Response to reviews on 'Impact of deoxygenation and warming on global marine species in the 21st century'

We thank the editor and both reviewers for their critical assessment of our work and their very helpful and constructive comments. We have addressed all comments and revised our manuscript accordingly. In the following, we address the editor and reviewer's comments point by point. Our response is given in italic text below and changes to the text in the manuscript are shown in blue.

Yours sincerely,

Anne Morée, on behalf of the co-authors

Associate Editor initial decision:

This manuscript fits within the scope of the journal and meets its basic scientific quality. I builds upon the previous work of the authors and other published work in this field of research.
While this approach is useful to assess the "potential" change in habitat space based on the change in temperature and oxygen relative to the metabolic demands of the animals, in reality habitat space is also defined by the food resources, predation pressure and the adaption of the animals to the higher temperatures and lower dissolved oxygen. The authors should acknowledge this in their Discussion section.

Thank you for noting this. We agree it is important to stress that there are many other factors of potential influence on species' habitats. The possibility of adaptation is mentioned in lines 420-421 and 427-428 but we now stress the 'potential' aspect by adding 'potential' to line 422: 'Further note that we considered potential loss of contemporary habitat only'. We decided to elaborate in lines 414-415 on other stressors to species' habitat space, which now reads: 'c) we do not include other potential stressors on species' habitats in our analysis such as acidification, changes in ecosystem structure, overfishing, marine phenology, disease pressure, food resources, predation pressure, pollution or eutrophication (e.g.; Poloczanska et al., 2016; Bindoff et al., 2019; Whalen et al., 2020).'.

Response to Comments by ‘Anonymous Referee #1’

General comments

I find this research using AGI to evaluate the effect of long-term warming and deoxygenation on contemporary habitat useful. It uses the AGI an index that represents the o2 supply to demand ratio for maintenance activity. It is handy as it requires few data somewhat easily accessible. The authors show how this index can be used to assess species vulnerability to environmental changes using only species-specific biogeographic data of 47 species. An interesting point, is that the authors show that tendencies and mean changes alone (warming, deoxygenation and mean changes in AGI) do not suffice to predict species vulnerability within their present habitat, but rather the quantity of habitat volume close to AGIcrit as show by the CDF of the AGIs. They also show the high inter-species variability in terms habitat preferences and critical thresholds greatly influence the changes in viable habitat. Indeed the mean changes do not reflect species-specific changes in habitat viability. It is also very interesting to present the results by degrees of global warming.

We thank the reviewer for the positive assessment of our manuscript.

A few improvements could be made to facilitate the reading of the results (see specific comments):

- More systematic presentation of the results

Please see our responses below

- Some methods of calculation are not given

Please see our responses below

- A bit more clarity is needed regarding the definition of some terms or choice of wording (e.g. habitat viability, potential habitat, AGIrel vs. ΔAGI…). I suggest they all be defined in the method section.

We define/clarify habitat viability, ΔAGI and AGIrel in Sect. 2.1 and check for their correct use throughout the manuscript. Regarding ‘potential habitat’ this was a writing error: Wherever the text read ‘large potential habitat loss’ it should have read ‘potential large habitat loss’ and we corrected this accordingly.

- Questions regarding the AGI need to be discussed.

See our responses below

Specific comments

In general, a more systematic presentation of results is need to ease the reading and further support the demonstration. In particular, a more systematic presentation of the figure (to facilitate the reading, so the reader doesn’t have to go back and forth in the main text. Also more consistency when choosing the warming level, scenario, etc. when presenting the figure in the main text. If you start presenting results for the levels of warming (Fig. 3 and 4), please do so for the rest of the manuscript. Even with figures in the supplemental.

With the current layout (global mean changes (Fig. 1 and Sect 3.1), local changes and drivers (Fig. 2 and Sect 3.2) to impacts (Fig. 3 and 4, Sect 3.3) and finally drivers of habitat loss (Fig. 5, Sect 3.4)), we aimed for a structured results section. We checked the manuscript for text with references to Figures much earlier in the text and reduced this such that back-and-forth reading is reduced (e.g., removed ‘Fig. 1a’ in line 288; removed ‘(black stars in Fig. 3)’ on line 330). All figures in the appendix are plotted for certain degrees of global warming, so we are unsure which figures the reviewer is referring to.

The only part of the text where SSP scenarios are described instead of global warming levels is at the end of Section 3.1. We do so to stress that the pathway (i.e., scenario) very much matters for the *maximum potential impact we quantify: In essence, we describe that the blue lines in Fig. 1 stop before the red lines. We think it is valuable for the reader to be aware of this but clarify by replacing line 180/181 with 'Even though our results in Fig. 1 are presented at warming levels, we here highlight that the scenario determines the maximum changes in temperature, pO_2 and AGIrel (Fig. C2):' (see also our response to your comment on Line 180-191).*

Abstract

Line 17-20: not clear, please rephrase.

