Final Author Comment

De Vleeschouwer et al. – cp-2021-151

We thank R2 for their assessment of our manuscript. The first major comment demands for a more comprehensive discussion of the effects of dolomitization, dissolution, and recrystallization on stable isotope measurements and their paleoclimate interpretations. The second, third and fourth major comment all refer to the concept of using isotopic gradients along the flow path of the Leeuwin Current as a proxy for its intensity. The skepticism and unclarities brought up by the reviewer can be addressed in full. Most detailed comments will also be addressed.

1. **The impact of diagenesis on stable isotope results**

A planktonic d18O record is presented from core depths (55-105 mcd) where partly severe dolomitization was reported previously (Proceedings of the International Ocean Discovery Program, vol. 356). Further, all samples are from a shallow carbonate rich ocean region close to coral reefs where carbonate diagenesis is very common. It is well known that diagenesis and recrystallisation at sea bottom alter foraminiferal d18O towards heavier values (e.g., Edgar et al., 2015, Geochimica et Cosmochimica Acta). It is also clear that these alterations (solution, recrystallisation) are not always visible in the crystal structure of the foraminifers (Kozdon et al., 2011, and refs. therein, Paleoceanography). The comparison to clumped isotope temperatures is not convincing to rule out diagenesis as there are only eight data points shown and it has been shown that clumped isotope temperatures from planktonic foraminifers are also biased towards colder temperatures by diagenesis (Leutert et al., 2019, Geochimica et Cosmochimica Acta). Hence, at least parts of the paleoclimatic interpretations with relatively high d18O during the warm Pliocene might be probably related to diagenesis.

We agree with the reviewer that our temperature reconstructions are not to be considered 100% reliable in terms of their absolute values. But when are they ever (Cisneros-Lazaro et al., 2022)?

Dolomite indeed constitutes between 2 – 24% of the dominant mineral phases in the studied portion of Site U1459 (based on XRD analyses reported in Table T6 of the U1459 Site Report in the Proceedings of the International Ocean Discovery Program, vol. 356). We infer this is cryptocrystalline dolomite as dolomite was not observed in smear slides between 0 – 120 m CSF-A (Figure F5 in the U1459 Site Report). A similar pattern was observed in terms of planktonic foraminifera, with dolomite crystallization affecting foraminiferal specimens at cored depths >136.9 m CSF-A (p. 19 in U1459 Site Report). Dolomite is thus recognized throughout Site U1459 and becomes a stronger influence downcore. However, we do not observe a systematic change towards more positive $\delta^{18}O$ values with increasing core depth. On the contrary, **our data behaves opposite to the expected diagenetic imprint in high-carbonate settings** (e.g., Stainbank et al., 2020). We thus conclude that dolomite did not impair the planktonic foraminifera as paleoclimate recorders in the studied interval.

The possible cold-bias due to diagenesis (recrystallization in particular) has also been raised by Clara Bolton (R1) and we recognize that a diagenetic cold-bias deserves a more extensive discussion in the revised version of the manuscript. Specifically, a cold-bias paragraph will be added to §4.1. Additionally, in §2.3, we will stipulate that, while foraminifera were generally of good preservation, some specimens were partly dissolved and filled with thin layer of microcrystalline sparitic cement. The revised manuscript will mention that partly-dissolved specimens were dismissed for geochemistry, and a cleaning protocol has been in place to remove secondary calcite prior to clumped isotope analysis.

2. **Comments on the reliability of isotopic gradients for the reconstruction of Leeuwin Current strength**

I see the method of calculating planktonic foraminiferal gradients to reconstruct changes in the paleo-Leeuwin Current (warmer-colder) very problematic. It is known that the d18O of planktonic foraminifers are dependent on local temperature changes, local salinity changes and the global ice volume. Even if the global ice volume is known from the past there are still two variables which are unknown for each site location (local temperature and local salinity). Also, the clumped isotope temperatures do not really support the presented d18O record from Site 1459 as a temperature signal. This is due to the very few (eight) data points over the whole time period studied, that makes it impossible to compare long-term trends in temperature. Additionally, these data points show a huge error bar of up to 10°C.

