, K. A., Lea, D. W., Spero, H. J., Eggins, S. M., Arbuszewski, J., deMenocal, P., Rosenthal, Y., Russell, A. D., and Elderfield, H.: The influence of salinity on Mg/Ca in planktic foraminifers–Evidence from cultures, core-top sediments and complementary δ^{18}O, Geochim Cosmo Acta, 121, 196-213, 2013.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp., 2013.

Jones, R. T., Turney, C. S. M., Lang, B., Brooks, S. J., Rundgren, M., Hammarlund, D., Björck, S., and Fogwill, C. J.: Delayed maximum northern European summer temperatures during the Last Interglacial as a result of Greenland Ice Sheet melt, Geology, 45, 23-26, 10.1130/g38402.1, 2017.

Jonkers, L., Reynolds, C. E., Richey, J., and Hall, I. R.: Lunar periodicity in the shell flux of planktonic foraminifera in the Gulf of Mexico, Biogeosciences, 12, 3061-3070, 2015.

Jonkers, L., Hillebrand, H., and Kucera, M.: Global change drives modern plankton communities away from the pre-industrial state, Nature, 570, 372-375, 10.1038/s41586-019-1230-3, 2019.

Kandiano, E. S., Bauch, H. A., and Müller, A.: Sea surface temperature variability in the North Atlantic during the last two glacial-interglacial cycles: comparison of faunal, oxygen isotopic, and Mg/Ca-derived records, Palaeogeography, Palaeoclimatology, Palaeoecology, 204, 145-164, 2004.

Kienast, S. S., Winckler, G., Lippold, J., Albani, S., and Mahowald, N. M.: Tracing dust input to the global ocean using thorium isotopes in marine sediments: ThoroMap, Global Biogeochem Cycles, 30, 1526-1541, doi:10.1002/2016GB005408, 2016.

Kim, S.-J., Crowley, T.J. and Stössel, A.: Local orbital forcing of Antarctic climate change during the Last Interglacial. In: Science, 1998.

Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M.: Probabilistic assessment of sea level during the last interglacial stage, Nature, 462, 863-867, 2009.

Deleted: Evans, H. K., Hall, I. R., Bianchi, G. G., and Oppo, D. W.: Intermediate water links to Deep Western Boundary Current variability in the subtropical NW Atlantic during marine isotope stages 5 and 4, Paleoceanography, 22, n/a-n/a, 10.1029/2006PA001409, 2007.¶

Deleted: http://dx.doi.org/10.1016/j.quascirev.2015.09.018,

Deleted: http://www.nature.com/articles/ncomms6076#supplementary-information, 2014.¶

Moved (insertion) [6]

Köhler, P., Nehrbass-Ahles, C., Schmitt, J., Stocker, T. F., and Fischer, H.: A 156 kyr smoothed history of the atmospheric greenhouse gases CO_2, CH_4, and N_2O and their radiative forcing, Earth Syst. Sci. Data, 9, 363-387, 10.5194/essd-9-363-2017, 2017.

Lange, M., and van Sebille, E.: Parcels v0.9: prototyping a Lagrangian ocean analysis framework for the petascale age, Geosci. Model Dev., 10, 4175-4186, 10.5194/gmd-10-4175-2017, 2017.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., and Levrard, B.: A long-term numerical solution for the insolation quantities of the earth, Astronomy & Astrophysics, 428, 261-285, 10.1051/0004-6361:20041335, 2004.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, PNAS, 105, 1786-1793, 2008.

Lisiecki, L. E., and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records, Paleoceanography, 20, doi:10.1029/2004PA001071, 2005.

Lunt, D. J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J. H., Khon, V. C., Krebs-Kanzow, U., Langebroek, P. M., Lohmann, G., Nisancioglu, K. H., Otto-Bliesner, B. L., Park, W., Pfeiffer, M., Phipps, S. J., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, E. J., Takahashi, K., Wei, W., Yin, Q., and Zhang, Z. S.: A multi-model assessment of last interglacial temperatures, Clim Past, 9, 699-717, 10.5194/cp-9-699-2013, 2013.

