Response to reviewer's comments (RC2)
Spatiotemporal heterogeneity in the increase of ocean acidity extremes in the Northeast Pacific

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General remarks

First and foremost, we thank the editor and this reviewer for their very supportive and insightful comments on our manuscript. We appreciate the valuable remarks that helped us to significantly improve the quality and clarity of this manuscript.

Many of the reviewer's comments were associated with the comprehensibility of the manuscript regarding the definition of key properties and the matching of numbers between figures and text. In the revised manuscript, we modified some figures and improved the clarity of the text based on the reviewer's comments. Furthermore, we considerably shortened the abstract to focus on the core research messages of the manuscript.

Herein, we provide a summary of each of the reviewer's comments (RC2) in black, followed by our point by point replies in blue and the text added or changed in the revised manuscript in red.

Specific replies

Reply to Reviewer's comments (RC2):

Overview

The manuscript titled "Spatiotemporal heterogeneity in the increase of ocean acidity extremes in the Northeast Pacific" undertook an assessment and quantification of ocean acidity extreme events (OAXs) in the Northeast Pacific region. This was accomplished using a high-resolution regional Earth System Model (ROMS-BEC) building upon prior research (Desmet et al. 2022). The authors comprehensively examined various properties of OAXs in the Northeast Pacific Ocean including their intensity, frequency, duration, and heterogeneities in time and space. By employing the return periods and time of emergence (ToE) framework, they substantially captured in the occurrences of OAXs in depths over the recent 30 years.

The paper is logically organized, and the figure are well-presented. The investigation into OAXs in the Northeast Pacific is particularly interesting and holds substantial value due to utilization of a high-resolution model validated against observations.

Authors: We thank the reviewer for the supportive comments.

Nonetheless, there remain certain questions and comments that require clarification prior to proceeding further consideration of publication.

Authors: Hereinafter we reply to the questions and comments, and show associated changes in the revised manuscript.

Major comments

1) The authors underscored the significance of mesoscale eddies in shaping the spatial heterogeneities of OAXs throughout the manuscript. This phenomenon was enabled by the employment of the high-resolution model (ROMS-BEC model), which resolves the mesoscale eddies and associated processes. Would the distinctive pattern of maximum intensity persist under coarser resolutions? To elucidate the reason for the spatial heterogeneities, I propose conducting the additional simulations using the same model with a coarse resolution. While a comparison with Burger's findings in Earth system model has been made, the models are different, and this evidence is indirect. By comparing outcomes from the coarse resolution experiment using the same simulation parameters, you could substantially bolster the argument for the role of mesoscale eddies in driving OAXs.

Authors: We thank the reviewer for this interesting suggestion. We agree that the resolution difference between the coarse-resolution Earth system model used in Burger et al. [2020] and our high-resolution model makes a direct comparison difficult. However, this issue cannot be overcome by running our model at lower resolution, since we are using a relative threshold to define OAX. As a result, very different OAXs are identified depending on the resolution. This is because the use of a coarse resolution model will result in a narrowing of the distribution of [H$^+$] values at a given location compared to a high-resolution modeling experiment (as illustrated in Figure 1), in particular in regions where mesoscale processes largely affect the distribution. If the relative threshold from the high resolution experiment is kept to detect OAX in both experiments, only very few events to no event will be detected in the coarser resolution experiment. If the relative thresholds are adjusted based on simulated distributions, then the identified OAXs will be very resolution dependent. This prevents a quantitative and meaningful comparison of events across simulated scales.

When it comes to studying extreme events, we believe that it is paramount to simulate the variability in a manner that is as close as possible to reality, and this is much better achieved with a high-resolution than a low-resolution model.