This comment is rooted in an important misunderstanding. The method of calculating planktonic foraminiferal gradients is **designed to reconstruct changes in Leeuwin Current strength, not Leeuwin Current temperature**. This method starts from the assumption that -when the Leeuwin Current was **strong**- both endmembers of the 29°S-19°S transect were essentially bathed in the same water mass. When the Leeuwin Current was **weak**, the southern endmember (Site U1459) is expected to experience enhanced local cooling and local salinization of mixed layer waters compared to the localities of the northern endmember (Site U1463 and Site 763). In the latter *weak Leeuwin Current* case, Site U1459 undergoes a stronger shift towards more positive mixed-layer $\delta^{18}O$ values than Site U1463 / Site 763, and the isotopic gradient steepens. To avoid this misunderstanding among future readers, we will rewrite and extend the final paragraph of the introduction.

Additional aliquots of the eight clumped isotope temperatures have been measured to reduce the error bars on those temperatures. These will be included in the revised manuscript.

It was not clear to me why the d18O gradient between sites at 29° S and 19 ° S reflect the evolution of the Leeuwin Current better than the difference between sites located northwards (sites 1463 and 763). Presented model simulations (Fig. 2b) show miniscule temperature changes at about 29° S at Site 1459 between cold and warm stages but the gradients presented by the authors are mostly driven by huge changes in the planktonic foraminiferal d18O of Site 1459.

The isotopic difference between the northwards located sites (Site U1463 and 763) has been discussed and interpreted in De Vleeschouwer et al. (2018, EPSL, Fig 5D therein, see below). Basically, we found negligible differences in the isotopic values between both Sites throughout the studied Pliocene interval, with the exception for glacial Marine Isotope Stage M2 (MIS M2 at ~3.3 Ma). The indistinguishable $\delta^{18}O$ values at Sites U1463 and 763 indicate that both sites were bathing in the same water mass throughout the studied interval. Except for MIS M2 of course, which is when the Leeuwin Current reached its weakest Pliocene intensity. This low in Leeuwin Current strength caused Site 763A to temporarily reflect an Indian Ocean, rather than an ITF signal. For a more detailed discussion of these results, we refer the reader to De Vleeschouwer et al. (2018).

The reviewer’s suggestion to look at the U1463-763 isotopic gradient to reveal Indian Ocean dynamics thus only works when the Leeuwin Current is exceptionally weak (like during MIS M2). For most of the Pliocene and early Pleistocene, though, the U1463-763 gradient is too small-scale to reveal ocean dynamics on glacial-interglacial (G-IG) timescales. Therefore, to reconstruct variations in Leeuwin Current strength and ITF connectivity on G-IG timescales, one needs to look at larger-scale gradients, over longer distances, for example, Perth Basin vs Carnarvon Basin.