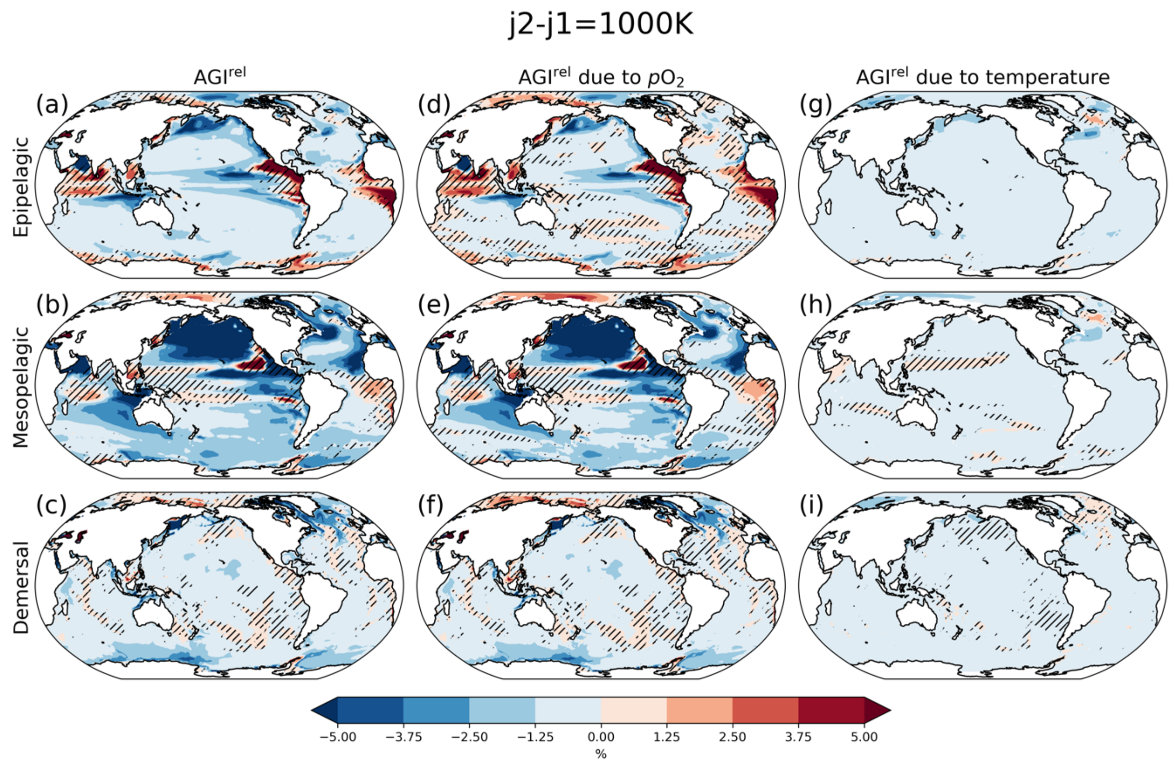
We rephrase these two sentences to 'We find that the in-habitat spatiotemporal variability of O_2 and temperature (and hence AGI) provides a quantifiable measure of a species' vulnerability to change. In the event of potential large habitat losses (over 5%), species vulnerability is the most important indicator. Vulnerability is therefore more critical than changes in habitat viability, temperature or pO_2 levels.'

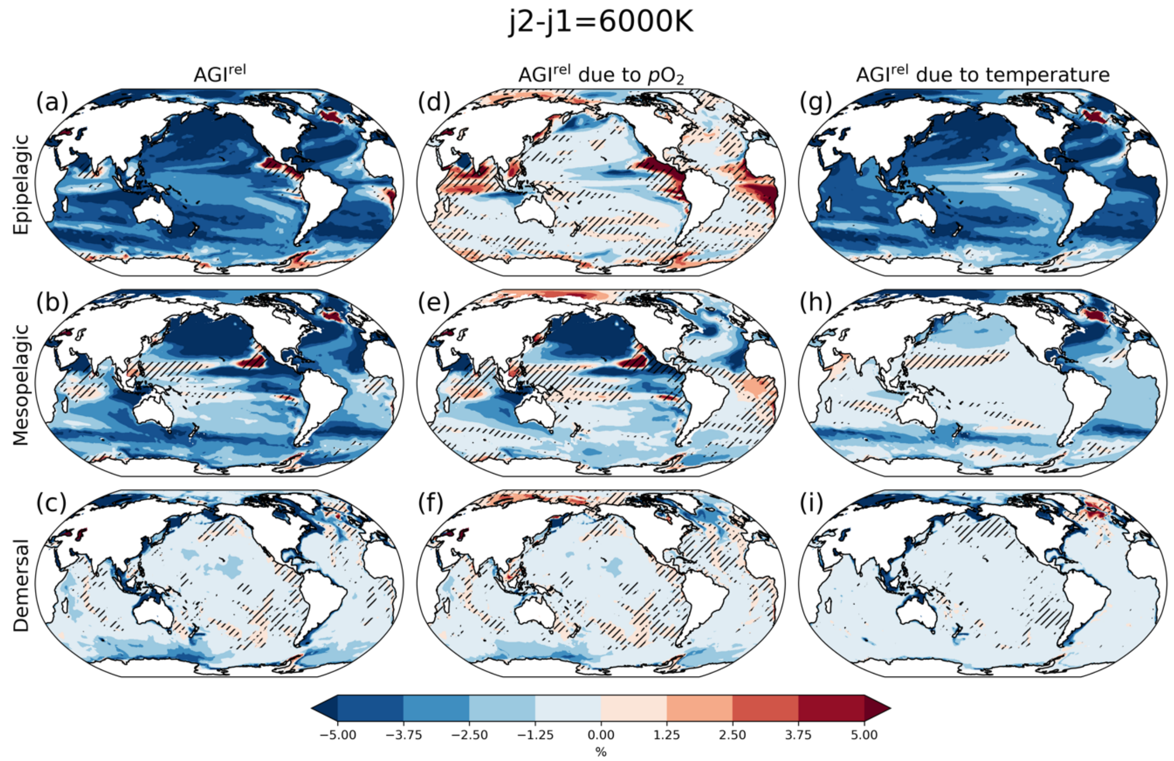
Methods and data

The choice of keeping a constant value for j1 and j2 across all species is indeed convenient and confers great value to the AGI and has been somewhat evaluated in the Clarke et al 2021 per comparison to the metabolic index. However, I still believe that sensitivity analysis to j1 and j2 would be useful to demonstrate the added power of the AGI since this index is quite sensitive to parameters j1 and j2. Given the formula and the scale to which it is applied, I imagine AGIrel at global scale will be only weakly affected by the choice of j1 and j2. But for species species-specific AGI, it is less certain, in particular for species from equatorial and tropical areas. In particular, it will affect AGIcrit and so the changes in volume of viable habitat (AGI>AGIcrit) and possibly the slope of the CDF used to assess species vulnerability to changes in AGI, as you demonstrate that changes in viable habitat are species-dependant. So sensitivity analysis of AGIrel and various AGI would be useful to demonstrate the degree of independence of the AGI to these parameters and would add great value to the results.

We evaluate the sensitivity of AGIrel to the constants j2 and j1 by varying both j2 and j1 ± 20% of their original values (i.e., j2=8000 ± 1600 K, j1=4500 ± 900 K). The j2-j1 difference is relevant for AGI and AGIrel (see equations 1 and 2) and is then at least 1000K (6400K-5400K) and at most 6000K (9600K-3600K). Note that the standard j2-j1 is 3500K (8000-4500K) and that j2-j1 is thus varied by +/- 71%.