Furthermore, the high-resolution modeling experiment, by resolving both mesoscale and larger scale processes, allows for differentiating the role of each, which would not be the case if we were to do a coarser resolution experiment. Thus, we consider our conclusion about the importance of mesoscale processes for generating extremes as a robust finding (cf., Desmet et al. [2022]), and a conclusion that cannot be bolstered by comparing the outcome to a low-resolution model.
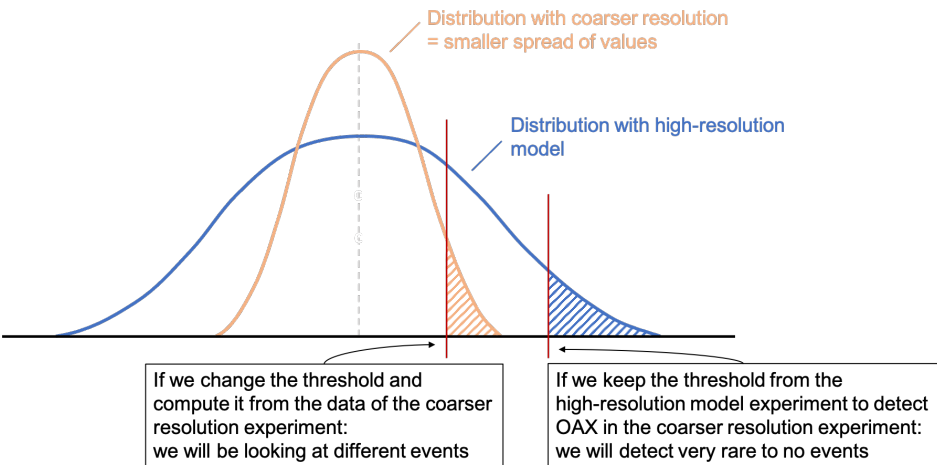
Figure 1: Schematic of two theoretical distributions of [H$^+$] at a given location from a high-resolution model (blue) and a coarser resolution model (orange). Corresponding theoretical thresholds are plotted in red.

Although the evidence is indirect, i.e., models and parameters are different, findings from Burger et al.

[2020] suggest that the distinctive pattern of maximum intensity found in our manuscript would be different in the coarser resolution study. Indeed, the distinctive pattern of maximum intensity found in our manuscript does not appear in Figure 7d of Burger et al. [2020] (Figure 2), supporting the argument that mesoscale processes are shaping the spatial heterogeneities in OAXs maximum intensity found in our study. Note that besides the difference in model and parameters, the definition of the baseline on which OAXs are detected also differs in the Figure 2 below (i.e., shifting baseline for Figure 2 versus fixed baseline in our manuscript).
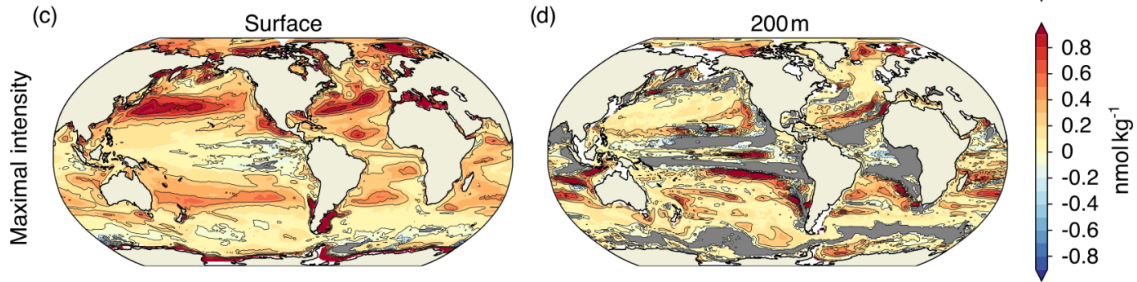
Figure 2: Figure 7 from Burger et al. [2020]: "Simulated regional changes in [H+] extreme-event characteristics from the preindustrial period to the 2081–2100 period under the RCP8.5 scenario at the surface and at depth for [...] the maximal intensity of events (c, d) [...]. The extreme events are defined with respect to a shifting baseline. Shown are changes averaged over all five ensemble members. Gray colors represent areas where no extremes occur during 2081–2100, and the black lines highlight pattern structures."

