Author’s Responses

We thank the reviewers for their time and effort reading the manuscript and offering valuable comments and suggestions. We have modified the manuscript according to their comments, as detailed below. The detailed changes can be found in the track-changes copy of the manuscript. Our direct responses to the reviewers’ comments, major and minor, are below. The original reviewers’ comments are listed, with our response in blue font.

RC1

Hoegler et al. presented a revised alkenone-based sea surface temperature (SST) record from ODP Site 1090, spanning the critical Pliocene-Pleistocene transition (~4.3 - 2.6 Ma), and challenging the earlier reconstruction by Martínez-Garcia et al. (2010) and the hypothesis that regional cooling in the Southern Hemisphere drove the intensification of Northern Hemisphere glaciation (iNHG). The authors have made robust methodological improvements, including sample purification, the use of HPLC-MS to verify the absence of C37:4, and an updated age-depth model. These methodological advances yield a SST record that is systematically warmer (~1.27°C on average) than the previous estimate by Martínez-Garcia et al. (2010). Also, the revised ODP 1090 record exhibits a cooling pattern synchronous with, and even milder than, those observed in the equatorial Pacific and North Atlantic, which supports a globally synchronous cooling mechanism. Overall, the manuscript is important for understanding the climatic fluctuations and the hidden mechanisms of the Cenozoic. Here, I am providing some concerns, questions, and suggestions that may help improve the manuscript.

Major questions:

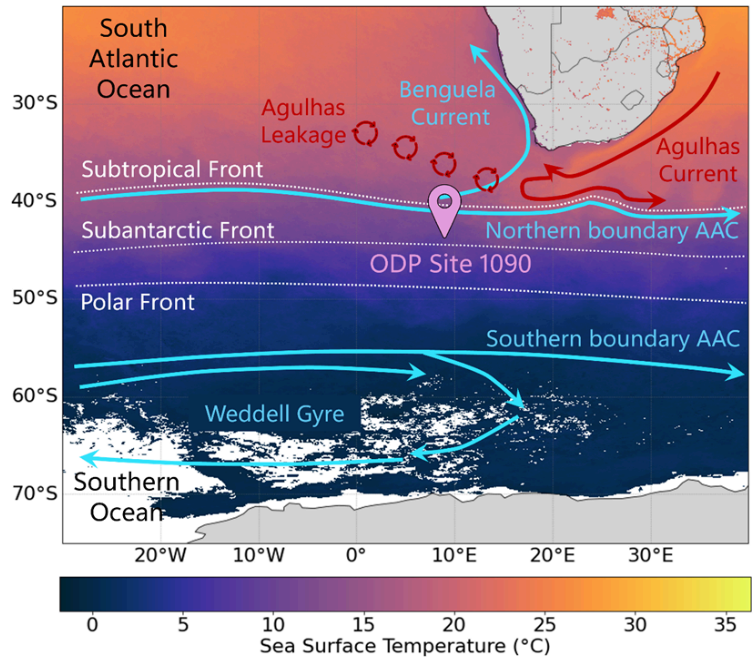
1) The authors rigorously addressed the potential bias introduced by silver-nitrate purification, as raised by Martin et al. (2024), by conducting control experiments using both an in-house alkenone standard and a Greenland standard. They concluded that their cleanup methods showed "little to no evidence of biases to the results." However, this conclusion may be overly reliant on the behavior of standards and not fully transferable to the actual ODP 1090 sediment samples. Martin et al. (2024) specifically demonstrated that the impact of silver-nitrate purification is not linked to initial alkenone concentration but is likely driven by lake-specific matrix effects. The complex, open-ocean sediment matrix of ODP Site 1090 is fundamentally different from the chemical environment of a purified standard. Therefore, while the standard experiments are valuable for assessing general method performance, they do not conclusively prove that the alkenone distributions in the geologically complex sediments of ODP 1090 were unaffected by the silver-nitrate purification process.

- We appreciate the reviewer’s insights and acknowledge that no single experiment can definitively prove that the alkenone distributions in the geologically complex sediments of ODP 1090 remain unaffected by the silver-nitrate purification process. However, the use of two standards, each reflecting different matrix characteristics, helps establish a more comprehensive understanding of our method's performance. While the standards do not replicate the exact conditions of the ODP Site 1090 sediments, our findings indicate a consistent pattern in the behavior of alkenones across both standards. This suggests that, when executed correctly, the cleanup procedures are unlikely to significantly impact the alkenone unsaturation of our samples. We also recognize that the complexity of the ODP 1090 sediment matrix introduces variables that must be considered. To enhance clarity, we will revise the manuscript to explicitly state that our control experiments are not direct comparisons with the sediment's chemical environment: "While this experiment was conducted using standards and is not a direct comparison to the sediment's chemical environment, the consistent behaviour of the alkenones across both standards suggests that, when executed correctly, the cleanup procedures are unlikely to significantly impact the alkenone unsaturation index of our samples." (Lines 258-261)

- Furthermore, we can propose additional research directions, such as conducting parallel analyses of ODP 1090 samples pre- and post-purification, and experimenting with various GC conditions to assess the impact of co-eluting compounds more thoroughly. This multifaceted approach will not only provide further validation of our findings but will also contribute valuable insights for future studies on chemically complex sediments: "Our experimental investigation into the potential bias caused by our cleanup methods confirmed that when performed correctly, the procedures are unlikely to significantly impact the alkenone signal. Future work could build on this foundation by conducting parallel analyses of ODP 1090 samples before and after purification, as well as systematically testing different GC conditions to better evaluate the influence of co-eluting compounds. This expanded approach would offer further validation and contribute to improved methodological confidence in studies of chemically complex sediments." (Lines 464-468)

