

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

RESPONSE TO REVIEWER 2

Reviewer comments are shown in **black**, with the author response in **blue**.

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

General comments

The article “Photic zone niche partitioning, stratification, and carbon cycling in the tropical Indian Ocean during the Piacenzian” present novel $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records from benthic and planktic foraminifera, and bulk coccolith fraction, which combined with assemblage data provides a unique view of the vertical structure in a low-latitude key region during the Piacenzian. Furthermore, this study also provides new insights to broaden the knowledge on the carbon cycling and ocean stratification in this location.

Overall, the manuscript reads well and presents a solid structure as all the critical points are addressed. Furthermore, the interpretation, which is deeply developed and grounded on a strong literature background, is supported by the data presented in the study. Particularly, findings on the processes connecting and biasing the $\delta^{13}\text{C}$ signal between the different water layers are of great interest and represents an advance in the understanding of the carbon cycle. Moreover, uncovering the effect of having high abundances of certain nannofossil species (e.g., *Florisphaera profunda*) represents a step forward in the interpretation of future proxy studies.

Based on the above-mentioned statements I recommend *minor revisions* before acceptance. Following lines provide a series of suggestions intended to improve the clarity and readability of the manuscript.

We thank the reviewer for their positive assessment of our manuscript and for their thoughtful suggestions. We are pleased that they find the data novel, the structure solid, and the interpretations well-developed and supported. We have carefully considered all points raised below and have revised the manuscript to improve its clarity and readability accordingly.

General comments

1. Methodology

In section 2.3 Benthic foraminifera carbon and oxygen stable isotopes, the authors clearly state a step-by-step process to achieve the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records presented. However, I wonder if there were any further cleaning steps to ensure the usage pristine benthic and planktonic foraminifera species or if samples were already good enough after the disaggregation and subsequent sieving process. In this regard, I would recommend adding a plate with some images of the remaining specimens from some of the samples used (if possible). Otherwise, I would clearly state that samples condition was already good enough for the measurements without further cleaning protocols.

We have now revised **Section 2.3** to provide a more detailed description of the cleaning protocol. The text now states that after hand-picking, the foraminiferal tests underwent a gentle rinsing in ultrapure DI water to remove any adhering fine carbonate material, followed by quick drying, crushing and homogenization. This additional step ensured the analysis of pristine calcite. We confirm that the foraminiferal tests were of excellent preservation quality, as assessed during picking, but we are unable to provide photographic plates as the samples were fully used during the isotopic analysis.

2. Results and discussion

First of all, I want to emphasise again how pleasant it was to read this section. It clearly expresses the authors hypotheses in a really narrative and natural way, which makes it easy for the reader to understand.

In section 3.1 Vertical water column plankton community structure, the authors present the $\delta^{13}\text{C}$ values for the benthic and planktonic foraminifera, and the bulk coccolith fraction. Specifically, the authors express in Lines 203-204 that “This similarity in the range of $\delta^{13}\text{C}$ values with the benthic record may indicate a partial integration of deep photic zone DIC signals, especially under stratified conditions.”. Despite that I absolutely agree with the fact that integration of deep waters signal within upper layers (especially during high stratified periods), I cannot happen but wonder, how is this relation working for getting lower $\delta^{13}\text{C}$ values on the bulk coccolith fraction. Lately (Lines 209-211), the authors evoke recycling of organic carbon and stratification as potential mechanisms explaining the difference between the bulk coccolith fraction and the planktonic foraminifera. Could this be also the case for the lower values compared with the benthic $\delta^{13}\text{C}$?

We thank the reviewer for their positive feedback and for raising this critical point. The reviewer is correct to identify this apparent paradox. The mechanism is indeed the same: the remineralization of organic matter at depth.

Within a strongly stratified water column, the deep photic zone (where *F. profunda* thrives) can become isolated and enriched in respired CO_2 , which is depleted in ^{13}C . This creates a reservoir of ^{13}C -depleted dissolved inorganic carbon (DIC). While the benthic foraminifera record the $\delta^{13}\text{C}$ of well-ventilated, ^{13}C -enriched deep waters, the coccolith fraction, dominated by a deep-dwelling species, records the ^{13}C -depleted DIC signature of this isolated, respired carbon pool in the lower photic zone. Consequently, the coccolith $\delta^{13}\text{C}$ can be lower than both the surface-dwelling planktic foraminifera and the underlying, well-ventilated deep waters.