For better clarity, we explicitly stated that the models were different while making the comparison between our findings and Burger et al. [2020]'s findings in the revised manuscript and modified the discussion in section 4.1 as follows:

Text added:
Lines 368-377: "[...] Despite different models used and associated distinct resolutions, the surface increase rates in number of OAX days are similar between our study (3.7 days.μ atm^{-1}) and the study by Burger et al. [2020] (cf. Figure 4a in their study). In the subsurface however, the increase rate in number of extreme days and OAX duration largely differs between the two studies. The increase in number of extreme days at 200 m depth is almost three times slower in our study than in Burger et al. [2020] (cf. Figure A1e of their study), and a similar difference is found for OAXs duration [cf. Figure A1c,d in Burger et al., 2020]. In subsurface waters, where mesoscale processes, such as eddies, largely contribute to broaden the distribution of [H$^+$] (Appendix Figure B6e,f), differences in OAX increase rate are more dependent on the model resolution than at the surface. In our high-resolution eddy-resolving study, broader distributions lead to thresholds more distinct from the mean than in coarser resolution model that do not resolve mesoscale processes. This likely lead to the slower but more realistic subsurface increase in number of OAX days and OAX duration in our study with respect to increasing atmospheric pCO$_2$."

We increased clarity with regard to the reason for the spatial heterogeneities of the maximum intensity in the revised manuscript by modifying the discussion as follows:

Text added:
Lines 451-454: "The distinctive pattern of subsurface maximum intensity does not appear in the analyses of Burger et al. [2020] (cf. Figure 7d in their manuscript). We also do not expect it to appear, since the resolution of their model is much coarser (horizontal resolution of ∼80 km), preventing it from resolving the mesoscale processes that we identify as shaping this spatial heterogeneities in subsurface OAX maximum intensity."

2) While authors use various properties of OAXs, some of these properties require explicit definitions prior to their usage in the manuscript such as volume fraction of OAX, contribution in Fig.2, near-

permanent OAX in Section 3.5, 4.2. Additionally, it's unclear whether the subsurface layers encompass both 100m and 200m or solely the 200m depth. While these undefined properties are conceptually understandable, but it is needed to provide more precise definitions in an academic context. These specific properties would be recommended within the methods or results sections. Additionally, because the manuscript includes substantial number of acronyms employed throughout the manuscript, it could be beneficial to present a comprehensive table listing these acronyms for clarity.

Authors: We thank the reviewer for pointing out that the definition of some of the OAXs properties were missing or unclear.
To enhance clarity, we renamed the yearly volume fraction into an annual mean volume fraction, and clarified the definition of the volume fraction of OAX in the methods of the revised manuscript as follows:

Lines 179-181: "We additionally derive an integrative metric, namely the annual mean volume fraction of OAX (in %; the average fraction of the daily volume of grid cells with $[H^+]$ above the 99th percentile relative to the total volume extending from 0 to 250 m depth) [...]"