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C., and Shackleton, N. J.: Age dating and the orbital theory of the Ice Ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy, Quaternary Research, 27, 1-29, 1987.

Masumoto, Y., Sasaki, H., Kagimoto, T., Komori, N., Ishida, A., Sasai, Y., Miyama, T., Motoi, T., Mitsudera, H., Takahashi, K., Sakuma, H., and Yamagata, T.: A fifty-year eddy-resolving simulation of the world ocean – Preliminary outcomes of OFES (OGCM for the Earth simulator), Journal of the Earth Simulator, 1, 35-56, 2004.

McKay, N. P., Overpeck, J. T., and Otto-Bliesner, B. L.: The role of ocean thermal expansion in Last Interglacial sea level rise, GRL, 38, L14605, 10.1029/2011gl048280, 2011.

Mercer, J. H., and Emiliani, C.: Antarctic ice and interglacial high sea levels, Science, 168, 1605-1606, 10.1126/science.168.3939.1605-a, 1970.

Mercer, J. H.: West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster, Nature, 271, 321-325, 1978.

Monroy, P., Hernández-García, E., Rossi, V., and López, C.: Modeling the dynamical sinking of biogenic particles in oceanic flow, Nonlin. Processes Geophys., 24, 293-305, 10.5194/npg-24-293-2017, 2017.

Müller, P. J., Kirst, G., Ruhland, G., von Storch, I., and Rosell-Melé, A.: Calibration of the alkenone paleotemperature index $U_{37}^{K'}$ based on core-tops from the eastern South Atlantic and the global ocean (60°N-60°S), Geochim Cosmo Acta, 62, 1757-1772, 10.1016/S0016-7037(98)00097-0, 1998.

NEEM Community Members: Eemian interglacial reconstructed from a Greenland folded ice core, Nature, 493, 489-494, 2013.

Nooteboom, P. D., Bijl, P. K., van Sebille, E., von der Heydt, A. S., and Dijkstra, H. A.: Transport bias by ocean currents in sedimentary microplankton assemblages: Implications for paleoceanographic reconstructions, Paleoceanography and Paleoclimatology, doi: 10.1029/2019pa003606, 10.1029/2019pa003606,

Nooteboom, P. D., Delandmeter, P., van Sebille, E., Bijl, P. K., Dijkstra, H. A., and von der Heydt, A. S.: Resolution dependency of sinking Lagrangian particles in ocean general circulation models, PLOS ONE, 15, e0238650, 10.1371/journal.pone.0238650, 2020.

Otto-Bliesner, B. L., Rosenbloom, N., Stone, E. J., McKay, N. P., Lunt, D. J., Brady, E. C., and Overpeck, J. T.: How warm was the last interglacial? New model–data comparisons, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371, doi: 10.1098/rsta.2013.0097, 10.1098/rsta.2013.0097, 2013.

Overpeck, J., Sturm, M., Francis, J. A., Perovich, D. K., Serreze, M. C., Benner, R., Carmack, E. C., Chapin, F. S. I., Gerlach, S. C., Hamilton, L. C., Hinzman, L. D., Holland, M., Huntington, H. P., Key, J., .R., Lloyd, A. H., MacDonald, G. M., McFadden, J., Noone, D., Prowse, T. D., Schlosser, P., and Vörösmarty, C.: Arctic system on trajectory to new, seasonally ice-free state, Eos Transactions AGU, 86, 309–313, 2005.

Overpeck, J., Otto-Bliesner, B., Miller, G., Muhs, D., Alley, R., and Kiehl, J.: Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise, Science, 311, 1747-1750, 10.1126/science.1115159, 2006.

