Supplement of Clim. Past, 21, 2541–2560, 2025
https://doi.org/10.5194/cp-21-2541-2025-supplement

Climate of the Past
Open Access

Supplement of

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

Deborah N. Tangunan et al.

Correspondence to: Deborah N. Tangunan (d.tangunan@ucl.ac.uk)

Section S1

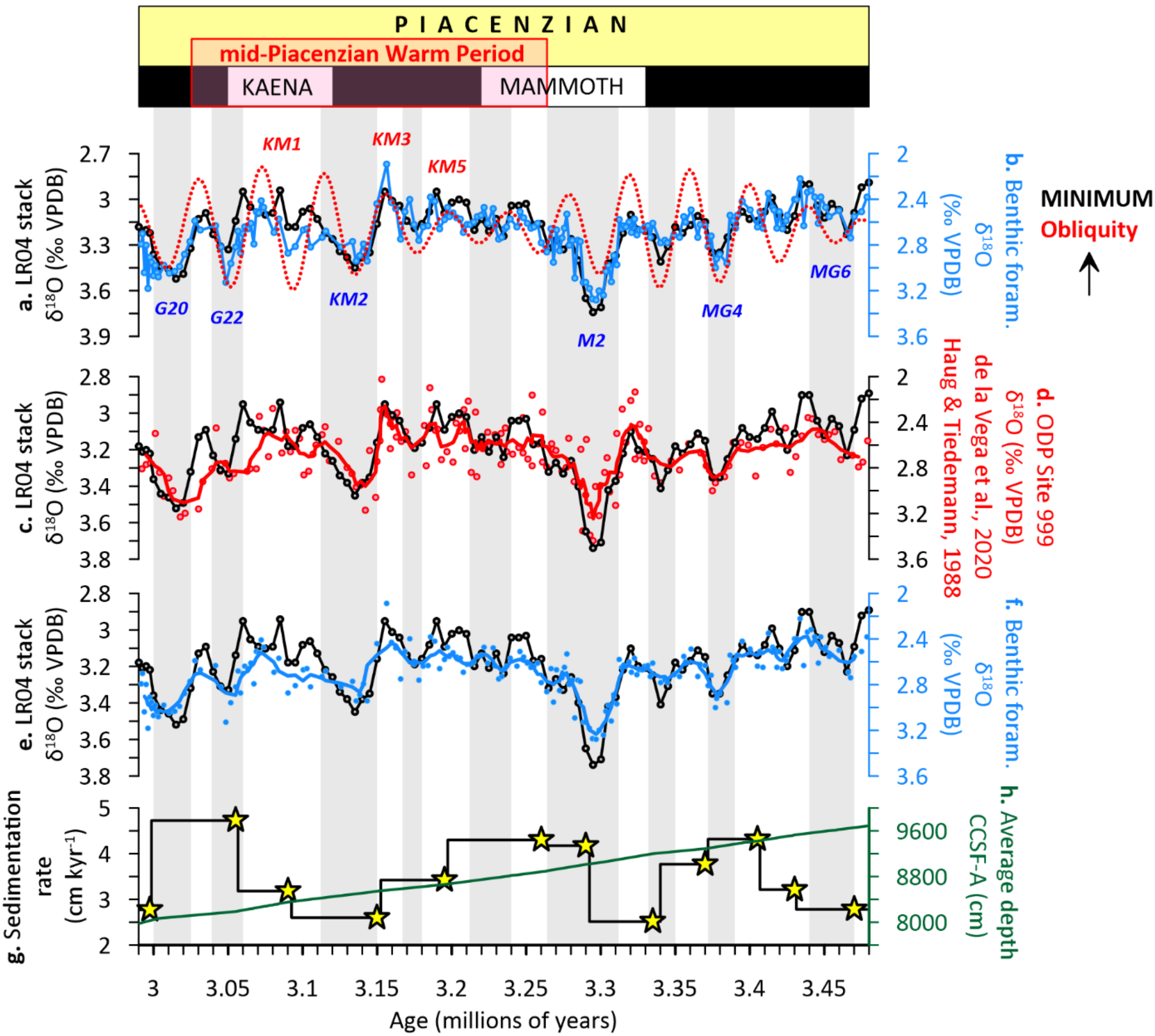

Fig. S1: Age model and sedimentation rates at Site U1476. (a, c, e) global benthic foraminiferal δ^{18}O stack (Lisiecki and Raymo, 2005), (b, f) Site U1476 benthic foraminifera δ^{18}O, (d) ODP Site 999 benthic foraminifera δ^{18}O (de la Vega et al., 2020; Haug & Tiedemann, 1988), (g) sedimentation rates, (h) average depth in the splice, stars indicate age control points. The obliquity curve (red) is from Laskar et al. (2011). Glacial stages are shown by grey horizontal bars (Lisiecki and Raymo, 2005).