We have clarified this explanation in **Section 3.1** to clearly state that the same process (i.e., remineralization of organic carbon under stratified conditions that limits vertical exchange) can lead to the coccolith fraction recording lower $\delta^{13}\text{C}$ values than both the surface-dwelling planktic foraminifera and the deep-sea benthic foraminifera.

As already stated by reviewer 1 (point 6 of major comments), I consider that adding a table with the $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and the $\text{D}\delta^{13}\text{C}$ and $\text{D}\delta^{18}\text{O}$ values for key intervals would improve accessibility and serve as core for readers while going through the discussion. Furthermore, in section 3.5 Regional feedback and global context in a warm, high CO_2 world, the authors evoke a series of very specific processes and scenarios, such as MIS M2, which is characterised by a low productivity, enhanced stratification and low export efficiency according to their interpretations. In this regard, I would suggest to add a figure with a sketch to help the reader to visualize the conditions described in the text and guide them through this part of the discussion.

In agreement with a similar suggestion from Reviewer 1, we have added a summary table in 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. We have also created a new schematic figure (**Figure 1**, see below) to visually summarise the proposed mechanisms and oceanographic conditions described in the discussion.

Table S4. Summary of key climatic intervals, associated $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ 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)	$\delta^{13}\text{C}$ Shifts & Gradients	$\delta^{18}\text{O}$ Shifts & Gradients	Hypothesized Primary Drivers
Pre-MIS M2 (~3.42–3.39 Ma)	Transient decline in $\Delta\delta^{13}\text{C}_{\text{BF-CO}}$ and $\Delta\delta^{13}\text{C}_{\text{PF-CO}}$	Amplified variability in $\Delta\delta^{18}\text{C}_{\text{BF-CO}}$	Intermediate-depth ventilation and mixing beneath a still-stratified surface layer.
Approaching MIS M2 (~3.31 Ma)	Increase in $\Delta\delta^{13}\text{C}_{\text{BF-CO}}$ and $\Delta\delta^{13}\text{C}_{\text{PF-CO}}$	Decrease in $\Delta\delta^{18}\text{C}_{\text{BF-CO}}$	Long-term warming and re-establishment of a stratified ocean with reduced vertical exchange.
MIS M2 Glacial (~3.30–3.28 Ma)	$\delta^{13}\text{C}_{\text{BF}}$ and $\delta^{13}\text{C}_{\text{CO}}$ minima; followed by recovery (stronger in $\delta^{13}\text{C}_{\text{BF}}$)	Peaks in $\Delta\delta^{18}\text{O}_{\text{BF-CO}}$ and $\Delta\delta^{18}\text{O}_{\text{BF-PF}}$ (deep cooling)	<i>Onset:</i> High-latitude cooling, suppressed Atlantic Meridional Overturning Circulation, intensified stratification.
			<i>Termination:</i> Increased deep ocean ventilation, potentially lagging surface reorganisation.
mPWP Peak Warmth (~3.264–3.025 Ma)	Stable but persistent vertical $\delta^{13}\text{C}$ gradients; high surface productivity but inefficient export.	Generally negative $\delta^{18}\text{O}$ 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 $\Delta\delta^{13}\text{C}$ gradients.	Decline in all vertical $\Delta\delta^{18}\text{O}$ 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 $\Delta\delta^{13}\text{C}_{\text{BF-CO}}$ and $\Delta\delta^{13}\text{C}_{\text{BF-PF}}$.	Pronounced variability in $\Delta\delta^{18}\text{O}_{\text{BF-CO}}$	Dynamic shifts in nutricline depth and reinvigorated biological pump; recurrent deep-water mass reorganisations.