2) While the data presented in Figure 1 is fundamental to the study, I would like to suggest several visual enhancements to improve its clarity and professional presentation, which would ultimately help the reader better interpret the geographical context. First of all, the current landmass polygons appear somewhat pixelated and exhibit a jagged, low-resolution outline. I would recommend using a higher-resolution coastline dataset to create smoother, more accurate continental outlines. Secondly, the chosen color bar for the SST data could be significantly optimized. The green-dominated palette is non-standard for representing temperature. It is highly advisable to adopt a more intuitive, red-to-blue diverging color scheme (e.g., similar to RdYlBu or other common palettes) where reds indicate warmer temperatures and blues indicate cooler ones. Besides, using white to represent the lowest temperatures causes the cold waters to visually blend with the white landmasses. I suggest ensuring the coolest tones in the new color scheme are distinctly non-white or changing the color of landmasses to maintain a clear distinction between ocean and land. Finally, the current y-axis labels (e.g., -20°, -30°) are clear to domain experts but do not explicitly state that they represent South latitude. For absolute clarity and adherence to cartographic standards, I strongly recommend appending an "S" to the labels (e.g., 20°S, 30°S).

- Thank you for your suggestions— I agree with you that the map figure (Fig. 1) could be improved with your recommendations. I improved the landmass outlines by using a higher-resolution (110m) coastline dataset from the Cartopy Python package. I also changed the colorbar, which now utilizes a more intuitive, cool-to-warm pallet to indicate cooler-to-warmer temperatures. Specifically, I used the cmoocean "thermal" colormap, which is both utilitarian and colorblind-friendly. The landmasses are now shaded gray, and sites with no data are in white. Per your suggestion, I also clarified the axis labels.

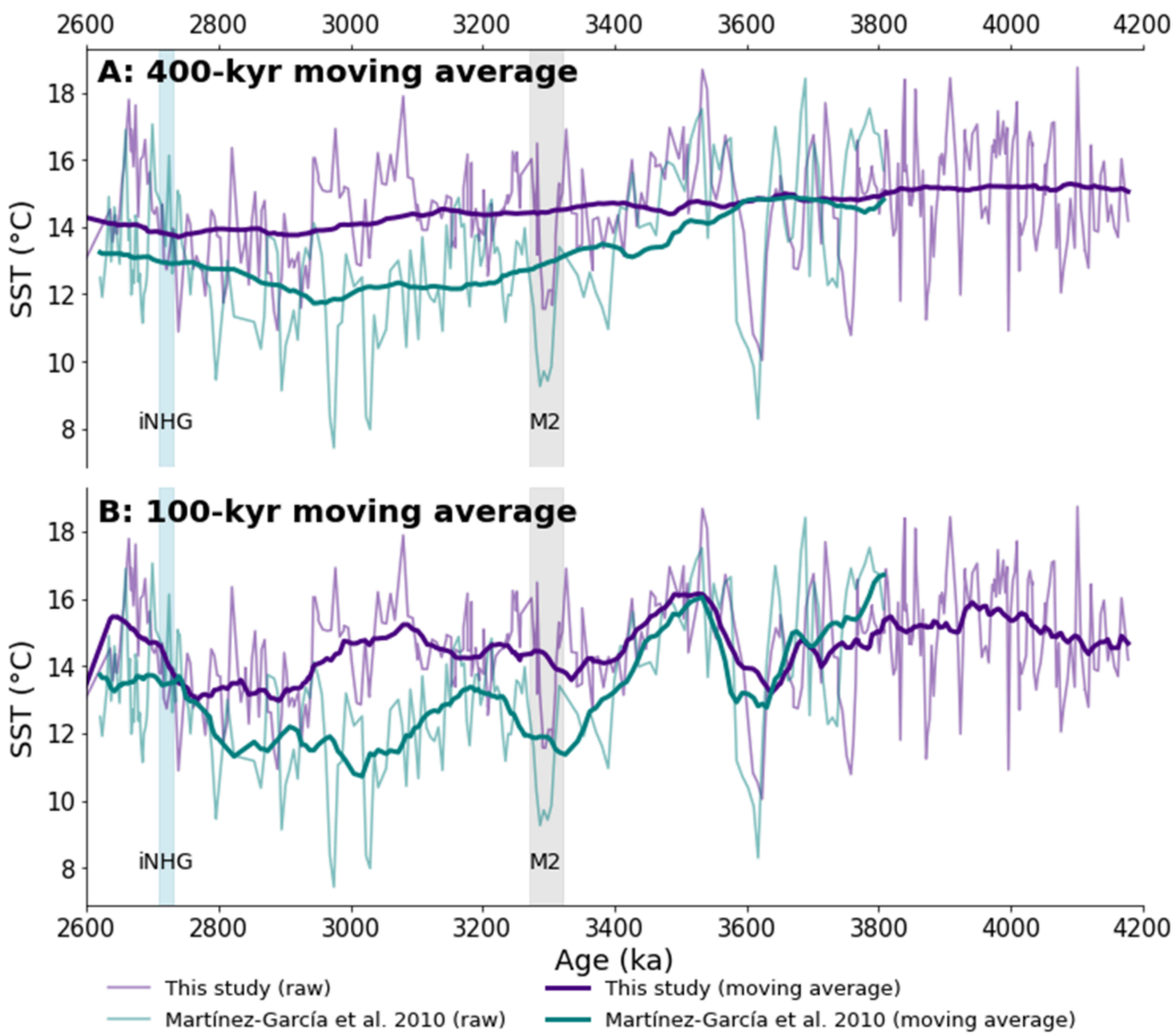


3) The authors used linear regression to compare the long-term trends between their revised record and that of Martínez-Garcia et al. (2010). To more effectively visualize and contrast the underlying low-frequency trends embedded within the high-amplitude orbital cycles, I strongly recommend supplementing the linear fits with a moving average (or Loess smoothing). Applying a consistent smoothing window (e.g., 100-kyr or 400-kyr) to both records would provide an intuitive visual representation of the long-term climate evolution and test the robustness of the trend without imposing a presupposed linear shape.

