

Climate–carbon-cycle interactions and spatial heterogeneity of the Late Triassic Carnian Pluvial Episode

Corresponding Author: Professor Bo Wang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The Carnian Pluvial Episode has gained increasing research interest in recent years. It represents a type of crisis rarely seen in the Phanerozoic. Zhao et al. provide a multi-proxy study on a mid-latitude lake succession. Contrary to the general conception that the climate shifted towards more humid conditions, the authors suggest increased aridity in continental interiors.

I don't see major issues with this manuscript. However, some revisions would significantly improve this manuscript. These include: 1) a better separation of results and discussion; 2) verify the modelling output. E.g., give a comparison of simulated equatorial SST with published proxy-derived records; 3) reconsider the marine methane hydrate scenario—I don't see the necessity to include such speculation, and it is detached from the main story; 4) include critical information in the method. For example, there is a lack of explanation of pCO₂ prescriptions (568 to 1758 ppm) for the CPE modelling. Inform the audience why these numbers were chosen. The analytical uncertainty of TOC and C and Hg isotope analyses are also missing.

I understand that some coauthors are experts on Mesozoic and Cenozoic hyperthermals/climate changes. However, there are quite some mentions of Triassic-Jurassic, Cretaceous OAEs, PETM, Oligo-Mio, and sometimes Carboniferous. These barely relate to this study (late Triassic) and, when appear so often, are distractions to the central theme of this manuscript. Nevertheless, all these are fixable and should not tarnish the overall quality of this manuscript.

Collectively, this is a comprehensive study combining the merits of multi-proxy geochemical records, high-precision geochronology and Earth system modeling. It will enhance our understanding of the CPE, and I recommend revising it before its formal publication.

Specific comments:

Line 32, “non-coldhouse climate” is not a very good term to me. Is non-coldhouse equal to warm house?

Line 35, not very clear what are the “eastern continents”. There was one continent at the time—the Pangea. I am not aware of any Carnian succession in either pole.

Line 47, the word “remarkable” should be avoided in scientific writing.

Line 56 the words in brackets are redundant and probably not entirely accurate. What is left today as the Wrangellia LIP was only a fraction of its original size.

Lines 77-78 I would change to “the manifestation of global hydrological cycle changes”

Lines 129-137 These are discussions rather than results. One might consider moving these words to later chapters.

Lines 119-121 Rock Eval analysis is not described in the method.

Lines 140-141 mis-citations of references

Line 147, not easy to follow here. of the CPE?

Line 179, I would delete the example. Methane hydrates are too speculative for the Carnian case and there is no evidence for it.

Lines 188-190, this is not an isolated case for the Carnian. As a matter of fact, most carbon emission estimations from major LIPs do not match corresponding d¹³C excursions.

Line 194 GMAT of 23-24 represents a significant warm interval. This sentence also miscites literature. These estimated GMATs are compiled and should be used with great caution if cited this way.

Lines 194-195, ambiguous. Under what specific conditions do the authors refer to as? What is the GMAT that AWI-ESM gives in this study?

Lines 199-204, The argument is not convincing. Yes, the dissociation of marine methane hydrates could account for the d¹³C excursion, but there is no evidence for such events. A decrease in d¹³C can be triggered in a few scenarios, e.g., a

decrease in primary productivity, less burial of organic carbon etc. What is the reason the methane hydrate scenario stands out in the Carnian case?

Lines 208-209 yes, this is a simple explanation but not necessarily represent the whole picture.

Line 226, I don't follow the symbol " $\uparrow$ ".

Lines 243-245, I couldn't follow the argument here. What does "climate-carbon-cycle interaction" really mean here? Carbon cycle is always coupled with the global climate.

Lines 245-247, My apologies for not following the argument here. The sentence is grammatically incorrect to me. What does the "last 6 Myr" refer to? and how does the Carboniferous example relate to this study (late Triassic)?

Lines 255-257, this lengthy part can be revised to "Our AWI-ESM simulations confirms a

Line 262 "poleward shift of precipitation patterns" is not a proper description and it's hard to guess what the authors mean.

Line 263 reword this sentence. Mountains can block moisture transport.

Lines 258-281 This paragraph could be improved after a proper rewrite.

Lines 295-297 Colleagues working on modern climate change won't be fond of such a statement.

Line 542 what is a Retsch RS200? I guess it is a rock saw.

Line 554 in per mille (‰) relative to

Line 557 Reproducibility and repeatability of

Line 582 delete units of

Line 587 There is no mention of the reproducibility of Hg isotopes.

Line 612 "the" change to a

Line 651, I don't follow the statement here. Solar luminosity and ice coverage of the Carnian world (ice-free) should differ significantly from the pre-industry world (iced world). Revise to clarify this unambiguity.

Lines 655, 658 I don't follow the term "quasi-equilibrium", i.e., the simulations did not reach equilibrium?

Line 657, 1000 model year is really low. Did the simulation collapse?

Figures:

Fig. 2 the black shaded parts in the log stand for black shales, do they? I didn't see any black shale in the field photo (Fig. S1). Maybe include some better field photos.

There are both extended data figures and supplementary figures (in the supplementary materials). The two systems are not very easy to follow.

Extended Data Fig. 3 The Tibetan record is very poor, and is not a good case to correlate. Ref 30 gave a $\delta^{13}\text{C}_{\text{carb}}$ value lower than -5 per mille and down to almost -10 per mille. This cannot be true for any normal marine carbonate. The numbers might have measured from carbonate cements in sandstone or diagenetically highly altered carbonates.

Supplementary materials:

Text S2-strangely, the U-Pb dating was not included in the Method but in the supplementary.

Fig. S8 (and other log figures) Mud/Sha is better to spell in full.

Text S4 Compound-specific carbon isotopes are not mentioned in the main text.

Reviewer #2

(Remarks to the Author)

The manuscript by Zhao et al. provides a new record of the CPE from the lacustrine Junggar Basin in northwestern China. This manuscript presents multiple data, including magnetic susceptibility, U-Pb age, C and Hg isotopes, elemental geochemistry, and palynological data, combined with Earth System modelling, to discuss potential driving mechanisms for the CPE, and coeval changes to the hydrological cycle. Overall, the methods are appropriate and the data are valuable. However, some important issues need to be addressed before it can be considered. My main suggestions are the following:

Major comment

1. Due to the lack of volcanic rocks in the study strata, the authors only determine the age using tuffaceous sandstone. The authors need more description how did your research identify Carnian Pluvial Episode? The CPE does not only mean carbon isotope excursion.
2. Please provide more discussions concerning spores and pollen in the manuscript. How to evaluate the contribution of eolian activity on palynological compositions? If the eolian activity is strong, the spores and pollen could be derived from other distant regions (not surrounding regions). Please clarify it. Besides, I strongly suggest that the authors add climate status in Extended Data Fig. 2. Since the authors have measured elemental content, I strongly suggest that they use geochemical proxies (e.g., CIA) to reconstruct climate evolution in the study area.
3. Lines 122-126: The studied section displayed a CIE with an amplitude of 6.5‰, which is larger than coeval sedimentary successions (lines 52-54). Lines 202-204: the authors suggest that the isotopically light carbon released during CIE1 may have mainly originated from dissociation of sub-ocean-floor methane hydrates. If it is true, both marine and lacustrine should exhibit a similar amplitude of carbon isotope excursion. Please clarify it.
4. Lines 126-129: It is recommended to define the CPE onset because CPE is Carnian Humid Episode, but not only carbon isotope excursion.
5. Lines 124, 127 and 138: The paper is astronomically tuned based on the long eccentricity cycle (405 kyr). However, the time intervals of CIE1, CIEs, and POE discussed in the text are significantly shorter than 405 kyr, such as "139.2 kyr," "19 kyr," and "374.2 kyr." This may lead to unreliable results for these age data. It is suggested that the authors employ certain methods to minimize errors or discuss and present the magnitude of the errors.

Minor comment:

1. Lines 82-84: The author stated that they provided high-resolution palaeontological, sedimentological and geochemical

data from the Dalongkou section to reconstruct the structure of the CPE onset. However, detailed sedimentological description is completely missing in the manuscript. Additionally, the coordinate of the studied section needs to be added in the Geological setting.

2. Line 140: The study of the Bagong Formation on the Qinghai-Tibet Plateau should be 30 of your references; Rather than 23, 23's study was a cyclostratigraphy study conducted by Miller et al., 2017 on a well in the UK;
3. Lines 154-456: It seems that elevated Hg occurred before the CPE onset (Extended Data Fig. 2). Besides, the vertical variation of $\delta^{13}\text{C}_{\text{org}}$ and Hg/TOC in Fig 3 and Extended Data Fig. 2 is different, please unify it.
4. Line 541: provides detection limits and accuracy of $\delta^{13}\text{C}_{\text{org}}$ and TOC;
5. Line 568: Detection limit and accuracy of mercury isotope.
6. Fig. S1: Please exhibit clearer filed photos in Fig. S1b and c. Besides, it is recommended to add the micrograph of tuffaceous sandstone.
7. Extended Data Fig. 3: The red dashed line (the onset of Volcanism) is placed before the rise in Hg/TOC, but the data for Central Japan seems not to align with this. So, some adjustments may be needed.
8. Although the English text is understandable, it can and should be improved to meet the journal's standard.

Reviewer #3

(Remarks to the Author)

Review of 'Climate-carbon-cycle interactions and spatial heterogeneity of the Carnian Pluvial Episode (Late Triassic)' by Zhao et al.

In this manuscript, Zhao et al. investigate the Carnian Pluvial Episode (CPE), a major climate change that occurred around 234 to 232 million years (Ma) ago. The study examines climate and carbon-cycle dynamics during the CPE using high-resolution multi-proxy data from a lacustrine succession in the Junggar Basin, northwestern China. The findings highlight the rapid onset of the CPE, potentially driven by volcanism and carbon-cycle feedbacks, as well as the in-phase relationship between terrestrial carbon cycling and orbital eccentricity. Changes in precipitation patterns across different latitudes are also discussed, highlighting the spatial complexity of the CPE and its diverse regional impacts.

The topic developed in the manuscript is of interest to the international scientific community, contributing to research on the CPE and its links to other warm events in Earth's history. While the study provides important insights into global climate-carbon-cycle interactions and the heterogeneous nature of the CPE, some aspects of its findings align with recent studies (e.g., Dal Corso et al., 2024; Zhang et al., 2024), making its novelty appear limited. Nonetheless, this study addresses gaps in the terrestrial record of CPE, where dating limitations often restrict detailed links to the CPE. Also, its multidisciplinary approach and focus on mechanisms driving the CPE's rapid onset offer valuable insights into this poorly understood climatic event. However, the text is wordy in some parts, contains several typos, and needs major revisions (rephrasing and rewriting) for clarity and presentation. I have provided a list of comments and suggestions, organised by line number, that the authors should address.

Comments on the main text of the manuscript

Line 46: Please cite the recent article by Lin et al. (2025) (DOI: <https://doi.org/10.1016/j.marpetgeo.2025.107289>) on deoxygenation preceding the CPE in the Qiangtang Basin. The findings on the environmental, paleoceanographic, and organic matter controlling processes preceding the CPE and the role of sedimentary organic matter in the global carbon cycle are relevant to your work and could be included in your discussion.

