Photic zone niche partitioning, stratification, and carbon cycling in the tropical Indian Ocean during the Piacenzian

RESPONSE TO REVIEWER 3
Reviewer comments are shown in **black**, with the author response in **blue**.

Deborah N. Tangunan, Ian R. Hall, Luc Beaufort, Melissa A. Berke, Alexandra Nederbragt, Paul R. Bown

General comments
The manuscript of Tangunan et al. "Photic zone niche partitioning, stratification, and carbon cycling in the tropical Indian Ocean during the Piacenzian" constitutes a valuable paleoceanographic reconstruction that provides new insights into the vertical structure and water masses dynamics of the tropical Indian Ocean during the Piacenzian.

The manuscript is well written, conceptually strong, and presents a novel dataset from a climatically critical but understudied region. The high quality of the research is expressed by the complex multiproxy approach based on high-resolution $\delta^{13}C$ and $\delta^{18}O$ records from benthic foraminifera and bulk coccolith fraction, low-resolution planktic foraminifera integrated with high resolution coccoliths assemblage data. The integration of multiple depth-habitat proxy and the calculation of isotopic gradients is a particular strength. The spectral and wavelet analyses clearly show the control of the different orbital parameters on stratification and global carbon cycling. The overall hypotheses are strongly supported by the data presented. The findings are significant for understanding low-latitude ocean dynamics and their role in global carbon cycling during intervals of global warmth and transient glaciation.

I believe the manuscript deserves to be published in Climate of the Past following minor revision before acceptance.

We thank the reviewer for their positive and supportive assessment of our manuscript. We are pleased that they find the multiproxy approach novel, the data high-quality, and the findings significant for understanding low-latitude ocean dynamics. We have carefully considered the specific comments provided below and have revised the manuscript accordingly.

1. Introduction

- I would suggest to include a map to show the location of the site, the eddies and the pathway of the Agulhas Current.

Agreed. A location map of Site U1476, with the modern Agulhas Current surface circulation has been added as new **Figure 1**.