- Thank you for this excellent suggestion! I opted to supplement the linear fits with a moving average, with both a 100-kyr and 400-kyr smoothing window. We amended this figure (Fig. 3) to contain these moving averages and will highlight this in the manuscript. While both show that our new SST record lacks the rapid cooling contained in the Martinez-Garcia record (ca. 2.89-3.03 Ma), the 400-kyr smoothing window especially shows that the late Pliocene cooling trend at ODP Site 1090 may be substantially more gradual than implied in their record.
- "To visualize and contrast the underlying low-frequency trends embedded within our new record and the original Martínez-Garcia et al. (2010) SST reconstruction, we applied 100- and 400-kyr moving averages to both records (Fig. 3). Both smoothing windows show that our SST estimates tended to fall above those of the previous record after 3.6

Ma. They also consistently show that the Martínez-Garcia et al. (2010) reconstruction diverges from our own during the interval we identified as having SST estimates considerably lower than those of Etourneau et al. (2010), with our SST estimates tending to fall between those of these two previously published records." (Lines 311-316)

- "Compared to the SST record of Martínez-Garcia et al. (2010), our SST estimates record only a gentle cooling trend leading up to iNHG (Fig. 3), made apparent by the gentler cooling and warmer SSTs evident in the 400-kyr moving average of our reconstruction, in addition to the gentler slope of our linear regression." (Lines 337-340)



4) The authors highlight a critical finding: the mildest late Pliocene cooling trend is observed at the sub-Antarctic ODP Site 1090, compared to the ODP Site 846 (eastern equatorial Pacific) and IODP Site U1313 (north Atlantic). However, the manuscript lacks critical metadata for the latter two sites, which is essential for assessing the validity of such comparisons. I recommend that the authors provide a summary table or explicitly state the temporal resolution, age model

construction principles, and estimated analytical errors for the ODP 846 and IODP U1313 SST records used in this study. Besides, the discussion lacks a mechanistic explanation for this counter-intuitive result. From a climatology perspective, one would expect polar amplification to drive stronger cooling at high latitudes under a decreasing CO_2 forcing (e.g., Snyder, 2016). The fact that the opposite is observed here is, in itself, a significant result that points to the operation of important regional climate feedbacks. I strongly recommend that the authors expand the discussion to address this point.

- This is a great suggestion— we will add metadata to Table 1 for all sites utilized in this study.
- We appreciate the insightful comments regarding the cooling trends observed at ODP Site 1090 and agree that it is counterintuitive that ODP Site 1090 would have a lesser degree of cooling compared to a low-latitude site— in fact, the SST data from ODP Site U1313, a Northern Hemisphere site of similar latitudinal extent, shows this expected polar amplification in comparison to the equatorial Site 846. The diminished long-term cooling trend at Site 1090 may be due in part to the greater degree of variability we observe in the temperature record at this site compared to the others.
- In addition, while it seems counterintuitive that a sub-Antarctic site would exhibit lesser cooling compared to equatorial and Northern Hemisphere sites, several mechanisms could account for this. For instance, changes in ocean circulation could influence regional climate dynamics, potentially leading to localized warming effects. We will expand our discussion to explore these possibilities further— see lines 370–387 for this discussion in our updated manuscript:
- “This more gradual cooling trend is likely influenced by the more variable SSTs observed at ODP Site 1090, particularly prior to 3600 ka, which dampens the expression of long-term trends, especially in SST reconstructions where we expect, and observe, non-monotonic cooling. Notably, the cooling trend observed at IODP Site U1313, in the North Atlantic, is approximately double that of the other sites— a possible indication that more Northern Hemisphere cooling preceded iNHG, which challenges the hypothesis that Southern Hemisphere cooling was a primary driver of northern glaciation.

  In addition, the relatively muted cooling at Site 1090 likely reflects regional oceanographic controls, rather than a simple response to large-scale cooling, as its location within a frontal transition zone makes it particularly sensitive to changes in ocean circulation. [MOU22.1]Site 1090 (~43°S) lies between the SAF and STF, where SSTs are highly sensitive to frontal migration, wind-driven circulation, and water-mass mixing. Latitudinal shifts in Southern Ocean fronts associated with changes in westerly winds and meridional temperature gradients during the late Pliocene (e.g., Martínez-Garcia et al., 2010; Hillenbrand et al., 2009) could cause the site to experience alternating influence of subtropical and subantarctic waters. Such variability would act to buffer or modulate the local expression of global cooling, producing a more gradual and variable SST trend compared to regions more directly coupled to large-scale radiative and thermocline forcing. Furthermore, Site 1090 is located just north of the SAF in the modern ocean (Fig. 1); had the location of this front been more poleward in the warmer-than-modern Pliocene (Hillenbrand et al., 2009; McClymont et al., 2016), Site 1090 may still have been located in the envelope between the SAF and STF throughout this transition period, potentially buffering regional SSTs from the global trend."

Minor comments:

Line 7-11: The background information in the abstract is somewhat lengthy. I would recommend to condense it to quickly lead into this study's own findings and contributions.

- I removed the first sentence and slightly edited the second to focus the background information on what is most relevant to this study. Here is the new abstract: "Understanding Pliocene (5.33-2.58 Ma) climate evolution is critical to establishing the conditions that enabled large ice sheets to form in the Arctic region during the intensification of Northern Hemisphere Glaciation (iNHG) around 2.72 Ma. The causes of iNHG remain unclear, with hypotheses ranging from tectonic changes to CO2 reductions. An anomalous, pre-iNHG cooling signal was recorded in a previously published alkenone-based sea surface temperature (SST) record from Ocean Drilling Program (ODP) Site 1090, located in the southeastern Atlantic Ocean. This record has been used to posit that late Pliocene cooling of the already-glaciated Southern Hemisphere could have driven planetwide cooling and the intensification of Northern Hemisphere Glaciation. Here, we expand the SST record of Site 1090 using the same proxy but with higher resolution and improved laboratory protocols. Our revisited record substantially revises conclusions based on prior work. We find that SST at ODP Site 1090 follows similar cooling trends to those found of equatorial and high latitude Northern Hemisphere sites, suggesting that a global forcing, such as a reduction in atmospheric CO2, prompted iNHG, as opposed to an early cooling of the Southern Hemisphere." (Lines 7-17)

Line 11: "iNGH" is a typographical error and should be corrected to "iNHG" for consistency with the standard abbreviation used throughout the manuscript.