Line 48: Please fix the typo: 'phenomana' to 'phenomena'

Line 55-59: The sentence could be rephrased for better clarity and flow. For example: 'The emplacement of the Wrangellia Large Igneous Province (LIP) (few basalts were submarine; most were subaerial) is considered a primary trigger of the CPE, likely amplified by the release of isotopically light CO_2 from surface feedbacks into the ocean-atmosphere system, driving a warmer, more humid climate and associated negative CIEs.'

Line 70: Please include the CPE record from the Miankuhi Formation, Turan Plate (NE Iran) based on Mazaheri-Johari et al. (2021, 2022) in both Text S1 and Fig. 1. Also, add the following references to the reference section:

- Mazaheri-Johari et al. (2021), DOI: <https://dx.doi.org/10.13130/2039-4942/15646>
- Mazaheri-Johari et al. (2022), DOI: <https://doi.org/10.1016/j.palaeo.2021.110777>

Line 70-72: I recommend refining the sentence for clarity, for example: 'However, given the lack of high-resolution chronostratigraphic framework, the correlation between enhanced humidity on land and the CPE interval remains unclear.'

Line 72-74: The sentence has a convoluted structure. I suggest rewriting it, for example: 'In several regions, including the basins of the Newark Supergroup in the USA, sedimentary evidence of increased humidity during the CPE has not been identified.'

Line 81: The reference to 'Supplementary Text 2' in the sentence could lead to confusion as it could be interpreted as covering both biostratigraphy and radiometric age information. Since it focuses on U-Pb dating methodology, I suggest

rephrasing it to 'radiometric methods in Supplementary Text 2' for clarity.

Line 82: This sentence is wordy and needs rephrasing, for example: 'The high-resolution palaeontological, sedimentological, and geochemical signals from the Dalongkou section enable the detection of the CPE onset.'

Line 90: Add a comma after the word 'together'

Line 102: The sedimentary wavelengths mentioned in the main text ('11 to 8 m') differ slightly from those in Supplementary Text 3 ('10.8 to 9 m'). Although the use of 'ca.' allows some flexibility, it would be better to justify these differences to ensure consistency and avoid confusion.

Line 110: The phrase 'high quality of our astronomical calibration' is somewhat subjective. It would be more appropriate to describe the calibration in terms of its reliability and precision. Please consider rephrasing it.

Line 110: 'shows' instead of 'show'

Line 127: Please fix the typo: 'stratigrapically' to 'stratigraphically'

Line 141: Please consider rephrasing, for example: 'However, the entire CPE with episodic CIEs is generally considered to have lasted longer than 1 Myr based on cyclostratigraphy (~1.1 Myr), biostratigraphy and magnetostratigraphy (1.6 to 1.7 Myr).

Line 171: Please fix the typo: 'redcution' to 'reduction'

Line 176-180: Please consider rephrasing, for example: 'A precursor carbon release or warming event may signal the growing instability of thermally sensitive carbon sources, such as sub-ocean-floor methane hydrates, potentially triggering a positive feedback loop to sustain subsequent warming.'

Line 194: Please add 'a' before 'global mean'

Line 203: Please add 'the' before 'dissociation'

Line 210: Change the punctuation: 'i.e.' to 'i.e.,'

Line 211: Please add 'the' before 'Earth system'

Line 211: Eliminate the preposition 'to' before 'the CPE'

Line 215-218: Please consider rephrasing, for example: 'The orbitally driven changes in Earth's hydrological processes and carbon cycles, occurring over tens of thousands to millions of years, form the underlying pattern of climate-carbon cycle interactions.'

Line 218-222: The sentence needs to be rephrased for better readability.

Line 219: Please fix the typo: 'rhtthm' to 'rhythm'

Line 222-226: Please break down the sentence and consider re-phrasing, for example: 'During eccentricity minima, cooler and more stable climates, within a generally warm background, facilitated the expansion of continental carbon reservoirs. This led to greater land storage of isotopically light carbon and a corresponding rise in marine dissolved inorganic carbon ($\delta^{13}\text{C-DIC}$), with the reverse occurring during maxima.'

Line 227-231: Please split the sentence and rephrase it.

Line 229: 'suggest' instead of 'suggests'

Line 246: Please add a comma before the word 'whereas' and apply this comment elsewhere in the text.

Line 247: Please change the punctuation 'e.g.' to 'e.g.,'

Line 254: Correct your spelling for the word 'approximately'

Line 265: Typo: change the 'northeastern' to 'northeastern' and apply this comment elsewhere in the text.

Line 275: Please add 'the' before the word 'implementation'

Line 484: 'volcanic' instead of 'volcanics'

Line 494: Please add 'the' before the word 'proportion'

Line 517: Please add a preposition (an or the) before the word 'expansion'

Line 520: The 'Geological Setting' is often treated as a standalone section, separate from 'Methodology' because it provides critical context for the study area, which is important for interpreting results and is not typically considered part of the experimental or analytical procedures.

Line 525: Please change the spelling: 'meters' instead of 'metres'

Line 525: Replace 'Formations' with 'formations' here and elsewhere in the text.

Line 541: There is structural issue in this section. The sentence 'Organic-carbon isotopes and TOC contents (n = 289) were analyzed at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences' appears misplaced because it interrupts the logical flow of the sample preparation and analysis steps.

Line 543: Clarify what 'n = 289' refers to (e.g., total sample numbers) and specify if it applies to $\delta^{13}\text{C}_{\text{org}}$, TOC, or both.

Line 552: 'Were measured' instead of 'was measured'

590: Ensure the methodology section is structured consistently across all analyses for clarity and readability (e.g., state the place of analysis, the number of samples analyzed, the procedure, and the analytical precision).

Line 591: Please fix the typo: 'power' to 'powder'

Line 591-592: I recommend re-phrase the sentence as follows: 'Then, the sample powder was digested in 1 ml of HNO_3 and 1.5 ml of HF at 190°C for 72 h.'

Line 632: Correct the word 'ime'

Line 650: Correct the word 'temperatue'

Line 659: Correct the word 'comparision'

Line 692: Correct the word 'dicussions'

Line 702: 'work' instead of 'works'

Comments on figures:

Fig. 1: Please include the CPE record from the Miankuhi Formation, Turan Plate (NE Iran) based on recent study by Mazaheri-Johari et al. (2021, 2022).

Fig. 3: The figure caption states that 'S2: the Wrangellia LIP began releasing isotopically light carbon, POE appeared, and temperatures started to rise,' but the figure lacks any temperature data/profile to support this. Since the manuscript includes palynological studies suggesting a warm, arid climate during the $\delta^{13}\text{C}_{\text{org}}$ fluctuations (POE to CIE2), it would be helpful to include temperature-related data in the figure or clarify how the temperature rise is being represented (e.g., using supporting data from previous studies).

Fig. 3: show 'CIE interval' in the figure.

Fig. 4: Please mark the study area (Junggar Basin) on the figure (e.g., with a star) to clarify the climate state in this basin before and during the CPE.

Comments on Supplementary Info.

Table of Contents, Text S7: Correct the word 'temperal'

Line 1: 'references' instead of 'reference'

Line 1: Eliminate the preposition 'on'

Line 55: Correct the words 'sandston' and 'samplless'

Line 65: 'was analyzed' instead of 'were analyzed'. Also apply the comment to line 70.

Line 92: Please add 'the' before 'Sliding window'

Line 93: Consider changing the verb form: 'are' instead of 'is'

Line 131: Correct the words 'amplifying'

Line 134: Correct the words 'eccenteicity'

Line 138: Change the preposition: 'to the' instead of 'the'

Line 141: 'intervals' instead of 'interval'

Line 249: Change the punctuation: 'e.g.,' instead of 'eg.,'

Line 265: Please add 'the' before the word 'potential'

Line 275: 'Fig. S13' instead of 'Fig. S12'

Line 277: Change 'on sample' to 'one sample'

Line 278: Please consider re-phrasing, for example: 'Previous studies have shown that Hg behavior is non-linear with host-phase abundance, resulting in elevated normalized Hg values when host phase abundance is low (e.g., low TOC or low TS).'

Line 313: Correct the word 'measureable'

Line 347: Remove the colon after the word 'including'
Line 573: Correct the word 'Cretaceous'

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Dear authors,

Thanks for responding to my comments and revising the manuscript.

After a careful read through the manuscript, I find it overall in good shape. I see most of my comments are addressed, but some are not ideally addressed.

I don't understand the obsession with the methane hydrate. How much methane hydrate contributed the carbon isotope excursion in the Carnian, if at all? If this is not testable in this paper, it will only make the overall paper somewhat speculative.

The term 'climate-carbon-cycle interaction' is not easy to follow. The authors did a fair job explaining it in the reply letter, but not so perfectly in the manuscript. If I don't understand it, >90% of the audience won't understand.

Nevertheless, these are all my personal opinions, and I don't impose them on the authors. I only wish this manuscript to be amongst the best.

Reviewer #2

(Remarks to the Author)

The revised version needs to be improved from the following aspects:

1) Line 103: silty or siltstone?

2) Lines 103-109: The studied section is different from the section in Reference 42 or not? If not, I strongly suggest that the authors add a lithological correlation map between two sections in the Supplementary Information and then mark the location of the observed fossils.

3) Line 119: sandstone or tuffaceous sandstone? Please clarify it. Why did you change tuffaceous sandstone to sandstone in the revised manuscript? If only the maximum depositional age of the sandstone is considered, it is difficult to constrain the onset of the CPE.

4) Lines 141-143: You mean "the onset of CPE corresponds to a negative carbon isotope excursion"? This is different with many previous studies.

5) Lines 151-154: The authors need to explain why the studied section displayed a CIE with an amplitude (6.5‰) larger than coeval sedimentary successions.

Reviewer #3

(Remarks to the Author)

Dear Editor, Dear Authors,

I have reviewed the revised manuscript and I believe that the major points have been addressed by the authors. The manuscript has now improved and can be considered for publication in this journal.

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RESPONSE TO REFEREES

Reference: NCOMMS-24-80380-T

Title: Climate – carbon-cycle interactions and spatial heterogeneity of the Carnian Pluvial Episode (Late Triassic)

Journal: Nature Communications

We thank the referees for their helpful comments that have greatly improved the quality of our interpretation and discussions of the Carnian Pluvial Episode. We have revised the paper in line with these comments, focusing on evidence and discussion for identification of the CPE in the section, addressing uncertainty/error in both geochemical data and dating, verifying the modelling output and improving discussions around other records from this period. We outline detailed responses to individual comments below.

Reviewer 1:

The Carnian Pluvial Episode has gained increasing research interest in recent years. It represents a type of crisis rarely seen in the Phanerozoic. Zhao et al. provide a multi-proxy study on a mid-latitude lake succession. Contrary to the general conception that the climate shifted towards more humid conditions, the authors suggest increased aridity in continental interiors.

I don't see major issues with this manuscript. However, some revisions would significantly improve this manuscript. These include: 1) a better separation of results and discussion; 2) verify the modelling output. E.g., give a comparison of simulated equatorial SST with published proxy-derived records; 3) reconsider the marine methane hydrate scenario—I don't see the necessity to include such speculation, and it is detached from the main story; 4) include critical information in the method. For example, there is a lack of explanation of pCO₂ prescriptions (568 to 1758 ppm) for the CPE modelling. Inform the audience why these numbers were chosen. The analytical uncertainty of TOC and C and Hg isotope analyses are also missing.

