Authors' response

August 2025

Editor:

"Dear authors,

I am now in receipt of two reviews of your revised manuscript. Reviewer is satisfied with the work and supportive of immediate publication, while Reviewer 2 suggests additional work.

I must agree with Reviewer 2 that the implications of additional breakpoints need to be more carefully discussed. From a methodological standpoint, it comes as no surprise that estimating the number of breakpoints from information-theoretic criteria would lead to additional breakpoints compared to those identified previously in Westerhold et al (2020). This begs the question of the geological significance of these new breakpoints. As such, Reviewer #2's suggestion of incorporating different lines of evidence (in addition to benthic d18O, 'd13Cb, relavant [sic] SST or BWT records with stages of cryosphere development + C3/C4' (the ratio of C3 to C4 plants)), is very well taken, and could shed light on whether transitions identified solely in d18O are geologically meaningful, or whether they are simply a methodological artifact. It may also be worth discussing how to integrate the Bai-Perron detection of breakpoints across multiple data streams (e.g. the ones cited above), though a formal investigation of this type is clearly out of scope for this paper.

Reviewer 2 also makes a number of useful, specific suggestions regarding additional references that would make the manuscript more current to the present state of the scholarship.

Finally, I agree that the choice of title could be improved, though for a different reason: while there is nothing wrong with using the mainstream word 'econometric', the issue I see is with the plural form 'methods'. This is misleading as only one such method (the Bai-Perron framework) is really used. Thus it would seem more truthful to choose the title 'Estimating breakpoints in the Cenozoic Era with the Bai-Perron framework', or 'Estimating breakpoints in the Cenozoic Era — an econometric approach', to avoid giving the impression that a whole array of econometric methods have been applied to the question.

In revising your manuscript, please make sure to observe the revisions checklist provided by the editorial office.

Best of lucks for your final revisions,"

We thank the editor for the constructive summary and for the opportunity to revise our manuscript further. We are pleased that Reviewer 1 supports immediate publication and that Reviewer 2 acknowledges substantial improvements in the revised version. We also appreciate the thoughtful comments from both the editor and Reviewer 2 on how to further clarify the implications of our findings and improve the broader paleoclimate context.

In line with the editor's suggestion, we have revised the title to: "Estimating breakpoints in the Cenozoic Era: An econometric approach." We agree that this better reflects the scope of the paper and avoids suggesting that multiple econometric methods were applied.

We also agree that a full formal analysis across multiple data streams is beyond the scope of this study. However, as suggested by Reviewer 2, we have now incorporated several relevant paleoclimate records, such as a $\delta^{13}C$ stack, atmospheric CO_2 concentration reconstructions, and sea-level reconstructions (Westerhold et al., 2020; Hönisch et al., 2023; Miller et al., 2020), into a new summary figure in the Discussion section. This provides geological context for the additional breakpoints and allows readers to better assess their significance. In addition, we have expanded the Conclusion to discuss how the Bai-Perron framework could be extended to analyze other proxy records in future work.

We have also addressed Reviewer 2's specific suggestions regarding additional references. The manuscript has been updated throughout to incorporate relevant recent work on recurrence analysis, Cenozoic climate records, and time series methods.

Finally, we have revised the reference list and appendices in accordance with the editorial office's checklist and instructions.

We hope that these revisions meet the expectations of both the editor and reviewers, and we thank you again for the valuable feedback.

Referee 2:

"Bennedsen et al. resubmission tackles applying econometric methods to estimate breakpoints. The previous version lacked context for wider paleoclimate science and was hard to discern the impact/importance of the new method for undersanding Cenozoic clmate better. They have modified the manuscript across all sections to deepen the context and implications of the work.

Specifically the authors have improved the manuscript however more details are needed to justify some changes and include additional references/previous work to make this contribution exhaustive. Some aspects are related to additional references related to recurrence analysis, Cenozoic d18Ob records, use of econometric methods in time series analysis, and impacts of age uncertainty on findings.

Although the authors now have added a discussion to provide wider paleoclimate context which expands the application more, there is additional work needed to refine this section including restruc-

turing and a summary figure.

With these revisions completed, this would make a good contribution for this journal.