- This has been corrected in the manuscript, thank you!

Line 11-14: The sentence is overly long and complex. Consider to break it into two shorter sentences for improved readability.

- Reworded: "An anomalous, pre-iNHG cooling signal was recorded in a previously published alkenone-based sea surface temperature (SST) record from Ocean Drilling Program (ODP) Site 1090, located in the southeastern Atlantic Ocean. This record has been used to posit that…" (Lines 9-11)

Line 13-14: The phrase "Earth's climatic descent into the Pleistocene" is somewhat poetic but could be perceived as subjective. Recommend rephrasing for a more neutral, scientific tone.

- Rephrased: "could have driven planetwide cooling and the intensification of Northern Hemisphere Glaciation" (Lines 12-13)

Line 63: "iNGH" should be corrected to "iNHG".

- This has been corrected in the manuscript, thank you!

Line 67: The sentence "We were motivated to re-examine... by two aspects..." uses first-person and has a slightly awkward structure.

- Rephrased: "Two aspects of the Martínez-Garcia data set appear anomalous, necessitating a re-examination of this alkenone-based SST record." (Lines 66-67)

Line 79: "iNGH" should be corrected to "iNHG".

- This has been corrected in the manuscript (I believe this was meant to indicate the error at line 69), thank you!

Line 70-71: The clause "which would be unusual given the moderate temperatures..." is a key rationale but is presented almost as an aside. Its logical importance should be emphasized.

- We expanded this section to better explain our reasoning and emphasize to the reader why we find this worthy of investigation: "The second aspect is the unusually high C37:4 content reported by Martínez-Garcia and coauthors. While the C37:4 alkenone is associated with the presence of sea ice (Liao, Wang, et al., 2023; Wang et al., 2021), the reconstruction reveals only moderate (>7°C) temperatures in the Pliocene, suggesting the need for an investigation to explain this anomalous result. We show below that improved analytical methods lead to significantly different results from data published by Martinez-Garcia et al. (2010)." (Lines 69-73)

Line 105: This is the first instance where "GC-FID" appears. Add the full name: "...using gas chromatography with flame-ionization detection (GC-FID)."

- I removed GC-FID from this sentence and later defined the acronym at its new first appearance (line 169)

Line 279: It is recommended to provide the limit of detection.

- We thank the reviewer for this helpful suggestion. To determine the limit of detection (LOD) for the C_{37} alkenones under the same analytical conditions used to construct the SST record, we conducted an additional experiment using a standard solution analyzed on the GC-FID with identical instrument settings (column, temperature program, and injection parameters). The standard was run at progressively lower concentrations until the peak height of the C_{37} alkenones was approximately three times the baseline noise level, consistent with a signal-to-noise ratio of ~3 commonly used to define the LOD. Based on this assessment, and considering the sediment mass extracted for our samples (7–10 g per sample), we determined that the detection limit corresponds to approximately 0.6–1.0 ng C_{37} alkenones per gram of sediment. We will include this detection limit in the revised manuscript to clarify the analytical sensitivity of our measurements: "Using GC-FID, the detection limit of C_{37} alkenones is approximately 0.6-1 ng per g sediment." (Lines 284-285)
- We additionally include this procedure and data in the supplementary information (Tables S5 and S6).

Line 308: "iNGH" should be corrected to "iNHG".

- This has been corrected in the manuscript, thank you!

Line 333: The phrase "does not exhibit a cooling trend that is distinct from" is wordy. Replace with "...does not show a cooling trend indistinguishable from...".

- Thank you for the wording suggestion; we edited the manuscript accordingly.

Line 339: The description of the SST record "sharing orbital-scale features" is clear, but the subsequent sentence about spectral analyses feels like a non-sequitur.

- Thank you for your feedback regarding the clarity of our description. In the revised manuscript, we will clarify the connection between the shared orbital-scale features and the subsequent spectral analyses. We believe that the spectral analysis provides critical insights into the dominant periods of variability, reinforcing the significance of the orbital features observed at ODP Site 1090: “The SST record of ODP Site 1090 shares orbital-scale features with records from other regions of the global ocean, highlighting its relevance within the broader context of global climatic patterns. To further explore these shared characteristics, spectral analyses were conducted using the multitaper method Fourier transform. This analysis identifies the dominant periods of variability in the SST records of ODP Site 1090, ODP Site 846, and IODP Site U1313, enabling assessment of the commonality of these orbital-scale features at the 95% confidence interval (Fig. 4).” (Lines 372-376)

Table 1: It is recommended to reformat the table using the standard three-line table format. This will clearly separate the table content from the notes below, improving its professionalism and readability.

- We will reformat as recommended.

Fig 2: I recommend that the authors add error envelopes to their own data.

- We thank the reviewer for this suggestion. We carefully considered the inclusion of error envelopes for the SST record but chose not to include them because the dominant uncertainty in proxy-derived SST estimates arises from calibration uncertainty rather than pointwise analytical error. Calibration uncertainty primarily affects the absolute temperature estimates and is largely systematic across the record, making it difficult to represent meaningfully as a time-varying error envelope. Plotting such envelopes could therefore imply a level of point-specific accuracy that the proxy does not provide. While Bayesian approaches can be used to propagate uncertainty and generate probabilistic SST estimates (e.g., Tierney & Tingley, 2018), these methods are most appropriate when absolute temperature values are a central focus. Given that our conclusions are based on relative changes (i.e., $\delta^{18}O$-linked warming-and cooling changes that are likely captured faithfully), we believe that including error envelopes would not materially affect the interpretations presented here.