I understand that some coauthors are experts on Mesozoic and Cenozoic hyperthermals/climate changes. However, there are quite some mentions of Triassic-Jurassic, Cretaceous OAEs, PETM, Oligo-Mio, and sometimes Carboniferous. These

barely relate to this study (late Triassic) and, when appear so often, are distractions to the central theme of this manuscript. Nevertheless, all these are fixable and should not tarnish the overall quality of this manuscript.

Collectively, this is a comprehensive study combining the merits of multi-proxy geochemical records, high-precision geochronology and Earth system modeling. It will enhance our understanding of the CPE, and I recommend revising it before its formal publication.

Reply: We feel great thanks for your professional review that have greatly improved the quality of our descriptions and interpretation. According to your nice suggestions, we have made extensive corrections to our previous draft. Hopefully we have addressed all of your concerns. The detailed corrections and responses are listed below.

[1] a better separation of results and discussion.

Reply: Thank you for your suggestion. We have chosen to combine the "Results" and "Discussion" sections to maintain a clear and direct link between our findings and their interpretation, which we believe enhances the flow of the paper. This structure is commonly used in *Nature Communications*. However, we are open to revising if the editorial team prefers a separate presentation.

[2] verify the modelling output. E.g., give a comparison of simulated equatorial SST with published proxy-derived records.

Reply: Thank you very much. We compare the simulated annual SST of eastern Tethys (South China) with the oxygen isotope records from conodont apatite of South China. Please see the Fig. S19 in the supplementary information.

[3] reconsider the marine methane hydrate scenario—I don't see the necessity to include such speculation, and it is detached from the main story.

Reply: Thank you for your comment. Our Hg concentrations and carbon isotopes data suggest that the CIE1 at the onset of the CPE was not directly caused by volcanic eruptions, but rather by the release of light carbon from sources unrelated to the volcanism. These sources may include marine methane hydrate, terrestrial vegetation, permafrost and peat. We propose that the total amount of methane released could provide the carbon required for CIE1, without excluding contributions from other

carbon sources. We believe this hypothesis is helpful to understanding the early stages of the CPE.

[4] include critical information in the method. For example, there is a lack of explanation of pCO₂ prescriptions (568 to 1758 ppm) for the CPE modelling. Inform the audience why these numbers were chosen.

Reply: Thank you very much for pointing out this issue. We have previously tried simulations with CO₂ forcings of 568 (2xCO₂), 1136 (4xCO₂), 1704 (6xCO₂), and 2272 (8xCO₂) ppm. At the end, the 568 ppmv experiment is used as an analogue of the climate prior to the CPE, while the 1704 ppmv experiment is used to mimic the relatively warmer climate during the CPE. Two criteria were used in the selection process: first, the selected CO₂ levels are close to the proxy-based reconstruction of atmospheric CO₂ before and during the CPE (Foster et al. 2017); second, the simulated global mean surface temperatures are close to those previously reconstructed (Judd et al. 2024; Scotese et al. 2021). A similar approach was also applied in the previous studies to reconstruct the deep-time Earth's climate (e.g., Li et al., 2022, 2023). It should be noted that the simulated climate change patterns due to the greenhouse effect do not differ much depending on the CO₂ level. Please see lines 436–446 of the revised manuscript (clean version).

Foster, G. L., Royer, D. L., & Lunt, D. J. Future climate forcing potentially without precedent in the last 420 million years. *Nat. Commun.* **8**, 14845 (2017).

Judd, E. J. et al. A 485-million-year history of Earth's surface temperature. *Science* **385**, eadk3705 (2024).

Li, X. et al. A high-resolution climate simulation dataset for the past 540 million years. *Sci. Data* **9**, 371 (2022).

Li, X. et al. Climate variations in the past 250 million years and contributing factors. *Paleoceanogr. Paleoclimatol.* **38**, e2022PA004503 (2023).

Scotese, C. R., Song, H., Mills, B. J. & van der Meer, D. G. Phanerozoic paleotemperatures: The earth's changing climate during the last 540 million years. *Earth Sci. Rev.* **215**, 103503 (2021).

[5] The analytical uncertainty of TOC and C and Hg isotope analyses are also missing.

Reply: Thanks, added. Please see lines 345–348 and 379.

[6] I understand that some coauthors are experts on Mesozoic and Cenozoic hyperthermals/climate changes. However, there are quite some mentions of Triassic-Jurassic, Cretaceous OAEs, PETM, Oligo-Mio, and sometimes Carboniferous. These barely relate to this study (late Triassic) and, when appear so often, are distractions to the central theme of this manuscript. Nevertheless, all these are fixable and should not tarnish the overall quality of this manuscript.

Reply: Thank you very much. We fully understand your concern regarding the inclusion of references to hyperthermals/climate events from other periods. The terminology used to describe hyperthermals, such as "Pluvial Episode", "Extinction Event" and "Oceanic Anoxic Event", is to some extent historically contingent and may obscure the underlying commonalities among these events. We think that these comparisons serve to highlight the common features and underlying processes that link the CPE to other well-documented climatic events. The similarities suggest these events share a fundamental nature as hyperthermal episodes.

[7] Line 32, “non-coldhouse climate” is not a very good term to me. Is non-coldhouse equal to warm house?

Reply: Thank you very much. We fully agree with you that “non-coldhouse climate” is not a good term. In order to clarify this issue, we changed the term “non-coldhouse” to “warmhouse”. Please see lines 32 and 271.

[8] Line 35, not very clear what are the “eastern continents”. There was one continent at the time—the Pangea. I am not aware of any Carnian succession in either pole.

Reply: Thank you very much. We have revised the sentence to: "The CPE hydrological cycle was typified by increased aridification in continental interiors and multiple precipitation centres at low-latitude eastern regions of Pangea and at the poles." We would like to clarify that the polar records are indeed limited, and this result is based on Earth system model simulations. Please see lines 33–35.

[9] Line 47, the word “remarkable” should be avoided in scientific writing.

Reply: Thanks. We changed “remarkable” to “significant”. Please see line 47.

[10] Line 56 the words in brackets are redundant and probably not entirely accurate. What is left today as the Wrangellia LIP was only a fraction of its original size.

Reply: Thank you very much for pointing out this issue. We fully agree with you that our original description is redundant and not entirely accurate. We deleted “few basalts were submarine; most were subaerial”. Please see line 55.

[11] Lines 77-78 I would change to “the manifestation of global hydrological cycle changes”

Reply: Thanks, done. Please see lines 77–78.

[12] Lines 129-137 These are discussions rather than results. One might consider moving these words to later chapters.

Reply: Thank you very much. Since we have chosen to combine the "Results" and "Discussion" sections in our paper, we believe that explaining the POE here provides a more coherent flow. We hope this structure enhances the overall clarity and connection of the ideas presented.

[13] Lines 119-121 Rock Eval analysis is not described in the method.

Reply: Thank you. The core experimental methods were included in the main text, while the additional experiments (U-Pb dating, Rock Eval, compound-specific carbon isotopes and kerogen macerals analysis) are placed in the supplementary information to avoid overwhelming the maintext of the paper. In order to clarify this issue, we added a citation in this text “analysis methods in Supplementary Text 4”. Please see line 148.

[14] Lines 140-141 mis-citations of references

Reply: Thanks, corrected. Please see lines 168–169.

[15] Line 147, not easy to follow here. of the CPE?

Reply: Thanks, corrected. Please see line 174.

[16] Line 179, I would delete the example. Methane hydrates are too speculative for the Carnian case and there is no evidence for it.

Reply: Thanks, done. We changed the sentence to “A precursor carbon release or

warming event may signal the growing instability of thermally sensitive carbon sources, potentially triggering a positive feedback loop to sustain subsequent warming”. Please see lines 203–205.

[17] Lines 188-190, this is not an isolated case for the Carnian. As a matter of fact, most carbon emission estimations from major LIPs do not match corresponding $\delta^{13}\text{C}$ excursions.

Reply: Thank you very much, and we fully agree with you. At your suggestions, we added a statement to acknowledge that this issue is not unique to the Carnian, as most carbon emission estimations from major LIPs do not match the corresponding $\delta^{13}\text{C}$ excursions, as observed in events such as the Triassic-Jurassic transition and the Paleocene-Eocene Thermal Maximum. Please see lines 217–221.

[18] Line 194 GMAT of 23-24 represents a significant warm interval. This sentence also miscites literature. These estimated GMATs are compiled and should be used with great caution if cited this way.

Reply: Thank you very much for pointing out this issue. We reconstructed the global air temperature and sea surface temperature separately in the simulation. Thus, we can verify the simulation output from two aspects: 1) comparing the modeling air temperature with the compiled global average temperature (Scotese et al., 2021; Judd et al., 2024). Although the estimated GMATs are compiled, these could initially constrain the fundamental climate state. 2) We supplement the comparison of SST reconstruction of simulation and oxygen isotope records from conodont apatite from eastern Tethys (South China) prior to the CPE ($p\text{CO}_2$ set as 568 ppmv). Following your suggestions, we changed the sentence to “Palaeotemperature reconstructions suggest relatively warm climatic conditions before the CPE, with a global mean air temperature of $\sim 23\text{--}24^\circ\text{C}$ (Judd et al., 2024; Scotese et al., 2021) and tropical sea surface temperatures in eastern Tethys of $\sim 27^\circ\text{C}$ (Sun et al., 2016).” Please see lines 221–224.

Judd, E. J. et al. A 485-million-year history of Earth’s surface temperature. *Science* **385**, eadk3705 (2024).

Scotese, C. R., Song, H., Mills, B. J. & van der Meer, D. G. Phanerozoic paleotemperatures: The earth’s changing climate during the last 540 million

years. *Earth Sci. Rev.* **215**, 103503 (2021).

Sun, Y. D. et al. Climate warming, euxinia and carbon isotope perturbations during the Carnian (Triassic) crisis in South China. *Earth Planet. Sci. Lett.* **444**, 88–100 (2016).

[19] Lines 194-195, ambiguous. Under what specific conditions do the authors refer to as? What is the GMAT that AWI-ESM gives in this study?

Reply: Thank you very much. The AWI-ESM simulated global mean surface temperature under 568 ppmv is 23.35 °C. The simulated global mean surface temperature heavily depends on the selected CO₂ level, which is artificial. Therefore, we changed this sentence to “Under such warm conditions (Fig. 4a), the global permafrost surface area should be much smaller than that it is today (Biskaborn et al., 2019).” Please see lines 224–225.

Biskaborn, B. K. et al. Permafrost is warming at a global scale. *Nat. Commun.* **10**, 264 (2019).

[20] Lines 199-204, The argument is not convincing. Yes, the dissociation of marine methane hydrates could account for the d¹³C excursion, but there is no evidence for such events. A decrease in d¹³C can be triggered in a few scenarios, e.g., a decrease in primary productivity, less burial of organic carbon etc. What is the reason the methane hydrate scenario stands out in the Carnian case?

Reply: Thank you. We acknowledge that presently there is no direct evidence for marine methane hydrate dissociation during the Carnian. While other processes, such as decreased primary productivity or less burial of organic carbon, can also cause a δ¹³C decrease, we would like to emphasize that we merely proposed a hypothesis. At the very least, the total amount of methane that could have been released is sufficient to account for the magnitude of the CIE observed. Hopefully, other researchers will find direct evidence for this hypothesis based on sedimentological or/and geochemical analyses.

[21] Lines 208-209 yes, this is a simple explanation but not necessarily represent the whole picture.