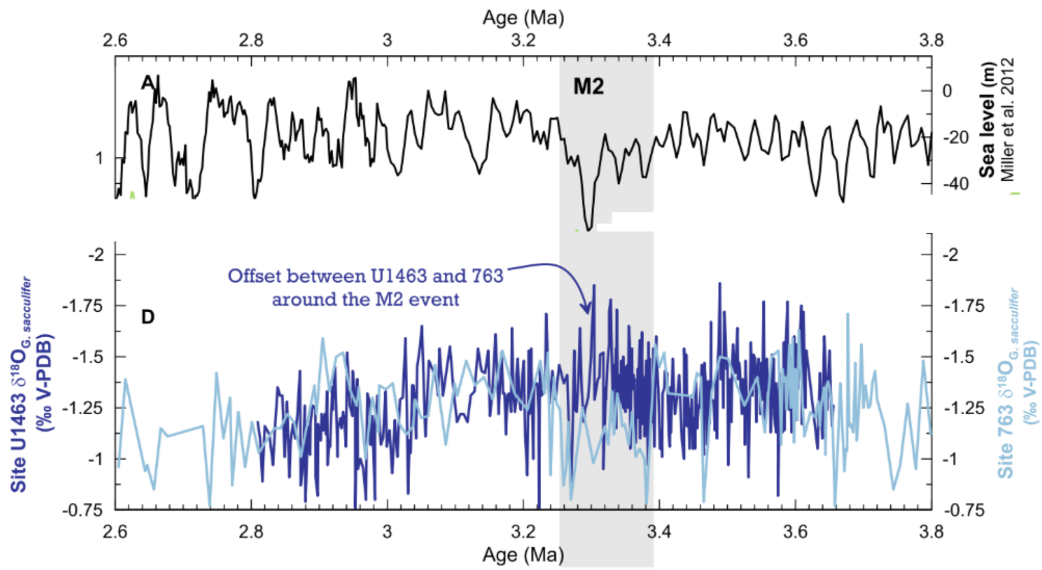


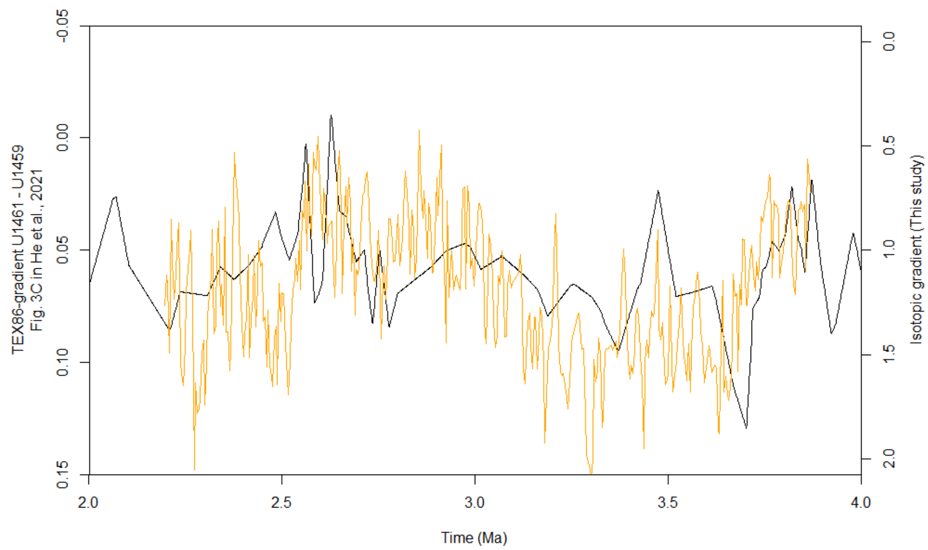
Figure 5A-D from De Vleeschouwer et al. (2018): This panel shows identical $\delta^{18}O$ values at Site U1463 and Site 763 throughout most of the studied interval, except for MIS M2.

Planktonic foraminiferal $\delta^{18}O$ of Site U1459 varies between -0.5 and +0.5 permille, which is not "*huge*" nor does the U1459 $\delta^{18}O$ overwhelm the isotopic gradient. We believe that this is sufficiently clear from Fig. 6a-b. Hence, no concrete changes to the manuscript are planned in response to this comment.

The numerical climate model simulations in Fig. 2 are included in the manuscript to illustrate a mismatch between state-of-the-art Pliocene climate simulations and proxy data. The mismatch is likely the result of the coarse spatial resolution of climate models, thereby failing to capture detailed yet important paleoceanographic dynamics. The discrepancy acts as an additional motivation for our study, which is indicated in the introduction and the figure caption. Hence, we do not understand why the reviewer puts forward this argument to question our interpretations.