Fig 3: The letter “C” in the figure is positioned too high; it should be moved down slightly.

- We will reposition the “C” during figure revisions; thank you!

RC2

Review of “South Atlantic lipid biomarkers support synchronous Plio-Pleistocene global cooling: Revising the ODP Site 1090 sea surface temperature record”

Hoegler et al. generated a late Pliocene UK’37 SST record of site 1090 using revised age model and laboratory procedure. Comparing to the record previously reconstructed by Martínez-Garcia et al. (2010) from the same site, the authors find slightly higher SSTs and support the hypothesis of synchronous global cooling in the late Pliocene. In general, the high-resolution revised SST record is important to understand both regional paleoceanography and global cooling mechanism. However, before accepting, I would like to see some further discussion, answers, clarification and polishing from the authors.

Major comments

1. Age model: In general, I am not very convinced by the tie points above 62m MCD because these two records do not mimic each other well. I am not in favour of using SST for tie points either. But if there is really no other record you can use, that is fine. Please also provide an age-depth plot including both new and old datums. Include the types and origins of the datums in your Table S3. F S4 is quite chaotic. It is better to use vertical lines in the panels and connect with oblique lines. Also move the age axis to the top. The position of of the first teal triangle is probably wrong. And why did you put the symbols on the SST curve? In the end you need to make it clear what is the difference in the SST record by applying the new age model.

- We reviewed our age model and agree that the constraints could be improved from what was originally shared in our manuscript. Consequentially, we are slightly revising the age-depth model for our revised manuscript with refined tie points based on magnetic susceptibility data, stable oxygen isotope records of Site 1090 (Hodell et al., 2003), the LR04 benthic oxygen isotope stack, and an orbital template of 1 part tilt, 1 part precession. The resulting age-depth model is more robust and integrates additional, non-SST records into our ties whenever possible. See our updated supplemental information and our bundled dataset on PANGAEA (https://doi.org/10.1594/PANGAEA.988391) for the updated age model and ties. We have re-written the age modelling section to reflect this:
  “To produce the most robust stratigraphy possible, we improved upon the existing shipboard composite depth estimations (Shipboard Scientific Party, 1999). Using our SST to enhance the shipboard magnetic susceptibility and cryomagnetic inclination data, we were able to establish a more accurate composite of ODP Site 1090 Holes D and E by correlating the two holes’ properties (Fig. S4, Table S2). Our revised composite section spans from around 55 to 71 MCD. Using this revised composite, we spliced together our Hole D and Hole E SST records to produce one continuous record (see data availability statement for information regarding data access). An abrupt change in

magnetic susceptibility data locates the Miocene/early Pliocene hiatus at ~70 MCD, consistent with shipboard biostratigraphy.

We used biostratigraphic and magnetostratigraphic data to establish initial age constraints for our age model (Shipboard Scientific Party, 1999). We found the magnetostratigraphic data to provide reliable age-depth ties from 3.04 to 3.594 Ma; however, we found it to be an unreliable indicator deeper in the core (MCD > 67, as measurements neared the hiatus), as putative polarity shifts could not be correlated between offset holes in the magnetic susceptibility framework. To more precisely assign ages to the Site 1090 SST data, we tuned the 1090 SST data as a function of composite depth to Lisiecki and Raymo's (2005) "LR04" δ18Obenthic record (Fig S5, Table S3), which allowed for finer age assignments than the biostratigraphic and magnetostratigraphic data alone while remaining consistent with the age estimates yielded from those data. Our age-depth model suggests that our SST record spans approximately 2.63–4.18 Ma. " (Lines 98-113)

- When revising figures and tables to include this improved age-depth model, we will integrate your suggestions, including providing both old and new datums on an age-depth plot (Fig S6), better indicating the metadata in Table S3, and streamlining and improving the readability of Figure S4 (now S5).

2. Chromatography: I would encourage you to show the chromatography before and after your cleanup procedure. Maybe also show the mass spectrum of the discussed alkenones. I believe this can help many others to better understand what you are doing and where to find the peaks.

- This is an excellent suggestion that will help us to make more clear to the reader why cleanup of lipid extracts is necessary to achieve the most reliable SST estimates from ODP Site 1090. We will include a figure showing the chromatography before and after the cleanup procedure in the supplementary information. (Fig S1)

3. Impact of cleanup on SST and absolute SST values in general: You argue that the impact of cleanup procedure is negligible because the difference is within 1.5℃ calibration error without a t-test. In your results, you report the new SSTs are on average 1.27℃ higher than the previous study. In my opinion this can be negligible as well just because it is still within the calibration error. Anyway, I will not take the absolute temperatures too serious because they can hardly be real. Additionally, there can be an inter-laboratory difference as well. But I agree the long-term cooling trend is much weaker in your record. Regarding the proxy-model comparison part in your discussion, you can also tone it down. Furthermore, as you mentioned Site 1090 is located in a region where strong oceanographic changes happen, for instances the migration of ACC and fronts. Thus, the modelling outputs may not be able to capture that, which may also explain the high variability in your record.

- We thank the reviewer for this thoughtful comment and for acknowledging the robustness of the long-term cooling trend. However, we would like to clarify the distinction between calibration error and analytical uncertainty in the context of our study. The stated ±1.5 °C uncertainty reflects the calibration error of the proxy, whereas the analytical reproducibility of our measurements is substantially smaller. When considering analytical uncertainty alone, the SST differences observed before and after the cleanup procedure are negligible. We have performed a paired t-test (two-tailed) to formally evaluate whether SST estimates before and after the cleanup procedure differ significantly and have confirmed that there is no significant difference: our in-house standard samples produced a p-value of 0.68, and the Greenland standard yielded a result of 0.93. We report these results in the revised manuscript (see section 3.5, lines 256-258): "We performed a paired t-test (two-tailed) to formally evaluate whether SST estimates before and after the cleanup procedure differ significantly and confirmed that there is no significant difference: our in-house standard samples produced a p-value of 0.68, and the Greenland standard yielded a result of 0.93."