PAGES2k Consortium, Emile-Geay, J., McKay, N. P., Kaufman, D. S., von Gunten, L., Wang, J., Anchukaitis, K. J., Abram, N. J., Addison, J. A., Curran, M. A. J., Evans, M. N., Henley, B. J., Hao, Z., Martrat, B., McGregor, H. V., Neukom, R.,

Moved up [6]: Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M.: Probabilistic assessment of sea level during the last interglacial stage, Nature, 462, 863-867, 2009.¶

Deleted: https://doi.org/10.1016/S0016-7037(98)00097-0,

Deleted: http://www.nature.com/nature/journal/v493/n7433/abs/nature11789.html#supplementary-information, 2013.

Pederson, G. T., Stenni, B., Thirumalai, K., Werner, J. P., Xu, C., Divine, D. V., Dixon, B. C., Gergis, J., Mundo, I. A., Nakatsuka, T., Phipps, S. J., Routson, C. C., Steig, E. J., Tierney, J. E., Tyler, J. J., Allen, K. J., Bertler, N. A. N., Björklund, J., Chase, B. M., Chen, M.-T., Cook, E., de Jong, R., DeLong, K. L., Dixon, D. A., Ekaykin, A. A., Ersek, V., Filipsson, H. L., Francus, P., Freund, M. B., Frezzotti, M., Gaire, N. P., Gajewski, K., Ge, Q., Goosse, H., Gornostaeva, A., Grosjean, M., Horiuchi, K., Hormes, A., Husum, K., Isaksson, E., Kandasamy, S., Kawamura, K., Kilbourne, K. H., Koç, N., Leduc, G., Linderholm, H. W., Lorrey, A. M., Mikhalenko, V., Mortyn, P. G., Motoyama, H., Moy, A. D., Mulvaney, R., Munz, P. M., Nash, D. J., Oerter, H., Opel, T., Orsi, A. J., Ovchinnikov, D. V., Porter, T. J., Roop, H. A., Saenger, C., Sano, M., Sauchyn, D., Saunders, K. M., Seidenkrantz, M.-S., Severi, M., Shao, X., Sicre, M.-A., Sigl, M., Sinclair, K., St. George, S., St. Jacques, J.-M., Thamban, M., Kuwar Thapa, U., Thomas, E. R., Turney, C., Uemura, R., Viau, A. E., Vladimirova, D. O., Wahl, E. R., White, J. W. C., Yu, Z., and Zinke, J.: A global multiproxy database for temperature reconstructions of the Common Era, Scientific Data, 4, 170088, 10.1038/sdata.2017.88, 2017.

Past Interglacials Working Group of PAGES: Interglacials of the last 800,000 years, Reviews of Geophysics, 54, 162-219, 10.1002/2015RG000482, 2016.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M.: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, Nature, 399, 429-436, 10.1038/20859, 1999.

Pisias, N. G., and Mix, A. C.: Spatial and temporal oceanographic variability of the eastern equatorial Pacific during the late Pleistocene: Evidence from radiolaria microfossils, Paleoceanography, 12, 381-393, 1997.

Prahl, F. G., Sparrow, M. A., and Wolfe, G. V.: Physiological impacts on alkenone paleothermometry, Paleoceanography, 18, 10.1029/2002pa000803, 2003.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, Journal of Geophysical Research: Atmospheres, 108, 4407, doi:4410.1029/2002JD002670, 10.1029/2002JD002670, 2003.

Rembauville, M., Manno, C., Tarling, G. A., Blain, S., and Salter, I.: Strong contribution of diatom resting spores to deep-sea carbon transfer in naturally iron-fertilized waters downstream of South Georgia, Deep Sea Research Part I: Oceanographic Research Papers, 115, 22-35, 10.1016/j.dsr.2016.05.002, 2016.

Rohling, E. J., Cane, T. R., Cooke, S., Sprovieri, M., Bouloubassi, I., Emeis, K. C., Schiebel, R., Kroon, D., Jorissem, F. J., Lorre, A., and Kemp, A. E. S.: African monsoon variability during the previous interglacial maximum, EPSL, 202, 61-75, 2002.