We further made sure that the name of this OAX property was consistently used throughout the revised manuscript and consequently changed the label of the y-axis in Figure 2 and 3 of the original manuscript as well as the caption of these figures.
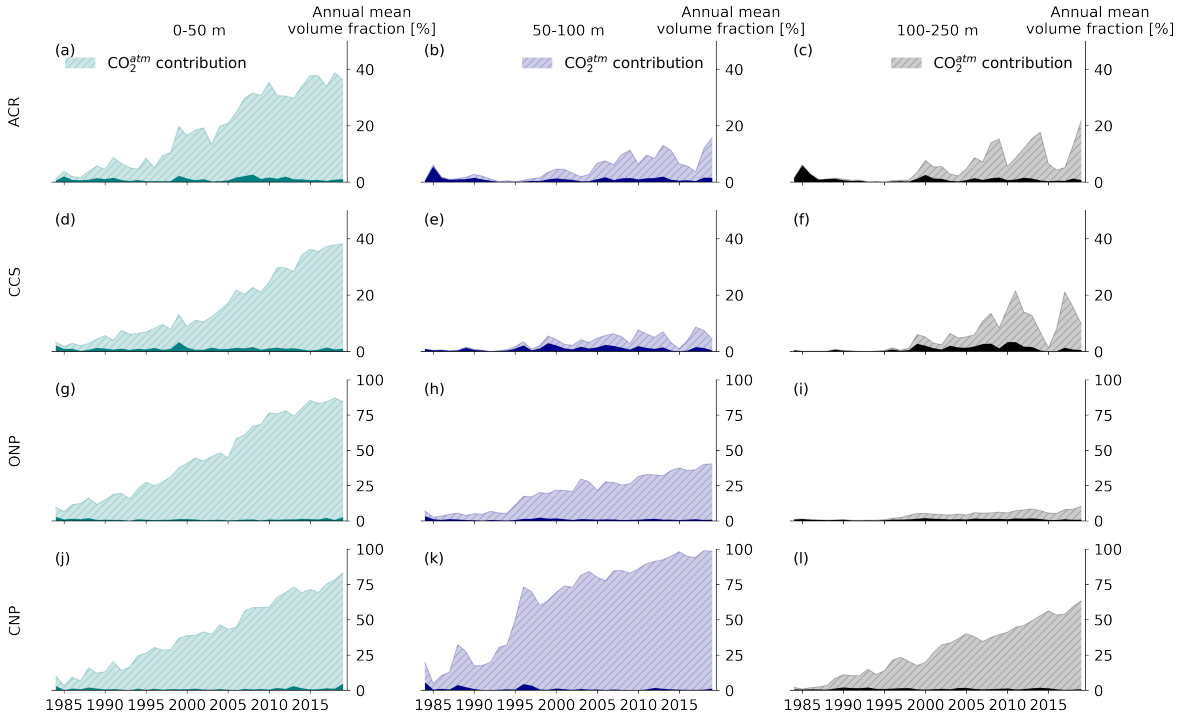
Figure 3: Figure 2 in the original manuscript: Time series of the annual mean volume fraction characterized by $[H^+]$ extremes (OAX) for the four different regions of the Northeast Pacific shown in Figure 1a (rows) and three different depth sections (from left to right: 0-50 m, 50-100 m and 100-250 m depth). Dark and light colours depict the OAX volume fraction in the CCons and HCast scenario, respectively, with the difference between the two denoting the contribution of the rise in atmospheric CO_2 to the OAX volume fraction from the HCast scenario (CO_2^atm contribution, hatched area). Note the different scales of the top two (0-50%) and bottom two rows (0-100%).
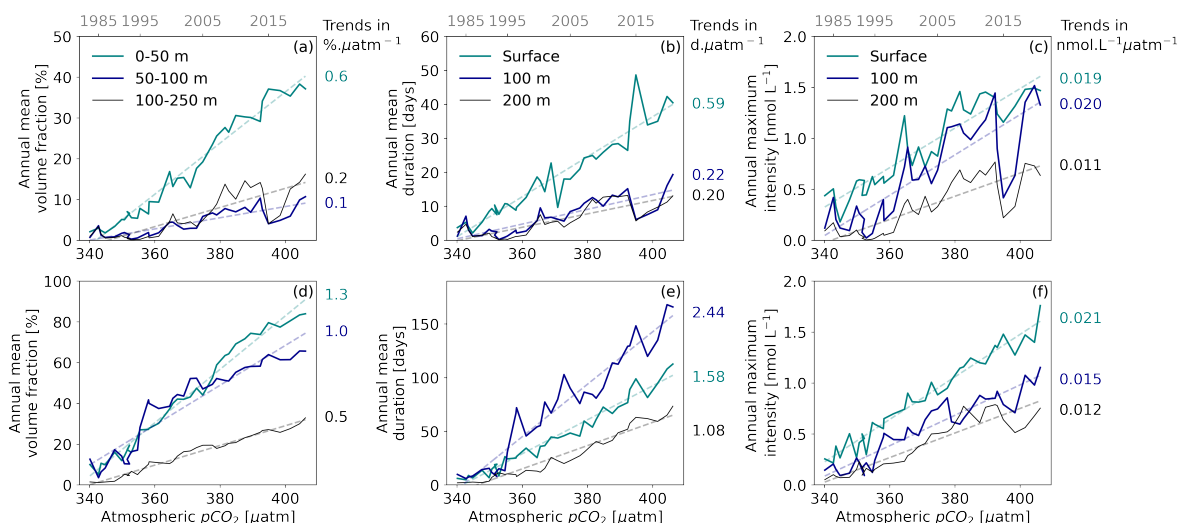
Figure 4: Figure 3 in the original manuscript: OAX characteristics as a function of atmospheric CO_2 between 1984 and 2019 in the (top row) two coastal and (bottom row) two open ocean regions of the Northeast Pacific analysis domain. (a,d) Annual mean OAX volume fraction in three different depth layers (0-50 m, 50-100 m and 100-250 m depth). (b,e) Annual mean event duration (days) and (c,f) annual maximum intensity (nmol L^{-1}) at surface (cyan), 100 m (darkblue) and 200 m (black) depth. In all panels, the simulated OAX characteristics are plotted against the yearly averaged atmospheric pCO_2 over the Northeast Pacific domain. Corresponding years are indicated at the top. Linear regressions ($r^2 > 0.7$) are plotted in each panel and the associated rates of increase (per μatm) are given.

