Response to the editor and reviewers

We thank the editor and the two reviewers for the critical assessment of our work and their very helpful and constructive comments. We have addressed all comments point by point and will revise our manuscript accordingly.

Reviewer 2

Summary of the manuscript

The manuscript uses the GFDL-ESM2M Earth System Model to examine the impact of climate warming scenarios on marine ecosystems based on the Aerobic Growth Index (AGI). They analyze how marine ecosystem habitats are affected under the overshoot vs. stabilization scenarios and quantifies how organisms' adaptation capabilities may mitigate habitat loss due to climate change. They find that under the overshoot scenario, although temperatures peak at 2°C and stabilize at 1.5°C, the maximum habitat loss still occurs over 150 years after the warming peak. Furthermore, they demonstrates that organisms' adaptation strategies will have a measurable impact on capping habitat loss under warming, depending on the adaptation rate.

Major review

The manuscript is generally well-written and structured. The authors outline a clear research question and provide nearly sufficient evidence to support it. I particularly appreciate the attempt to predict adaptability within this approach; although not extensive, it will be a valuable contribution. Adaptation has typically not been quantitatively applied in these types of studies.

We thank the reviewer for the positive assessment and detailed comments, which further improved our manuscript.

That said, there are a couple of limitations inherent to the study's approach that warrant clarification. First, the authors chose to use the relative AGI formulation, which, by definition, removes the species-scale oxygen supply versus demand. Because of the elimination of physiological oxygen dependence, the relative AGI only provides a general “sense” of ecosystem sensitivity to a warming climate, rather than an objective quantitative prediction. While this formulation is mathematically useful and allows for a more flexible analytical framework, it is unclear whether the relative AGI remains instructive for quantifying changes in species abundance. The argument here is that habitat gain or loss with changing environmental conditions depends on organisms' metabolic resource management (the ability to sustain respiration), which varies among species. Thus, vulnerability to stress is also variable among species, which is a key aspect of ecosystem resilience. Namely, not all species are equally important or vulnerable; the loss of some species is more detrimental to the ecosystem than others. Therefore, to appropriately quantify long-term changes in species abundance, it is necessary to assess species' vulnerability to environmental stress. To my understanding, species-vulnerability information is excluded when using the relative AGI, habitability is estimated by a generic count. Thus, it is not clear that the “sense” of habitat changes with warming based on relative AGI is quantitatively meaningful beyond serving as an indicator for potentially hazardous and habitable regions under a warming climate.

For example, during environmental stress events like heat waves or cold spells, it is the extremes of the physiological trait space that matter most for the entire system's ecosystem response and survival. Although the authors mention some of these limitations, they remain quantitative. My main point can be summarized as follows: while relative AGI serves as a meaningful metric for understanding climate change's impact on marine ecosystems by integrating oxygen and temperature changes into a single ecosystem-relevant proxy, it may not be sufficient quantitatively as an indicator of changes in ecosystem abundance. Perhaps I'm missing something; please clarify.

Thank you for the comment. In the manuscript, we applied the relative AGI that does not represent species-specific biological information to indicate ecosystem-level vulnerabilities to the impacts of ocean warming and deoxygenation. However, we also calculated species-specific AGI (see first paragraph of section 2.5 and equation 1) to examine the potential impacts on viable habitat volume at the species level (see Fig. 5, A3 and A4). In the latter application, species-specific oxygen thresholds were calculated and used from biogeographical data. The entire section 3.3 'Impacts on contemporary habitat volume of individual species' describes and discusses the species-specific results.

To further clarify the different formulations and application of AGI, we will clarify this at the beginning of section 2.5: "*We applied two alternative formulations of AGI as indicators of species-level and ecosystem level vulnerabilities to the impacts of ocean warming and deoxygenation (see eq. 1 and 2, respectively).*"

Secondly, the authors repeatedly mention the advantages of AGI over the classical metabolic index proposed by Deutsch et al., citing differences in requirements for lab-based physiological data. However, this difference appears to stem from the application of relative AGI, which removes physiological constraints. I believe the metabolic index can also be applied in a similar manner by simplifying it to yield a relative metabolic index that eliminates physiological parameters. Thus, it is not clear how physiological requirement data differ between classical AGI and the metabolic index; perhaps I am missing something here again; please clarify.

As discussed above, we used species specific thresholds. Also, we think that the comparison with metabolic index is not directly relevant in the discussion. Thus, we will remove the sentences in the revised manuscript to avoid confusion.

