Dear editor and reviewers, this document contains a point by point reply to the issues raised by the reviewers (in red); changes made in the MS are indicated in blue. All original comments by the reviewers are left in black font. Line numbers correspond to those of the manuscript with changes marked.

Review #2

Evaluation of the revised manuscript

In the revised manuscript, the author has addressed all of my comments and all the issues that I pointed out in my first review. The introduction now provides a better overview over previous research efforts in the field, putting the current study into a broader context. In addition, the Discussion now has a much clearer structure, clearly pointing out the advances/differences of the current study compared to previous research and discussing the uncertainties of the projections made. The structure and readability of the Methods section has greatly improved as well, making the workflow much more understandable and easier to follow. All in all, the overall readability and narrative of the manuscript have improved significantly due to the revisions implemented by the author. However, a few minor issues and technical corrections remain that should be addressed before final acceptance of the manuscript.

Specific Comments

L. 58-63: This paragraph was rewritten down below but forgotten to delete.

Author reply: Deleted the doubling upper paragraph.

Section 2.3: Some aspects are mentioned multiple times in this section; maybe it was forgotten to delete rewritten sentences.

Author reply: Deleted the doubling upper paragraph.

L. 78-79: I don't see how Fig. 2 verifies this statement.

Author reply: Delted "(Fig. 2)".

L. 80-84: This paragraph seems to contradict itself; in the first sentence, you state that short-term events are independent of long-term climate changes, while shortly after, you say that the long-term decline in mantle potential temperature affects these short-term events. Can you please explain that again?

Author reply: Revised to "Abrupt events (Equation 9) are treated independently from long-term climate change (Equation 10), because their short duration means they are not significantly affected by the gradual evolution of climate. Accordingly, the equations in Section 2.5 are designed to calculate the number of families after an event (DnR) based on the number of families before the event (D(n–1)A). On the other hand, by combining temperature variations caused by long-term cyclic climate changes—driven by increasing solar radiation and declining mantle potential temperature—with those from abrupt events, and comparing the resulting habitat temperatures with the thermal tolerance limits of each animal group, the Survival Rate by Climates (SRC) in Section 2.5 can be derived.

The long-term increase in solar radiation leads to declines in both atmospheric oxygen and carbon dioxide. The progressive atmospheric CO_2 drawdown—accelerated by intensified continental weathering—will trigger recurrent plant crises, while a concurrent decline in atmospheric oxygen will ultimately lead to the extinction of metazoan life.

Since fluctuations in atmospheric oxygen and carbon dioxide have already been reported, those values are used to determine the proportional impact on the number of families for insects, terrestrial tetrapods, and marine animals. Based on these impacts and temperature changes, the number of families is calculated, and their trends are used to determine the timing of diversity shifts and eventual extinction.".

L. 144-145: Isn't temperature only highlighted in red?

Author reply: Deleted ", yellow, and green".

L. 161-186: Old and rewritten paragraphs seem to have gotten mixed up here.

Author reply: Depelted the upper paragraph.

L. 248: This sentence is misunderstandable. May be you could write: "was set to be 20 °C and 14 °C, which is_3_°C_larger". _

Author reply: Added ", which is 3 °C".

Sect. 2.4.4: Why do you use 45° as reference latitude here and not 37° like in the other cases?

Author reply: I selected 45° as a representative mid-latitude because only deep-sea temperature is not directly related to global average temperature (GAT), unlike surface temperatures. This value provides a more appropriate reference for evaluating deep-sea temperature effects.

L. 295-296: Don't you only need one survival rate per metazoan group for event 0?
Author reply: In the Worst Anthropocene Model (Table 4), I used multiple survival rates—0.95, 0.85, and 0.90—to reflect uncertainty in species-level estimates. However, for the Anthropocene event scenario without a large-scale nuclear war between the US and Russia, the survival rate is set to zero at the family level, corresponding to species-level survival rates between 0.95 and 0.90.
L. 299: Do you mean survival rate?
Author reply: Revised to "survival rate".
L. 376: Where is PER used in the model?
Author reply: Remove (PER) from here and Table 5.
L. 436: Do you mean events 0-4?
Author reply: revised to "events 0–4".
L. 496-499: I cannot follow the argumentation here. You state that in simulations without abrupt warming, diversity decline is not delayed. As far as I understand, this implies that the results are quite independent of the presence or absence of abrupt warming. Still, you conclude from these results that abrupt warming is the key driver of final extinction. Can you please ex-plain that further?
Author reply: Revised to "The half-life of diversity, occurring at 0.65–0.74 Gyr, is delayed by approximately 0.1–0.2 Gyr in simulations where O_2 or CO_2 decline is excluded, but not in simulations where abrupt warming is excluded (Table 9). This suggests that while long-term decreases in atmospheric O_2 and CO_2 gradually reduce metazoan diversity, abrupt warming is the dominant factor driving the final extinction, which occurs at 0.9–1.0 Gyr. Specifically, abrupt warming events cause sharp drops in SRC, directly leading to complete metazoan extinction.".
L. 532: I would not use the word "accurate" here. Maybe "robust"?
Author reply: Revised to "robust".
Figure 5: I think the color scheme is a bit difficult to understand. As far as I understand, the color scheme is as follows:
Dark color: Conservative Model
Light color: New Evolutional Model
Red curves: Worst Anthropocene Model

