Final Author Comment

De Vleeschouwer et al. – cp-2021-151

We found the review comment by Clara Bolton (R1) very useful in several aspects. First, it helps refining the presentation of one of the main points of the manuscript, (i.e., Leeuwin Current variability on secular timescales). Second, it prompts us to clarify ambiguities regarding δ^{18}O-based temperature reconstructions. Third, it corrects a handful of editorial glitches. We warmly thank Clara Bolton for her constructive review of our work.

1. Leeuwin Current intensity on secular timescales

I find it interesting that there is no clear unidirectional trend in isotopic gradient over the intensification of northern hemisphere glaciation interval, and LC current intensity on secular timescales thus seems to be almost independent of this (although LC intensity is apparently strongly linked to sea level changes at the G-IG scale) – this aspect is not discussed much.

The reviewer refers to one of the key-messages of the paper: On orbital timescales, a significant portion of Leeuwin Current (LC) variability can be explained by sea level variations and orbital forcing of wind patterns. Yet, on secular timescales, LC variability seems partly decoupled from the global eustatic sea-level evolution. Our results do show a steepening of the isotopic gradient (hence a Leeuwin Current weakening) across the Plio-Pleistocene boundary. Yet, these steep isotopic gradients are not unique, as we report equally-steep isotopic gradients between 3.7 – 3.1 Ma.

We will implement two things to refine the presentation of this point, which is one of our main messages.

a. First, we will add a paragraph in §4-2., in which we compare the two intervals of steep isotopic gradient (weak Leeuwin Current). The Pliocene interval between 3.7 – 3.1 Ma is characterized by a steep gradient with relatively low amplitude changes. The Pleistocene interval between 2.6 – 2.2 Ma is characterized by an equally-steep gradient but with higher amplitude variability.
b. Second, we will highlight the fact that the SST records in the Agulhas/Benguela region exhibit similar behavior on secular timescales by means of cross-spectral analysis (see also answer to Referee #3). At those sites, early Pleistocene sea surface temperatures are similar or even somewhat warmer than late Pliocene (3.7 – 3.1 Ma) sea surface temperatures.

2. Comments on temperature reconstructions

Figure 4a: perhaps add modern SST and T at proposed calcification depth of T. sacculifer (base of mixed layer) onto the Figure for comparison.

We will follow this suggestion.

Fig. 5: Calcification temperature reconstruction based on d18Oplanktic and Rohling Sea Level curve: I had a hard time assessing the robustness of this. Is the calculation of T in this way therefore based on the assumption that local d18Osw (i.e. the part of d18Osw related to local hydrological cycle effects and not global sea level) was constant? Is this assumption reasonable both on the long-term and on G-IG timescales (in the context of salinity/water mass changes associated with L current and upwelling changes in your study area) at your site? I think some discussion of expected local d18Osw changes on GIG timescales, and how this would impact the temperature reconstruction, would be nice.

The calcification temperature calculation is based on a *global* δ^{18}Osw reconstruction, assuming that *local* δ^{18}Osw was constant. In the revised version of the manuscript, we will explicitly acknowledge and argue for this assumption. Based on the modern-day oceanography of the Perth Basin, we do not expect more than 0.6 psu salinity difference between phases of strong Leeuwin Current (Interglacial, present-day analogue: austral winter) and weak Leeuwin Current (Glacial, present-day analogue: austral summer). This estimate of salinity change on G-IG timescales is based on the present-day seasonal variability of the Leeuwin Current system. This analogy can be made because the Leeuwin Current is observed to be very active during austral winter, but very weak during summer (due to opposing wind patterns). Thus, the dynamic of the Leeuwin Current during glacials was likely quite similar to that of present-day austral summer, and vice versa. This analogy, however, likely represents an over-estimation of salinity change because the Leeuwin Current never shut down completely during glacial intervals.

