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

RESPONSE TO REVIEWER 1
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
This is an excellent, data-rich contribution that sheds new light on the vertical structure of the tropical Indian Ocean during the Piacenzian. The integration of $\delta^{13}C$ and $\delta^{18}O$ records from benthic and planktic foraminifera and bulk coccolith fractions, combined with assemblage data, is novel and highly relevant for understanding carbon cycling and stratification in a key low-latitude region.

The manuscript is generally well-written, and the interpretations are thoughtful and supported by the data. The findings on the role of *Florisphaera profunda* in biasing bulk coccolith isotope signals are particularly important for future proxy studies. The linkage between orbital-scale variability, stratification, and global carbon cycling is compelling.

I recommend minor revisions before acceptance. The main points below aim to improve clarity, strengthen interpretations, and enhance the broader impact of this study.

We thank the reviewer for their positive and constructive evaluation of our manuscript. We appreciate the recognition of the novelty, data quality, and contribution of this study to understanding vertical ocean structure and carbon cycling during the Piacenzian. The reviewer's comments have been carefully considered, and we have revised the manuscript accordingly to improve clarity, strengthen the interpretations, and highlight the broader significance of our findings.

Major Comments
1. Novelty and Broader Context
The study fills an important spatial gap in Piacenzian reconstructions by providing a tropical Indian Ocean perspective. Emphasizing how these findings complement better-studied Atlantic and Pacific records (e.g., in the Abstract and Conclusions) would highlight the significance of this work for global carbon cycle reconstructions.

We have revised both the **Abstract** and **Conclusions** to better emphasize how our results complement existing Piacenzian reconstructions from the Atlantic and Pacific. Specifically, we now highlight that IODP Site U1476 provides the first vertically resolved $\delta^{13}C$-$\delta^{18}O$ and assemblage dataset from the tropical Indian Ocean, a region previously underrepresented in global syntheses. The revised text notes that these results bridge the gap between well-documented Atlantic and Pacific records, thereby strengthening the global framework for understanding ocean-atmosphere carbon cycling during the Piacenzian.

2. Age Model and Orbital Phasing
The age model, tuned to LR04, is robust but introduces potential circularity when discussing phase relationships with orbital forcing. Because the phasing between pCO_2, $\delta^{13}C/\delta^{18}O$, and insolation is a core conclusion, a brief discussion of age-model uncertainties (e.g., ±kyr at tie-points) and their implications for inferred leads/lags would be valuable (e.g., Section 3.4 and Fig. 4).

We thank the reviewer for this important point. We agree that age-model uncertainty must be considered when interpreting orbital phasing and phase relationships. We have added the following paragraph to **Section 3.4** to explicitly address this point:

Since the Site U1476 benthic $\delta^{18}O$ record is tuned to the LR04 global stack, we acknowledge that tie-point uncertainties of approximately ±3 to 5 kyr may affect the precise alignment of $\delta^{13}C$ and $\delta^{18}O$ signals with individual insolation peaks. This uncertainty reflects both the ~2.25 kyr resolution of our isotope sampling and the correlation accuracy achievable during visual and statistical tuning to LR04 at orbital timescales (Lisiecki and Raymo, 2005; Meyers, 2014). While such uncertainties may influence the exact timing of proxy responses relative to insolation maxima or minima, they do not compromise the identification of obliquity- and precession-scale periodicities in our spectral and wavelet analyses. Accordingly, our interpretations emphasize the pacing and amplitude of orbital-scale variability rather than precise phase relationships among orbital parameters, pCO_2, and proxy records. We did not attempt to resolve detailed lead–lag relationships, as our focus lies in characterizing the expression and pacing of orbital-scale variability in carbon cycling and stratification. The lead–lag patterns discussed later (**Section 3.5**) provide a qualitative comparisons with the independently derived $\delta^{11}B$-based pCO_2 record from ODP Site 999 (de la Vega et al., 2020), which explicitly resolved orbital-scale pCO_2 variability during the mid-Piacenzian. Our aim is to contextualise the Site U1476 isotope trends within that global CO_2 framework, rather than to infer mechanistic phase relationships. Thus, while age-model uncertainties may affect the precision of phase estimates, they do not undermine the broader interpretation of orbital forcing and its expression in the tropical Indian Ocean.