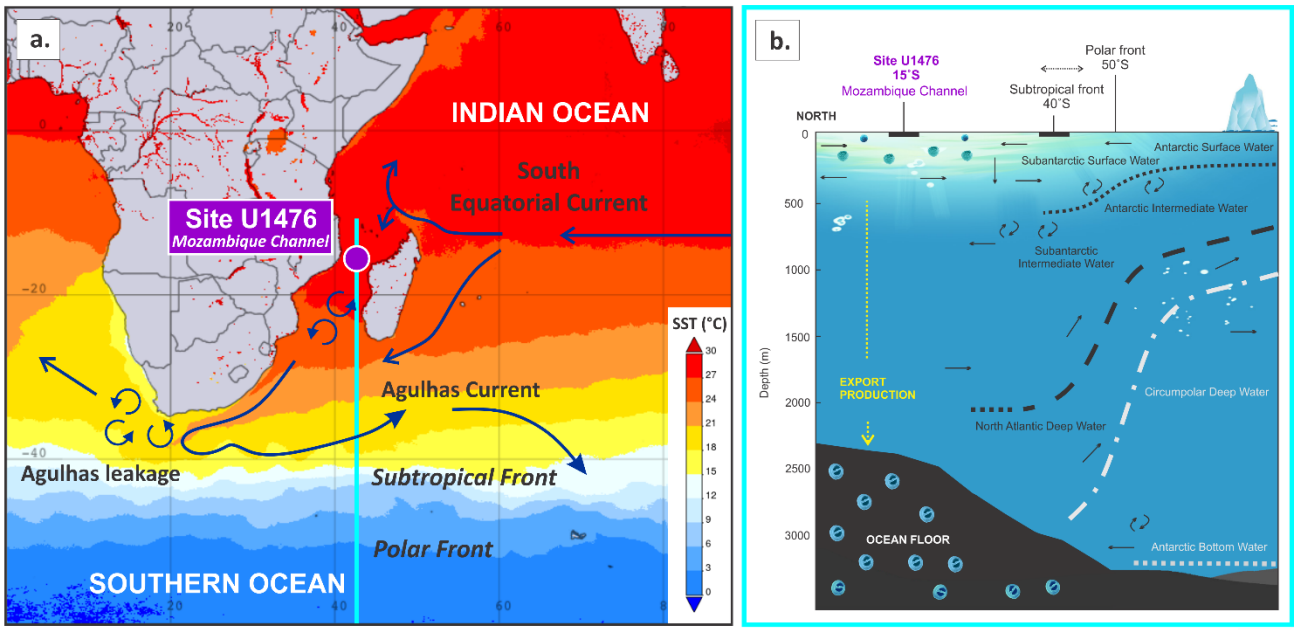

Figure 1. (a) Sea surface temperature (SST, °C; Acker & Leptoukh, 2007) and major currents in the Indian Ocean (Beal et al., 2011), showing the location of IODP Site U1476 in the Mozambique Channel. (b) Schematic cross-section showing the position of Site U1476 relative to major water masses (adapted from Westall and Fenner, 1991) and the Southern Ocean fronts.

- Please specify that even the coccolith assemblage data are at high resolution (Lines 86-91).

We have specified in the **Introduction** that the coccolith assemblage data are also at high resolution.

2. Methodology

- At the beginning of section 2.3 the author writes that "In intervals where there is not enough *wuellerstorfi*, other *Cibicidoides* species (i.e., *Cibicidoides bradyii*, *Cibicidoides mundulus*) or *Uvigerina* s pecies were chosen". Can you please clarify why you excluded $\delta^{13}C$ *Uvigerina* values? (Line 120)

We have added a sentence to **Section 2.3** to clarify this point. We excluded $\delta^{13}C$ values from *Uvigerina* because this genus is known to incorporate a significant metabolic (vital) effect, resulting in $\delta^{13}C$ values that are consistently ~1.0‰ lower than the ambient dissolved inorganic carbon, unlike the *Cibicidoides* group which more reliably records the $\delta^{13}C$ of seawater. This is a standard practice in paleoceanography (e.g., Zahn et al., 1986).

- I suggest specifying the preservation state of the shells and/or if a cleaning procedure of the shells has been followed. Please specify even if the picked shells have been crushed before the measurements.

As also raised by Reviewer 2, we have now revised **Section 2.3** to provide a more detailed description. The text now states that the foraminiferal tests were of good preservation, were gently rinsed with ultrapure DI water to remove adhering clays, quick-dried, and were crushed between glass plates prior to isotopic analysis.

- Please add some information in section 2.7 concerning the slides preparation technique and how many coccoliths have been counted/ number of frames analyzed.

We have added the following details to **Section 2.7**: Slides were prepared using the random settling technique (Beaufort et al., 2014). For each sample, 150 fields of view were automatically captured and

analyzed with the SYRACO (SYstème de Reconnaissance Automatique de Coccolithes) software at the European Centre for Research and Teaching in Environmental Geosciences (CEREGE, France), yielding counts ranging from 1,565 to 20,443 coccolith specimens (average ~6,219 per sample).

3. Results and discussion

The detailed discussion of the *Florisphaera profunda* dominance and its isotopic implications is remarkable, underscoring the role of deep-photic species in shaping bulk isotopic signature. However, I agree that the influence of the dominant taxon may obscure signals from shallower-dwelling forms. This might be the case of *Reticulofenestra* spp. which shows an important contribution not only in the assemblage, but also in the coccolith mass and especially in the carbonate contribution where the mean value (43%) is higher than *F. profunda*. I agree with the authors which state "This highlights the need for species-specific geochemical analyses to resolve the contributions of individual taxa to the bulk signal". As pointed out by reviewer 1, the inclusion of a table summarizing expected $\delta^{13}C$–$\delta^{18}O$ offsets for key taxa (e.g., *F. profunda*, *Reticulofenestra, Calcidiscus*, *Helicosphaera*) is recommended.

We thank the reviewer for this insightful comment and their agreement on the need for species-specific analyses. In line with this suggestion and a similar one from Reviewer 1, we have added a supplementary table (**Table S3**) that summarizes the expected $\delta^{13}C$-$\delta^{18}O$ offsets and ecological preferences for the key coccolithophore taxa discussed.