We recreate Fig. 2 for a j2-j1=1000K and j2-j1=6000K:





These two figures show how j2-j1 modulates the importance of temperature changes on AGIrel (which also follows from Eq. 2). The sensitivity of AGIrel to j2-j1 is largest in regions where the temperature changes are largest, i.e., in the epipelagic. So, while the results in the figure panels d-f remain the same for any j2-j1 (see main text for values), epipelagic AGIrel changes and to some extent mesopelagic AGIrel changes (panels a and b) due to the contribution from temperature to AGIrel as governed by j2-j1:

	AGIrel	*AGIrel due to T*
j2-j1=1000: Epipelagic	*-0.84 +/- 5.08 %*	*-0.67 +/- 0.39 %*
j2-j1=1000: Mesopelagic	*-2.28 +/- 6.93 %*	*-0.26 +/- 0.34 %*
j2-j1=1000: Demersal	*-0.73 +/- 2.03 %*	*-0.11 +/- 0.28 %*
j2-j1=3500: Epipelagic	*-2.49 +/- 5.10 %*	*-2.32 +/- 1.36 %*
j2-j1=3500: Mesopelagic	*-3.41 +/- 6.97 %*	*-0.91 +/- 1.18 %*
j2-j1=3500: Demersal	*-1.00 +/- 2.22 %*	*-0.39 +/- 0.95 %*
j2-j1=6000: Epipelagic	*-4.10 +/- 5.28 %*	*-3.92 +/- 2.28 %*
j2-j1=6000: Mesopelagic	*-4.03 +/- 7.04 %*	*-1.54 +/- 1.99 %*
j2-j1=6000: Demersal	*-1.26 +/- 2.55 %*	*-0.07 +/- 1.60 %*

For the lower limit j2-j1 (1000K), global mean changes in the epipelagic are therefore 34% of the 'standard' (j2-j1=3500) while upper limit j2-j1 (6000K) leads to global mean changes 65% larger than in the standard case. In the mesopelagic the effects of changing j2-j1 are smaller due to the smaller changes in temperature, and the mean of the lower limit j2-j1 (1000K) is 67% of the standard case (j2-j1=3500K) while the upper limit is 18% larger. In the demersal realm the lower limit j2-j1 (1000K) is 73% of the standard case (j2-j1=3500K) while the upper limit is 26% larger. Note that the j2-j1 range of +/- 70% was used to explore the sensitivity of our results to changes in j2 and j1. Further work is needed to explore the uncertainty in j2 and j1.

We will summarize this analysis by adding a sentence to our Sect. 2.1 'Eqs. 1 and 2 show that j2-j1 (8000-4500=3500K) modulates the influence of the temperature effect on AGI.' and to our discussion in Sect 3.2: 'Besides considering this model uncertainty, we performed a sensitivity analysis of AGIrel to the choice of generalized temperature dependence parameters (i.e., j2-j1). If j2-j1 is adjusted to represent low temperature sensitivity of 1000K, global mean AGIrel is 34% of the standard case j2-j1=3500K in the epipelagic, 67% in the mesopelagic and 73% in the demersal realm. On the other hand, for high temperature sensitivity (j2-j1=6000K), global mean AGIrel is 165% of the standard case j2-j1=3500K in the epipelagic, 118% in the mesopelagic and 126% in the demersal realm. Projections for epipelagic species are therefore most sensitive to the choice of j2-j1, as temperature changes are largest there. Further work is needed to explore the uncertainty in j2 and j1.'

Regarding species-specific impacts of j2-j1, we agree with the reviewer that changing j2-j1 will change AGI and therefore AGIcrit as well as the PDF and the slope of the CDF (i.e., for every new set of j2-j1 we need to redo the analysis). We now present a sensitivity analysis for the species Gadus morhua and Thunnus Atlanticus (new Fig. C7), as most of the projected habitat loss of these species is caused by warming (Fig. 3) and therefore changes in j2-j1 may influence the potential habitat loss. We discuss the result by adding the following to Sect. 3.3 'Moreover, a sensitivity analysis for species Thunnus atlanticus and Gadus morhua shows that our median result is robust to the choice of the generalized temperature dependence parameters j2-j1 (we explored j2-j1 ± 71%; Fig. C7).'

As the AGI is comparable the metabolic index and given that it has recently been shown that it cannot be applied to certain species such as D. gigas or other species performing vertical migrations (Seibel & Birk, 2022), I wonder if the same limitations may apply to the AGI? which case this type of species should be excluded from the study. Also it may need to be discussed in the manuscript.

We have two vertical migrators in our study: Dosidicus gigas and Aphanopus carbo. A low pO2 sensitivity, which could provide a representation of the different aerobic scopes of vertical *migrators, is found for Dosidicus gigas (36 mbar), but not for Aphanopus carbo. Furthermore, the generalized temperature dependence of AGI may inaccurately cause loss of contemporary habitat due to warming for vertical migrators, while Seibel and Birk (2022) show that distribution ranges are limited at the cold boundary for these species. Because of ongoing discussion on the fate of these species and limited studies available, we decided to keep the species in our study but include a critical discussion on their results (following the suggestion by the other reviewer): 'Our results for the mesopelagic include two vertical migrators (Dosidicus gigas and Aphanopus carbo). As opposed to most other species, the distribution range of vertical migrators is limited at the cold boundary of the distribution because of their low aerobic scope in cold waters (Seibel and Birk, 2022). Therefore, the temperature sensitivity of these species is likely not captured by the generalized temperature dependence in AGI, and contemporary habitat loss due to warming and deoxygenation as estimated for Aphanopus carbo is likely overestimated. We nevertheless project negligible loss of contemporary habitat for Dosidicus gigas (Fig. 3) due to its low vulnerability and low pO2threshold, which is in good agreement with the findings of Seibel and Birk (2022) despite the generalized temperature dependence of AGI.'*

Line 139: which data? O2, T, salinity?

We replaced 'all' with 'these environmental data' such that it is clear that all environmental data we need are those described in the previous sentence.

Line 156: please detail a bit more. You mean global mean SST reached by 2100?

We present our results at different global warming levels, that is global mean air temperatures at 2m. To clarify this, we include a definition as follows: 'All results are presented at global warming levels (i.e., global mean air temperature at 2 m; e.g., Hausfather et al., 2022).'

Results

Line 174 : «habitat viability» suggests you refer to where AGI>AGIcrit, but you refer to AGIrel. It can be confusing. AGIrel would indicate «potential viable habitat»? Also, « AGIrel reduction » is incorrect. AGI is either negative or positive reflecting a decrease or increase in AGI between t0 and t1. Please rephrase.

