

Answer reviewer comments for manuscript

[egusphere-2026-3415]

Comments from the reviewers are marked as “**rev {reviewer no./comment no.}**” in italicized font. The answers of the authors follow immediately after the reviewer comments and are **given in blue**. . General statements made by the reviewers are not reproduced here. Line numbers (L) mentioned in our replies correspond to the original single-column (unrevised) version of the manuscript.

Reviewer 1

rev 1/1 Line 18: Please clarify “lower values” of benthic $\delta_{18}\text{O}$ as either more enriched or more depleted.

We suggest to retain the terminology of “lower values”, since the Coplen et al 2011 guidelines reserve the use of “depleted” for characterizing a ratio relative to a standard, and here our intention is comparing the typical values of benthic $\delta_{18}\text{O}$ across two time intervals.

Coplen, T. B. (2011). “Guidelines and recommended terms for expression of stable-isotope-ratio outcomes.” Published in *Rapid Communications in Mass Spectrometry*, 25(17), 2538–2540

rev 1/2 Line 18: I suggest being more specific about what is meant by “limited warming”. What is the magnitude of warming if any?

We agree and propose to clarify to: “When benthic $\delta_{18}\text{O}$ recovers to the lower values typical of the pre- Mi-1 excursion, there is only limited ($<2^{\circ}\text{C}$) warming in average temperature between 23 and 22 Ma”

rev 1/3 Line 20: I’m not sure what is meant by “consistent cooling”. The previous sentences stated there were different magnitudes of cooling between the sites. Is ‘synchronous’ what is meant here?

We propose to clarify to : “These results suggest cooling of SST occurred in both hemispheres during the Mi-1 glaciation”

rev 1/4 Line 22-23: I suggest clarifying that bulk carbonate $\delta_{18}\text{O}$ at Site 1168 is being compared to benthic $\delta_{18}\text{O}$ at Site 1264.

We propose to clarify to : ...” and bulk carbonate from Site 1168 shows similar magnitude and timing of change as **benthic $\delta_{18}\text{O}$** in the deep South Atlantic Site 1264.”

rev 1/5 Lines 40-50: I find this paragraph a bit confusing to follow as a reader as it jumps between many topics. I suggest some restructuring here to more tightly focus on explaining the motivation of this study to the reader. I strongly agree with the authors’ point that high resolution surface temperature records are needed, and their data helps fill this important gap.

We propose revision of this paragraph to the following:

Yet, because the $\delta^{18}\text{O}_{\text{benthic}}$ reflects not only ice volume changes but also changes in the deep-ocean temperature, its climatic interpretation does not entail unique history of ice volume, deep ocean temperature, or global temperature. For example, modeling experiments suggested that deep ocean temperatures and Antarctic ice sheet (AIS) may be closely coupled due to surface albedo effects when AIS expansion involves changes in the areal extent of the ice sheet, but weakly coupled when ice volume changes only entail changes in AIS height (Bradshaw et al., 2021). At the same time, a recent comparison of results from a wide range of atmosphere-ocean general circulation models (AOGCM) suggests that deep ocean temperature closely tracks earth's mean annual surface temperature (Evans et al., 2024). Compilation of surface ocean temperature records can clarify the relationships between earth surface temperature, deep ocean temperature, and Antarctic expansions over the OMT. Yet, one challenge in such comparisons is that high-amplitude astronomical variations during the late Oligocene and early Miocene increase the risk of aliasing in the available sea surface temperature trends, which are in many cases sampled at much lower resolution than astronomical variability. Adequately addressing this challenge requires higher temporal resolution records of surface ocean conditions.

rev 1/6 Lines 80-87: *I find it a bit confusing why this description of Oligocene-Miocene deep ocean circulation is within the section about describing Site 1168.*

Lines 80-87 focus on the Southern Ocean circulation which is relevant to the location of 1168, and for this reason it is part of the Paleoceanographic setting at 1168. Comparable discussion of surface currents in the North Atlantic relevant to Site 1406 is described in lines 104 to 111 under the subheading for Site U1406. We propose to retain this structure associating the relevant regional currents with each site so that the interpretations of influence of currents on temperature evolution in the discussion are readily linked to the appropriate region.

rev 1/7 Figure 1: *How were the positions of the subtropical front reconstructed? A "subtropical" front approaching 60°S seems unrealistic even during warm interglacials.*

Thanks for the prompt to better reference the source of proposed information on the frontal positions. We propose to add to the figure 1 caption the citations to (Hou et al., 2023) and (Thöle et al., 2023) which were previously referenced only in the text section 5.3 which described the dinoflagellate assemblages indicating frontal positions.

rev 1/8 Lines 187-190: *I suggest including information on how variable U_{K37} of the in-house alkenone standard as well as if any replicate measurements were made on samples to give an estimate of the analytical uncertainties associated with these measurements.*

L189-190: "The in-house alkenone standard measurement also served to identify instrument drift and ensure long-term validation."