Major comments:

Discussion section hints at potential additional break points however this is alongside of methods aspects. I would recommend adding a section in the results around 'additional breakpoints' to highlight method/criteria used, number of additional breakpoints identified, and then leave the implications of this for the discussion. Info about binning and regime length in discussion make it difficult to digest. I also recommend making a new figure to go along with this section.

Authors highlight there are potential additional breakpoints detectable in the time series. This section refers to Figure 5 only but highlights changes in carbon cycle, cooling and wider climate systematics. It would be useful to make an additional figure which includes d18Ob, d13Cb, relavant SST or BWT records with stages of cryosphere development + C3/C4 to showcase timing of possible new breakpoints and wider features. This could have the initial westerhold points and the new potential ones."

We thank the reviewer for their careful reading of the revised manuscript and for recognizing the improvements made across all sections. We appreciate the constructive feedback on how to further enhance the contextualization, structure, and clarity of the manuscript, and we agree that these revisions strengthen the overall contribution.

We have made the following revisions in response to the major comments:

- We have added further detail to support the interpretation of additional breakpoints, drawing on multiple lines of evidence from existing studies, including sea-level and CO_2 reconstructions, $\delta^{13}C$ data, and C_4 vegetation shifts. While a full multi-proxy analysis is beyond the scope of this study, we now highlight how the Bai-Perron framework could be applied to other records in future work, and we have included new figures to support this discussion.

- We have restructured the Results and Discussion sections to improve clarity. Specifically, we have moved methodological and technical details (e.g., criteria used to identify breakpoints and binning procedures) to the Results section, leaving the Discussion to focus on interpretation and broader implications.

Specific comments:

- *"Title has changed to include 'econometric' methods - however this term is not known in paleoclimate field and only mentioned at the end of the introduction very briefly defining it (line 83). I would recommend reconsidering title change or expanding on the use of these types of methods more widely or explaining why applying this from another field is worthwhile or novel or beneficial."*

- We have revised the title to reflect that we are referring to a specific econometric method rather than the field more broadly. In addition, we have clarified the introduction of the econometric method earlier in the text and improved the explanation of its relevance to paleoclimate research.

- *"Lines 30-33 it is worth mentioning that there are not only shifts in data set but the resolution is varying as well and reference accordingly"*

  - We have chosen not to modify this passage. Variation in resolution is discussed at multiple points throughout the manuscript, and adding this detail here would, in our view, detract from the clarity of the message in the introduction.

- *"Line 33- there are more recent publications to include as well (Mudelsee et al 2014) in addition to Zachos"*

  - We have added a citation to Mudelsee et al. (2014) as suggested.

- *"Line 45 are there other applications in the field of climate science that can be summarized used using recurrence analysis (e.g Liang et al 2025). It would be useful to provide exhaustive background on application of recurrence analysis and metrics used in this analysis in addition to westerhold"*

  - We have included references to Liang et al. (2025) and Fischer et al. (2024) to reflect more recent applications of recurrence analysis in climate science. As we already provide a detailed description of recurrence analysis and its metrics on lines 43–80, and since our contribution lies in presenting an alternative approach rather than extending recurrence analysis itself, we prefer not to expand further on this background to maintain the focus of the paper.

- *"Line 81 sets out the study but does not mention Westerhold dataset, could be useful to say this work applies approach on climate stack"*

  - We thank the reviewer for noticing this. We have clarified this by explicitly stating that the proposed approach is applied to the Westerhold et al. (2020) δ^{18}O stack.

- *"Line 89 here the econometric framework is then then referred to as the Bai-Perron framework and using this term for the remaining. It is useful to introduce both econometric and Bai-Perron framework?"*

  - We have restructured the end of the introduction to clarify the novelty of applying this framework to paleoclimate data. We chose not to introduce both terms separately, as the

Bai-Perron framework is thoroughly presented in the methodology section, and 'econometric' refers to a broader research field that is not easily defined in a few sentences.