In addition, we explicitly defined the contribution of atmospheric CO_2 to the volume fraction of OAX in the caption of Figure 2 in the original manuscript (Figure 3 in the present letter), and the concept of near permanent OAX in the methods section 2.4 as follows:

Figure 2. [...] Dark and light colours depict the OAX volume fraction in the CCons and HCast scenario, respectively, with the difference between the two denoting the contribution of the rise in atmospheric CO_2 to the OAX volume fraction from the HCast scenario ($CO_2{}^{atm}$ contribution, hatched area). [...]

Text added:

Lines 203-205: "We refer to as "near permanent OAX" when emergence has occurred, i.e., when the linear long-term trend signal has exceeded the 99th percentile threshold used to detect OAX."

Line 354: "The area experiencing near permanent OAX before the end of the hindcast (ToE < 41 years)"

We further made sure that these terms were used consistently throughout the revised manuscript.

We thank the reviewer for pointing out that the definition of the subsurface layers was unclear. We clarified that it encompasses both 100 m and 200 m depth by defining the subsurface layers in the methods of the revised manuscript and we made sure that is was used consistently throughout the text.

Line 176: "These metrics are computed at three depths, i.e., the surface layer in direct interaction with the atmosphere, and two subsurface layers, namely 100 m corresponding to the transition from the euphotic zone to the twilight zone, and 200 m, corresponding to the upper thermocline."

Line 224: while the subsurface (i.e., below 50 m depth) [...]

3) The manuscript employs substantial numbers to elucidate OAX properties. However, the manuscript is inconvenient for matching the numbers with the figures. Consequently, the manuscript is difficult

to follow, and the messages of research can be hindered. For instance, the discussion of Time of Emergence (ToE) is described as 16 years, 25years, 30-32years (L400). However, the ToE years are represented by the year ranging from 1984 to 2020 in figure 7. Authors need to make consistency by providing supplementary for matching ToE explained in the discussion. Similarly in Section 3.2, matching the numbers with figure 3 is also difficult to follow. This issue of mismatching or uncomfortable explanations are abundant through the manuscript. So, the manuscript is needed to enhance its comprehensibility.

Authors: We thank the reviewer for pointing out that the manuscript requires some modifications to enhance its comprehensibility. We increased clarity with regard to matching figures and numbers in the revised manuscript.
For instance, we modified the definition of the ToE in the methods, and the labels of the colorbar in Figure 7 to match the ToE explained in the introduction and the discussion.

Line 199: "We compute the time of emergence (ToE) as a measure of the time it takes for the linear long-term trend signal to exceed the 99th percentile threshold used to detect OAX. [...] We then calculate the number of years after 1979 when this linear trend exceeds the 99th percentile threshold [...]"