AGI>AGIcrit can only be assessed for a specific species and, indeed, we here just discuss relative changes in AGI which are species independent. We rephrase lines 172-176 to clarify that AGIrel is negative when AGI at t=t1 is lower than contemporary AGI (t=0, i.e., the 1995-2014 mean): 'The warming (Fig. 1a) and deoxygenation (Fig. 1b) reduce AGI relative to its contemporary state (i.e., a negative AGIrel), which we interpret as a loss of habitat viability (Sect. 2.1; Fig. 1c) that is independent of species (Eq. 2). In the epipelagic, AGI decreases 2.17±0.69 % per degree of global warming (Fig. 1c), while AGI decreases 2.33±1.64 % per degree of global warming in the mesopelagic/bathypelagic realm. Last, demersal decrease in AGI is 0.86±0.48 % per degree of global warming, making it the least pronounced of the three studied depth intervals.' We also understand that AGIrel reduction can be confusing and corrected this throughout the manuscript by replacing AGIrel with AGI where necessary.

Line 180-191: A figure to show this would be better.

The values provided here are all shown in Fig. 1: The text aims to emphasize the fact that the maximum ssp1-2.6 scenario changes (the blue lines) are much smaller than the changes in the ssp5-8.5 scenario (the red lines). We made a new appendix Figure C2 where we plot against time, referring to it in the new sentence at line 180: 'Even though our results in Fig. 1 are presented at warming levels, we here highlight that the scenario determines the maximum changes in temperature, pO2 and AGIrel (Fig. C2):'.

Line 201: «A relative reduction in habitat viability […] we expect a reduction in habitat viability ». Please rephrase. See comment above (line 174) relative to «habitat viability ».

We rephrased this throughout the manuscript as described above. We also clarified the definition of habitat viability and relative changes in habitat viability at the end of Sect. 2.1: 'Where ΔAGI is AGI(t1)-AGI(t0). Relative changes are thus entirely species-independent (in contrast to the metabolic index of Deutsch et al., 2015) and are interpreted as relative changes in habitat viability. We maintain a reference period 1995-2014 throughout this study (i.e., AGI(t0) is the mean AGI over the years 1995-2014).'

Line 207: Please detail somewhere how the contribution of po2 and T to AGI and AGIrel is calculated.

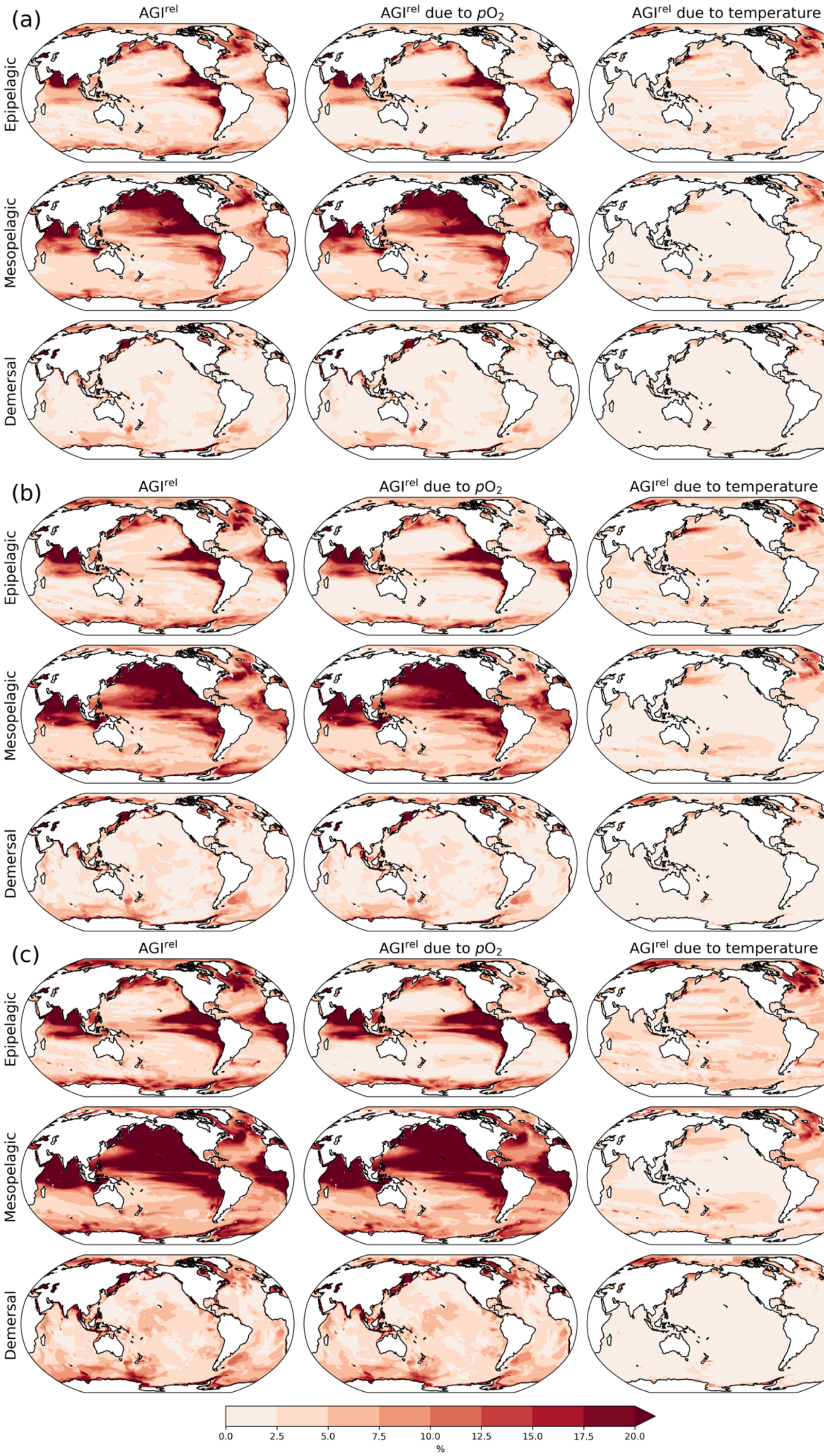
This is explained in the caption of Fig. 2. We made this more prominent by moving it to the main text at end of Sect. 2.1: 'Contributions from pO2 (temperature) to AGIrel are calculated by keeping temperature (pO2) constant at its 1995-2014 mean state when calculating AGIrel.'),and repeating it in the caption of Fig. 1. See also our response to the next comment.