However, it is important to note that quantitative species-specific $\delta^{13}C$–$\delta^{18}O$ offsets remain incompletely constrained, particularly for deep-photic zone species, such as *F. profunda*, which has not been successfully cultured. Because coccoliths cannot yet be reliably isolated for single-species isotopic measurements in fossil assemblages, most of the available data are derived from a limited number of culture experiments and modern core-top calibrations that focus on surface-dwelling taxa (e.g., *Emiliania huxleyi*, *C. leptoporus*).

The new supplementary table should therefore be regarded as a qualitative synthesis, indicating the expected direction and approximate magnitude of isotopic offsets rather than fixed numerical corrections. This addition allows readers to evaluate the plausibility of the proposed link between assemblage composition and bulk $\delta^{13}C$–$\delta^{18}O$ variability, while acknowledging the current analytical and experimental constraints in single-species coccolith isotope research.

Table S3. Summary of depth habitat and expected $\delta^{13}C$ and $\delta^{18}O$ vital effects for key coccolithophore taxa, based on culture, core-top, and fossil studies. The direction and magnitude of the isotopic offset (vital effect), reported as more positive or more negative, is given relative to inorganic calcite equilibrium or other taxa. The bulk sediment isotopic signal must therefore be interpreted as a mixture of these species-specific signatures.

Taxon	**Typical Depth Habitat** (Winter et al., 1994)	**$\delta^{13}C$ Behaviour**	**$\delta^{18}O$ Behaviour**	**Summary of Isotopic Offsets (Vital Effects)**
Calcidiscus leptoporus	Upper to middle photic zone (e.g., ~0-100m)	**More negative.** Substantial negative vital effect (~ -2.5‰ offset from inorganic) (Hermoso et al., 2016).	**More negative.** Substantial negative vital effect (~ -1.4‰ offset from inorganic); shows 1.5‰ variation with growth rate (Ziveri et al.,	**"Light Group"**. At high DIC (~12 mmol/kg), the negative $\delta^{13}C$ vital effect decreases significantly (to -0.4‰) and the negative $\delta^{18}O$ effect also decreases (moves towards inorganic) (Hermoso et al., 2016).

Taxon	Typical Depth Habitat (Winter et al., 1994)	$\delta^{13}C$ Behaviour	$\delta^{18}O$ Behaviour	Summary of Isotopic Offsets (Vital Effects)
			2003; Hermoso et al., 2016).	
Coccolithus pelagicus	Upper to middle photic zone (e.g., ~0-100m)	**More negative.** Substantial negative vital effect (~ -2.5‰ offset from inorganic) (Hermoso et al., 2016).	**Near Inorganic.** Very small positive vital effect (~ +0.5‰) (Hermoso et al., 2016).	**"Near-Equilibrium Group"** (for O). Shows a large "jump" in $\delta^{13}C$ between 2-4 mmol/kg DIC. At high DIC, the negative $\delta^{13}C$ vital effect vanishes; the small $\delta^{18}O$ effect remains constant and is insensitive to DIC/pH (Hermoso et al., 2016).
Emiliania (Gephyrocapsa) huxleyi	Upper photic zone (e.g., ~0-50m); often forms blooms in well-lit, stratified surface waters.	**More positive.** Substantial positive vital effect (~ +2‰ offset from inorganic) (Hermoso et al., 2016).	**More positive.** Substantial positive vital effect (~ +2‰ offset from inorganic) (Hermoso et al., 2016).	**"Heavy Group"**. At high DIC (~12 mmol/kg), both $\delta^{13}C$ and $\delta^{18}O$ vital effects decrease significantly; $\delta^{13}C$ converges to inorganic value, leaving a residual +1.3‰ $\delta^{18}O$ vital effect (Hermoso et al., 2016).
Florisphaera profunda	Deep photic zone (~60–200 m); deep chlorophyll maximum	**More positive.** Heaviest $\delta^{13}C$ relative to expectation from depth (Bolton et al., 2012).	**More positive.** Heaviest $\delta^{18}O$ of all size-separated fractions (Bolton et al., 2012).	No culture data; composition inferred from core-top/fossil records. Records the heaviest isotopes; in the Plio-Pleistocene Transition (PPT), its $\delta^{18}O$ is ~1.5–2‰ heavier than large *Helicosphaera*. (Bolton et al., 2012).
Gephyrocapsa oceanica	Upper photic zone (e.g., ~0-50m); similar habitat to *E. huxleyi*.	**Variable.** Large range of $\delta^{13}C$ values (5‰) both above and below expected equilibrium (Ziveri et al., 2003).	**Variable.** Large range of $\delta^{18}O$ values (5‰) both above and below expected equilibrium (Ziveri et al., 2003).	Exhibits strong interspecific vital effects for both oxygen and carbon isotopes (Ziveri et al., 2003).
Helicosphaera carteri	Upper to middle photic zone (e.g., ~0-100m)	**More negative.** (Bolton et al., 2012).	**More negative** (Bolton et al., 2012). Temperature-dependent, consistent with equilibrium paleotemperature relationship	The "large cell" end-member. In PPT, $\delta^{13}C$ and $\delta^{18}O$ are ~1.5–2‰ lighter than small reticulofenestrids (Bolton et al., 2012).