Lines 353-360: "The area experiencing near permanent OAX before the end of the hindcast (ToE $\leq$ 41 years) decreases with depth. [...] Both at 100 and 200 m depth, ToE less than $\sim$41 years are confined to the offshore regions that do not have an imprint from coastal variability, i.e., in the CNP west of the eddy front. At P_{CNP}, the ToE is as short as 18 years at 100 m depth, matching [...]"
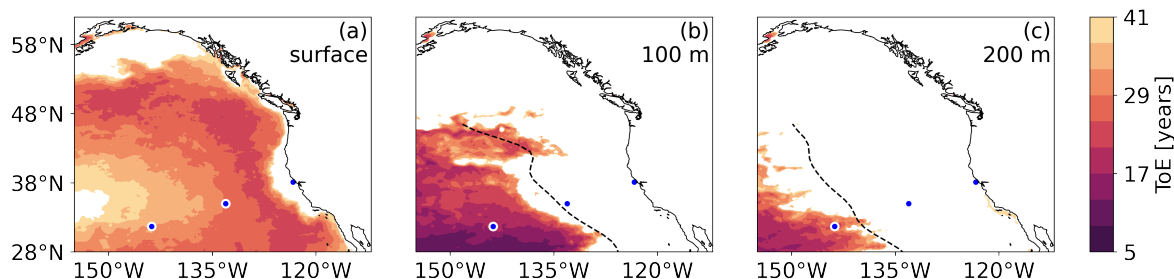
Figure 5: Figure 7 in the original manuscript: Maps of the Time of Emergence (ToE) of the yearly mean [H$^+$] (long-term trend in [H$^+$]) above the local [H$^+$] threshold at (a) the surface, (b) 100 m depth, and (c) 200 m depth in the HCast simulation. White areas denote regions where the long-term trend does not exceed the threshold at the end of 2019 (i.e., ToE>41 years). The three blue disks with white contours in each map denote the locations where the time series in Figures 1 and 6 were extracted. The black dashed lines denote the westward eddy propagation fronts.

Additionally, we modified the unit of the trends given in the model evaluation section to match the unit of Table 1 in the revised manuscript, as follows:

Lines 144-152: "The modeled surface pH in the subtropical North Pacific decreases by 0.015 per decade from 1981 to 2011, which is within the range of the observed trend of -0.016 $\pm$ 0.002 decade^{-1} [Lauvset et al., 2015]. The model's trend of -0.016 pH unit decade^{-1} from 1991 to 2011 in the subpolar North Pacific, although overestimated compared to observations, is also within the range of the observed trend of -0.013 $\pm$ 0.005 decade^{-1} [Lauvset et al., 2015]. [...] The average modeled surface pH (Ω_A) trend across the five line P stations is -0.019 decade^{-1} (-0.06 decade^{-1}) against -0.014 decade^{-1} (-0.05 decade^{-1}) in Franco et al. [2021]."

Finally, we enhanced the comprehensibility of the results in Section 3.2 with regard to Figure 3 by adding the linear trends, i.e., the rate of increase, on the revised Figure 3 (see Figure 4 in this response letter) and by modifying the text in the results section as follows:

Lines 259-284:"Near the surface, the increase in OAX volume fraction linearly follows the atmospheric CO_2 rise in both coastal and open ocean regions ($r^2 > 0.96$), with a rate of change in the open ocean regions that is twice as large as that in the coastal regions, [...]. The increase rate decreases substantially below 50 m in the coastal regions [...]. The rate of increase in the open ocean regions is largest at 100 m, being about 50% larger than that at the surface, and more than twice as large as at 200 m. [...] Down to 100 m depth in coastal regions and in the surface of open ocean regions, the intensities increase at nearly the same rate than simulated at the surface of coastal regions. At 200 m depth however, and in the subsurface of open ocean regions, the increase is [...]. By contrasting the above results (Figure 3; HCast simulation) with those from the CCons simulation, [...]"

4) The abstract, while comprehensive, stretches to approximately 550 words, which surpasses the typical length of around 380 words. To effectively encapsulate the core research messages, I recommend shortening the abstract to a more concise form.