Reply: Thank you very much for your valuable comment. We fully agree with you

that the scenario is a simplified explanation and does not capture the full complexity of the event. While we propose the rapid release of isotopically depleted carbon from methane hydrates as one possible mechanism, we acknowledge that other factors may have played significant roles in shaping the CPE. Following your suggestion, we added the statement: “However, we recognise that this is a simplified scenario, and the complexity of the event likely reflects multiple contributing factors. Further investigation is needed to understand fully the interplay of various processes that could have shaped the CPE”. Please see lines 238–241.

[22] Line 226, I don't follow the symbol “↑”.

Reply: Thanks, deleted. Please see line 255.

[23] Lines 243-245, I couldn't follow the argument here. What does “climate-carbon-cycle interaction” really mean here? Carbon cycle is always coupled with the global climate.

Reply: Thank you very much. Climate and carbon cycle are profoundly coupled systems, as the carbon-cycle processes covary with climate-related factors (e.g. temperature, hydrological cycle, soil respiration, net primary productivity, CO₂ solubility, weathering). For the carbon cycle-climate feedback system, the carbon cycle controls the concentrations of key greenhouse gases (CO₂ and CH₄) in the atmosphere, thereby modulating Earth's global temperature. Furthermore, the cycle-climate feedback could be paced by the orbital forcing (e.g. for the last 6 Myr, spanning from the earliest Pliocene to present, during eccentricity minima, cooler and more stable climates, within a generally warm background, facilitated the expansion of continental carbon reservoirs, leading to greater land storage of isotopically light carbon and a corresponding rise in marine dissolved inorganic carbon ($\delta^{13}\text{C-DIC}$), with the reverse occurring during maxima). Therefore, based on the proposed orbital forcing of climate-carbon-cycle interaction in Cenozoic (De Vleeschouwer et al., 2020), we refer to the feedback system including carbon cycle and climate changes as ‘climate-carbon-cycle interaction’.

De Vleeschouwer, D. et al. High-latitude biomes and rock weathering mediate climate–carbon cycle feedbacks on eccentricity timescales. *Nat. Commun.* **11**, 5013 (2020)

[24] Lines 245-247, My apologies for not following the argument here. The sentence is grammatically incorrect to me. What does the “last 6 Myr” refer to? and how does the Carboniferous example relate to this study (late Triassic)?

Reply: Thank you very much. We refer here to the last 6 Myr, spanning from the earliest Pliocene to present, which is typical of unique coldhouse climate–carbon cycle dynamics. In order to avoid the confusion, we rephrased this sentence as: “Therefore, this climate–carbon interaction may be the norm after the emergence of vascular plants, whereas the coldhouse climate–carbon cycle dynamics of the earliest Pliocene may represent a more unusual situation.” Please see lines 275–278.

[25] Lines 255-257, this lengthy part can be revised to “Our AWI-ESM simulations confirms a

Reply: Thanks. We changed the sentence to “Our AWI-ESM simulations confirm a more arid and warmer climate during this interval in the Junggar Basin”. Please see lines 285–286.

[26] Line 262 “poleward shift of precipitation patterns” is not a proper description and it’s hard to guess what the authors mean.

Reply: Thank you very much. We here refer to the poleward shift of pre-existing precipitation zones. The poleward shift of existing climatic/precipitation zones driven by rising global temperatures has generally occurred during the warm periods of geological history (e.g. Pliocene warmth, Abell et al., 2021). In order to avoid the confusion, we rephrased this sentence: “Our results show that precipitation changes during the CPE exhibited spatial heterogeneity, accompanied by a poleward shift of pre-existing precipitation zones and no evidence of global humidification”. Please see lines 287–289.

Abell, J. T., Winckler, G., Anderson, R. F., & Herbert, T. D. Poleward and weakened westerlies during Pliocene warmth. *Nature*, **589**, 70–75 (2021).

[27] Line 263 reword this sentence. Mountains can block moisture transport.

Reply: Thanks, done. We revised the sentence to “Moreover, mountains and extensive continental areas can block moisture transport, resulting in enhanced net evaporation

within the interior of supercontinents (Pangaea)”. Please see lines 292–294.

[28] Lines 258-281 This paragraph could be improved after a proper rewrite.

Reply: Thank you very much. We rephrased this paragraph. Please see lines 287–312:

“Our results show that precipitation changes during the CPE exhibited spatial heterogeneity, accompanied by a poleward shift of pre-existing precipitation zones and no evidence for global humidification. The heterogeneous pattern of precipitation changes is characterized by predominantly increased precipitation near the Equator and at high latitudes, while subtropical latitudes exhibit diminished rainfall (Fig. 4b). Moreover, mountains and extensive continental areas can block moisture transport, resulting in enhanced net evaporation within the interior of supercontinents (Pangaea)⁴⁷. In contrast to previous hypotheses regarding unusual global humidification during the CPE^{2,7,13,26}, the integrated stratigraphy and Earth system model highlight the spatial variations in global precipitation patterns, characterized by increased aridification in continental interiors and the emergence of multiple precipitation centres in low-latitude eastern continents and polar regions, including the Arctic, northeastern Tethys, northeastern Gondwana, and the Antarctic (Fig. 4b). These precipitation changes are corroborated by geological records throughout the CPE (e.g. the progradation of the largest delta system in geological history in the Boreal Ocean and the westward migration of its main depocenter⁶⁶; the large-scale increase of terrigenous inputs and the extinction of carbonate platforms in the southwestern Tethys continental shelf^{67,68} and South China^{11,69}) (Fig. 1). Our modelling of annual global changes, consistent with other palaeoclimatic simulations^{32,70,71}, is unable to replicate the wetter climate in the western and northwestern Tethys as indicated by previous sedimentological evidence (e.g., ref.^{3,51}). The remaining proxy–model differences may be due to unresolved local features in precipitation or the implementation of palaeotopography. Nevertheless, the newly proposed pattern appears to largely conform to established hydroclimate features observed in other past warm periods⁷², thereby amplifying the spatial heterogeneity in precipitation distribution.”

[29] Lines 295-297 Colleagues working on modern climate change won't be fond of such a statement.

Reply: Thank you very much. At your suggestion, we deleted this statement, which

does not influence the paper.

[30] Line 542 what is a Retsch RS200? I guess it is a rock saw.

Reply: Thanks. Retsch RS200 is a machine for sample crush. We revised the sentence to “Samples were trimmed to remove visible veins and weathered surfaces and ground using a sample crush (Vibratory Disc Mill RS 200)”. Please see lines 332–333.

[31] Line 554 in per mille (‰) relative to

Reply: Thanks, corrected. Please see line 342.

[32] Line 557 Reproducibility and repeatability of

Reply: Thanks, added. Please see lines 345–348: “The analytical uncertainty for TOC was calculated as a relative error of less than $\pm 5\%$, and the standard deviation for $\delta^{13}\text{C}_{\text{org}}$ was $\pm 0.2\text{‰}$ (1σ), both determined through replicate analyses of standard samples.”

[33] Line 582 delete units of

Reply: Thanks, deleted. Please see line 372.

[34] Line 587 There is no mention of the reproducibility of Hg isotopes.

Reply: Thanks, added. Please see line 379: “Reproducibility of $\Delta^{199}\text{Hg}$ was better than $\pm 0.05\text{‰}$ (2σ).”

[35] Line 612 “the” change to a

Reply: Thanks, done. Please see line 402.

[36] Line 651, I don’t follow the statement here. Solar luminosity and ice coverage of the Carnian world (ice-free) should differ significantly from the pre-industry world (iced world). Revise to clarify this unambiguity.

Reply: Thank you very much. We fully agree with you that the solar constant should be different from today. However, this will not affect the model results on the simulated climate changes induced by CO_2 . In our simulations, the Earth’s orbit and solar constant are kept the same as present-day. While there is no continental ice sheet. We added detailed explanation in the revision: “There is no continental ice

sheet”. Please see lines 433–434.

[37] Lines 655, 658 I don’t follow the term “quasi-equilibrium”, i.e., the simulations did not reach equilibrium?

Reply: Thank you very much for pointing out this issue. Strictly speaking, without 6000 years simulation, the deep ocean cannot reach an equilibrium state (Li et al. 2013). However, 1000 years is enough for the model to reach a surface equilibrium state, which is sufficient for us to examine the climate change on the precipitation pattern. In order to clarify this issue, we have revised the text from “quasi-equilibrium” to “surface equilibrium”. Please see lines 449–452: “The 568 ppmv experiment was run for 2000 years to allow the climate system to reach a surface equilibrium state. The 1704 ppmv experiment, initialized from the first experiment, was run for 1000 years. This procedure allows the upper ocean and surface climate to achieve an equilibrium state.”

Li et al. Deep-ocean heat uptake and equilibrium climate response. *Clim. Dyn.* **40**, 1071 – 1086 (2013).

[38] Line 657, 1000 model year is really low. Did the simulation collapse?

Reply: Thanks. For the surface climate, 1000 years are enough to reach an equilibrium state, which is usually quantified as a surface temperature trend being less than 0.1 degrees/century. The initial state of Triassic simulation is very difficult to obtain, with many times collapses. However, after 10 years simulation, the model works fine. In order to clarify this issue, we added detailed explanation in the revision. Please see comment 37.

[39] Fig. 2 the black shaded parts in the log stand for black shales, do they? I didn’t see any black shale in the field photo (Fig. S1). Maybe include some better field photos. There are both extended data figures and supplementary figures (in the supplementary materials). The two systems are not very easy to follow.

Reply: Thank you very much. At your suggestion, we added additional field photos in Fig. S1. We have now moved all extended data figures to the supplementary information section and updated the figure numbers accordingly.

[40] Extended Data Fig. 3 The Tibetan record is very poor, and is not a good case to correlate. Ref 30 gave a $\delta^{13}\text{C}_{\text{carb}}$ value lower than -5 per mille and down to almost -10 per mille. This cannot be true for any normal marine carbonate. The numbers might have measured from carbonate cements in sandstone or diagenetically highly altered carbonates.

Reply: Thanks. We fully agree with you that the Tibetan record is quite poor. We deleted the Tibetan record. Please see the Fig. S16.

[41] Text S2-strangely, the U-Pb dating was not included in the Method but in the supplementary.

Reply: Thank you very much. The core experimental methods are already included in the main text, while the additional experiments (U-Pb dating, Rock Eval, compound-specific carbon isotopes, and kerogen macerals analysis) are primarily supportive and provide supplementary data. As such, we have placed them in the supplementary information to avoid overwhelming the maintext of the paper.

[42] Fig. S8 (and other log figures) Mud/Sha is better to spell in full.

Reply: Thank you very much. We added the full explanations of the abbreviations in the figure captions for Fig. 2, Fig. S9, Fig. S11 and Fig. S15.

[43] Text S4 Compound-specific carbon isotopes are not mentioned in the main text.

Reply: Thank you very much. The compound-specific carbon isotopes data support our interpretation that the bulk organic carbon-isotope record from the Dalongkou section dominantly reflects the atmospheric $\delta^{13}\text{C}\text{-CO}_2$ signal, which in turn indicates global carbon-cycle perturbations. We have mentioned this in lines 146–150.

However, given that the results are not directly relevant to the main discussion, we have included them in Text S4 instead.