A recent study by He et al., (2021, EPSL, mentioned by the authors) presented alkenone derived SST gradients from regions close to what the authors used to reconstruct their planktonic foraminiferal d18O gradients. However, the temporal development of these alkenone SST gradients is different from what the authors show from their d18O gradients.

This is not true. The results of He et al. (2021) corroborate our stable-isotope-based paleoclimate interpretations. The black line in the plot below (i.e. Fig. 3C in He et al., 2021) shows the TEX_{86} gradient between Sites U1461 (also in the northern Carnarvon Basin, just as Sites U1463 and 763) and U1459 (Perth Basin) in TEX_{86} units. This low-resolution reconstruction of Leeuwin Current intensity by He et al. (2021) is in agreement with our high-resolution $\delta^{18}O$-based reconstruction (orange line). As the TEX_{86} gradient is independent of temperature-calibrations, foraminiferal calcite diagenesis, or local $\delta^{18}O_{sw}$ changes, this co-variation provides strong support for our paleoclimatic interpretations, especially for the inferred period of weak Leeuwin Current between 3.7 – 3.1 Ma. This additional line of argumentation will be implemented in the revised version of the manuscript.



Comparison of the TEX_{86} gradient between Sites U1461 and U1459 (Fig. 3C in He et al., 2021) and the isotopic gradient from our work. Both proxies are completely independent of each other, yet show similar patterns throughout the Plio-Pleistocene, indicating the robustness of these results.

3. Detailed comments

- Lines 21, 39, 280-288 will be rephrased
- Line 81-86: The point made in the study of He et al. (2011) is relevant because it challenges the current paradigm that Leeuwin Current is weaker during glacials compared to interglacials.
- Line 245-255 and first paragraph of §3.2 will be moved to the methods section, as suggested by the reviewer.
- Line 297-301: A similar comment was made by Clara Bolton (R1). More information on the assumptions on δ^{18}Osw will be provided
- Line 334: Quantitative information will be provided
- Line 372 – 388: A similar comment was made by Clara Bolton (R1). It is true that our inferred habitat depth is rather deep, in closer agreement with the results of Rippert et al. (2016, equatorial Pacific) than with the results of Meinicke et al. (2021, West Pacific Warm Pool). 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 460-461 and 472-473: Results from cross-spectral analysis will be incorporated in the revised manuscript to convince the reviewer of time-series coherence on multiple timescales.
- Line 464-471: These indicators of relatively cold conditions in the Southern Hemisphere between 3.7 – 3.1 Ma will be added to Figure 8.
- Fig 1C: A similar comment was made by Clara Bolton (R1). This has to do with the resolution of the Copernicus Marine Service Information model, which seems to somewhat overestimate 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.

- Fig 3C: The distinction between new and previously-published data is clearly described in the text. We think it would make the figure unnecessary busy to indicate this here with different colors.
- Fig 7A: The long-term discrepancy is exactly our argument for delineating a secular period of weak Leeuwin Current between 3.7 – 3.1 Ma, coinciding with generally cooler conditions in the Southern Hemisphere.
- Fig. 8 will be redrawn with more distinct colors.

Cisneros-Lazaro, D., et al. (2022). Fast and pervasive diagenetic isotope exchange in foraminifera tests is species-dependent. *Nature Communications, 13*(1), 113. 10.1038/s41467-021-27782-8

De Vleeschouwer, D., et al. (2018). The amplifying effect of Indonesian Throughflow heat transport on Late Pliocene Southern Hemisphere climate cooling. *Earth and Planetary Science Letters, 500*, 15-27. https://doi.org/10.1016/j.epsl.2018.07.035

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

Stainbank, S., et al. (2020). Assessing the impact of diagenesis on foraminiferal geochemistry from a low latitude, shallow-water drift deposit. *Earth and Planetary Science Letters, 545*, 116390. https://doi.org/10.1016/j.epsl.2020.116390