- With respect to the comparison with Martínez-García et al., we note that the reported +1.27 °C offset represents an average difference across the record. While this mean offset falls within the calibration uncertainty, individual samples show substantially larger deviations. In many cases, SST differences exceed 2°C, and at one comparable marine core depth interval exceed 6°C. These larger sample-specific differences suggest that the offset cannot be attributed solely to calibration uncertainty or inter-laboratory effects. We therefore conclude that, while absolute SST values should indeed be interpreted cautiously, the observed differences related to the cleanup procedure are analytically meaningful. We will revise the manuscript to better distinguish calibration uncertainty from analytical error and to clarify the significance of both the average offset and the sample-to-sample variability. This includes revising the Fig S1 and S2 captions to specify that "All samples that underwent both forms of cleanup were well within our window of calibration error of 1.5°C." This also includes specifying in our results the standard deviation and range of SST differences in our overlapping record interval (see lines 302–304).
- Regarding the proxy-model comparison paragraph, we will more cautiously discuss the implications of our new record, being sure to recognize the limitations of models in this oceanographically complex region:
  "... indicating that the paleo-record suggested temperatures were on average colder than the model output (Burton et al., 2024). Using our revised SST estimates, which are on average ~0.8 °C warmer than the Martínez-Garcia et al. (2010) record over MIS KM5c (3.205 ± 0.01 Ma), reduces, but does not eliminate, the data–model discrepancy at this site. The magnitude of disagreement would be approximately halved relative to that reported by Burton et al. (2024). We emphasize, however, that Site 1090 is located in a region strongly influenced by Southern Ocean frontal dynamics and latitudinal shifts of the Antarctic Circumpolar Current. Such processes are unlikely to be fully resolved in model simulations and could contribute to both the relatively high variability in the proxy record and persistent model–data offsets. Nevertheless, our results highlight the importance of accurately constrained regional proxy records for evaluating model performance in dynamically complex settings." (Lines 423-431)

Minor comments

All figures need some revising. Check the quality, axis titles, ticks and units.

- We will revise all figures for quality and readability. Suggestions made by both reviewers regarding style and additional features that could improve figures (e.g. changing the colormap of Fig. 1, adding a moving average to Fig. 2) were taken into account.

Specific comments

Line 10: glaciation–Glaciation

- I capitalized this in the manuscript.

Line 11: iNGH–iNHG, check thoroughly

- This has been corrected in the manuscript, thank you!

Line 12: I think the work you are referring to also used alkenones, so I would mention it here.

- Updated to refer to this work as “a previously published alkenone-based sea surface temperature (SST) record”

Line 13: what does the “early” mean here? Earlier than the northern hemisphere (I think it is this.)? The Pliocene is earlier than the Pleistocene? Early Pliocene?

- Changed “early” to “late Pliocene”

Line 14: following line 12, rephrase as “Here, we expand the SST record of Site 1090 using the same proxy but with higher resolution and improved laboratory protocols. Our revisited record substantially revises...”

- This has been rephrased as suggested.

Line 22: “concentration (pCO2)”

- Added to the manuscript.

Line 24: mid-Piacenzian is better, because it is actually late-Pliocene.

- Corrected this in the manuscript.

Line 32: Why suddenly Eocene?

- We wanted to make it clear that the cooling leading up to the iNHG was part of a long-term cooling trend from a greenhouse to icehouse climate state and that, ultimately, better constraining Pliocene climate is helping us to better understand the backend of that trend. Framing Earth’s climate throughout the Cenozoic helps us to frame our argument that the glaciation of the Northern Hemisphere is an extension of this long-term cooling, rather than a response to a Southern Hemisphere-led regional feedback (i.e., increased ice-albedo cooling).

Line 50: Consider citing De la Vega et al. (2020) for Pliocene pCO2.

- They are already cited later in the paper, but I agree citing them here as well is appropriate. Manuscript has been updated to reflect this.

Line 77: You may want to show a vertical profile next to your surface map if you are discussing CDW/NADW? Furthermore, I don’t think these two terms should be separated. NADW is the lower branch of CDW. If you are not discussing water masses later (which is the case), just delete these and focus on the surface oceanic processes.

- Since we are not focusing on watermasses, we opted to simply delete the extraneous information to now read: “Located on the southern flank of the Agulhas Ridge at a water depth of 3702 m, ODP Site 1090 contains one of the most southerly records recovered of late Pliocene/early Pleistocene climate. Today, the site sits within the sub-Antarctic

Zone of the AAC, between the Subantarctic Front (SAF) and Subtropical Front (STF), and below the southernmost Polar Front (PF).” (Lines 78-81)

Line 81: sea surface temperature (SST) of Site 1090

- Rephrased to “The SST of Site 1090” and defined acronym earlier in the manuscript (line 60): “The alkenone-based reconstruction of ODP Site 1090’s sea surface temperature (SST)”

Figure 1: I would make the figure more intuitive. Warm colour=high temperature. Regarding the ocean currents, why is the Agulhas retro current a cold current? Please also denote the Agulhas leakage.

- I changed the colorbar to utilize a warm-to-cool palette for the temperature. I also fixed the Agulhas retroflection current to reflect its warm nature, and added the Agulhas Leakage as you recommended.

Line 100: This part and section 1.2 belong to the method.

- We have opted to separate the site description and age-depth model from the overall methods section to enhance transparency and facilitate reproducibility and revision, as the age model is a scientific interpretation in itself and not just a laboratory or statistical procedure.

Line 132: ~50 mbsf of which hole?