We thank the reviewer for this helpful suggestion. The in-house alkenone standard was regularly measured throughout the analytical period to monitor instrument drift and analytical reproducibility.

We propose to add in methods section (end of the second paragraph of section 3.2) the following details: “ Repeated measurements of the in-house alkenone standard yielded a standard deviation of 0.1°C for $U_{k'37}$, indicating high analytical reproducibility. No replicate measurements of individual samples were performed.”

rev 1/9 Lines 195-196: *The $U_{k'38Me}$ calibration of Novak et al. (2022) saturates at 30.5°C, not 32°C. Also, they analyzed core tops with a maximum mean annual SST of 29.5°C, so I think the authors should also emphasize the uncertainty associated with extrapolating to temperatures beyond the calibration range. I suggest showing the calibration equations used for $U_{k'37}$ and $U_{k'38Me}$ in the main text or supplement, as $U_{k'38Me}$ is less commonly applied and less well-known among the community*

We appreciate the prompt to clarify more precisely the discussion of the Novak calibration upper limits and the equation used since three equations are provided for $U_{k'38ME}$ in Novak et al (2022).

We propose the following to the third paragraph in section 3.2:

“ Where C_{38} methyl alkenones were sufficiently abundant for robust quantification, $U_{k'38me}$ values were also determined and converted to annual mean SSTs estimate using the global core-top calibration from (Novak et al., 2022) which extends the linear upper temperature range of the proxy to approximately 30.4°C, where the equation describes annual mean SST with sea ice settings excluded from the calibration:

Equation: $UK38ME = SST * 0.032 + 0.016$ »

rev 1/10 Lines 204-215: *Some of this is repetitive.*

~~L209-215: “Bulk carbonate was measured for all samples from both sites and smear slides confirm that it consists dominantly of coccoliths of genera Reticulofenestra, as described in previous studies (Gutián et al., 2020). For the $\delta^{18}O_{bulk}$ and $\delta^{13}C_{bulk}$ measurements, we used on average 150 µg of the freeze-dried sediment employed previously for organic extraction. Analyses were made using the GAS-BENCH II system coupled to a Delta V Plus IRMS from Thermo Scientific, following the procedures described by (Breitenbach and Bernasconi, 2011). Analytical precision after the system was calibrated with two in-house standards was 0.07‰ for both stable isotopes. Values are reported relative to the VPDB standard. , an average of 150 µg of freeze-dried sediment, previously used for organic extraction, was analyzed following the procedures described by Breitenbach and Bernasconi (2011).”~~

We thank the reviewer for pointing out the repetition. We have revised Section 3.3 to describe the analytical system, standards, analytical precision, and isotope reporting convention only once. The corresponding information was removed from Section 3.3.1, which now focuses on the sample material and analytical procedure specific to the bulk carbonate measurements.

rev 1/11 Line 211: Bulk $\delta_{13}\text{C}$ measurements are mentioned here and in line 204, but are not shown in any figures in either the main text or supplement. Could the authors please clarify why this is? Is $\delta_{13}\text{C}$ data reported here? If not, I suggest removing references to that data.

We propose to add in section 3.3. introductory paragraph “Carbon isotope results are not reported or discussed here.” We still acknowledge that they are simultaneously measured.

rev 1/12 Figures 3 and 4: I think it would be helpful to show in the figure where Mi1 and Mi1.1 are. Also, I suggest that the y-axis label for panel (b) be changed to “ $\Delta\delta_{18}\text{O}_{\text{sw}}$ ” or similar to clarify that these are not absolute $\delta_{18}\text{O}$ values of seawater, but rather changes relative to the lightest sample.

We agree that these are excellent suggestions and will implement them in the revision.

rev 1/13 Line 314: It is unclear what “cold extreme” means here. From Figure 4, the temperatures around 22.58 Ma look fairly unremarkable compared to temperatures observed both before and after.

We propose to replace with “local temperature minimum”

rev 1/14 Line 339: Specifically, what is the “age model uncertainty” being referred to here? Within how many kyr?