Line 209 – 216: Not clear what the difference is between the calculation method of the contribution of po2 and T is between line 208-210 and 212-216. For instance, «the AGIrel due to T is -xx % for the epipelagic» (line 209) and « an average 87 % of AGIrel is driven by… warming » (line 212). What is the difference be the two? please detail calculation.

Lines 209-211 quantify Fig. 2 while lines 212-214 are based on the black line versus multi-model mean fits in Fig. 1. As these are slightly different approaches, we understand this is confusing. We updated the values in lines 212-214 to match the values in lines 209-211.
The contribution from pO2 is calculated by keeping temperature at its 1995-2014 and recalculating AGIrel (and vice versa) as described in the caption of Fig. 2. We explain this calculation now in the main text as well as repeating it in the captions of Fig. 1 and 2 (see response to previous comment).

Figure 2: please provide the same map as Fig. 2 (and C2) for 1.5 °C and 3°C to be consistent with the remainder of the paper.

We added the 1.5ºC and 3ºC versions of Fig. 2 to the appendix as new Figs. C3 and C4 and refer to these in the first sentence of Sect. 3.2 'A relative reduction in habitat viability (i.e., a negative AGIrel; Fig. 1c) is projected to occur almost everywhere at 2 ºC of global warming (Fig. 2a-c; see Fig. C3 and C4 for 1.5 and 3 ºC of global warming, respectively)'. For Original Fig C2 (the original Fig. 2 model range), we notice differences are very small between warming levels (see figure on next page). Therefore, we provide still only the 2ºC warming level in Fig. C2 (which is newly numbered C5).



As original figure C2 but for (a) 1.5, (b) 2, and (c) 3 degC warming.

Fig C3 caption: « AGIcrit as the minimum in-habitat AGI value, the 5th percentile, the 10th percentile, the 15th percentile and the 20th percentile ». Word missing?

We rephrase as 'AGIcrit is taken as the minimum in-habitat AGI value, the 5th percentile, the 10th percentile, the 15th percentile and the 20th percentile, respectively.'

Line 242-246: in the text, changes in viable habitat are expressed in terms of habitat loss, but in the referenced figure (Fig. 3) changes in viable habitat are expressed in terms of remaining habitat. Please be consistent.

Thank you for noting that. We have replaced original Figs. 3, C3 and C7 to have habitat change on the y-axis (with habitat loss being negative).

Line 256: please define "absolute loss".

We add a definition here: 'loss expressed in volumetric terms instead of a percentage'

Figure 3: not clear how the different models/scenarios are represented or used for the calculation of changes in viability.

*In the caption we state 'For 1.5°C global warming both the SSP1-2.6 and SSP5-8.5 scenarios are included (number of datapoints n=2 scenarios * 6 models = 12 for each boxplot), while at higher levels of global warming we use SSP5-8.5 as not all models reach these warming levels under the SSP1-2.6 scenario (n=6 models).' Such statements are made in every figure caption where this is relevant. To clarify this approach, we added a sentence at the end of Section 2.3 where we explain how we handle the presentation of our results for warming levels: 'For warming levels above 1.5ºC, we only use the results for SSP5-8.5 as not all models reach warming of more than 1.5ºC in SSP1-2.6.'*

Fig. 5: for which degree of warming? Scenario? Period of AGI? Please precise in the figure caption. Also C4 is presented for a 3°C global warming. For the purpose of the demonstration, I understand that the chosen level is not determining, but consistency between figs within the same result section would be better to support the demonstration. Also distribution of AGI +/.

Fig. 5 is a schematic/conceptual figure, therefore only the 1995-2014 contemporary state is 'real' and representative of the chosen species. ΔAGI is chosen at 0.1 just for illustrative purposes and does not represent a specific warming level, period or scenario (as a specific choice there would create a different ΔAGI for each species, preventing us from illustrating that for the same ΔAGI a different Δvolume is realized). We extended the caption of Fig. 5 to clarify: 'Conceptual figure based on Thunnus atlanticus (a,c) and Thunnus obesus (b,d) showing the difference in impact (change in volume ΔV) of an example mean AGI reduction of 0.1 (i.e., habitat-mean ΔAGI=0.1) below the 1995-2014 contemporary mean (black lines). This difference is shown to be related to the shape of the PDF and the slope of the CDF at 0.1 (i.e., at AGIcrit), which we refer to as the species' "vulnerability".'. In contrast to Fig. 5, the original Fig. C4 contains actual results and we chose to show the most extreme warming level studied here (i.e., 3degC) alongside the contemporary state (the black lines). We propose to clarify this choice in the first sentence of Section 3.4: 'The differences in habitat loss between species as shown in Figs. 3 or 4 are better understood from the probability density of contemporary (1995-2014) in-habitat AGI for each species (conceptual Fig. 5 and species results in Fig. C8).'

Line 316: "The correspondent linear equation taken across all depth realms is $volume\ loss$ (%) = 7.31 ∗ vulnerability − 0.10." not useful.

We realize this linear fit depends on the warming level chosen and therefore remove this sentence.

Line 322: ΔAGI is AGI(t1) – AGI(t0)? please define.

We now define ΔAGI in the methods section with Eq. 2: 'Where ΔAGI is AGI(t1)-AGI(t0).'

Fig 6: please provide same for 1.5 and 3 °C. Also, why only SSP5-8.5?

We clarified our use of SSP5-8.5 as described in our response to the comment on Fig. 3. Similar figures for 1.5 and 3degC warming are added to the appendix and we add the text 'This result holds across different levels of global warming: At 1.5°C of global warming, 85% of the variance in volume loss can be explained by vulnerability, and at 3°C of global warming this is 88% (see Figs. C10 and C11).' As the highlighted species are based on fixed thresholds, we clarify that this discussion is just for the results of 2degC warming: 'We highlight three groups of species for further discussion of the results at 2°C of global warming' and keep the scatter plot black in the new appendix figures.

Line 336-337: any hypothesis regarding those two species?

We explain in some more detail by adding the sentence: 'These two species are both demersal-dwelling and are very pO_2 tolerant (i.e., low pO_2threshold; Table A1) and have a wide range of different AGI values in their habitat, with a relatively large volume of high-AGI values causing the right skew (Fig. C8) and resilience (Fig. C12).'

Technical comments

Line 43: ref Bopp et al. 2013 is about CMIP5

We moved the IPCC (2019) and Bopp et al. (2013) to the more general statement two sentences before: 'This negative trend is projected to continue during the 21st century for all climate scenarios (Bopp et al., 2013; IPCC, 2019; Kwiatkowski et al., 2020).'