Reviewer 2:

The manuscript by Zhao et al. provides a new record of the CPE from the lacustrine Junggar Basin in northwestern China. This manuscript presents multiple data, including magnetic susceptibility, U-Pb age, C and Hg isotopes, elemental geochemistry, and palynological data, combined with Earth System modelling, to

discuss potential driving mechanisms for the CPE, and coeval changes to the hydrological cycle. Overall, the methods are appropriate and the data are valuable. However, some important issues need to be addressed before it can be considered. My main suggestions are the following:

Reply: We are grateful to you for your positive and encouraging comments. Please see the responses below.

[44] Due to the lack of volcanic rocks in the study strata, the authors only determine the age using tuffaceous sandstone. The authors need more description how did your research identify Carnian Pluvial Episode? The CPE does not only mean carbon isotope excursion.

Reply: Thank you very much. We fully agree with you that the CPE does not only mean a carbon isotope excursion. In the original description, the Carnian Pluvial Episode (CPE) onset corresponds with an initial pulse of siliciclastic material and the shift of the carbonate factory from predominantly microbial reefs to metazoan-dominated reefs (e.g., Dal Corso et al., 2020). However, this lithofacies change cannot be used in some other marine and continental deposits (e.g., marine carbonate, deep-sea bedded chert, lacustrine mudstone). Based on the U-Pb geochronology and biostratigraphic results, the carbon isotope excursion can provide an additional constrain on the onset of the CPE (Dal Corso et al., 2015), especially for lacustrine deposits that lack the marine biozones (e.g., Lu et al., 2021). In our study, we combined biostratigraphy (palynology and vertebrate fossils; Peng et al., 2024) and U-Pb dating to place the CPE (234–232 Ma) in the lower part of the Huangshanjie Formation, and further constrained the onset of the CPE using carbon isotope data. In conclusion, we identified the CPE based on the combination of U-Pb geochronology, biostratigraphy, and carbon-isotope stratigraphical evidence, thereby avoiding the uncertainty inherent in interpreting data from a single proxy. To clarify this point further, we added the following sentence in the revised manuscript: “We combined biostratigraphy (palynology and vertebrate fossils) and U-Pb dating to place the CPE in the lower part of the Huangshanjie Formation, and further constrained the onset of the CPE using carbon isotope data.” Please see lines 141–143.

Dal Corso, J. et al. Carbon isotope records reveal synchronicity between carbon cycle perturbation and the “Carnian Pluvial Event” in the Tethys realm (Late Triassic).

- Global Planet. Change* **127**, 79–90 (2015).
- Dal Corso, J. et al. Extinction and dawn of the modern world in the Carnian (Late Triassic). *Sci. Adv.* **6**, eaba0099 (2020).
- Lu, J. et al. Volcanically driven lacustrine ecosystem changes during the Carnian Pluvial Episode (Late Triassic). *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2109895118 (2021).
- Peng, J. et al. Floral and faunal biostratigraphy of the Middle–Upper Triassic Karamay and Huangshanjie formations from the southern Junggar Basin, China. *Geol. Soc. Spec. Publ.* **538**, 41–66 (2024).

[45] Please provide more discussions concerning spores and pollen in the manuscript. How to evaluate the contribution of eolian activity on palynological compositions? If the eolian activity is strong, the spores and pollen could be derived from other distant regions (not surrounding regions). Please clarify it. Besides, I strongly suggest that the authors add climate status in Extended Data Fig. 2. Since the authors have measured elemental content, I strongly suggest that they use geochemical proxies (e.g., CIA) to reconstruct climate evolution in the study area.

Reply: Thank you very much. Traverse (2007) evaluates the contribution of eolian activity to palynological compositions, noting that while pollen is small, low in specific gravity, and suited for air transport, 95% of airborne pollen typically settles within a kilometer of the source plant (p. 503). Even when airborne pollen travels farther, they are largely overwhelmed by those transported by water (p. 507). As such, airborne pollen makes up a tiny component of local palynofloras and are rarely detected in sediments. In our study, due to the restricted nature of the inland Junggar Basin, the palynological data are primarily derived from pollen and spores transported by water, making them well-suited for reconstructing the region’s palaeovegetation. Therefore, we suggest that eolian activity has minimal impact on our data and interpretations. In revision, we add some discussions: “As suggested by Traverse (2007), most pollen and spores are transported by water, with airborne pollen being a minor component and primarily derived from nearby regions rather than distant areas. Furthermore, since the Junggar Basin was a highly restricted basin, aeolian activity is likely to have had a minimal impact on the palynological compositions. Therefore, our palynological data are well-suited for reconstructing the palaeoclimate of the Junggar Basin”. Please see lines 402–408 in the supplementary information.

For the Extended Data Fig. 2, we added the xerophytic/hygrophytic (X/H) ratio as an indicator of variations in aridity and humidity in the climate. Please see the Fig. S15.

We have previously analysed the CIA index of the Huangshanjie Formation. Unfortunately, the index of compositional variability (ICV) shows that the Huangshanjie Formation in the Dalongkou section has experienced multiple weathering cycles. Therefore, the CIA is not applicable in the Dalongkou section.

Traverse, A. 2007. Paleopalynology. Dordrecht, Springer.

[46] Lines 122-126: The studied section displayed a CIE with an amplitude of 6.5‰, which is larger than coeval sedimentary successions (lines 52-54). Lines 202-204: the authors suggest that the isotopically light carbon released during CIE1 may have mainly originated from dissociation of sub-ocean-floor methane hydrates. If it is true, both marine and lacustrine should exhibit a similar amplitude of carbon isotope excursion. Please clarify it.

Reply: Thank you very much. The carbon isotope curves from the sediments of the CPE indicate that the magnitude of each negative carbon isotope excursion can vary significantly depending on the geological context (Dal Corso et al., 2018). The $\delta^{13}\text{C}$ values of both terrestrial and marine organic carbon are influenced by various factors, including the source of the carbon during photosynthesis by primary producers, the type of photosynthetic pathway employed, and the environmental conditions at the time (Diefendorf et al., 2010; Dal Corso et al., 2017, 2018). Additionally, in other global warming events, such as the Paleocene-Eocene Thermal Maximum (PETM), the magnitude of the negative organic carbon isotope excursions varies across different geological records (e.g., North Sea and Svalbard cores), even though the release of methane has also been implicated in driving the carbon isotope negative excursion during this event (Kender et al., 2021).

Dal Corso, J. et al. Evaluating the use of amber in palaeoatmospheric reconstructions: the carbon-isotope variability of modern and Cretaceous conifer resins. *Geochim. Cosmochim. Acta* **199**, 351–369 (2017).

Dal Corso, J. et al. Multiple negative carbon-isotope excursions during the Carnian Pluvial Episode (Late Triassic). *Earth Sci. Rev.* **185**, 732–750 (2018).

Diefendorf, A.F. et al. Global patterns in leaf ^{13}C discrimination and implications for the studies of past and future climate. *Proc. Nat. Acad. Sci. U. S. A.* **107**, 5738 – 5743 (2010).

Kender, S. et al. Paleocene/Eocene carbon feedbacks triggered by volcanic activity. *Nat. Commun.* **12**, 5186 (2021).

[47] Lines 126-129: It is recommended to define the CPE onset because CPE is Carnian Humid Episode, but not only carbon isotope excursion.

Reply: Thank you for your suggestion. Although the CPE is defined by increased humidity, its climatic changes exhibit significant spatial variability, making a purely climate-based definition unsuitable. Indeed, many regions did not experience a marked increase in humidity (Figs. 1 and 4 in the maintext). We fully agree with you that the CPE can not be solely defined by the carbon isotope excursions. In our study, we identified the CPE based on the combination of U-Pb geochronology, biostratigraphy, and carbon-isotope stratigraphical evidence, thereby avoiding the uncertainty inherent in interpreting data from a single proxy. Based on previous CPE records, the CIE1 is considered to coincide with climate change and biological turnover, making it a globally significant marker for the onset of the CPE (e.g., Dal Corso et al., 2012, 2015, 2018, 2020; Lu et al., 2021; Miller et al., 2017; Sun et al., 2016). Therefore, we have used the CIE1, rather than POE, as the onset of the CPE. A similar approach has been used for defining other major events, such as OAE 1a, with carbon isotope excursions serving as global markers even in the absence of black shales, as seen in marine records from the Mid-Pacific Mountains (Ando et al., 2008) and terrestrial records from northwestern China (Sun et al., 2024).

Ando, A., Kaiho, K., Kawahata, H., Kakegawa, T. Timing and magnitude of early Aptian extreme warming: Unraveling primary $\delta^{18}\text{O}$ variation in indurated pelagic carbonates at Deep Sea Drilling Project Site 463, central Pacific Ocean. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **260**, 463–476 (2008).

Dal Corso, J. et al. Discovery of a major negative ^{13}C spike in the Carnian (Late Triassic) linked to the eruption of Wrangellia flood basalts. *Geology* **40**, 79–82 (2012)

Dal Corso, J. et al. Extinction and dawn of the modern world in the Carnian (Late

- Triassic). *Sci. Adv.* **6**, eaba0099 (2020).
- Dal Corso, J. et al. Multiple negative carbon-isotope excursions during the Carnian Pluvial Episode (Late Triassic). *Earth Sci. Rev.* **185**, 732–750 (2018).
- Dal Corso, J. et al. Carbon isotope records reveal synchronicity between carbon cycle perturbation and the “Carnian Pluvial Event” in the Tethys realm (Late Triassic). *Global Planet. Change* **127**, 79–90 (2015).
- Lu, J. et al. Volcanically driven lacustrine ecosystem changes during the Carnian Pluvial Episode (Late Triassic). *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2109895118 (2021).
- Miller, C. S. et al. Astronomical age constraints and extinction mechanisms of the Late Triassic Carnian crisis. *Sci. Rep.* **7**, 2557 (2017).
- Sun, Y. D. et al. Climate warming, euxinia and carbon isotope perturbations during the Carnian (Triassic) crisis in South China. *Earth Planet. Sci. Lett.* **444**, 88–100 (2016).
- Sun, F. et al. Methane fueled lake pelagic food webs in a Cretaceous greenhouse world. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2411413121 (2024).

[48] Lines 124, 127 and 138: The paper is astronomically tuned based on the long eccentricity cycle (405 kyr). However, the time intervals of CIE1, CIEs, and POE discussed in the text are significantly shorter than 405 kyr, such as "139.2 kyr," "19 kyr," and "374.2 kyr." This may lead to unreliable results for these age data. It is suggested that the authors employ certain methods to minimize errors or discuss and present the magnitude of the errors.

Reply: Thank you very much. Firstly, the high-resolution sedimentological and petrographic evidence has indicated no remarkable unconformity within the Huangshanjie Formation. Then, we presented two tuning schemes based 405-kyr long eccentricity cycle and 173-kyr obliquity cycle, revealing highly correlated astronomical signals corresponding to the 405-kyr long eccentricity, 173-kyr obliquity, and 131–95-kyr short eccentricity components. The two tuning schemes constrain the CPE interval within basically consistent temporal range. This demonstrates the continuity of our strata on the 10⁵-year scale. Because the obliquity and precession terms are not stable through geological history and susceptible to sedimentary noise, there is currently no reliable method to evaluate the error of astrochronology on 10⁴-year scale and smaller scales. The recent classical

cyclostratigraphic studies are also limited by this problem and widely accepted the 405-kyr tuned timeframe. We interpolate and estimate the duration using the average sedimentation rate within a 405-kyr cycle.