3. Coccolith Isotopic Interpretation

The discussion convincingly attributes the lower $\delta^{13}C$ and heavier $\delta^{18}O$ of the coccolith fraction to the dominance of deep-photic *F. profunda*. Still, the relative influence of vital effects versus habitat depth and any diagenetic alteration remains qualitative.

- Please clarify how smear-slide observations (≥95 % coccoliths) support the interpretation of minimal diagenetic overprint.

We agree that our evaluation of the relative influence of diagenetic alteration is qualitative, as it is based on visual assessment under a light microscope. To clarify, we have added a sentence addressing this in **Section 3.2**. Smear-slide inspection under light microscopy shows that the <20 µm fraction is almost entirely composed of coccoliths (≥95 % by visual estimation), with only trace or no occurrences of other very fine-grained carbonate particles. The coccoliths display well-preserved, intact shields with no visible secondary calcite overgrowth, dissolution pitting, or micritic cement, all of which would indicate diagenetic alteration.

- A table or schematic summarizing expected $\delta^{13}C$–$\delta^{18}O$ offsets for key taxa (e.g., *F. profunda*, *Reticulofenestra*, *Calcidiscus*, *Helicosphaera*) based on culture or core-top studies would help readers contextualize the bulk isotopic signal (can be in supplemental material)

We thank the reviewer for this suggestion. We have now added a new table to the supplement (**Table S3**, see below), which compiles isotopic offsets (vital effects) and depth habitats of representative taxa, based on data from published culture experiments, core-top, and fossil studies.

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., 2003; Hermoso et al., 2016).	**"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).
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

Taxon	**Typical Depth Habitat** (Winter et al., 1994)	**$\delta^{13}C$ Behaviour**	**$\delta^{18}O$ Behaviour**	**Summary of Isotopic Offsets (Vital Effects)**
				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 (Ziveri et al., 2003).	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).
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. Productivity and Export Efficiency

The inference that high surface productivity during the mPWP did not lead to efficient export due to stratification is plausible but indirect. Acknowledging the lack of independent export-production proxies (e.g., opal, Ba/Al, % C org) and noting that this remains a hypothesis would make the discussion more balanced.

The discussion has been updated to clarify that the suggested link between stratification and reduced export efficiency is inferred from isotopic patterns and assemblage composition and remains tentative given the lack of independent export-production proxies. We have added the following statement in **Section 3.3**:

The apparent decoupling between elevated surface productivity and stable vertical $\delta^{13}C$ gradients during the mPWP likely reflects nutrient recycling within the surface layer under strong stratification rather than enhanced export to depth. However, as this inference is derived solely from isotopic and assemblage patterns without supporting geochemical tracers of export flux (e.g., opal, Ba/Al, organic carbon), it should be considered a first-order interpretation subject to validation by additional proxy records.

5. Conceptual Framework for Orbital Controls

The evidence for obliquity-dominated deep-water variability versus precession-dominated surface variability is compelling. A simple schematic summarizing the proposed mechanisms (linking Southern Ocean ventilation, Indian Ocean stratification, and orbital forcing) would help communicate these insights to a broad readership.

We have added a new **Figure 1** to illustrate the regional oceanographic setting and the proposed mechanistic framework linking orbital forcing to water mass structure at our study site.