Black curves: Continuous Worst Anthropocene Model

However, there are two red curves in each plot, so what does the second red curve show?
Author reply: Revised the figure and the caption "The red curves illustrate diversity changes under the *Worst Anthropocene Model*.".
Tables 2a-2c: What is NC? I could neither find a definition in the text nor in Table 3.
Author reply: I deleted "and [NC]" from the revised three tables. "NC" referred to nuclear conflict in an earlier version, but it is no longer used. I have since reorganized the scenarios into three separate tables—2-4—corresponding to three distinct models, which eliminates the need for the "NC" label.
Technical corrections
Author reply:
L. 136-137: diversity remaining at ~1.0~~,~~ by the end-Silurian
Author reply: Deleted ",".
L. 270: the year~~.~~; the difference
Author reply: Revised "the year. The difference"
L. 272: limits, for subterranean animal
Author reply: No change: "46 °C points, representing lethal thermal limits," because "representing lethal thermal limits," is the explanation for 46 °C.
L. 303: global average surface temperature equivalent?
Author reply: Delete the phrase resulting in "GATEL" only.
L. 314: CO_2~~,~~ and the
Author reply: Deleted ",".
L. 334: ~~L~~latitude
Author reply: Revised to latitude.
L. 346-347: Recovery Rates in the Conservative Model (Table 2a; Recovery Rates in the New Evolutional Model and the Continuous Worst Anthropocene Model are shown in Tables 2b and 2c, respectively):
Author reply: Done.
L. 396-397: Consequently, Equation 15 is used ~~for~~to calculate the recovery rate (RR) ~~for~~ of marine metazoans,

because the GAT exceeds the highest GAT at the end-Permian ~~highest GAT~~ of 36 °C
Author reply: Done.

Review of EGUSPHERE-2025-1853
General comments
The author uses a combination of geological and biological data to model the survival and extinction of life in the future, and conclude that metazoans will become extinct in approximately one billion years. The manuscript is original and the conclusion is novel. This is my first time reading this work, but the manuscript has been substantially improved following the suggestions of other reviewers and is now much clearer. Overall, I think it is a great and intriguing paper. However, I have concerns about the robustness of the results.
In this study, all model parameters were assigned single fixed values, such as abrupt temperature perturbation and extinction rate. Although the author has performed several sensitivity tests by removing individual processes, which is very great, the robustness of the conclusion remains difficult to assess without exploring a boarder range of values for key parameters. As shown in the manuscript, the ultimate demise of metazoans will be driven by episodic warming events. The temperature perturbation ΔTe is based on the mean cooling and warming anomalies associated with past mass extinctions. However, these anomalies vary substantially among the five major extinctions (e.g., the temperature increase during the Permian-Triassic extinction were much greater than that during the Late Devonian extinction, as noted by the author; Kaiho et al., 2022, Biogensciences). In addition, paleo-temperature reconstructions based on different models show considerable discrepancies (e.g., Scotese et al., 2021; Judd et al., 2024, Science). Therefore, it would be very helpful to assess how the predicted timing of metazoan extinction changes under different parameter settings. For instance, if the magnitude of temperature perturbation is comparable to that of the Permian-Triassic extinction, what lifespan of metazoans does the model predict? Similarly, what outcome is obtained if temperature shifts are similar to those of the Late Devonian extinction? Besides, the timing of final extinction is determined by a threshold proportion of surviving diversity, and this threshold will therefore influence the lifespan of metazoans. Although other parameters may also affect the results, sensitivity analyses of these key parameters are essential for evaluating the reliability of the model conclusions.
Author reply: I have explored a boarder range of values for three key parameters: temperature anomaly, extinction rate, and threshold of number of families for the complete extinctions of insect, terrestrial tetrapods, and marine metazoans.

