Anonymous referee #1

Thank you to the authors for the revised manuscript. I appreciate the effort that has gone into the revision, and think the manuscript is much improved as a result. My only comment for this round is that it would be good if the equation for generating the CO2 doublings in figure 8 was written out explicitly, rather than just explained narratively within the text. Alternatively, if a previous paper that has used this approach already has the equation written out, it could be referenced. As-is, it isn't immediately obvious how you go from a dependence of "ln(CO2(aq) of 2.66" plus the temperature correction to the axes of the figure expressed in doubling/halving of CO2. Presumably you're normalising to the mean of the dataset to do so?

We have clarified the CO2 doubling calculations. A paragraph and equation 7 has been added at the end of section 3.3 aiming to detail the relationships:

"From the εp time series we estimate the change in CO2 relative to the maximum values at 29 Ma, using the adjustment in εp for temperature sensitive growth rate described in the previous paragraph, and Eq. (3) as applied in (González-Lanchas et al., 2021), where I reflects the size and light influences on εp and is assumed constant across all time intervals, and the εp dependence on ln [CO2[aq]] of 2.66 is the 50th percentile estimate of the modern cultures. We then estimate the doubling/halving of CO2 relative to the CO2 at the reference age (R) applying the solubility for the measured temperature (Zeebe and Wolf-Gladrow, 2001) which can be reduced to:

$$doubling\ CO_2 = \frac{\varepsilon_p(t) - \varepsilon_p(R)}{2.66\ ln2} + log_2\left(\frac{sol\ (R)}{sol\ (t)}\right)"$$

Additionally clarified at section 4.4:

"Although the calculation of absolute CO2 concentrations from εp in the Oligocene and early Miocene remains challenging, the logarithmic dependence of εp on CO2[aq] observed in cultures allows us to estimate the relative changes in CO2 if the sensitivity of εp to CO2 in the Oligocene were similar to modern cultured species ***using Eq. (7).*** *If we incorporate a temperature correction and apply the 50th percentile estimate of the modern culture εp dependence on ln [CO2[aq]] of 2.66, it implies major changes in CO2 concentrations, with potentially 4 halvings of CO2 concentration from 29 to 16 Ma (Fig. 8)"*

Figure 8 footnote now specifies the reference date for CO2 doubling of the sites plotted:

"*Implications of CO2 as main climate driver. a) pCO2 doubling for the discussed sites* ***from εp referenced at 29 Ma (Site 608 referenced to maximum at 23 Ma). Solid lines are calculated using the SST corrected εp*****"**

Other minor comments and typos:
Line 87: b should be italicised

Corrected

Line 217: “Although the foraminifera content in Site 1406 and 925 is very low, features sufficient well preserved benthic foraminifera, mainly epifaunal Cibicidoides spp. larger than 200 µm.” Sentence needs restructuring?

Text adjusted: “*Although the foraminifera content in Site 1406 and 925 is very low,* ***sediments*** *feature sufficient well preserved benthic foraminifera, mainly epifaunal Cibicidoides spp.* ***in the size range*** *larger than 200 µm.*”

Figure 3: x-axis labels should be below the figure.

Corrected

Anonymous referee #2

I appreciate the authors' efforts in addressing my previous suggestions. However, some of my minor comments were not clearly addressed in their response. For example, they often state “will be adjusted” without showing the actual modifications. As a reviewer—at least in my case—I prefer to see the specific changes directly in the response, rather than having to search through the revised manuscript to verify them. Most of my comments have been adequately resolved. However, one important point remains unaddressed: the relationship between εp and benthic δ18O at orbital scales (Figures 7b and 7c) does not yield a clear conclusion. Even in the revised manuscript, the abstract states “at orbital timescale, the relationship between εp and benthic δ18O, albeit weak, implies greater ice volume or colder deep ocean at higher CO2”. This statement remains vague, and the authors do not offer a definitive interpretation. As the authors interpret εp variations as the change in atmospheric CO2 levels, comparing εp with benthic δ18O evolution, a signal of global climate change, is reasonable to evaluate the global impact of CO2 changes. However, without decomposing benthic δ18O signal into ice volume/sea level component and deep ocean temperature component, it is unlikely that a meaningful conclusion can be drawn from this comparison. Instead, comparing εp with the estimated global mean SST (Gaskell et al., 2022; https://doi.org/10.1073/pnas.2111332119) or surface temperature (Evans et al., 2024; https://doi.org/10.1029/2023PA004788) would likely provide more direct insights, as these records more directly reflect the climatic signals the authors aim to assess.

We recognize the value and appeal of conversions of benthic $\delta^{18}O$ to estimated global mean SST or surface temperature from the approaches of the suggested references.