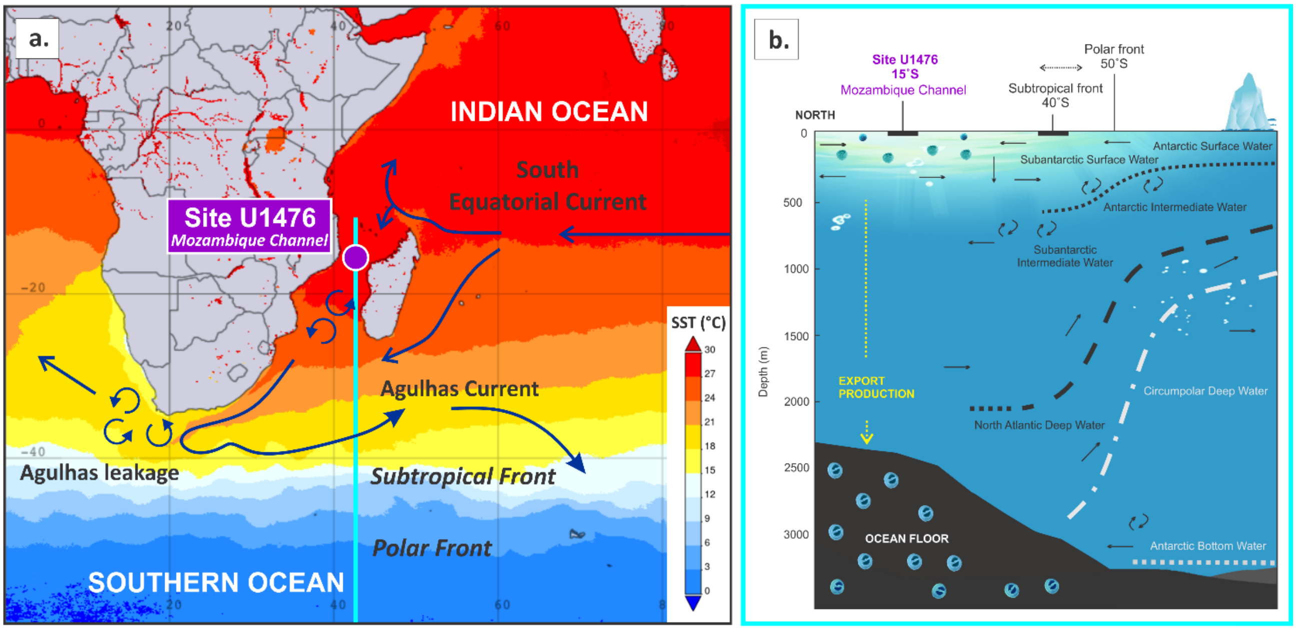

Figure 1. (a) Sea surface temperature (SST, °C; Acker & Leptoukh, 2007) and major currents in the Indian Ocean (Beal et al., 2011), showing the location of IODP Site U1476 in the Mozambique Channel. (b) Schematic cross-section showing the position of Site U1476 relative to major water masses (adapted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

6. pCO_2 and Isotopic Gradients

The discussion of leads/lags between $\delta^{13}C/\delta^{18}O$ and pCO_2 (Fig. 5) is rich but dense. A brief table summarizing the key intervals (e.g., MIS M2 onset, KM2 event, mPWP peak), the sign of isotopic shifts, and hypothesized drivers (e.g., AMOC weakening, Southern Ocean ventilation) would improve accessibility.

We thank the reviewer for this suggestion. To improve the clarity and accessibility of the discussion on the leads/lags between $\delta^{13}C/\delta^{18}O$ and pCO_2, we have added a summary table to the supplement (**Table S4**, see below). This table outlines the key climatic intervals, the observed isotopic shifts, and the primary drivers as proposed in our study.

Table S4. Summary of key climatic intervals, associated $\delta^{13}C$ and $\delta^{18}O$ shifts, and hypothesized drivers across the mid-Piacenzian Warm Period (mPWP) at Site U1476. BF (benthic foraminifera), PF (planktic foraminifera), CO (coccolith fraction).