Section S2

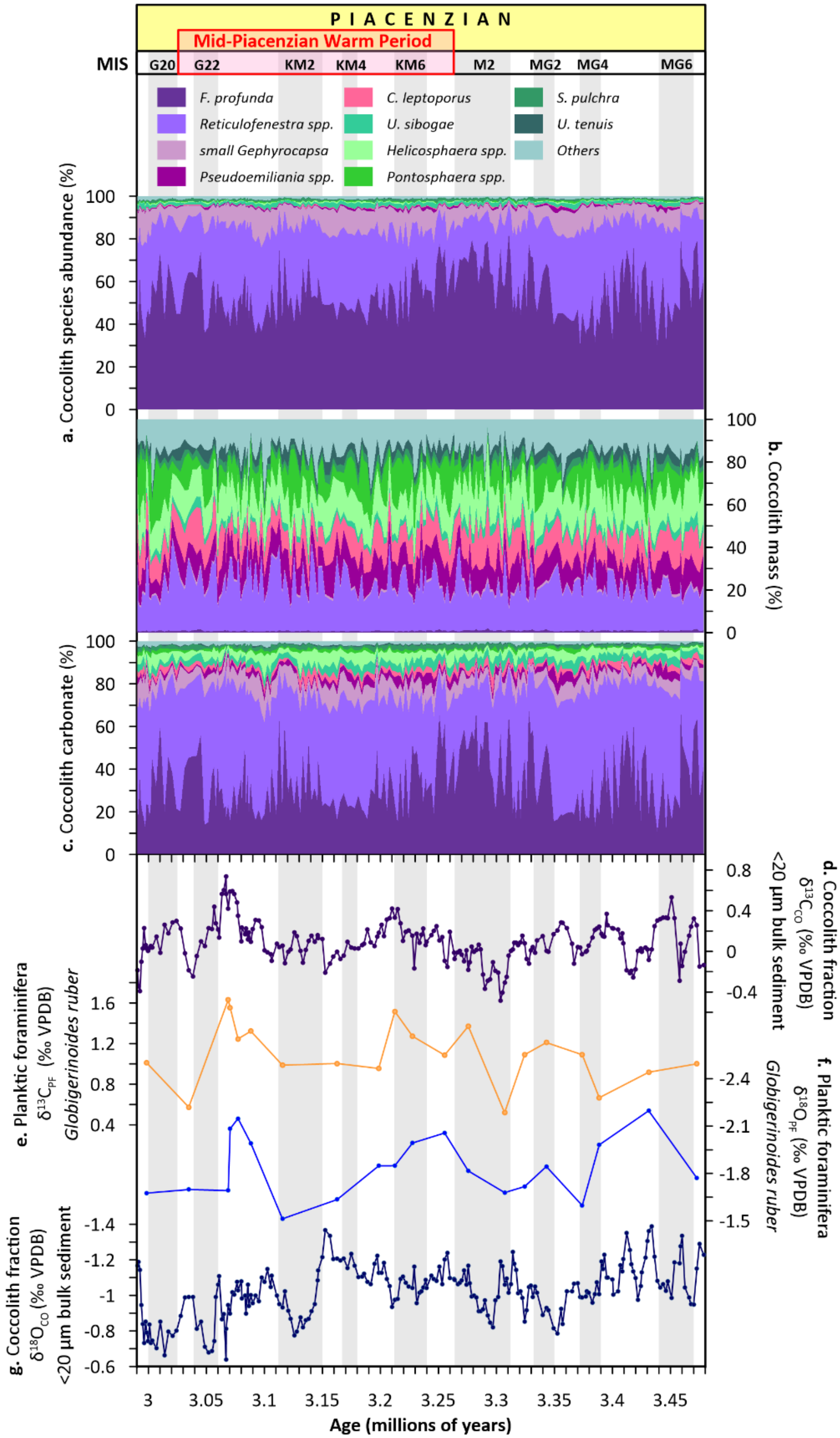

Fig. S2: Summary of coccolithophore assemblage composition, carbonate mass contribution, and stable isotope records from IODP Site U1476 during the Piacenzian (~3.0–3.5 Ma). (a) relative species abundance of coccolithophores, (b) coccolith mass contribution by each taxon, (c) total coccolith calcium carbonate contribution of individual species in the fine fraction (<20 µm = coccolith fraction), (d) $\delta^{13}C$ and (g) $\delta^{18}O$ values of the coccolith fraction, (e) $\delta^{13}C$ and (f) $\delta^{18}O$ values from the surface-dwelling planktic foraminifer *Globigerinoides ruber*. Glacial stages are shown by grey horizontal bars (Lisiecki and Raymo, 2005).

Section S3

Table S3: Summary of depth habitat and expected δ^{13}C and δ^{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)	**δ^{13}C Behaviour**	**δ^{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 δ^{13}C vital effect decreases significantly (to -0.4‰) and the negative δ^{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 δ^{13}C between 2-4 mmol/kg DIC. At high DIC, the negative δ^{13}C vital effect vanishes; the small δ^{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 δ^{13}C and δ^{18}O vital effects decrease significantly; δ^{13}C converges to inorganic value, leaving a residual +1.3‰ δ^{18}O vital effect (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)
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 (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).

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

Section S4

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 $\Delta\delta^{13}C_{BF-CO}$ and $\Delta\delta^{13}C_{PF-CO}$	Amplified variability in $\Delta\delta^{18}C_{BF-CO}$	Intermediate-depth ventilation and mixing beneath a still-stratified surface layer.
Approaching MIS M2 (~3.31 Ma)	Increase in $\Delta\delta^{13}C_{BF-CO}$ and $\Delta\delta^{13}C_{PF-CO}$	Decrease in $\Delta\delta^{18}C_{BF-CO}$	Long-term warming and re-establishment of a stratified ocean with reduced vertical exchange.