Rohling, E. J., Grant, K., Hemleben, C., Siddall, M., Hoogakker, B. A. A., Bolshaw, M., and Kucera, M.: High rates of sea-level rise during the last interglacial period, Nature Geosci, 1, 38-42, 10.1038/ngeo.2007.28, 2008.

Rohling, E. J., Hibbert, F. D., Williams, F. H., Grant, K. M., Marino, G., Foster, G. L., Hennekam, R., de Lange, G. J., Roberts, A. P., Yu, J., Webster, J. M., and Yokoyama, Y.: Differences between the last two glacial maxima and implications for ice-sheet, δ^{18}O, and sea-level reconstructions, Quatern Sci Rev, 176, 1-28, 10.1016/j.quascirev.2017.09.009, 2017.

Rohling, E. J., Hibbert, F. D., Grant, K. M., Galaasen, E. V., Irvalı, N., Kleiven, H. F., Marino, G., Ninnemann, U., Roberts, A. P., Rosenthal, Y., Schulz, H., Williams, F. H., and Yu, J.: Asynchronous Antarctic and Greenland ice-volume contributions to the last interglacial sea-level highstand, Nature Communications, 10, 5040, 10.1038/s41467-019-12874-3, 2019.

Schellnhuber, H. J., Rahmstorf, S., and Winkelmann, R.: Why the right climate target was agreed in Paris, Nature Climate Change, 6, 649, 10.1038/nclimate3013, 2016.

Schneider, R., Schmitt, J., Köhler, P., Joos, F., and Fischer, H.: A reconstruction of atmospheric carbon dioxide and its stable carbon isotopic composition from the penultimate glacial maximum to the last glacial inception, Climate of the Past, 9, 2507-2523, 2013.

Schneider, R. R., Müller, P. J., and Acheson, R.: Atlantic alkenone sea-surface temperature records, in: Reconstructing Ocean History: A Window into the Future, Kluwer Academic/Plenum Publishers, New York, 33-55, 1999.

Segev, E., Castañeda, I. S., Sikes, E. L., Vlamakis, H., and Kolter, R.: Bacterial influence on alkenones in live microalgae, Journal of Phycology, 52, 125-130, 10.1111/jpy.12370, 2016.

Shackleton, S., Baggenstos, D., Menking, J. A., Dyonisius, M. N., Bereiter, B., Bauska, T. K., Rhodes, R. H., Brook, E. J., Petrenko, V. V., McConnell, J. R., Kellerhals, T., Häberli, M., Schmitt, J., Fischer, H., and Severinghaus, J. P.: Global ocean heat content in the Last Interglacial, Nature Geosci, 13, 77-81, 10.1038/s41561-019-0498-0, 2020.

Deleted: https://www.nature.com/articles/sdata201788#supplementary-information, 2017.¶

Deleted: https://doi.org/10.1016/j.dsr.2016.05.002,

Deleted: https://doi.org/10.1016/j.quascirev.2017.09.009,

Deleted: Comms

Sikes, E. L., O'Leary, T., Nodder, S. D., and Volkman, J. K.: Alkenone temperature records and biomarker flux at the subtropical front on the Chatham Rise, SW Pacific Ocean, Deep Sea Research Part I: Oceanographic Research Papers, 52, 721-748, 2005.

Spindler, M.: On the salinity tolerance of the planktonic foraminifer *Neogloboquadrina pachyderma* from Antarctic sea ice, Proc. NIPR Symp. Polar Biol, 1996, 85-91,

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., and Schellnhuber, H. J.: Trajectories of the Earth System in the Anthropocene, PNAS, 115, 8252-8259, 10.1073/pnas.1810141115, 2018.

Sutter, J., Gierz, P., Grosfeld, K., Thoma, M., and Lohmann, G.: Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse, GRL, 43, 2675–2682, 10.1002/2016GL067818, 2016.