Climatic Interval (Age, Ma)	$\delta^{13}C$ Shifts & Gradients	$\delta^{18}O$ Shifts & Gradients	Hypothesized Primary Drivers
Pre-MIS M2 (~3.42–3.39 Ma)	Transient decline in $\Delta\delta^{13}C_{BF\text{-}CO}$ and $\Delta\delta^{13}C_{PF\text{-}CO}$	Amplified variability in $\Delta\delta^{18}C_{BF\text{-}CO}$	Intermediate-depth ventilation and mixing beneath a still-stratified surface layer.
Approaching MIS M2 (~3.31 Ma)	Increase in $\Delta\delta^{13}C_{BF\text{-}CO}$ and $\Delta\delta^{13}C_{PF\text{-}CO}$	Decrease in $\Delta\delta^{18}C_{BF\text{-}CO}$	Long-term warming and re-establishment of a stratified ocean with reduced vertical exchange.
MIS M2 Glacial (~3.30–3.28 Ma)	$\delta^{13}C_{BF}$ and $\delta^{13}C_{CO}$ minima; followed by recovery (stronger in $\delta^{13}C_{BF}$)	Peaks in $\Delta\delta^{18}O_{BF\text{-}CO}$ and $\Delta\delta^{18}O_{BF\text{-}PF}$ (deep cooling)	*Onset:* High-latitude cooling, suppressed Atlantic Meridional Overturning Circulation, intensified stratification. *Termination:* Increased deep ocean ventilation, potentially lagging surface reorganisation.
mPWP Peak Warmth (~3.264–3.025 Ma)	Stable but persistent vertical $\delta^{13}C$ gradients; high surface productivity but inefficient export.	Generally negative $\delta^{18}O$ values (warming); muted vertical gradients.	Strong thermal stratification, reduced overturning, and weakened thermocline ventilation limiting nutrient supply and carbon export.
MIS KM2 Event (within mPWP)	Sharp collapse in all vertical $\Delta\delta^{13}C$ gradients.	Decline in all vertical $\Delta\delta^{18}O$ gradients (subsurface warming)	Pulse of enhanced ventilation; breakdown of vertical stratification, possibly linked to high latitude forcing and lateral advection.
Post-KM2 mPWP	Amplified variability in $\Delta\delta^{13}C_{BF\text{-}CO}$ and $\Delta\delta^{13}C_{BF\text{-}PF}$.	Pronounced variability in $\Delta\delta^{18}O_{BF\text{-}CO}$	Dynamic shifts in nutricline depth and reinvigorated biological pump; recurrent deep-water mass reorganisations.

Minor Comments

- Ensure consistent use of "coccolith fraction" vs. "bulk fine fraction (<20 µm)".

We have now implemented this change. The term is defined once at its first mention as "fine fraction bulk carbonate (<20 µm, herein referred to as the coccolith fraction)" and is now used consistently as "coccolith fraction" throughout the remainder of the manuscript.

- Improve legibility of figure axes and legends (Figs. 3–5; Supplementary Figs. S1–S2) for print and grayscale viewing (i.e., increase font size slightly)

We have now increased the font sizes and improved the contrast for all axes and legends.

- A few recent studies on Indo-Pacific upwelling and Plio-Pleistocene productivity (e.g., Ford et al., 2022) could be cited to further contextualize results.

We have now incorporated the recommended reference (Ford et al., 2022; Ford et al., 2025) into Section 3.5 to better contextualize our findings on carbon cycling within the broader framework of Plio-Pleistocene ocean ventilation.

- Language is generally excellent; only minor copy-editing is needed to shorten some long sentences.

We thank the reviewer for their positive feedback. We have performed a thorough copy-edit of the manuscript to shorten long sentences and improve overall readability.

Recommendation: Minor revisions

This manuscript is a substantial and timely contribution to understanding tropical controls on Pliocene carbon cycling and orbital-scale climate feedbacks. Addressing the points above (particularly clarifying age-model uncertainty, refining coccolith isotope interpretation, and contextualizing productivity–export relationships) will further strengthen an already strong study.

We thank the reviewer for their positive and constructive feedback. We have carefully addressed all comments, with particular focus on clarifying the age-model uncertainty, refining the interpretation of the coccolith isotope records, and contextualizing the productivity-export relationships. We believe these revisions have strengthened the manuscript as suggested.

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