Taxon	Typical Depth Habitat (Winter et al., 1994)	$\delta^{13}C$ Behaviour	$\delta^{18}O$ Behaviour	Summary of Isotopic Offsets (Vital Effects)
			(Ziveri et al., 2003).	
Paleocene Placoliths (e.g., *Toweius, Coccolithus*)	Upper to middle photic zone (inferred from morphology and assemblage context).	**Minimal difference.** Mean $\Delta\delta^{13}C$ = 0.17‰ (Bolton et al., 2012).	**Small difference**. Mean $\Delta\delta^{18}O$ = 0.66‰; smaller fraction slightly enriched (Bolton et al., 2012).	Paleocene-Eocene Thermal Maximum data show drastically reduced vital effects compared to modern, suggesting more uniform carbon acquisition strategies under high-pCO_2 conditions (Bolton et al., 2012).
Reticulofenestra spp. (e.g., *R. minutula*)	Upper–middle photic zone	**More positive.** Slightly lighter (by ~0.5–1 ‰) than equilibrium and smaller taxa; varies with size and productivity (Bolton et al., 2012).	**More positive.** Lower $\delta^{18}O$ compared to smaller-celled species (Bolton et al., 2012).	Larger cell size associated with lower isotopic fractionation. In PPT/Last Glacial Maximum, $\delta^{13}C$ and $\delta^{18}O$ are ~1.3 to 2‰ heavier than in large *Helicosphaera* (Bolton et al., 2012).

4. Conclusion

- I would specify that coccolith abundance data are at high resolution here as well.

We have specified in the conclusion that the coccolith assemblage data are high-resolution.

Specific comments

- Using both “coccolith fraction” and “bulk fine fraction (<20 µm)” could confuse the reader. I also recommend adopting a single term and applying it consistently through the manuscript.

We have addressed this point, as also suggested by other reviewers. The term "coccolith fraction" is now used consistently throughout the manuscript.

- Please add the reference for the orbital parameter curves in the figure captions 3 and S1 (obliquity).

We have added the reference for the orbital parameter curves (Laskar et al., 2011) to the captions of **Figures 3** and **S1**.

- Overall, the language is excellent, requiring only minor copy-editing to improve sentence conciseness.

We thank the reviewer for their positive assessment. We have performed a thorough copy-edit of the manuscript to improve sentence conciseness and overall readability.

Recommendation: Minor revisions

The manuscript has clear scientific merit and represents an important contribution to understanding tropical ocean stratification and carbon cycling during Pliocene. Addressing the above-mentioned points will strengthen the paper and its clarity.

We thank the reviewer for their positive recommendation and valuable comments. We have addressed all points raised, which has significantly improved the clarity and robustness of the manuscript.

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