Thomas, Z. A., Kwasniok, F., Boulton, C. A., Cox, P. M., Jones, R. T., Lenton, T. M., and Turney, C. S. M.: Early warnings and missed alarms for abrupt monsoon transitions, Clim Past, 11, 1621-1633, 10.5194/cp-11-1621-2015, 2015.

Thomas, Z. A.: Using natural archives to detect climate and environmental tipping points in the Earth System, Quatern Sci Rev, 152, 60-71, 10.1016/j.quascirev.2016.09.026, 2016.

Thomas, Z. A., Jones, R. T., Turney, C. S. M., Golledge, N., Fogwill, C., Bradshaw, C. J. A., Menviel, L., McKay, N. P., Bird, M., Palmer, J., Kershaw, P., Wilmshurst, J., and Muscheler, R.: Tipping elements and amplified polar warming during the Last Interglacial, Quatern Sci Rev, 233, 106222, 10.1016/j.quascirev.2020.106222, 2020.

Turney, C. S. M., and Jones, R. T.: Does the Agulhas Current amplify global temperatures during super-interglacials?, J Quatern Sci, 25, 839-843, 2010.

Turney, C. S. M., and Jones, R. T.: Response to Comment on 'Does the Agulhas Current amplify global temperatures during super-interglacials?, J Quatern Sci, 26, 870-871, 10.1002/jqs.1556, 2011.

Turney, C. S. M., Jones, R., McKay, N., Van Sebille, E., Thomas, Z., Hillenbrand, C.-D., and Fogwill, C.: A global reconstruction of sea-surface temperatures for the Last Interglacial (129-116 kyr). In: PANGAEA, 10.1594/PANGAEA.904381, 2019.

Turney, C. S. M., Fogwill, C. J., Golledge, N. R., McKay, N. P., van Sebille, E., Jones, R. T., Etheridge, D., Rubino, M., Thornton, D. P., Davies, S. M., Ramsey, C. B., Thomas, Z. A., Bird, M. I., Munksgaard, N. C., Kohno, M., Woodward, J., Winter, K., Weyrich, L. S., Rootes, C. M., Millman, H., Albert, P. G., Rivera, A., van Ommen, T., Curran, M., Moy, A., Rahmstorf, S., Kawamura, K., Hillenbrand, C.-D., Weber, M. E., Manning, C. J., Young, J., and Cooper, A.: Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica, PNAS, 117, 3996-4006, 10.1073/pnas.1902469117, 2020.

Tzedakis, P. C., Drysdale, R. N., Margari, V., Skinner, L. C., Menviel, L., Rhodes, R. H., Taschetto, A. S., Hodell, D. A., Crowhurst, S. J., Hellstrom, J. C., Fallick, A. E., Grimalt, J. O., McManus, J. F., Martrat, B., Mokeddem, Z., Parrenin, F., Regattieri, E., Roe, K., and Zanchetta, G.: Enhanced climate instability in the North Atlantic and southern Europe during the Last Interglacial, Nature Comms, 9, 4235, doi: 4210.1038/s41467-41018-06683-41463, 10.1038/s41467-018-06683-3, 2018.

van Sebille, E., England, M. H., Zika, J. D., and Sloyan, B. M.: Tasman leakage in a fine-resolution ocean model, GRL, 39, L06601, 10.1029/2012GL051004, 2012.

van Sebille, E., Scussolini, P., Durgadoo, J. V., Peeters, F. J. C., Biastoch, A., Weijer, W., Turney, C., Paris, C. B., and Zahn, R.: Ocean currents generate large footprints in marine palaeoclimate proxies, Nature Comms, 6, 6521, 10.1038/ncomms7521, 2015.

Viebahn, J. P., Heydt, A. S., Le Bars, D., and Dijkstra, H. A.: Effects of Drake Passage on a strongly eddying global ocean, Paleoceanography and Paleoclimatology, 31, 564-581, 2016.

Visser, K., Thunell, R., and Stott, L.: Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation, Nature, 421, 152-155, 2003.