MIS M2 Glacial (~3.30–3.28 Ma)	$\delta^{13}C_{BF}$ and $\delta^{13}C_{CO}$ minima; followed by recovery (stronger in $\delta^{13}C_{BF}$)	Peaks in $\Delta\delta^{18}O_{BF-CO}$ and $\Delta\delta^{18}O_{BF-PF}$ (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 $\Delta\delta^{13}C_{BF-CO}$ and $\Delta\delta^{13}C_{BF-PF}$.	Pronounced variability in $\Delta\delta^{18}O_{BF-CO}$	Dynamic shifts in nutricline depth and reinvigorated biological pump; recurrent deep-water mass reorganisations.

References

Bolton, C.T., Stoll, H.M., and Mendez-Vicente, A.: Vital effects in coccolith calcite: Cenozoic climate-pCO2 drove the diversity of carbon acquisition strategies in coccolithophores?, Paleoceanography, 27, 4, 10.1029/2012PA002339, 2012.

de la Vega, E., Chalk, T. B., Wilson, P. A., Bysani, R. P., and Foster, G. L.: Atmospheric CO2 during the Mid-Piacenzian Warm Period and the M2 glaciation, Sci Rep, 10, 11002, 10.1038/s41598-020-67154-8, 2020.

Haug, G. H., & Tiedemann, R.: Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. Nature, 393, 6686, 673-676, 1998.

Hermoso, M., Chan, I. Z. X., McClelland, H. L. O., Heureux, A. M. C., and Rickaby, R. E. M.: Vanishing coccolith vital effects with alleviated carbon limitation, Biogeosciences, 13, 301-312, 10.5194/bg-13-301-2016, 2016.

Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records, Paleoceanography, 20, 10.1029/2004pa001071, 2005.

Winter, A., Jordan, R. W., and Roth, P. H.: Biogeography of living coccolithophores in ocean waters, in: Coccolithophores, edited by: Winter, A., and Siesser, W. G., Cambridge University Press, New York, 37, 1994.

Ziveri, P., Stoll, H., Probert, I., Klaas, C., Geisen, M., Ganssen, G. and Young, J., 2003: Stable isotope 'vital effects' in coccolith calcite. Earth and Planetary Science Letters, 210, 1-2, pp.137-149, 10.1016/S0012-821X(03)00101-8, 2003.