1. Temperature anomaly variation:

In section 2.3., added "The above ΔTe is in the mean temperature anomaly case. When accounting for mantle temperature, warming anomalies in the maximum and minimum temperature anomaly cases are 3 °C higher and 2 °C lower, respectively, than the anomaly in the mean temperature anomaly case, 0.7–1.1 Gyr (events 8–12) from now (Table S2). These differences are 4 °C higher and 3 °C lower, respectively, when based on modern mantle temperature (Table S2).".
In section 3.2, added "The maximum and minimum temperature anomaly cases can shift the timing of complete extinction by approximately ±0.1 Gyr—advancing or delaying it, respectively. This is because temperature anomalies between event intervals range from +2 °C to +3 °C during warming periods, while the anomalies in the maximum and minimum cases are 3 °C higher and 2 °C lower, respectively, than those in the mean temperature anomaly scenario. As a result, the timing of metazoan complete extinction varies within the range of 0.9–1.1 Gyr from now (events 10–12).".
In section 4.4, added "Additionally, variations in warming anomalies can contribute an estimated ±0.1 Gyr of uncertainty.".

2. Extinction rate variation: I have analyzed on not only the average extinction rates, but also maximum and minimum extinction rates.

In section 2.5. revised to
Average Extinction Rate Case
(Family-level extinction rates: 0.19 for insects, 0.37 for tetrapods, 0.26 for marine metazoans):

$$SRC_I = 1 - (0.19 + 0.77 \times ERW_{SI} + 0.04 \times ERW_U) \quad (11a)$$

$$SRC_T = 1 - (0.37 + 0.60 \times ERW_{ST} + 0.03 \times ERW_U) \quad (12a)$$

$$SRC_M = 1 – (0.26 + 0.50 \times ERW_{SM} + 0.24 \times ERWA_D) \quad (13a)$$

Maximum Extinction Rate Case

(Family-level extinction rates: 0.35, 0.54, 0.35):

$$SRC_I = 1 – (0.35 + 0.62 \times ERW_{SI} + 0.03 \times ERW_U) \quad (11b)$$

$$SRC_T = 1 – (0.54 + 0.44 \times ERW_{ST} + 0.03 \times ERW_U) \quad (12b)$$

$$SRC_M = 1 – (0.35 + 0.44 \times ERW_{SM} + 0.31 \times ERWA_D) \quad (13b)$$

Minimum Extinction Rate Case

(Family-level extinction rates: 0.08, 0.21, 0.15):

$$SRC_I = 1 – (0.08 + 0.87 \times ERW_{SI} + 0.05 \times ERW_U) \quad (11c)$$

$$SRC_T = 1 – (0.21 + 0.75 \times ERW_{ST} + 0.04 \times ERW_U) \quad (12c)$$

$$SRC_M = 1 – (0.15 + 0.57 \times ERW_{SM} + 0.28 \times ERWA_D) \quad (13c)$$

Note: ERW (extinction rate by warming) is calculated based on the mean, maximum, and minimum temperature anomaly scenarios.

In section 3.2, added "The average, maximum, and minimum extinction rate cases do not affect the timing of complete extinction. However, abrupt negative spikes in diversity within each metazoan group occur, as extinction rates driven by short-term warming (ERW) become significant near the point of complete extinction (Tables S6, S7). The following results are presented under the average extinction rate scenario.".

3. Threshold of number of families for the complete extinctions

In section 2.5, added "Complete extinctions of metazoans are defined as the point at which the number of species reaches zero—effectively less than one species in the model. This corresponds to fewer than 0.4 calculated families on land and fewer than 0.2 families in the oceans, based on family-to-species extinction ratios: a 30% family-level extinction rate corresponds to a 70% species-level extinction for terrestrial tetrapods, and an 18% family-level extinction rate corresponds to a 70% species-level extinction for marine metazoans, as shown in Figures 1b and 1c of Kaiho (2022a).".

In section 3.2, added "Although complete extinction of metazoans is defined as fewer than 0.4 families on land and fewer than 0.2 families in the oceans, the timing of complete extinctions remains unchanged even when the threshold is set at half, double, or less than one family (Table S6, S7).".

In section 4.4, added "Despite these factors, variations in extinction rates from paleontological records and differences in extinction threshold values (i.e., the number of surviving families ranging from 0.1 to 1.0) have little impact on the overall lifespan of metazoans. This is because final extinction is primarily driven by abrupt global warming events—especially those triggered by large-scale volcanism—which ultimately override other extinction processes.".

Additionally, I revised and added the following explanation for methods in section 2.1.

Abrupt events (Equation 9) are treated independently from long-term climate change (Equation 10), because their short duration means they are not significantly affected by the gradual evolution of climate. Accordingly, the equations in Section 2.5 are designed to calculate the number of families after an event (DnR) based on the number of families before the event (D(n–1)A). On the other hand, by combining temperature variations caused by long-term cyclic climate changes—driven by increasing solar radiation and declining mantle potential temperature—with those from abrupt events, and comparing the resulting habitat temperatures with the thermal tolerance limits of each animal group, the Survival Rate by Climates (SRC) in Section 2.5 can be derived.