Line 139: please specify «all data»

We replaced 'all' with 'these environmental data' here such that it is clear that all environmental data we need are these described in the previous sentence.

Line 201: «reduction in AGIrel», see comment above.

We rephrased this throughout the manuscript as described above.

Line 204: «AGIrel reduction» see comment above.

We rephrase this throughout the manuscript as described above.

Line 229: «decrease in AGIrel», see comment above. See also line 231, 239

We rephrase this throughout the manuscript as described above.

Line 240: habitat volume is where AGI>AGIcrit? Please precise.

We clarified this by elaborating on the definition of loss of contemporary habitat volume 'loss of contemporary habitat volume (i.e., newly exposed volume with AGI<AGIcrit) […]'

Line 291-296: Please precise which period of the AGI is used for the PDF.

We extended both the caption of Fig. 5 which now reads 'Conceptual figure based on Thunnus atlanticus (a,c) and Thunnus obesus (b,d) showing the difference in impact (change in volume ΔV) of an example mean AGI reduction of 0.1 (i.e., habitat-mean ΔAGI=0.1) below the 1995-2014 contemporary mean (black lines). This difference is shown to be related to the shape of the PDF and the slope of the CDF at 0.1 (i.e., at AGIcrit), which we refer to as the species' "vulnerability".' as well as the first sentence of this section which now reads 'The differences in habitat loss between species as shown in Figs. 3 or 4 are better understood from the probability density of contemporary (1995-2014) in-habitat AGI for each species (conceptual Fig. 5 and species results in Fig. C8).' to clarify how we calculated the vulnerability.

Line 302: Only → only

Done

Line 303: In → An

Done

Line 306: indicates → remove s

Done

Response to Comments by 'Anonymous Referee #2'

The manuscript «Impact of deoxygenation and warming on global marine species in the 21st century» assesses the potential effects of changes in ocean temperature and pO2 on the viability of current marine habitats. The computation of a metabolic index (the AGI), which depends on temperature, oxygen and few easily-accessible species-specific parameters, allows the authors to explore the species' (47 selected species) vulnerability to environmental changes during the current century. Environmental data rely on six ESM. The authors first discuss the projected global and regional changes on ocean temperature, pO2, and AGI by degrees of global warming. Then, they present the loss/gain of viable habitat volume with respect to current habitats as future AGI index falls below a critical value considered to be a threshold for holding aerobic activity. Moreover, authors assess the "vulnerability" of a species by computing the probability density function of AGI computations for each species, and evaluate the volume of viable habitat loss with respect to reductions in AGI. Authors discuss the novelties (including vertical and seasonal variability, species representativeness,..) and limitations (temporal resolution, deoxygenation underestimation, adaptation capability of species,...) of their approach. They finally highlight the key points of the study.

As I understand from the manuscript, three-dimensional monthly data (temperature, oxygen content, and salinity) from six ESM simulations (bias and drift corrected) following historical and two (low and high) emission scenarios were used to determine the habitat viability of 47 different marine species. Species were selected in order to be representative for different climatic zones, sizes and vertical levels. Viability was analyzed by using the AGI index, which depends on temperature and pO2along with two species-specific parameters (they can be determined by using the species distribution data), and which gives information on the aerobic state of an ecosystems and, hence, of the species. Global and regional variation of temperature, pO2 and AGI, as well as the relative contribution of each of AGI drivers (i.e., AGI due to pO2, and AGI due to temperature) were evaluated. Then, the relative change of AGI with respect to current situation was assessed giving information of the habitability loss/gain for each species. From the probability density distribution of each species' AGI, a "vulnerability" of each individual species was computed. This exercise highlighted that the vulnerability of a species not only depends on the volume loss (volume below a critical value of AGI) but also on the habitat volume in sub-critical values of AGI. According to the loss in habitable volume and the vulnerability, species were classified in three groups; highly affected, resilient, and vulnerable species. From these results, authors discussed the limitations of the study and highlighted the main messages.

The study is scientifically relevant and worth publishing as it introduces the potential utility of a metabolic state index like AGI to evaluate how species will be affected by changes in their environment. I only have some comments which, I hope, are useful to improve the manuscript.

We thank the reviewer for the positive assessment of our manuscript.

I have some doubts understanding the vertical distribution of the layers considered. As I understand, horizontal distributional data is extended in the vertical over the depth range of species distribution. However, this is not exactly the case as some species crosses the limits of epipelagic and mesopelagic layers as they are defined in the text. This is especially true for some mesopelagic species that live in the deepest limit of the layer to below, while others are considered in the same layer but lives closer to epipelagic waters. I think a detailed analysis (maybe out of the intention of this study) should include the "real" depth range for each species as informed in their distributional data.

We agree that including the 'real depth range' would be desirable, however this is not possible due to data sparsity: We have this described in original lines 383-387: "Our assumption to extend the 2D distributions provided by Close et al. (2006) over the entire depth range of each species' depth realm is driven by data sparsity and reliability of 3D species distributions for our selection of species. When reliable 3D habitats can be constructed from species' observations these could be included (e.g., distribution data are continuously collected in the Ocean Biodiversity Information System but currently are too sparse to provide 3D distribution data) "

We extended our current discussion (near original lines 383-387) on the impact of our assumption to vertically extend the 2D habitats over a 'grouped' depth range: 'Some species may be limited to only part of their assigned depth range or live partly (and possibly temporarily) above or below it. Nevertheless, we expect that the assigned depth range generally provides a good estimate of in-habitat pO2 and temperature variability, which affects pO2threshold, Tpref and therefore AGI and AGIcrit.'

Moreover, as has been recently pointed out (Seibel & Birk, 2022), organisms carried out vertical migration have specific metabolic constraints that make them difficult to assess using current metabolic indexes. Do the authors think this might be plausible as well for AGI? How this affects results? I think these issues should be commented in the text.

Thank you for pointing this out. We extended our discussion with the following text to address our study's potential limitation: 'Our results for the mesopelagic include two vertical migrators (Dosidicus gigas and Aphanopus carbo). As opposed to most other species, the distribution range of vertical migrators is limited at the cold boundary of the distribution because of their low aerobic scope in cold waters (Seibel and Birk, 2022). Therefore, the temperature sensitivity of these species is likely not captured by the generalized temperature dependence in AGI, and contemporary habitat loss due to warming and deoxygenation as estimated for Aphanopus carbo is likely overestimated. We nevertheless project negligible loss of contemporary habitat for Dosidicus gigas (Fig. 3) thanks to its low vulnerability and low pO2threshold, which is in better agreement with the findings of Seibel and Birk (2022) despite the generalized temperature dependence of AGI.'