[49] Lines 82-84: The author stated that they provided high-resolution palaeontological, sedimentological and geochemical data from the Dalongkou section to reconstruct of the structure of the CPE onset. However, detailed sedimentological description is completely missing in the manuscript. Additionally, the coordinate of the studied section needs to be added in the Geological setting.

Reply: Thank you for your comment. All the sedimentological descriptions have been provided in Supplementary Data 2. Additionally, we have added the coordinates of the studied section to the Geological Setting section. Please see line 96.

[50] Line 140: The study of the Bagong Formation on the Qinghai-Tibet Plateau should be 30 of your references; Rather than 23, 23's study was a cyclostratigraphy study conducted by Miller et al., 2017 on a well in the UK;

Reply: Thanks, corrected.

[51] Lines 154-456: It seems that elevated Hg occurred before the CPE onset (Extended Data Fig. 2). Besides, the vertical variation of $\delta^{13}\text{C}_{\text{org}}$ and Hg/TOC in Fig 3 and Extended Data Fig. 2 is different, please unify it.

Reply: Thanks. Sure, elevated Hg occurred before the CPE onset (CIE 1), corresponding to the POE. Due to the limitations of the Extended Data Fig. 2, which shows data spanning 316.20 m, it is difficult to clearly discern the relationship between POE and Hg/TOC. Therefore, in the Fig. 3, we have zoomed in on the region at the onset of the CPE, which is the main focus of this study. The data in Extended Data Fig. 2 and Fig. 3 are consistent.

[52] Line 541: provides detection limits and accuracy of $\delta^{13}\text{C}_{\text{org}}$ and TOC;

Reply: Thanks, added. Please see lines 345–348.

[53] Line 568: Detection limit and accuracy of mercury isotope

Reply: Thanks, added. Please see line 379.

[54] Fig. S1: Please exhibit clearer filed photos in Fig. S1b and c. Besides, it is recommended to add the micrograph of tuffaceous sandstone.

Reply: Thank you very much for your suggestion. We added clearer filed photos in the Fig. S1. Our previously collected dating samples have all been used up, and we recently flew back to Xinjiang to collect new samples. We conducted a series of thin section analyses on these fresh samples and identified the presence of tuffaceous material, although in very low amounts, please see Fig. S1. After discussions with our petrological colleagues, we have revised the classification to sandstone, ensuring that the terminology is both accurate and rigorous.

Therefore, the ages we analyzed provide the maximum depositional ages for the studied strata and serve as supplementary evidence for the palynological and carbon isotope stratigraphy. We added some discussions in the supplementary information: “According to the “law of detrital zircon”, the deposition of the strata in question cannot not be older than the age calculated from the youngest zircon grains from the youngest magmatic events^{33–36}. Therefore, the maximum depositional age (MDE) can be close to the real depositional age, especially when the former is consistent with the biostratigraphical age^{37–40}. In this study, the youngest zircons are morphologically uniform with no visible signs of rounding due to even minor sedimentary abrasion during transportation, a conclusion also supported by the angular shapes of quartz grains (Fig. S1f, g). These observations indicate that the depocenter of two sandstone samples from the Dalongkou section was situated near the magmatic source of the zircons. Considering that the maximum depositional ages of two samples are consistent with the age analyzed from the spore-pollens, we use the maximum depositional ages to tightly constrain the age of the CPE in this study.”

The vertebrate *Fukangichthys* fauna and the palynological zonation (*Aratrisporites*, *Dictyophyllidites*-*Aratrisporites*, and *Lycopodiacidites*-*Stereisporites*) suggest that the boundary between the Middle Triassic and Upper Triassic lies between the uppermost Karamay Formation and the bottom of the Huangshanjie Formation (Peng et al., 2022). The U-Pb radioisotopic dating on two sandstone samples from the uppermost Karamay and lower Huangshanjie layers shows a maximum depositional age of 234.8 ± 0.8 Ma to 232.9 ± 0.7 Ma (Fig. 2, Supplementary Text 2), further constraining the lower Huangshanjie Formation to the lower–middle Carnian. This places the CPE (234–232 Ma) in the lower Huangshanjie Formation (between the lowest layer and the stratigraphic level of the sample with the youngest depositional age of 232 Ma). The

CPE interval within the stratigraphy was further determined by carbon isotope data. We have revised the petrological description, please see lines 109–116.

[55] Extended Data Fig. 3: The red dashed line (the onset of Volcanism) is placed before the rise in Hg/TOC, but the data for Central Japan seems not to align with this. So, some adjustments may be needed.

Reply: Thank you very much. We have made the adjustments. Please see Fig. S16.

[56] Although the English text is understandable, it can and should be improved to meet the journal's standard.

Reply: Thank you very much. We invited two native English speakers (our co-authors Hugh C. Jenkyns and Philippe Claeys) to proofread our text.

Reviewer 3:

[57] In this manuscript, Zhao et al. investigate the Carnian Pluvial Episode (CPE), a major climate change that occurred around 234 to 232 million years (Ma) ago. The study examines climate and carbon-cycle dynamics during the CPE using high-resolution multi-proxy data from a lacustrine succession in the Junggar Basin, northwestern China. The findings highlight the rapid onset of the CPE, potentially driven by volcanism and carbon-cycle feedbacks, as well as the in-phase relationship between terrestrial carbon cycling and orbital eccentricity. Changes in precipitation patterns across different latitudes are also discussed, highlighting the spatial complexity of the CPE and its diverse regional impacts.

The topic developed in the manuscript is of interest to the international scientific community, contributing to research on the CPE and its links to other warm events in Earth's history. While the study provides important insights into global climate–carbon-cycle interactions and the heterogeneous nature of the CPE, some aspects of its findings align with recent studies (e.g., Dal Corso et al., 2024; Zhang et al., 2024), making its novelty appear limited. Nonetheless, this study addresses gaps in the terrestrial record of CPE, where dating limitations often restrict detailed links to the CPE. Also, its multidisciplinary approach and focus on mechanisms driving the CPE's rapid onset offer valuable insights into this poorly understood climatic event.

However, the text is wordy in some parts, contains several typos, and needs major revisions (rephrasing and rewriting) for clarity and presentation. I have provided a list

of comments and suggestions, organised by line number, that the authors should address.

Reply: We are grateful for the positive and encouraging comments. Please see the responses below.

[59] Line 46: Please cite the recent article by Lin et al. (2025) (DOI: <https://doi.org/10.1016/j.marpetgeo.2025.107289>) on deoxygenation preceding the CPE in the Qiangtang Basin. The findings on the environmental, paleoceanographic, and organic matter controlling processes preceding the CPE and the role of sedimentary organic matter in the global carbon cycle are relevant to your work and could be included in your discussion.

Reply: Thanks, done. Please see lines 45–47.

[60] Line 48: Please fix the typo: 'phenomana' to 'phenomena'

Reply: Thanks, done. Please see line 48.

[61] Line 55-59: The sentence could be rephrased for better clarity and flow. For example: 'The emplacement of the Wrangellia Large Igneous Province (LIP) is considered a primary trigger of the CPE, likely amplified by the release of isotopically light CO₂ from surface feedbacks into the ocean-atmosphere system, driving a warmer, more humid climate and associated negative CIEs.'

Reply: Thanks, done. Please see lines 55–58.

[62] Line 70: Please include the CPE record from the Miankuhi Formation, Turan Plate (NE Iran) based on Mazaheri-Johari et al. (2021, 2022) in both Text S1 and Fig. 1. Also, add the following references to the reference section:

- Mazaheri-Johari et al. (2021), DOI: <https://dx.doi.org/10.13130/2039-4942/15646>
- Mazaheri-Johari et al. (2022), DOI: <https://doi.org/10.1016/j.palaeo.2021.110777>

Reply: Thanks, done. Please see lines 20–21 in the Supplementary Information.

[63] Line 70-72: I recommend refining the sentence for clarity, for example: 'However, given the lack of high-resolution chronostratigraphic framework, the correlation between enhanced humidity on land and the CPE interval remains unclear.'

Reply: Thanks, done. Please see lines 69–71.

[64] Line 72-74: The sentence has a convoluted structure. I suggest rewriting it, for example: 'In several regions, including the basins of the Newark Supergroup in the USA, sedimentary evidence of increased humidity during the CPE has not been identified.'

Reply: Thanks, done. Please see lines 71–73.

[65] Line 81: The reference to 'Supplementary Text 2' in the sentence could lead to confusion as it could be interpreted as covering both biostratigraphy and radiometric age information. Since it focuses on U-Pb dating methodology, I suggest rephrasing it to 'radiometric methods in Supplementary Text 2' for clarity.

Reply: Thanks, done. Please see lines 79–83: “In this study, we report on a continuous lacustrine sequence (Dalongkou section) in the southern Junggar Basin, northwestern China, which provides a record of the CPE based on biostratigraphy and radiometric ages (radiometric methods in Supplementary Text 2) and allowed the construction of an integrated astronomically calibrated age model.”

[66] Line 82: This sentence is wordy and needs rephrasing, for example: ‘The high-resolution palaeontological, sedimentological, and geochemical signals from the Dalongkou section enable the detection of the CPE onset.’

Reply: Thanks, done. Please see lines 83–85.

[67] Line 90: Add a comma after the word 'together'

Reply: Thanks, done. Please see line 90.

[68] Line 102: The sedimentary wavelengths mentioned in the main text ('11 to 8 m') differ slightly from those in Supplementary Text 3 ('10.8 to 9 m'). Although the use of 'ca.' allows some flexibility, it would be better to justify these differences to ensure consistency and avoid confusion.

Reply: Thank you very much for pointing out this issue. Due to sedimentation rate changes, specific orbital frequency bands may correspond to spectral peak clusters composed of distinct depth wavelengths. Thus, we use the high-confidence level spectral peaks corresponding to the wavelengths of ~10.8 m and ~9 m for calculation in the Supplementary Text 3. In the main text, we use a large range of the spectral

peak clusters associated with short eccentricity. We corrected the sedimentary wavelengths in the main text to 10.8 to 9 m to ensure the consistency with the Supplementary Text. Please see lines 124–131: “The spectral analysis of the MS series indicates a series of obvious sedimentary wavelengths, i.e., ca. 34 m, 13.3 m, 10.8 m, 9 m, 8 m, 3 m and 1.6 to 1.3 m (Supplementary Text 3), approximately in accord with the ratios of the 405-kyr long-eccentricity, 173-kyr obliquity, 125–95-kyr short-eccentricity, ~33-kyr obliquity and ~21–17-kyr precession cycles around 234 Ma, based on the La2004 astronomical solution.”

[69] Line 110: The phrase 'high quality of our astronomical calibration' is somewhat subjective. It would be more appropriate to describe the calibration in terms of its reliability and precision. Please consider rephrasing it.

Reply: Thank you. We rephrased this sentence as 'The spectral analysis of the two tuning schemes shows highly correlated astronomical signals corresponding to the 405-kyr long eccentricity, 173-kyr obliquity, and 131–95-kyr short eccentricity components, thereby confirming the reliability of the astronomical calibration'. Please see lines 135–138.

[70] Line 110: 'shows' instead of 'show'

Reply: Thanks, done. Please see line 135.

[71] Line 127: Please fix the typo: 'stratigrapically' to 'stratigraphically'

Reply: Thanks, done. Please see line 155.

[72] Line 141: Please consider rephrasing, for example: 'However, the entire CPE with episodic CIEs is generally considered to have lasted longer than 1 Myr based on cyclostratigraphy (~1.1 Myr), biostratigraphy and magnetostratigraphy (1.6 to 1.7 Myr).