The long-term increase in solar radiation leads to declines in both atmospheric oxygen and carbon dioxide. The progressive atmospheric CO_2 drawdown—accelerated by intensified continental weathering—will trigger recurrent plant crises, while a concurrent decline in atmospheric oxygen will ultimately lead to the extinction of metazoan life.

Since fluctuations in atmospheric oxygen and carbon dioxide have already been reported, those values are used to determine the proportional impact on the number of families for insects, terrestrial tetrapods, and marine animals. Based on these impacts and temperature changes, the number of families is calculated, and their trends are used to determine the timing of diversity shifts and eventual extinction.

Minor comments

Line 117. The classic paper by Raup and Sepkoski (1982, Science), which defined the 'Big Five' mass extinctions, should be cited as well.

Author reply: Added "Raup and Sepkoski (1982)".
Line 134. The unit of diversity is unclear, and it is difficult for readers to understand why diversity can be low than one.
Author reply: Revised to "diversity rate for the Paleozoic maximum".
Line 150. Please clarify why the uncertainty of abrupt event timing was set to 0.03 Gyr.
Author reply: Revised to "±0.03 Gyr (standard deviation for numerical ages of "Big Five" mass extinctions)".
Line 151. Please specify whether past GAT were derived from this study or from previously published papers?
Author reply: Added "(Mello and Friaça, 2019; Scotese et al., 2021; Kaiho, 2022a)".
Line 176-186. Repeated content.
Author reply: Removed the former paragraph.
Line 187-200. See general comments.
Author reply: Added "The above ΔTe is in the mean temperature anomaly case. When accounting for mantle temperature, warming anomalies in the maximum and minimum temperature anomaly cases are 3 °C higher and 2 °C lower, respectively, than the anomaly in the mean temperature anomaly case, 0.7–1.1 Gyr (events 8–12) from now (Table S2). These differences are 4 °C higher and 3 °C lower, respectively, when based on modern mantle temperature (Table 2).".
Line 291. Several parameters throughout the manuscript were referred to as 'rates', but their definitions suggest that they represent percentages, rather than rates in conventional palaeobiological sense. The terminology should be clarified or revised for clarity.
Author reply: Revised to "recovery rates (referring to completeness, not speed)", "survival rate (referring to completeness, not speed)", and "extinction rate (referring to completeness, not speed; 0.19, 0.37, 0.26)".
Line 295-300. I think it would be helpful to provide an example of the calculations. And it is unclear what 'this value' refers to in Line 296. Based on the current description, diversity after recovery (0R) does not appear to be the product of post-extinction diversity (0E) and the recovery rate. For example, if 70% of 100 families survived, and the recovery rate is 1, the recovered diversity would be 70 × 1 = 70 (i.e., 0A). This is inconsistent with the results shown in Figure 5. Please revise these sentences.
Author reply: Revised 'this value' to "the post-event diversity".
Line 297. Why the value 0.029 is used?
Author reply: Added "since Event 1 occurs at that time".
Line 301. The term 'extinction percentage' is clearer here and improves readability.
Line 402-404. The complete extinction of metazoans on land is defined as fewer than 0.4 families. Please justify the choice of this threshold. Life persisted and diversified after the end-Ordovician extinction and Permian-Triassic extinction despite more severe losses.
Author reply: Revised to "Complete extinctions of metazoans are defined as the point at which the number of species reaches zero—effectively less than one species in the model. This corresponds to fewer than 0.4 calculated families on land and fewer than 0.2 families in the oceans, based on family-to-species extinction ratios: a 30% family-level extinction rate corresponds to a 70% species-level extinction for terrestrial tetrapods, and an 18% family-level extinction rate corresponds to a 70% species-level extinction for marine metazoans, as shown in Figures 1b and 1c of Kaiho (2022a).".
Line 556. More references supporting the duration of the cycles are needed.
Author reply: Added Scotese et al., 2021 and Mather et al., 2026.
Line 639-662. Key parameters, including extinction thresholds and temperature perturbations, should be reported together with the corresponding extinction times. This would help readers understand the conditions under which the reported results are obtained.
Author reply: Added "The maximum and minimum temperature anomaly scenarios can shift the timing of complete metazoan extinction by approximately ±0.1 Gyr, either advancing or delaying it. In contrast, variations in extinction rates based on paleontological records and differences in extinction threshold values (i.e., the number of surviving families ranging from 0.1 to 1.0) have minimal impact on the overall lifespan of metazoans.".