In my opinion, some lines should be added to the discussion section to proper discuss the implications of the results. What differences were found between scenarios? How this new method can be help in managing fisheries for example in the future? Although I recognize this can be out of the scope of the paper, I think the manuscript would benefit from a short discussion on these issues.

We include a discussion on the implications of our work in the revised version of our manuscript by extending the last paragraph of our discussion which now reads as follows: 'For most species we find a loss of habitat volume of less than 10%. It is found for example by Gotelli et al. (2021) that only a small percentage of species drives the observed changes in marine species assemblages, showing that even when only a few species experience large losses, impacts can be profound for the ecosystem. For the individual species however, the loss of only a small fraction of their contemporary habitat likely provides adaptation opportunities. Our results imply that species that are deemed vulnerable due to their limited range of in-habitat pO2 and temperature are likely to be the most impacted by global warming (i.e., 'vulnerable species' in Fig. 6 and species with steep CDF slopes in Fig. C9). Our study can therefore inform e.g., fisheries management by identifying species particularly vulnerable to ocean warming and deoxygenation. Such identification provides species-specific information complementing earlier studies that found reduced impact on fisheries at lower levels of global warming (Cheung et al., 2016). Indeed, for every tenth of a degree of additional global warming, our study shows increased marine deoxygenation and warming as well as increased loss of contemporary habitat across all species albeit with a strongly species-specific magnitude.

These results confirm the need to limit global warming levels to the minimum to prevent loss of contemporary habitat and support the identification of the species that would be most vulnerable to marine deoxygenation and warming.'

Regarding the conclusions of the paper, I think the authors could make a more narrative presentation of the key messages.

Thank you for your suggestion. We prefer a list of conclusions and keep the text as is

Finally, I found some sections hard to understand, especially, section 3.4. which in fact I consider it is the 'key' of the manuscript. I feel that some more information is needed, maybe in a supplementary methodology section, to better explain the computation of vulnerability.

We extended the methodology paragraphs (~first half of Sect. 3.4) to better explain the computation of vulnerability and make it clearer that Fig. 5 is a schematic/conceptual figure. We refer to this in the main text as it indeed is a key part of our result. Our new text reads: 'The differences in habitat loss between species as shown in Figs. 3 or 4 are better understood from the probability density of contemporary (1995-2014) in-habitat AGI for each species (conceptual Fig. 5 and species results in Fig. C8). The spatial variability of the contemporary pO2 and temperature in each species' habitat results in a species-specific probability density function (PDF) for AGI (black lines in Fig. 5a,b). Depending on this shape, a given reduction in AGI (ΔAGI) exposes a relatively large or small part of the species' habitat to subcritical AGI values (red lines and stippling in Fig. 5a,b), thereby causing volume loss. We can quantify the "vulnerability" of a species to changes in AGI by calculating the cumulative sum of the PDFs (i.e., the cumulative density function, CDF, conceptual Figs. 5c,d and species-specific results in C9). The slope of the CDF at a cumulative density of 0.1 (i.e., 10% of the volume where AGIcrit is defined) indicates the potential loss in habitat for a certain change in AGI (Fig. 5 and C9). If the slope of the CDF is steep at the critical threshold, the species is relatively vulnerable to warming and deoxygenation: only a small reduction in habitat viability (i.e., AGI) will push a relatively large volume below the critical threshold. An example is given in Fig. 5, where for an identical change in mean in-habitat AGI of 0.1 just 1% of the volume is pushed below AGIcrit for a species with a small slope of 0.14 (Fig. 5b,d, 'Thunnus obesus' schematic), while the same change in AGI results in 9% volume loss for a species with a large slope of 1.67 (Fig. a,c, 'Thunnus atlanticus' schematic). Changes in the slope of some species' CDFs indicate that different vulnerabilities exist for different parts of that species' habitat (Fig. C9). Hence, in habitat areas that are represented by a part of the CDF with a relatively steep slope, a relatively small change in AGI is needed to bring a relatively large volume closer to AGIcrit. Nevertheless, only the CDF slope at AGIcrit relates directly to viable habitat volume loss as only AGI values below AGIcrit are considered to have an impact on habitat volume.'

Specific comments about the text and figures:

Line 9: I would change to: "...the observed and projected warming and deoxygenation of the world's ocean in the 21st century may strongly affect marine species' habitats.".

Done

Line 11: Change "We" to "in a particular location, to assess…".

We prefer to keep this split as otherwise the sentence is 4 lines long.

Lines 19 – 20: I find this can be rephrased.

We rephrased this sentence in the revised version of the manuscript: 'In the event of potential large habitat losses (over 5%), species vulnerability is the most important indicator. Vulnerability is more critical than changes in habitat viability, temperature or pO2 levels.'

Line 21: I think this “is” should be after “epipelagic species”.

Done

Line 43: Bopp et al., 2013 is about CMIP5, not SSP5-8.5 scenario.

We moved the IPCC (2019) and Bopp et al. (2013) to the more general statement two sentences before: ‘This negative trend is projected to continue during the 21st century for all climate scenarios (Bopp et al., 2013; IPCC, 2019; Kwiatkowski et al., 2020).’

Line 46: I think this is not about “impacts” but just trends. In addition, I would split here the paragraph, and start a new one with temperature.

We replaced by ‘.., indicating the possibility of even stronger trends of deoxygenation toward the future’. And started a new paragraph with temperature.

Line 72: “to a species,”.

We added ‘to’ as suggested.

Line 105: I think considering the nomenclature of mesopelagic and bathypelagic is problematic. As only 200 to 1000 m is considered, I would say mesopelagic layer. Bathypelagic is usually considered for depths ranging 1000 m to below.

Thank you for noting this. We have removed the wording ‘bathypelagic’ from the text and figures as only the depth range 200-1000m was analysed.

Line 132: It is in fact the 200 to 1000 m depth range representative of the species considered? Daily migration can have some effects?