- *"Line 101- 'weight difference' consider defining as ratio of heavy to light for instance"*
  - We have changed the definition accordingly.
- *"Line 110-can you provide example resolution across key time intervals, the average resolution is only so useful as there are few records in early Cenezoic with orbital resolution"*
  - We have added a sentence with examples of resolutions across the climate states defined by Westerhold et al. (2020).
- *"Line 113- age model uncertainty is mentioned but also said it is not accounted for, can you add the biggest drivers of uncertainty here? It is later mentoned but would be worth to introduce reader to the issues here broadly also it is useful to highlight why it does not need to be addressed in this study. See lines 327-330."*
  - Thank you for the suggestion. We have revised this section to include the primary sources of age model uncertainty, such as orbital tuning and sedimentation rates, and now clarify that the magnitude of this uncertainty is small relative to the duration of the climate states we estimate. We believe this provides sufficient context for why age model uncertainty is not explicitly addressed in our analysis.
- *"Line 336-337 it is stated that the authors 'expect our main findings to be robust' despite age uncertainties across the Westerhold. Are the authors able to conduct a sensitivity test in some way to showcase this?"*
  - We appreciate the reviewer's suggestion. While a formal sensitivity analysis would be valuable, it is beyond the scope of the present study.
- *"Line 355- the authors mention the post-MECO cooling and refer to Bohaty & Zachos, 2003, however there are additional insights into the MECO and carbon cycle and temperature trends since this publication."*
  - We have added more details to this part of the discussion by considering the findings of Henehan et al. (2020).
- *"Line 368-denote average resolution for the record"*
  - We have reported the average resolution of the record here.

- *"Figure 1 and 3-add the geological time scale for reference as well as the climate states for reader context. This would help also understand changes in data density/resolution with time."*
  - We have added geological time scales to the two figures.
- *"Figure 3-caption should include more description of the data for instance including time interval, data resolution and number of core sites."*
  - We have added more description of the data in the caption of Figure 3.
- *"Heading 3.1-consider changing to 'breakpoint number sensitivity tests 'or more general than current"*
  - We have changed the titles of Sections 3.1 and 3.2 to make them more accurate.

References

Fischer, M. L., Munz, P. M., Asrat, A., Foerster, V., Kaboth-Bahr, S., Marwan, N., Schaebitz, F., Schwanghart, W., and Trauth, M. H. (2024). Spatio-temporal variations of climate along possible african–arabian routes of h. sapiens expansion. *Quaternary Science Advances*, 14:100174.

Henehan, M. J., Edgar, K. M., Foster, G. L., Penman, D. E., Hull, P. M., Greenop, R., Anagnostou, E., and Pearson, P. N. (2020). Revisiting the middle eocene climatic optimum "carbon cycle conundrum" with new estimates of atmospheric pco2 from boron isotopes. *Paleoceanography and Paleoclimatology*, 35(6):e2019PA003713. e2019PA003713 2019PA003713.

Hönisch, B., Royer, D. L., Breecker, D. O., Polissar, P. J., Bowen, G. J., and Henehan, M. J., et al. (2023). Toward a cenozoic history of atmospheric co_2. *Science*, 382(6675):eadi5177. The Cenozoic CO2 Proxy Integration Project (CenCO2PIP) Consortium.

Liang, J., Wang, Y., Zhang, S., Huang, C., Xu, E., and Zhang, Z. (2025). Astronomical Forcing of late oligocene to early Miocene Paleoclimate: A case study from the Northern South China Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 673:113007.

Miller, K. G., Browning, J. V., Schmelz, W. J., Kopp, R. E., Mountain, G. S., and Wright, J. D. (2020). Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. *Science Advances*, 6(20):eaaz1346.

Mudelsee, M., Bickert, T., Lear, C. H., and Lohmann, G. (2014). Cenozoic climate changes: A review based on time series analysis of marine benthic δ18O records. *Reviews of Geophysics*, 52(3):333–374.

Westerhold, T., Marwan, N., Drury, A. J., Liebrand, D., Agnini, C., Anagnostou, E., Barnet, J. S. K., Bohaty, S. M., Vleeschouwer, D. D., Florindo, F., Frederichs, T., Hodell, D. A., Holbourn, A. E., Kroon, D., Lauretano, V., Littler, K., Lourens, L. J., Lyle, M., Pälike, H., Röhl, U., Tian, J., Wilkens, R. H., Wilson, P. A., and Zachos, J. C. (2020). An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science*, 369(6509):1383–1387.