Reply: Thanks, done. Please see lines 169–171.

[73] Line 171: Please fix the typo: 'redcution' to 'reduction'

Reply: Thanks, done. Please see line 197.

[74] Line 176-180: Please consider rephrasing, for example: 'A precursor carbon

release or warming event may signal the growing instability of thermally sensitive carbon sources, such as sub-ocean-floor methane hydrates, potentially triggering a positive feedback loop to sustain subsequent warming.'

Reply: Thanks, done. Please see lines 203–205: “A precursor carbon release or warming event may signal the growing instability of thermally sensitive carbon sources, potentially triggering a positive feedback loop to sustain subsequent warming (Fig. 3).”

[75] Line 194: Please add 'a' before 'global mean'

Reply: Thanks, done. Please see line 222.

[76] Line 203: Please add 'the' before 'dissociation'

Reply: Thanks, done. Please see line 231.

[77] Line 210: Change the punctuation: 'i.e.' to 'i.e.,'

Reply: Thanks, done. Please see line 237.

[78] Line 211: Please add 'the' before 'Earth system'

Reply: Thanks, done. Please see line 238.

[79] Line 211: Eliminate the preposition 'to' before 'the CPE'

Reply: Thanks, done. Please see line 238.

[80] Line 215-218: Please consider rephrasing, for example: 'The orbitally driven changes in Earth's hydrological processes and carbon cycles, occurring over tens of thousands to millions of years, form the underlying pattern of climate-carbon cycle interactions.'

Reply: Thanks, done. Please see lines 245–247: “The orbitally driven changes in Earth's hydrological processes and carbon cycles, occurring over tens of thousands to millions of years, form the underlying pattern of climate-carbon-cycle interactions.”

[81] Line 218-222: The sentence needs to be rephrased for better readability.

Reply: Thanks, we revised the sentence to “Previous research has indicated that the climate–carbon-cycle interaction was paced by 405-kyr long-eccentricity rhythm

throughout the Oligo–Miocene, time interval followed by a striking phase reversal at 6 Ma, signalling a reorganization of the climate–carbon-cycle system in response to coldhouse conditions.” Please see lines 248–251.

[82] Line 219: Please fix the typo: 'rhtthm' to 'rhythm'

Reply: Thanks, done. Please see line 249.

[83] Line 222-226: Please break down the sentence and consider re-phrasing, for example: 'During eccentricity minima, cooler and more stable climates, within a generally warm background, facilitated the expansion of continental carbon reservoirs. This led to greater land storage of isotopically light carbon and a corresponding rise in marine dissolved inorganic carbon ($\delta^{13}\text{C}$ -DIC), with the reverse occurring during maxima.'

Reply: Thanks, done. Please see lines 251–256: “During eccentricity minima, cooler and more stable climates, within a generally warm background, facilitated the expansion of continental carbon reservoirs. This expansion led to greater land storage of isotopically light carbon and a corresponding rise in marine dissolved inorganic carbon ($\delta^{13}\text{C}$ -DIC), with the reverse occurring during maxima.”

[84] Line 227-231: Please split the sentence and rephrase it.

Reply: Thanks, done. Please see lines 257–261: “Our results reveal the pronounced in-phase variation between the filtered long-eccentricity cycles and the amplitude modulation of short eccentricity in the MS series over the CPE. This relationship suggests that the higher values of the filtered eccentricity cycles are correlated with high eccentricity (corresponding to high variance of precession), and *vice versa* (Fig. 2b).”

[85] Line 229: 'suggest' instead of 'suggests'

Reply: Thanks, done. Please see line 259.

[86] Line 246: Please add a comma before the word 'whereas' and apply this comment elsewhere in the text.

Reply: Thanks, done. Please see line 276.

[87] Line 247: Please change the punctuation 'e.g.' to 'e.g.,'

Reply: Thanks, we deleted the Carboniferous example. Please see line 276.

[88] Line 254: Correct your spelling for the word 'approximately'

Reply: Thanks, done. Please see line 285.

[89] Line 265: Typo: change the 'northeastern' to 'northeastern' and apply this comment elsewhere in the text.

Reply: Thanks, done. Please see lines 299.

[90] Line 275: Please add 'the' before the word 'implementation'

Reply: Thanks, done. Please see line 309.

[91] Line 484: 'volcanic' instead of 'volcanics'

Reply: Thanks, done. Please see line 704.

[92] Line 494: Please add 'the' before the word 'proportion'

Reply: Thanks, done. Please see line 713.

[93] Line 517: Please add a preposition (an or the) before the word 'expansion'

Reply: Thanks, done. Please see line 740.

[94] Line 520: The 'Geological Setting' is often treated as a standalone section, separate from 'Methodology' because it provides critical context for the study area, which is important for interpreting results and is not typically considered part of the experimental or analytical procedures.

Reply: Thank you very much. We moved this section to the maintext. Please see lines 94–116.

[95] Line 525: Please change the spelling: 'meters' instead of 'metres'

Reply: Thanks, 'meters' is British English, which is more in line with the style of *Nature Communications*.

[96] Line 525: Replace 'Formations' with 'formations' here and elsewhere in the text.

Reply: Thanks, done. Please see lines 98 and 105.

[97] Line 541: There is structural issue in this section. The sentence ‘Organic-carbon isotopes and TOC contents (n = 289) were analyzed at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences’ appears misplaced because it interrupts the logical flow of the sample preparation and analysis steps.

Reply: Thank you for pointing out the structural issue in this section. We have revised the paragraph by moving the sentence “Organic-carbon isotopes and TOC contents (n = 289) were analyzed at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences” to the beginning of the paragraph. This adjustment ensures a more logical flow in describing the sample preparation and analysis steps. Please see lines 329–331.

[98] Line 543: Clarify what ‘n = 289’ refers to (e.g., total sample numbers) and specify if it applies to $\delta^{13}\text{C}_{\text{org}}$, TOC, or both.

Reply: Thanks, we changed the sentence to "Both organic-carbon isotopes ($\delta^{13}\text{C}_{\text{org}}$) and TOC contents were analysed for a total of 289 samples at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences." Please see lines 329–331.

[99] Line 552: 'Were measured' instead of 'was measured'

Reply: Thanks, done. Please see line 340.

[100] 590: Ensure the methodology section is structured consistently across all analyses for clarity and readability (e.g., state the place of analysis, the number of samples analyzed, the procedure, and the analytical precision).

Reply: Thank you for your constructive suggestion. I have revised the methodology section to ensure consistency in structure across all analyses. For the elemental analyses section, I have reorganised the text to clearly state the place of analysis, the number of samples analysed, the procedure, and the analytical precision and accuracy. The revised section now follows a consistent format to enhance clarity and readability. Please see lines 380–384: “Major and trace elements were analysed for a total of 154 samples at the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. An approximate 50 mg of sample powder was weighed and

ashed at 110°C for 3 h. Then, the sample powder was digested in 1 ml of HNO₃ and 1.5 ml of HF at 190°C for 72 h”.

[101] Line 591: Please fix the typo: 'power' to 'powder'

Reply: Thanks, done. Please see line 382.

[102] Line 591-592: I recommend re-phrase the sentence as follows: 'Then, the sample powder was digested in 1 ml of HNO₃ and 1.5 ml of HF at 190°C for 72 h.'

Reply: Thanks, done. Please see lines 383–384.

[103] Line 632: Correct the word 'ime'

Reply: Thank you. We correct the word to 'time'. Please see line 422.

[104] Line 650: Correct the word 'temperatue'

Reply: Thanks, done. Please see line 443.

[105] Line 659: Correct the word 'comparision'

Reply: Thanks, done. Please see line 453.

[106] Line 692: Correct the word 'dicussions'

Reply: Thanks, done. Please see line 678.

[107] Line 702: 'work' instead of 'works'

Reply: Thanks, done. Please see line 689.

[108] Fig. 1: Please include the CPE record from the Miankuhi Formation, Turan Plate (NE Iran) based on recent study by Mazaheri-Johari et al. (2021, 2022).

Reply: Thanks, done. Please see Fig. 1.

[109] Fig. 3: The figure caption states that 'S2: the Wrangellia LIP began releasing isotopically light carbon, POE appeared, and temperatures started to rise,' but the figure lacks any temperature data/profile to support this. Since the manuscript includes palynological studies suggesting a warm, arid climate during the $\delta^{13}\text{C}_{\text{org}}$ fluctuations (POE to CIE2), it would be helpful to include temperature-related data in

the figure or clarify how the temperature rise is being represented (e.g., using supporting data from previous studies).

Reply: Thanks. We fully agree with you that adding a temperature curve would be beneficial and attempted to do so. However, due to the high-resolution analysis in our study, we found that no palaeotemperature reconstruction work currently can offer the necessary precision at this level, so we decided not to include it. In revision, we have added the reference to Sun et al. (2016), which reconstructed palaeotemperature curves based on oxygen isotopes from conodonts and supports the idea that temperatures began to rise before the onset of CIE1. Please see line 724.

Sun, Y. D. et al. Climate warming, euxinia and carbon isotope perturbations during the Carnian (Triassic) crisis in South China. *Earth Planet. Sci. Lett.* **444**, 88–100 (2016).

[110] Fig. 3: show 'CIE interval' in the figure.

Reply: Thanks, added. Please see Fig. 3.

[111] Fig. 4: Please mark the study area (Junggar Basin) on the figure (e.g., with a star) to clarify the climate state in this basin before and during the CPE.

Reply: Thanks, added. Please see Fig. 4.

[112] Table of Contents, Text S7: Correct the word 'temperal'

Reply: Thanks, we have corrected "spatial-temperal" to "spatial-temporal".

[113] Line 1: 'references' instead of 'reference'

Reply: Thanks, done. Please see line 1 in Supplementary Information.

[114] Line 1: Eliminate the preposition 'on'

Reply: Thanks, done. Please see line 1 in Supplementary Information.

[115] Line 55: Correct the words 'sandston' and 'samplless'

Reply: Thanks, done. Please see line 59 in Supplementary Information.

[116] Line 65: 'was analyzed' instead of 'were analyzed'. Also apply the comment to line 70.

Reply: Thanks, done. Please see lines 69 and 74 in Supplementary Information.

[117] Line 92: Please add 'the' before 'Sliding window'

Reply: Thanks, done. Please see line 108 in Supplementary Information.

[118] Line 93: Consider changing the verb form: 'are' instead of 'is'

Reply: Thanks, done. Please see line 109.

[119] Line 131: Correct the words 'amplifying'

Reply: Thanks, done. Please see line 151.

[120] Line 134: Correct the words 'eccenteicity'

Reply: Thanks, done. Please see line 154.

[121] Line 138: Change the preposition: 'to the' instead of 'the'

Reply: Thanks, done. Please see line 158.

[122] Line 141: 'intervals' instead of 'interval'

Reply: Thanks, done. Please see line 161.

[123] Line 249: Change the punctuation: 'e.g.,' instead of 'eg.,'

Reply: Thanks, done. Please see line 271.

[124] Line 265: Please add 'the' before the word 'potential'

Reply: Thanks, done. Please see line 287.

[125] Line 275: 'Fig. S13' instead of 'Fig. S12'

Reply: Thanks, done. Please see line 297.

[126] Line 277: Change 'on sample' to 'one sample'

Reply: Thanks, done. Please see line 299.