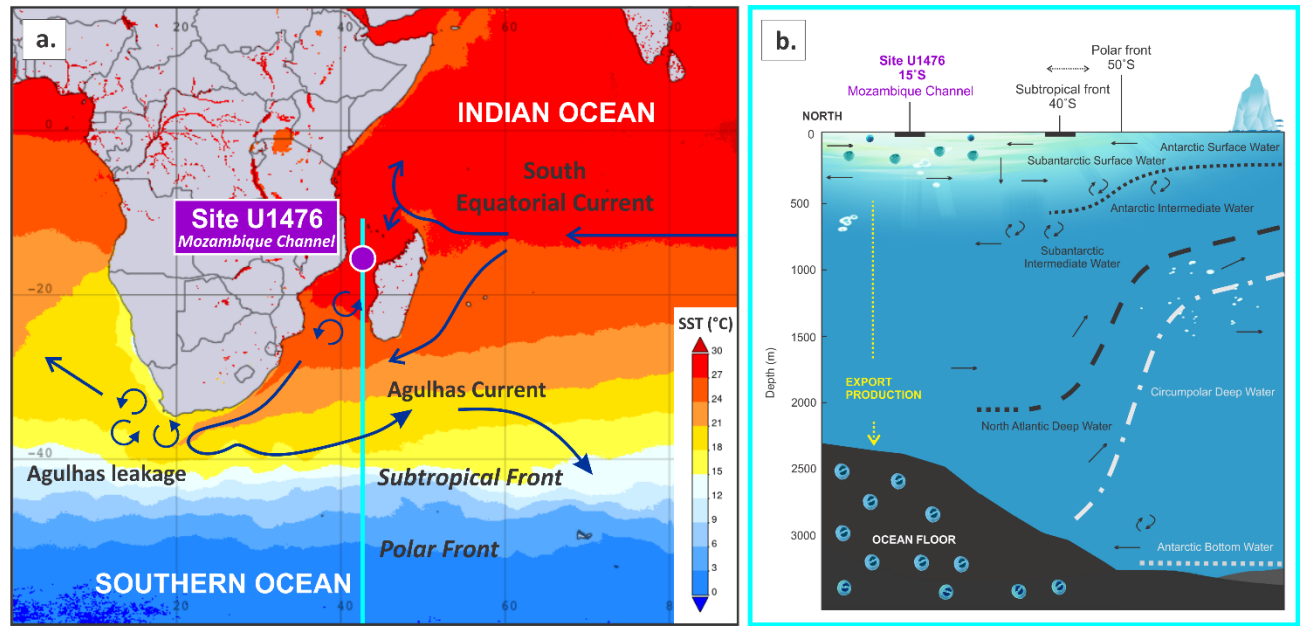


Figure 1. (a) Sea surface temperature (SST, °C; Acker & Leptoukh, 2007) and major currents in the Indian Ocean (Beal et al., 2011), showing the location of IODP Site U1476 in the Mozambique Channel. (b) Schematic cross-section showing the position of Site U1476 relative to major water masses (adapted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

Specific comments

- As stated by reviewer 1, using both “coccolith fraction” and “bulk fine fraction (<20 μm)” can be confusing. Therefore, I suggest to use one of the terms consistently through the manuscript.

We have addressed this point, consistent with our response to Reviewer 1. The term "coccolith fraction" is now used consistently throughout the manuscript.

- The benthic foraminifera species *wuellerstorfi* has recently be renamed as *Lobatula wuellerstorfi* (please, for specific details refer to <https://www.marinespecies.org/aphia.php?p=taxdetails&id=112890>). However, I understand that most of the studies still consider the name *C. wuellerstorfi* when referring to this benthic species.

We thank the reviewer for pointing out the updated taxonomy. We have revised the manuscript to use the format *Cibicidoides wuellerstorfi* (syn. *Lobatula wuellerstorfi*) to align with common usage in palaeoceanographic literature while acknowledging the current taxonomic revision.

- Writing and grammar are excellent and only a quick check to correct typos need to be done.

We thank the reviewer for their positive assessment. We have performed a thorough proofreading to correct minor typos.

Decision: Minor revisions

The manuscript provides a novel contribution to understanding the carbon cycle, and its relation to orbital-scale feedback processes during the Pliocene. I believe that implementing the above-mentioned comments within the manuscript will provide clarity and accessibility to a broader audience and provide additional support for this work.

We thank the reviewer for their positive decision and valuable recommendations. We have implemented all suggested changes to enhance clarity, accessibility, and scientific robustness of the manuscript. We believe it is now significantly strengthened.

References

- Acker, J.G. and Leptoukh, G.: Online Analysis Enhances Use of NASA Earth Science Data. Eos, Transactions American Geophysical Union, 88, 14-17, 2007.
- Beal, L. M., Ruijter, W. P. M. D., Biastoch, A., Zahn, R., and 136, S. W. I. W. G.: On the role of the Agulhas system in ocean circulation and climate, Nature, 472, 429-436, doi:10.1038/nature09983, 2011.
- Westall, F. and Fenner, J.: Pliocene-Holocene polar front zone in the South Atlantic changes in its position and sediment-accumulation rates from holes 699A, 710C, and 704B. In Proc ODP, Sci Results, 114, pp. 609-646, 1991.