- Hole D; we will add this to the revised manuscript: “We sampled the sediment core from ODP Site 1090 approximately every 5 cm, beginning at ~50 meters below the seafloor (MBSF, hole D), corresponding to about 55.3 meters composite depth (MCD), and ending at ~61 MBSF (~70 MCD).” (Lines 135-136)

Line 168: Did you inject the total lipid extract?

- Yes, we will clarify this in the manuscript: “After initial gas chromatography with flame ionization detection (GC-FID) results conducted on the total lipid extract yielded chromatograms with noisy baselines, likely due to other organic residues that can co-elute with the ketones we seek to measure, we conducted compound purification.” (Lines 169-171)

Line 170: It is a bit confusing here. If I understand correctly, you first did the apolar-polar fractionation using silica gel column then a silver nitrate-impregnated silica gel column to separate unsaturated-saturated compounds. Anyway, you should make it clear here.

- We will revise this to make it more clear in the manuscript: “... we conducted compound purification: apolar-polar fractionation via flash column silica gel chromatography followed by a silver nitrate-impregnated silica gel column chromatographic procedure” (Lines 171-172)

Line 177: What is considered as very low?

- C_{37} total is highly variable throughout the global ocean, but is often present in concentrations >0.1 ug/g sediment (dry mass) throughout the global ocean and in the range of several ug/g in highly productive regions (e.g., in Raja & Rosell-Mele’s 2020 global appraisal of core-top sedimentary alkenones, ~84% of samples had C_{37} total > 0.01). However, at our site the average C_{37} total was considerably lower, ~0.02 ug/g. We will add this value to the manuscript, and we have reported the measured C_{37} total values in our dataset uploaded to PANGAEA: “While total C_{37} alkenone concentrations ($C_{37total}$) is highly variable throughout the global ocean, it is often present in concentrations >0.1 μg/g sediment; at sites with very low $C_{37total}$, such as ODP Site 1090 (where our average $C_{37total}$ was ~0.02 μg/g sediment), it can prove difficult to differentiate the biomarker signal from baseline noise using the typical GC-FID method." (Lines 181-185)

Line 183: remove the "_"

- This has been removed.

Line 186: This is not the first time abbreviation "GC-FID" is used.

- I removed "gas chromatography with flame ionization detection" from before this usage of the acronym and ensured it was placed before its first usage in the main text (Line 169)

Line 241: I find this paragraph difficult to understand. What are these 13 samples? According to your previous paragraph I see 8 in-house standards plus one Greenland standard. When I look at Figure S1, what is the A23 standard? Please make the names consistent. And why would the rehydration matter, you need to dissolve your extracts before measuring anyway?

- The eight in-house standards referred to the two dried and reconstituted standards plus the six that underwent cleanup. We clarified what each of the 13 samples are to make it easier for the reader to understand: "The average SST of all experimental samples (N = 13)— our typical lab standard (n = 5), the de- and re-constituted standard (n = 2), and the cleaned standards (n = 6)— were within a few hundredths of a degree of each other." (Lines 251-253)
- We will amend Figure S1 to say "in-house alkenone standard" to match what is in the text, rather than the abbreviated name A23.
- We included a de- and re-constituted standard to ensure that no alkenones were being lost by our evaporation method, which was not being captured by the experimental control alone.

Line 245: I don't think the ±4℃ changes are negligible.

- Thank you for highlighting this important point. The resulting ±4℃ temperature changes in sample #5 of this experiment was an anomaly that we did not discuss carefully enough— after further investigation into our chromatograms, we have found that this anomalous temperature change was the result of faulty peak selection by our graphical user interface that we neglected to catch. After re-integrating the peak area, we found that the $U^{k'}_{37}$ SST estimate of this sample is 0.93℃ (0.7° difference from the Greenland standard) and the U^{k}_{37} SST estimate of this sample is 1.05℃ (0.7° difference from the Greenland standard). These findings confirm what we have observed in our lab, where we have frequently examined the effect of silica gel cleanup and found no systemic evidence that it tends to fractionate alkenones. We will amend the data and Fig. S2 (now S3) to reflect this change.

Line 266 and Fig.S5; I don't agree with your observation and I don't think there should be a relationship between age model and alkenone concentrations. Check the x-axis in Fig. S5, it is in depth domain instead of age.

- I am unsure of what observation the reviewer is referring to— assuming it is our observation that depths with the highest age model disagreement tended to feature low alkenone concentrations, this is the case for three of the four peaks in disagreement, as can be seen in Fig. S5. The reviewer is correct that the x-axis in the figure should be changed to the depth domain instead of age, and we could make that change in the revised manuscript. However, the reviewer is also correct that there is not likely to be a notable reason for this relationship, as the Martinez-Garcia age model was created by aligning the n-alkane record to the Lisiecki and Raymo (LR04) global benthic δ18O stack, rather than being based off of the alkenone record. Therefore, we instead will opt to remove this part of the manuscript and the related figure, as they only distract from the main points of the paper.

Line 271: Present a figure of the chromatography here.

- We will include a chromatography figure as mentioned earlier (now Fig S1).

Line 291-295: You have got a very small R2 and a small slope, which probably mean the temperature trend is not monotonic. What does the "ned" mean here, or you mean "end"?

- I agree; we already note that the large degree of orbital variability could contribute to the small R^2 but will add that this and the small slope indicate a non-monotonic trend: "The R2 of both records is small, likely due to the large degree of orbital variability superimposed on any trend. This small R2 and small slope likely also result from the non-monotonic nature of the cooling observed. The P-values of the regression for both records are <0.05." (Lines 322-324)
- "Ned" was a typo and was supposed to be "end."

Line 300, Figure 2: Are the data from Martínez-Garcia et al. (2010) plotted using the new age model? I would like to see the Martínez-Garcia et al. (2010) record using original and new age model parallel to each other somewhere so we know better about the original argument. In your y-axis titles, SST is good enough. And there is a right bracket missing. In you x-axis, you can use "ka" instead of "kya".