[127] Line 278: Please consider re-phrasing, for example: 'Previous studies have shown that Hg behavior is non-linear with host-phase abundance, resulting in elevated

normalized Hg values when host phase abundance is low (e.g., low TOC or low TS).'

Reply: Thanks, done. Please see lines 300–302: “Previous studies have shown that Hg behavior is non-linear with host-phase abundance, resulting in elevated normalized Hg values when host phase abundance is low (e.g., low TOC or low TS).”

[128] Line 313: Correct the word 'measureable'

Reply: Thanks, done. Please see line 354.

[129] Line 347: Remove the colon after the word 'including'

Reply: Thanks, done. Please see line 396.

[130] Line 573: Correct the word 'Cretaceousi'

Reply: Thanks, done. Please see line 676.

RESPONSE TO REFEREES

Reference: NCOMMS-24-80380-A

Title: Climate–carbon-cycle interactions and spatial heterogeneity of the Carnian Pluvial Episode (Late Triassic)

Journal: Nature Communications

We thank the referees for their helpful comments that have greatly improved the quality of our interpretation and discussions of the Carnian Pluvial Episode. We have revised the paper in line with these comments, focusing on moderating the speculative discussion on methane hydrates, improving clarity throughout the manuscript, and better integrating our findings within the context of previous studies. We outline detailed responses to individual comments below.

Reviewer 1:

[1] I don't understand the obsession with the methane hydrate. How much methane hydrate contributed the carbon isotope excursion in the Carnian, if at all? If this is not testable in this paper, it will only make the overall paper somewhat speculative.

Reply: Thank you. We changed the sentence “Therefore, the isotopically light carbon released during CIE1 may have mainly originated from the dissociation of sub-ocean-floor methane hydrates” to “Therefore, the dissociation of sub-ocean-floor methane hydrates might be an important source of the isotopically light carbon released during the CIE1 (Fig. 3). Other feedback sources, such as peat and forest, could also contribute to the supply of ^{13}C -depleted carbon”. Please see lines 235–238.

[2] The term ‘climate-carbon-cycle interaction’ is not easy to follow. The authors did a fair job explaining it in the reply letter, but not so perfectly in the manuscript. If I don't understand it, >90% of the audience won't understand.

Reply: Thank you for pointing this out. To improve clarity, we have added a definition of this term in the revised manuscript, as follows: “Here, we use the term climate–carbon-cycle interaction to describe the coupled feedback system in which climate variables (e.g., temperature, hydrology and weathering) influence carbon-cycle processes (e.g., soil respiration, net primary productivity and CO_2 solubility), while the carbon cycle, in turn, regulates global climate by modulating atmospheric

greenhouse gas concentrations (CO₂ and CH₄)”, please see lines 252–257.

Reviewer 2:

[3] Line 103: silty or siltstone?

Reply: Thanks. We changed the word “silty” to “siltstone”. Please see line 104.

[4] Lines 103-109: The studied section is different from the section in Reference 42 or not? If not, I strongly suggest that the authors add a lithological correlation map between two sections in the Supplementary Information and then mark the location of the observed fossils.

Reply: Thank you very much. The studied section is the same as the section in Reference 42. The author (Jungang Peng) of the Reference 42 is also the co-author of this manuscript.

[5] Line 119: sandstone or tuffaceous sandstone? Please clarify it. Why did you change tuffaceous sandstone to sandstone in the revised manuscript? If only the maximum depositional age of the sandstone is considered, it is difficult to constrain the onset of the CPE.

Reply: Thank you for your comment. Initially, we identified the samples as tuffaceous sandstone because the zircon ages yielded from LA-ICP-MS U-Pb dating were highly concentrated, suggesting a possible volcanic origin. In the first round of review, you kindly suggested that we add a micrograph of the dated sample. We specifically conducted an additional field trip to Xinjiang to recollect samples. We then prepared thin sections and obtained a detailed photomicrograph (now included as Fig. S1). After careful petrographic examination and discussions with petrology experts, we revised the lithological classification to sandstone.

Although sandstone can only provide a maximum depositional age, in this case, the combined biostratigraphic and radiometric evidence is sufficient to constrain the onset of the CPE, as follows: (1) the vertebrate *Fukangichthys* fauna and palynological zonation (including *Aratrisporites*, *Dictyophyllidites-Aratrisporites*, and *Lycopodiacidites-Stereisporites*) suggest that the boundary between the Middle and Upper Triassic (~ 237 Ma) lies between the uppermost Karamay Formation and the base of the Huangshanjie Formation; (2) The U-Pb age obtained from the lower Huangshanjie Formation yield a maximum depositional age of 232.9 ± 0.7 Ma,

indicating that the true depositional age of this horizon must be equal to or younger than 232.9 ± 0.7 Ma. Therefore, the onset of the CPE (approximately 234 Ma) must fall between the Middle-Upper Triassic boundary (237 Ma) and the dated horizon at 232.9 ± 0.7 Ma. We changed the sentence “These absolute ages place the CPE (234–232 Ma) in the lower Huangshanjie Formation (between the lowest layer and the stratigraphic level of the sample with the youngest depositional age of 232 Ma)” to “These absolute ages place the onset of the CPE (approximately 234 Ma) between the Middle-Upper Triassic boundary (237 Ma) and the stratigraphic level of the sample with the youngest depositional age of 232.9 ± 0.7 Ma” to make the statement more concise. Please see lines 114–117.

Based on this stratigraphic framework, we further use carbon-isotopes data to pinpoint the onset of the CPE more precisely.

[6] Lines 141-143: You mean “the onset of CPE corresponds to a negative carbon isotope excursion” ? This is different with many previous studies.

Reply: Thanks a lot for your comment. Yes, here we mean that the onset of CPE corresponds to a negative carbon-isotope excursion (CIE). This CIE has been consistently identified across a wide range of depositional settings, including the Tethyan Ocean (e.g., Dal Corso et al., 2012, 2018; Mueller et al., 2016a; Sun et al., 2016), the Boreal realm (Mueller et al., 2016b), and the continental interiors of Pangea (e.g., Baranyi et al., 2019; Lu et al., 2021; Miller et al., 2017), indicating a globally carbon cycle perturbation at the onset of the CPE. Importantly, previous studies have shown that this CIE coincided with a transition to siliciclastic-dominated sedimentation, and a marked shift in carbonate production mode—from microbially induced carbonate precipitation to metazoan biomineralization (Please see Dal Corso et al., 2018).

Based on a well-constrained chronological framework, we further emphasise that reliable and unaltered carbon-isotope records should serve as the primary stratigraphic tool for high-resolution correlation of the CPE. Because carbon isotopes reflect global perturbations in the carbon cycle, with CO_2 circulating throughout the ocean–atmosphere–terrestrial system, thus providing a more globally coherent signal. In contrast, humidity changes are inherently regional and cannot be expected to occur synchronously or uniformly across all palaeogeographic settings. As demonstrated in

our study, not all regions experienced increased humidity during the CPE, underscoring that the negative CIE is a more robust and diagnostic marker for recognising and correlating the event on a global scale.

- Baranyi, V., Miller, C. S., Ruffell, A., Hounslow, M. W. & Kürschner, W. M. A continental record of the Carnian Pluvial Episode (CPE) from the Mercia Mudstone Group (UK): palynology and climatic implications. *J. Geol. Soc. London* **176**, 149–166 (2019).
- Dal Corso, J. et al. Discovery of a major negative ^{13}C spike in the Carnian (Late Triassic) linked to the eruption of Wrangellia flood basalts. *Geology* **40**, 79–82 (2012).
- Dal Corso, J. et al. Multiple negative carbon-isotope excursions during the Carnian Pluvial Episode (Late Triassic). *Earth Sci. Rev.* **185**, 732–750 (2018).
- Lu, J. et al. Volcanically driven lacustrine ecosystem changes during the Carnian Pluvial Episode (Late Triassic). *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2109895118 (2021).
- Mueller, S., Krystyn, L. & Kürschner, W. M. Climate variability during the Carnian Pluvial Phase—a quantitative palynological study of the Carnian sedimentary succession at Lunz am See, Northern Calcareous Alps, Austria. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **441**, 198–211 (2016a).
- Mueller, S., Hounslow, M.W. & Kürschner, W.M. Integrated stratigraphy and palaeoclimate history of the Carnian Pluvial Event in the Boreal realm: new data from the Upper Triassic Kapp Toscana Group in central Spitsbergen (Norway). *J. Geol. Soc. London* **173**, 186–202 (2016b).
- Miller, C. S. et al. Astronomical age constraints and extinction mechanisms of the Late Triassic Carnian crisis. *Sci. Rep.* **7**, 2557 (2017).
- Sun, Y. D. et al. Climate warming, euxinia and carbon isotope perturbations during the Carnian (Triassic) crisis in South China. *Earth Planet. Sci. Lett.* **444**, 88–100 (2016).

[7] Lines 151-154: The authors need to explain why the studied section displayed a CIE with an amplitude (6.5‰) larger than coeval sedimentary successions.

Reply: Thank you very much for your comment. Variability in carbon isotope excursion (CIE) amplitude is commonly observed in the geological record, including well-studied events such as the Paleocene-Eocene Thermal Maximum (PETM), where the magnitude of the negative $\delta^{13}\text{C}$ excursion varies significantly across different sedimentary records and substrates (McInerney & Wing, 2011; Sluijs & Dickens, 2012). Such variability reflects the influence of multiple factors, including organic matter source, depositional environment, diagenesis, and photosynthetic pathways (Dal Corso et al., 2017, 2018; Diefendorf et al., 2010). Therefore, direct comparison of CIE amplitudes across terrestrial and marine records must be made with caution, and the amplitude alone is not a diagnostic indicator of the carbon source.

In the previous version, we have included a discussion of the relatively large amplitude ($\sim 6.5\text{‰}$) observed in our studied section in the Supplementary Information. Please see lines 259–266 for “Compound-specific long-chain *n*-alkane ($\text{C}_{23}\text{--}\text{C}_{31}$) $\delta^{13}\text{C}$ values in the DLK section show both a distinct $\sim 6.5\text{‰}$ negative isotopic excursion and a $\sim 4.0\text{‰}$ negative isotopic excursion, corresponding to the bulk $\delta^{13}\text{C}_{\text{org}}$ CIE1 and CIE2, respectively (Fig. S12). This result indicates that carbon-cycle perturbations in the atmosphere are consistent with the bulk $\delta^{13}\text{C}_{\text{org}}$ in the lacustrine deposits, suggesting that the mix of organic matter from algae, pollen and spores, waxy leaf and wood could have amplified the magnitude by a few permil compared to the average $\sim 3\text{--}4\text{‰}$ CIE1 in marine deposits (Dal Corso et al., 2018)”.

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McInerney, F.A. & Wing, S. L. The Paleocene-Eocene thermal maximum: a perturbation of carbon cycle, climate, and biosphere with implications for the

future. *Annu. Rev. Earth Planet. Sci.* **39**, 489 – 516 (2011).

Sluijs, A. & Dickens, G. R. Assessing offsets between the $\delta^{13}\text{C}$ of sedimentary components and the global exogenic carbon pool across early Paleogene carbon cycle perturbations. *Glob. Biogeochem Cycles* **26**, GB4005 (2012).

Reviewer 3:

[8] I have reviewed the revised manuscript and I believe that the major points have been addressed by the authors. The manuscript has now improved and can be considered for publication in this journal.

Reply: Thank you very much.