On the orbital scale, our submitted manuscript describes the trends between εp and $\delta^{18}O$ benthic, not specific climate sensitivities. The interpretation of this observed trend is unchanged if the $\delta^{18}O$ benthic signal is partitioned into a temperature and ice volume component using one of the proposed slopes in Evans *et al*., (2024). Because we have not quantified absolute CO_2 concentrations over these orbital cycles, we believe there is little added value in attempting an uncertain partitioning of the 1406 benthic signal into ice volume and temperature components at this stage. As further constraints improve quantitative CO_2 interpretation from εp during this time period, and detailed geochemical studies, such as Brzelinski *et al*., 2020 (deconvolving the benthic $\delta^{18}O$ with benthic Mg/Ca during a younger Oligocene interval at 1406), provide further support for deep temperature and ice volume deconvolutions, more quantitative interpretation of the ice volume and CO_2 relationships should become possible.

Brzelinski, Swaantje, André Bornemann, Diederik Liebrand, Tim E. van Peer, Paul A. Wilson, and Oliver Friedrich. "Large obliquity-paced Antarctic ice-volume fluctuations suggest melting by atmospheric and ocean warming during late Oligocene." *Communications Earth & Environment* 4, no. 1 (2023): 222.

Specific comments

Line 12: please specify “what is expected to drive the climate observation”

Text adjusted.

Line 30: what long-term CO2 trend? Please specify it.

Text adjusted.

Line 32: temperature and nutrients are considered as environmental factors, rather than physiological factors.

Text adjusted.

Line 44: how did estimated Antarctic ice sheet volume and sea level evolve? How did their evolution contrast with the long term decline in CO2?

Text adjusted.

Line 56-57: environmental factors are not consistent with ‘physiological factors’ mentioned before.

Now reads as: “*One approach to evaluate the relative contribution of physiological factors vs CO2 is to produce εp records from sites of widely contrasting oceanographic setting, where the CO2 signal may be expected to be common to both locations but the environmental factors* ***affecting the fractionation*** *such as nutrient availability might not be expected to change in unison*”

Line 64: full name of m.y. is needed here.

Corrected

Line 83-89: The term is inconsistently written as b value, b value, b-value, and bvalue. Please choose one format and use it consistently throughout the text.

Corrected

Line 153: a period is needed after (Hou et al., 2023b)

Adjusted

Line 240: full name of GDGT is needed

Corrected

Line 242: change ‘GDGTS’ to ‘GDGTs’

Corrected

Line 282: does correlation indicate correlation between the study sites? Please clarify it.

We now clarify: "***The inference of rapid declines is also affected by the age models and the*** *correlation of rapid εp shifts* ***among different sites*** *might be hindered by uncertainties in chronology among the different sites*"

Line 418-419: Figure 7e should be referenced after "a temperature-corrected εp record for the 29.6 to 29 Ma interval would still not exhibit an inverse relationship between εp and δ18O benthic"

Corrected

Line 441: referenced are needed for modern climate sensitivity

Modern climate sensitivity has been adjusted and referenced to IPCC report Chapter7

Line 442: The estimates of 12 to 20°C cooling from Oligocene to early Miocene seems quite large and may be overestimated, especially considering that Early Eocene global mean surface temperature was only about 10-16°C warmer than pre-industrial levels (Inglis et al., 2020).

Adjusted for clarity and accounting for the broader uncertainty estimates of climate sensitivity of 2 to 5°C:

"*Modern General Circulation Models (GCM) summarized by the IPCC estimate climate sensitivity as "very likely" in the range of 2 to 5°C per doubling or halving of CO_2 (IPCC AR6 Assessment, Forster et al., 2021), which if representative for the Oligocene to early Miocene, would imply 8 to 20°C of cooling of earth's mean surface temperature (6 to 15°C incorporating the lower confidence interval of modern culture ε_p dependence on ln [$CO_{2[aq]}$] of 3.5, which would imply 3 halvings of CO_2). Although ocean is 70% of the globe and temperature changes are around 1.5-fold less than land temperature (Sutton et al., 2007), such a temperature change of at least 6C would be expected to be reflected in paleoceanographic proxies*."

Line 476-477: is there any evidence to support that the temperature trend of ODP Site 1168 is more representative of global average temperature trends

We propose to add the following caveat to the end of the paragraph:

"*Yet, temperature trends at either site may be subject to both global factors as well as regional temperatures, and with only two sites with temperature records paired to ε_p proxy records it is difficult to ascertain which, if any, of the sites may better reflect global temperature forcing*."

We note that the subsequent paragraph already highlighted the need for further temperature records to clarify this effect:

"*The discrepancies between alkenone and published TEX86 at ODP 1168 suggests continued reevaluation of SST proxy interpretation are needed, along with evaluation of*

the potential influence of changing surface ocean circulation on SST in some locations such as the North Atlantic."

Figures and supplementary figures: in several figures, the y-axis is labeled as "Ep", but it should use the Greek letter epsilon p (εp) to remain consistent with the notation used in the main text. Please update the labels accordingly.

Notation adjusted.

Figure 2 and Figure S1: Using red and green in the same figure is not color-blind-friendly. Please adjust the color scheme.

Symbols were adjusted.