Vogelsang, E., Sarnthein, M., and Pflaumann, U.: δ^{18}O stratigraphy, chronology, and sea surface temperatures of Atlantic sediment records (GLAMAP-2000 Kiel), Universität Kiel, Kiel, Germany, 244, 2001.

von Gyldenfeldt, A.-B., Carstens, J., and Meincke, J.: Estimation of the catchment area of a sediment trap by means of current meters and foraminiferal tests, Deep Sea Research Part II: Topical Studies in Oceanography, 47, 1701-1717, 10.1016/S0967-0645(00)00004-7, 2000.

Waelbroeck, C., Frank, N., Jouzel, J., Parrenin, F., Masson-Delmotte, V., and Genty, D.: Transferring radiometric dating of the last interglacial sea level high stand to marine and ice core records, EPSL, 265, 183-194, 2008.

Deleted: http://dx.doi.org/10.1016/j.quascirev.2016.09.026,

Deleted: In: PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.904381,

Deleted: . R

Deleted: Bronk-

Deleted: in press

Deleted: https://doi.org/10.1016/S0967-0645(00)00004-7,

Wang, Y. J., Cheng, H., Edwards, R. L., Kong, X. G., Shao, X. H., Chen, S. T., Wu, J. Y., Jiang, X. Y., Wang, X. F., and An, Z. S.: Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years, Nature, 451, 1090-1093, 10.1038/nature06692, 2008.

White, J. W. C.: Don't touch that dial, Nature, 364, 186, 1993.

Page 2: [1] Deleted	**Chris Turney**	**15/10/2020 19:21:00**

Page 2: [2] Deleted	**Chris Turney**	**15/10/2020 19:21:00**

Page 9: [3] Deleted	**Chris Turney**	**15/10/2020 19:21:00**

Page 13: [4] Deleted	**Chris Turney**	**15/10/2020 19:21:00**

Page 13: [4] Deleted	**Chris Turney**	**15/10/2020 19:21:00**

Page 16: [5] Inserted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Inserted Cells

Page 16: [6] Inserted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Inserted Cells

Page 16: [7] Deleted	**Chris Turney**	**15/10/2020 19:21:00**

Page 16: [8] Deleted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Deleted Cells

Page 16: [9] Formatted	**Chris Turney**	**15/10/2020 19:21:00**

Font: Not Bold

Page 16: [10] Formatted	**Chris Turney**	**15/10/2020 19:21:00**

Font: Not Bold

Page 16: [11] Formatted	**Chris Turney**	**15/10/2020 19:21:00**

Font: Not Bold

Page 16: [12] Formatted	**Chris Turney**	**15/10/2020 19:21:00**

Font: Not Bold

Page 16: [13] Formatted	**Chris Turney**	**15/10/2020 19:21:00**

Font: Not Bold

Page 16: [14] Inserted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Inserted Cells

Page 16: [15] Deleted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Deleted Cells

Page 16: [16] Inserted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Inserted Cells

Page 16: [17] Inserted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Inserted Cells

Page 16: [18] Inserted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Inserted Cells

Page 16: [19] Deleted Cells	**Chris Turney**	**15/10/2020 19:21:00**

Deleted Cells

Page 16: [20] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [21] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [22] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [23] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [24] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [25] Deleted Cells Chris Turney 15/10/2020 19:21:00

Deleted Cells

Page 16: [26] Deleted Cells Chris Turney 15/10/2020 19:21:00

Deleted Cells

Page 16: [27] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [28] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [29] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [30] Inserted Cells Chris Turney 15/10/2020 19:21:00

Inserted Cells

Page 16: [31] Deleted Cells Chris Turney 15/10/2020 19:21:00

Deleted Cells

Page 16: [32] Deleted Cells Chris Turney 15/10/2020 19:21:00

Deleted Cells

Page 17: [33] Deleted Chris Turney 15/10/2020 19:21:00