Thanks for this prompt. In response to this and Reviewer 2 comments, we propose to clarify:

This new record confirms the onset of surface ocean cooling in the Southern Hemisphere mid-latitudes by 23.8 Ma and its subsequent intensification starting around 23.3 Ma; this is coincident **within the uncertainty in ^{87}Sr age tiepoints** with the positive $\delta^{18}\text{O}_{\text{benthic}}$ shift interpreted as the two-step AIS expansion (Liebrand et al., 2017).

rev 1/15 Line 348: Please be specific about the timescale of “abrupt” cooling here. Within how many kyr?

We propose to remove the descriptor “abrupt”

rev 1/16 Figure 5: I again suggest showing where Mi-1 and Mi-1.1 are to give context to the reader.

We agree that these are excellent suggestions and will implement them in the revision.

rev 1/17 Line 352: “High amplitude orbital scale variability” of what? SSTs, benthic $\delta_{18}\text{O}$, or both?

We propose to add “high amplitude orbital scale variability **in SST** in both hemispheres.”

rev 1/18 Lines 358-359: *Would changes in albedo from ice sheet changes during this interval be relevant to both site locations in this study? Temperature changes in both hemispheres are synchronous, but continental-scale ice sheets were presumably limited to only the Southern Hemisphere. I am skeptical that albedo changes on Antarctica are a significant “global climate forcing” during this interval and would significantly impact mid-latitude ocean temperatures.*

In referring to snow and ice coverage we intended the phrase to generically refer to albedo changes in either polar region.

We propose to clarify explicitly this sentence as

“...major changes in albedo due to changes in areas of snow and sea ice coverage in either polar region”

rev 1/19 Figure 6 caption: *“MI index” is redundant, as MI stands for methane index.*

Thank you for the clarification, we will remove the extraneous term.

rev 1/20 Line 384: *“The magnitude of $\delta_{18}O_{benthic}$ change at Site 1168” over what time interval? This refers to the same time interval in preceeding sentence which starts “ Between 24 to 23 Ma...”*

We can repeat the time interval in the following sentence to improve clarity for the reader:

“We attribute this larger amplitude change **between 24 and 23 Ma...**”

rev 1/21 Lines 399-408: *The authors argue here that the large changes in benthic $\delta_{18}O$ at Site 1168 arise from large temperature changes in intermediate waters, which originate from “significant temperature change in high latitude regions where such waters outcrop” (Line 405). However, they do not address that the other benthic $\delta_{18}O$ records shown in Figure 7 (with presumably less temperature variability) reflect deep waters that also originate from the Southern high-latitudes, likely from even higher latitudes than intermediate water sources. If sea ice extent and duration and/or polar-amplified cooling influenced large temperature variability in both Southern high-latitude surface waters and intermediate waters, why would it not most strongly influence the deepest waters sourced most directly from the regions of sea ice formation?*

Evidence for greater temperature change in intermediate waters compared to deep waters has been emerging on both anthropogenic and paleoclimate timescales. Intermediate waters cool more significantly at the LGM compared to deep waters, as evidenced by greater mean whole-ocean cooling than possible for deepest waters like AABW (eg Roberts et al., 2016; Bereiter et al 2018, Knorr et al 2021). Conversely during periods of warming, increasing ocean heat content at intermediate depths (700-1400 m) is attributed to surface ocean-atmosphere interactions in Southern Ocean (Roemmich et al 2015; Rosenthal 2017).

We will add to the text a proposal that AO-GCM modeling experiments further explore this issue for the OMT.

Rev 1/22 Lines 429-430: *It is unclear to me what the connection between surface salinity at U1406 and deep ocean reconstructions are here. I suggest explaining this point further.*

Over the latest Oligocene, the site shows more saline conditions during warmer SST (Fig. 4; Fig S3), which is the opposite expectation for the response of high latitude (and deep ocean) temperature and global ice volume based on middle Oligocene paired benthic $\delta^{18}\text{O}$ and Mg/Ca (Brzelinski et al., 2023).

We propose to clarify, rewriting:

“This contrasts with the correlation of deep ocean warming with lower deep ocean $\delta^{18}\text{O}_{\text{sw}}$ in the middle Oligocene which been attributed to coupling of Antarctic ice retreat and warmer deepwater (Brzelinski et al., 2023). Potentially, the trend in local surface $\delta^{18}\text{O}_{\text{sw}}$ at this site reflects not only a component due to Antarctic ice volume but also variations in salinity due to changing Gulf Stream, a process consistent with the positive correlation between $\delta^{18}\text{O}_{\text{sw}}$ and SST given the influence of the Gulf Stream on both heat and salt in this setting (Fig. 2).”