If we were to include a salinity-driven local δ^{18}Osw component, it would result in an increase of the amplitude of the δ^{18}Osw reconstruction by about 0.10 – 0.15‰. This, in turn, leads to a reduction of the amplitude of the temperature reconstruction. The amplitude of possible salinity-driven δ^{18}Osw variability is however small compared to the ice-volume-related change in δ^{18}Osw. Moreover, salinity-driven variability is virtually unconstrained for the studied region and period, and the expected 0.6 psu amplitude is too small to be accurately reconstructed with SSS proxies. For all those reasons, we will continue calculating calcification temperatures solely based on a *global* δ^{18}Osw reconstruction, assuming that *local* δ^{18}Osw was constant. But, as mentioned before, we will acknowledge the underlying assumptions regarding local δ^{18}Osw in the revised manuscript.

In Figures 5 and 6, different sea-level reconstructions appear to be shown or used in calculations – Rohling 2014 in Fig. 5 and Rohling 2021 in Fig. 6. Is the more up-to-date sea-level record not also suitable for calculating the glacial contribution to d18Osw in Fig. 5?

Figure 5 will be updated to use the Rohling et al. (2021) reconstruction for δ^{18}Osw.

It would be interesting to consider the G-IG amplitude of the G. sacculifer d18O signal in the context of contemporaneous and/or regional records from surface-dwelling species such as G. ruber, to see if this can give you any support for the proposed deep mixed layer depth habitat or relatively constant d18Osw conditions. Also, in the methods, it is not mentioned whether individuals with gametogenic calcite final chambers were avoided or included during picking.

Contemporaneous records in the region have reported similar amplitude on G-IG timescales between *G. ruber* and *G. sacculifer*. However, Shackleton and Hall (1990), Karas et al. (2009) and Karas et al. (2011) all added a 0.25‰ inter-species offset for *G. ruber* to be comparable with *G. sacculifer*. This offset is in agreement with the interpretation that *G. ruber* is a surface dweller, while *G. sacculifer* thrives in the (bottom of the) mixed layer.

During picking, specimens with gametogenic calcite final chambers were avoided. This information will be added to the manuscript in §2.3.

It may also be relevant to consider and compare the new paper by Meinicke et al. (2021, already cited) that also contains D47 measurements on Trilobatus trilobus and a deeper dwelling species for the Plio-Pleistocene from the Western Pacific Warm Pool - I think their interpretations re: depth habitat for T. trilobus are not the same as in this paper, are the two interpretations compatible?

The two interpretations regarding the depth habitat of *Trilobatus trilobus*, formerly known as *G. trilobus* or *G. sacculifer* without sac-like final chamber are not exactly the same, but compatible.

a. Meinicke et al. (2021) determined the average calcification depth for *T. trilobus* to be roughly around 75 m (see their Fig 3a). Their data thus indicate an apparent calcification depth of *T. trilobus* at Site U1488 (West Pacific Warm Pool) within the lower mixed layer.
b. Rippert et al. (2016) report calcification depths around 120 m in the equatorial Pacific Ocean. This represents bottom of the mixed layer or top of the thermocline.
c. In our manuscript, we report clumped-isotope calcification temperatures for *T. trilobus* between 18-20°C. Compared to modern-day water column profiles at Site U1459, this corresponds to water depths between 100 – 150 m. Hence, our results are in closer agreement with the results of Rippert et al. (2016) than with the results of Meinicke et al. (2021). At Site U1459, *T. trilobus* calcification temperatures seem to indicate bottom of the mixed layer.

The results of Meinicke et al. (2021) will be more explicitly discussed in §4.1, in conjunction with the discussion of the Rippert et al. (2016) results.

Line 349: This is interesting, I wonder is there any evidence in support of the hypothesis that Thaumarchaeota thrive/are more successful when phytoplankton biomass is low under oligotrophic conditions?

We will back-up this statement by citing the work of Guo et al. (2021) (Frontiers in Marine Science, https://doi.org/10.3389/fmars.2021.715708).

Line 361: Perhaps add that diagenesis (seafloor recrystallisation?) of foraminifera would specifically lead to a cool bias on D47 temperatures.