"Relative changes in pO_2 supply over pO_2 demand ratios have been implied to assess ecosystem-level impacts (Battaglia & Joos, 2018; Deutsch, Ferrel, Seibel, et al., 2015; Oschlies, 2021; Santana-Falcón et al., 2023), but species-specific thresholds and preference windows are needed for such estimates (Morée et al., 2023). ~~Unlike the Metabolic Index, which depends on 425 laboratory estimates of critical thresholds, AGI is widely applicable to all species for which the distributions are known thanks to its generalized temperature dependence and species' distribution-based critical thresholds.~~ In the future, the application of the AGI to more species will allow the assessment of a wider range of interspecies responses."

Beyond these two points, the manuscript is well-written and would be an important contribution to the community.

Below are some minor and specific comments

This is a minor point, while I appreciate the application of adaptability in marine organisms, it would be helpful to briefly discuss how robust this adaptation methodology is (or discuss the limitations). While this time-based adaptation may as well reflect how marine species will develop resilience against warming stress, ecosystems often experience tipping points leading to significant habitat loss or gain; such changes can tip systems on short timescale when important species are lost or gained. Moreover, tipping point climate variability and extremes occur over much shorter timescales. I'm curious to how you think about this, it might be worth clarifying.

Thank you for highlighting this important research question about the role of tipping points/events in species adaptation. This is one of many critical questions regarding how adaptation shapes biodiversity and biogeography under global change. For instance, some studies suggest that rapid environmental changes impose strong selection pressures on organisms, potentially driving adaptation or extinction (e.g., Grant et al. 2017). However, due to the scarcity of data on tipping events and evolutionary responses, these dynamics remain challenging to study.

Our analysis represents a first step in exploring the potential implications of adaptation for marine biogeography under centennial-scale climate change. We hope this paper inspires future research to delve deeper into these complex and pressing issues.

To clarify this, we will add to the discussion in the revised manuscript: "*In addition, one of many critical questions regarding how adaptation shapes biodiversity and biogeography under global change is the role of extreme events and tipping points in species adaptation. However, these dynamics remain challenging to study due to the scarcity of data on tipping events and evolutionary responses (Grant et al. 2017). Our analysis represents a first step in exploring the potential implications of adaptation for marine biogeography under centennial-scale climate change. Our findings could inspire future research to delve deeper into these complex and pressing issues.*"

Line 25: Missing. Howard et al., 2019; Mongwe et al., 2024.

We thank the reviewer for pointing us to those two important references, which will be included in the revised text.

Line 50: This description is unclear and seems incomplete. Perhaps first define what AGI is or move this section to the methods where you can define things more clearly. At this stage, the text assumes the reader knows what AGI is, which is not a reasonable expectation. You only define AGI later in the text.

We will define AGI when the term is first mentioned in the manuscript.

"*The AGI indicates the potential habitat conditions that theoretically support the aerobic scope required for the growth of marine water-breathing ectotherms, represented by the ratio of pO_2 supply to metabolic demand.*"

Line 165: Here you say that relative AGI gives a "sense of the direction and magnitude of habitability." Maybe only the direction, but not the magnitude; it is not still clear to me that you can

quantify change without information on organisms' physiological constraints as stated above. Maybe you can, please clarify.

As explained in the response above, in the manuscript, we did calculate species-specific AGI. Critical partial oxygen threshold for each species was calculated from biogeographical data as described in Clarke et al. (2021).

Line 170: Once again, "AGI can be a poor indicator of which specific species thresholds are needed." How do you make this distinction when this information is needed or not to make a good prediction? When you don't include this information, how do you know the magnitudes of change are robust?

This sentence refers to the fact that the relative AGI does not account for species-specific thresholds. To avoid confusion, we will delete this sentence.

Line 219: This description is not clear; the text requires familiarity with Logan et al., 2014. I had to refer to Logan et al., 2014 to understand your point here. Perhaps rephrase and make it a bit clearer

We will clarify this in the manuscript by noting that the approach used by Logan et al. (2014) to represent adaptation is described in detail in the subsequent paragraph: "*We thereby follow the approach applied to corals by Logan et al. (2014), as outlined in the paragraphs below.*"

Reference:

Grant, P. R., Grant, B. R., Huey, R. B., Johnson, M. T. J., Knoll, A. H., and Schmitt, J. (2017). Evolution caused by extreme events. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1723), 20160146. https://doi.org/10.1098/rstb.2016.0146