- The Martínez-Garcia et al. (2010) data in our submitted manuscript is plotted using their original age model in Fig. 2; we will modify this figure to show both the original and new age model as suggested by the reviewer. We will also edit the axis titles as recommended.

Line 308: You may want to mark iNHG in your figure. I don't understand the 45% part either.

- We will denote iNHG in the figure as suggested.
- We will revise the section stating "our record showing cooling at ~45% of the rate of the prior record between 2.63-3.81 Ma"; this was meant to refer to the fact that the linear trend derived from our SST record is 45% of the slope of the trend derived from the Martinez-Garcia record. However, we have revised our discussion of cooling trends in line with Reviewer 1's suggestions to use a moving average and will refrain from over-reliance on linear trends in our revised discussion:
- "Compared to the SST record of Martínez-Garcia et al. (2010), our SST estimates record only a gentle cooling trend leading up to iNHG (Fig. 3), [b1.1]made apparent by the gentler cooling and warmer SSTs evident in the 400-kyr moving average of our reconstruction, in addition to the gentler slope of our linear regression. In addition, both our new high-resolution dataset and the lower-resolution SST data of Etourneau et al., (2010) indicate that SSTs were on average 1.22℃ warmer during the late Pliocene at ODP Site 1090 than Martínez-Garcia et al. (2010) estimate. Minimum temperatures in the interval spanning ca. 2.8-3.2 Ma are often 1-2°C warmer in our recor[b2.1]d, but some differences were even greater— at one comparable depth interval, the SST

difference between records exceed 6°C. These larger sample-specific differences suggest that the offset between our records cannot be attributed solely to calibration uncertainty or inter-laboratory effects, and that the observed differences are analytically meaningful. There is little to no indication of anomalously cold events at ODP Site 1090 uniquely preceding iNHG (Figs. 3, 4). We believe that most of the differences between data sets result from the very difficult sample matrix presented by Site 1090 and the optimization of sample purification and strategic use of HPLC in the present study." (Lines 337-347)

Line 310: How many degrees warmer?

- On average 1.22℃; will add this to the manuscript here: "In addition, both our new high-resolution dataset and the lower-resolution SST data of Etourneau et al., (2010) indicate that SSTs were on average 1.22℃ warmer during the late Pliocene at ODP Site 1090 than Martínez-Garcia et al. (2010) estimate." (Lines 339-341).

Line 313: I don't understand this. In both of your and Martínez-Garcia et al. (2010) records, I see a warming trend from 2700 to 2600ka. But what is the link between the temperature trend and your method?

- We don't discuss this temporary warming trend in our record because it is not a part of the long-term picture: we are most interested in the long-term cooling trend we see throughout the Pliocene leading up to the Pleistocene, not just the ~100 kyr interval where our record ends. There likely is no link between our method and this warming, other than the fact that our measurements allow us to reconstruct SST from alkenones; as the reviewer said, this trend is seen in both records. The anomalously cold events to which we refer in this section are the dip in temperatures seen in the Martinez-Garcia record from about 3100-2800 ka and the resulting dramatic cooling trend seen in their temperature record throughout the plotted interval (Fig. 2). To avoid future confusion, we will highlight more clearly in the manuscript that there is only one specific interval where our data diverge significantly from Martínez-Garcia et al. (2010), including providing a figure that clearly illustrates the multi-degree differences in estimated SST in this key interval by overlying the records (Fig 3): "To visualize and contrast the underlying low-frequency trends embedded within our new record and the original Martínez-Garcia et al. (2010) SST reconstruction, we applied 100- and 400-kyr moving averages to both records (Fig. 3). Both smoothing windows show that our SST estimates tended to fall above those of the previous record after 3.6 Ma. They also consistently show that the Martínez-Garcia et al. (2010) reconstruction diverges from our own during the interval we identified as having SST estimates considerably lower than those of Etourneau et al. (2010), with our SST estimates tending to fall between those of these two previously published records. Strongest divergence between our SST record and that of Martínez-Garcia et al. (2010) occurs ~3.0 Ma." (Lines 311-317).

Figure 3: You need to present the R2 for all regressions.

- We will include the R^2 in our figure revisions.

Line 336: ka in stead of kya

- This has been corrected.

Line 337: kyr instead of kya

- This has been corrected.

Line 351: Which literature first proposed the asynchronous global cooling?

- McKay et al., 2012; we will re-arrange the in-text citation order to put them first so this is more clearly attributed to them.

Line 363: You should either mark the periods or the orbital parameter names next to the pink bars.

- We will make this addition to Fig. 4 (now Fig. 5) in the revised manuscript.

Line 364: You need references here.

- This is an introductory sentence for the paragraph; all of the papers to which it refers are cited in the immediate next sentences, with explanations for how these findings link to our own.

Line 378: It is unnecessary to have a separate paragraph here and I am not sure if I understand you here.

- We will combine this sentence with the previous paragraph. We rephrased the sentence to make it more clear: "Similarly, recent analyses of global temperature change during the past 4.5 million years by Clark et al. (2024) show that no region of the ocean displays an accelerated degree of cooling from the mean global cooling trend occurring throughout the Pliocene; this pattern is apparent even with the inclusion of the previously published, likely erroneously cold SST estimates from ODP 1090 (Martinez-Garcia et al., 2010)." (Lines 428-431)

Line 384: late-Pliocene

- This has been corrected.

Line 390-393: see major comments

- Major comments have been addressed.

Line 410: reference

- Citation (McKay et al., 2012) added.

Line 411: What does the amplification mean here? This the only time you use the word in the main text.

- Thank you for your careful eye and pointing out the ambiguous use of the term "amplification." We rephrased this sentence: "Our spectral analysis shows that both SST and the global benthic $\delta^{18}O$ stack (LR04) exhibit increased variance at the obliquity band during the late Pliocene, expressed as larger-amplitude oscillations relative to earlier intervals." (Lines 472-474)