The possibility of a cool bias on D47 temperatures has also been raised by Referee #2. A corresponding paragraph will be added to §4.1.

Line 362: please briefly define "isotopic scrambling" for non-clumped specialists

OK. We will mention that this implies the reset of the clumping of ^{13}C and ^{18}O atoms in $CaCO_3$.

Line 498: Not clear how exactly low-resolution clumped isotope and TEX86 temperatures "demonstrate that the LC continued to operate […]" – do you deduce this from absolute temperatures? Or latitudinal gradients?

From absolute temperatures. Without the Leeuwin Current, Site U1459 would be under the influence of the West Australian Current and SSTs would be <20°C. This reasoning will be added to the manuscript.

3. **Minor editorial comments**

- The last sentence of the abstract will be rephrased to emphasize that ITF forcing exerted a long-range influence on Southern Hemisphere climate throughout the Plio-Pleistocene.
- Carnarvon and Perth Basin will be labeled on the map in Fig. 2C
- The Figure 1 caption is indeed wrong: January and July will be flipped.
- The U1459 time-depth plot in Fig. 1C is for the locality of Site U1459. However, the spatial resolution of the bathymetry that underpins the Copernicus Marine Service Information model somewhat overestimates the water depth. This is no surprise, as Site U1459 is on a steep continental slope, and just a few kilometers further offshore, one encounters water depths >500 m. We will use a datapoint from the Copernicus Marine Service Information model higher-up on the slope, so that water depth is not exceeding 200 meters.
- We will specify equal weights for the two forcings in the composite.
- We will lay out more clearly that sub-surface upwelling of SAMW onto the shelf is the most likely process to explain the observed early-Pleistocene increase in paleo-productivity and organic carbon burial. This assessment is based on our observation that (1) TEX_{86} SSTs are stable throughout the early Pleistocene, (2) we see an important cooling in D47-derived *T. trilobus* calcification temperatures (upper thermocline / bottom mixed layer), and (3) we see a simultaneous increase in U/Th (especially during glacials). This proxy co-evolution is most compatible with sub-surface upwelling of nutrient-rich waters when LC is weak. If productivity would be eddy-mixing driven, this would result in stable mixed layer temperatures because the overall LC would still be deep and stable over the site. But that is not what we observe, as we report an important drop in calcification temperatures of *T. trilobus* (both in δ^{18}O and D47).

Guo, J., et al. (2021). Variation of Isoprenoid GDGTs in the Stratified Marine Water Column: Implications for GDGT-Based TEX86 Paleothermometry. *Frontiers in Marine Science, 8*. 10.3389/fmars.2021.715708

Karas, C., et al. (2009). Mid-Pliocene climate change amplified by a switch in Indonesian subsurface throughflow. *Nature Geosci, 2*(6), 434-438.

Karas, C., et al. (2011). Pliocene Indonesian Throughflow and Leeuwin Current dynamics: Implications for Indian Ocean polar heat flux. *Paleoceanography, 26*. doi:10.1029/2010pa001949

Meinicke, N., et al. (2021). Coupled Mg/Ca and Clumped Isotope Measurements Indicate Lack of Substantial Mixed Layer Cooling in the Western Pacific Warm Pool During the Last ~5 Million Years. *Paleoceanography and Paleoclimatology, 36*(8), e2020PA004115. https://doi.org/10.1029/2020PA004115

Rippert, N., et al. (2016). Constraining foraminiferal calcification depths in the western Pacific warm pool. *Marine Micropaleontology, 128*, 14-27. https://doi.org/10.1016/j.marmicro.2016.08.004

Rohling, E. J., et al. (2021). Sea level and deep-sea temperature reconstructions suggest quasi-stable states and critical transitions over the past 40 million years. *Science Advances, 7*(26), eabf5326. doi:10.1126/sciadv.abf5326

Shackleton, N. J., & Hall, M. A. (1990). Pliocene oxygen isotope stratigraphy of Hole 709C. In R. Duncan, J. Backman, & L. Peterson (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results* (Vol. 115). College Station, TX: Ocean Drilling Program.