The entire 200-1000 meter depth range is considered for mesopelagic species, considering bathymetry as well as the 2D habitat (Fig. C1). We decided to do the grouping of species into depth groups due to lack of observational data on 3D habitats (let alone how these change within or between days). Daily migration and even seasonal migration within this space (in both the vertical and horizontal, or only part of this space) may indeed occur for some species, however we still expect the entire volume to represent the O2 and temperature variability that is needed to calculate o2threshold and Tpref. We explore the effects of different AGIcrit (which would be found for different o2thresh and Tpref estimates) in original Fig. C3. We extended the discussion by adjusting line 385 to: ‘When reliable 3D habitats, or even time-varying habitats, can be constructed from species’ observations these could be included (e.g., distribution data are continuously collected in the Ocean Biodiversity Information System but currently are too sparse to provide 3D distribution data).’

Line 160: In figure 1 it is indicated a 20-year running.

Thank you for noting this. This should have been removed from an earlier version of the manuscript, we plot the actual data here in light blue/red and take the model mean (no running mean) in opaque blue and red. Only the denoted years are based on 20-year model-mean data. Therefore, the caption now reads: ‘The multi-model mean is given in opaque blue (SSP1-2.6) and red (SSP5-8.5) and has for several decades the corresponding 20-year multi-model mean year labelled.’

Line 203: “is generally larger in”.

Done

Line 211: I would remove “Globally”, it seems redundant here.

Removed

Line 223: “uncertain” refers to multimodel uncertainty?

Yes: we replace ‘is uncertain’ with ‘has large model uncertainty’.

Line 223: I don't understand what regions are referred to with "eastern-boundary equatorial upwelling regions".

We removed the word equatorial, thank you for noting this.

Line 229: "to some small parts".

Done.

Line 240: I would substitute or remove "local extinction". Organisms may also move or adapt to new conditions.

We removed this as suggested.

Lines 256 to 264: This is somehow expected; big losses in large-distributed species would account for small relative losses.

We agree: We do want to highlight this as the relatively minor relative losses should not be disregarded as necessarily unimpactful. We keep the text as it is.

Line 286: What "realized loss" is referred to?

We meant to refer to the loss at a certain degree of global warming but now removed the word 'realized' in order to make this more general.

Line 304: I think some concepts here should be better explained/introduced, like ΔAGI.

We propose to define ΔAGI already in Sect. 2.1 after defining AGIrel in Eq. 2: 'Where ΔAGI is AGI(t1)-AGI(t0).', as well as clarifying ΔAGI in the caption of Fig. 5 which now reads: 'Conceptual figure based on Thunnus atlanticus (a,c) and Thunnus obesus (b,d) showing the difference in impact (change in volume ΔV) of an example mean AGI reduction of 0.1 (i.e., habitat-mean ΔAGI=0.1) below the 1995-2014 contemporary mean (black lines). This difference is shown to be related to the shape of the PDF and the slope of the CDF at 0.1 (i.e., at AGIcrit), which we refer to as the species' "vulnerability".'.

Line 316: This is an important point of the study that can be put upfront in the discussion/conclusions.

We find that this linear equation is naturally dependent on the warming level chosen for the figure (2°C) and should therefore not be overinterpreted. In order to prevent this, we remove the equation from the text and add the same figure but then for 1.5 and 3°C warming in the appendix (also following the feedback from the other reviewer, see our response to their comments on Fig. 6).

Line 350: It might be good to include a discussion on the implications of the results that complement the discussion of the limitations of the work.

We include a discussion on the implications of our work in the revised version of our manuscript by extending the original last paragraph of the discussion (see our response above to your similar comment).

Figure 1:

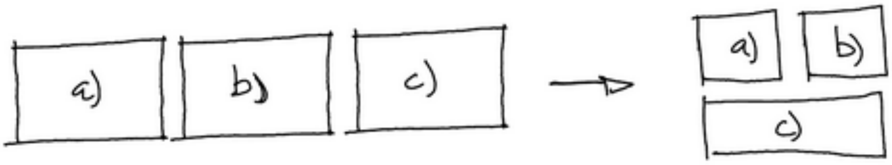
- I think "transparent blue and red" may be changed to "light blue and red".

Done

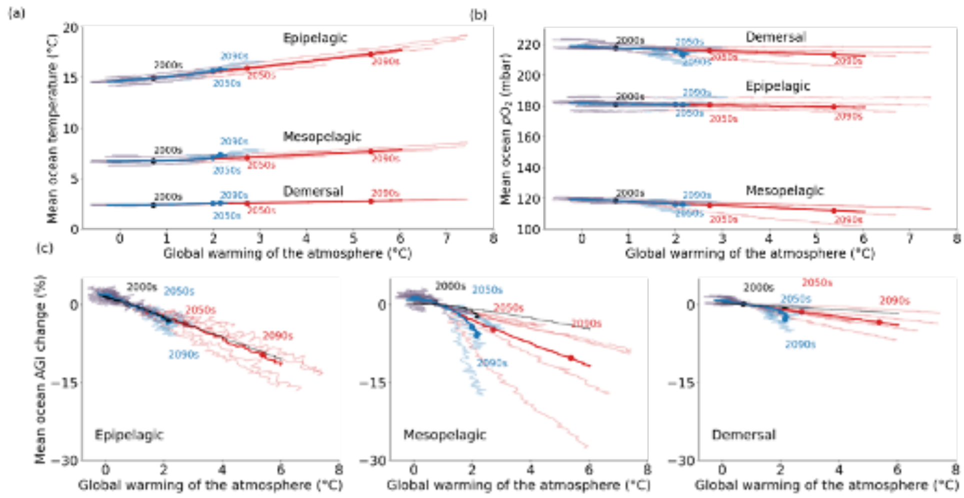
- Indicate that AGI is given in percentage in the first time it is called within the caption.

We updated the caption to include the units of temperature, pO2 and AGIrel in its first sentence: 'Global mean changes in ocean in-situ temperature in ºC (a), pO2 in mbar (b) and AGIrel in % (c) for different global warming levels, where global warming is calculated as global surface air *temperature increase relative to the 1850-1900 mean.'. and remove the percentage '(%)' later in the caption.*

- Though I like the idea of presenting results relative to global warming, I think it is somewhat more difficult to read because of the length of y-axis. I suggest to increase the readability of the figure to change the order to two lines; in the top line, panels a) and b) are displayed, and in a second line below that, panel c) is displayed. Something like (sorry for the bad picture…).



We thank you for this suggestion. We tried the new layout but found it too busy and repetitive as compared to the original:



Instead, we hope to have addressed your concern regarding the y-axis by making the original figure taller.

Very minor, but color of Fig. C1 is blue but it is indicated in the figure caption to be dark grey.

We corrected 'dark grey' to 'blue' in the caption of Fig. C1.