Authors: We agree with the reviewer that the abstract needs to be shortened in order to effectively transmit the core research messages of the manuscript. In the revised manuscript, we shortened the abstract from approximately 550 words to 370 words, as follows:

The acidification of the ocean (OA) increases the frequency and intensity of ocean acidity extreme events (OAXs), but this increase is not occurring homogeneously in time and space. Here we use daily output from a hindcast simulation with a high-resolution regional ocean model coupled to a biogeochemical-ecosystem model (ROMS-BEC) to investigate this heterogeneity in the progression of OAX in the upper 250 m of the Northeast Pacific from 1984 to 2019. OAX are defined using a relative threshold approach and using a fixed baseline. Concretely, conditions are considered extreme when the hydrogen ion concentration ($[H^+]$) exceeds the 99th percentile of its distribution in the baseline simulation where atmospheric CO_2 was held at its 1979 level. Within the 36 years of our hindcast simulation, the increase in atmospheric CO_2 causes a strong increase in OAX volume, duration, and intensity throughout the upper 250 m. The increases are most accentuated near the surface, with 88% of the surface area experiencing near permanent extreme conditions in 2019. At the same time, a larger fraction of the OAX become undersaturated with respect to aragonite ($\Omega_A < 1$), with some regions experiencing increases up to nearly 50% in their subsurface. There is substantial regional heterogeneity in the progression of OAX, with the fraction of OAX volume across the top 250 m increasing in the Central Northeast Pacific up to 160-times, while the deeper layers of the nearshore regions experience "only" a 4-fold increase. Throughout the upper 50 m of the Northeast Pacific, OAXs increase relatively linearly with time, but sudden rapid increases in yearly extreme days are simulated to occur in the thermocline of the far offshore regions of the Central Northeast Pacific. These differences largely emerge from the spatial heterogeneity in the local $[H^+]$ variability. The limited offshore reach of offshore propagating mesoscale eddies, that are an important driver of subsurface OAX in the Northeast Pacific, causes a sharp transition in the increase of OAX between the rather variable thermocline waters of nearshore regions and the very invariant waters of the Central Northeast Pacific. The spatially and temporal heterogeneous increases in OAX, including the abrupt appearance of near permanent extremes, likely have negative effects on the ability of marine organisms to adapt to the progression of OA and its associated extremes.

Minor comments

L152: What about the mean biases in the spatial patterns of pH and OmegaA? Comparing these biases with data from the Global Ocean Data Analysis Project (GLODAP) could provide the better information for model validation.

Authors: We thank the reviewer for this important question. As stated in the original manuscript (Lines 136-138), for the evaluation of the mean biases in the spatial patterns of pH and Ω_A we refer the reviewer to Desmet et al. [2022], where the model representation of mean conditions in pH and Ω_A has been evaluated, including against GLODAPv2. The HCast simulation in our manuscript uses the same model configuration and forcing as employed by Desmet et al. [2022]. There were some small changes owing to our use of slightly different initial conditions as a result of a change in the forcing

used for the model spin up. While Desmet et al. [2022] used daily fields from the year 1979 as the forcing for the spin up, we use a normal year forcing (apart from atmospheric CO_2, which is transient). The normal year forcing is created by adding daily anomalies of the year 2001 to the climatological mean surface fields of wind stress, short and long-wave radiations, and freshwater fluxes derived from ERA-5 [Hersbach et al., 2020; Copernicus Climate Change Service (C3S), 2017]. The two simulations are therefore not numerically equivalent, but present very similar evaluation results (cf. Figure 6 and Figures 3 and 4 in response to RC1, and Desmet et al. [2022]).

The evaluation of the mean biases in the modeled spatial patterns of pH and Ω_A against GLODAPv2 for the HCast simulation can be seen in the Figure 6 below. Figure 6 shows that ROMS-BEC captures the large-scale interior distribution of pH and Ω_A in the northeast Pacific and especially the spatial pattern of the depth of the pH=7.9 isosurface and of the aragonite saturation horizon with good fidelity. The simulated depths correlate with a Spearman coefficient of respectively r=0.96 and r=0.94 with the depths derived from the climatological GLODAPv2 1°×1° gridded Ω_A observational product [Lauvset et al., 2016]. The model depth of the pH=7.9 isosurface (saturation horizon) is on average 42m (20 m) shallower than that derived from the observations.
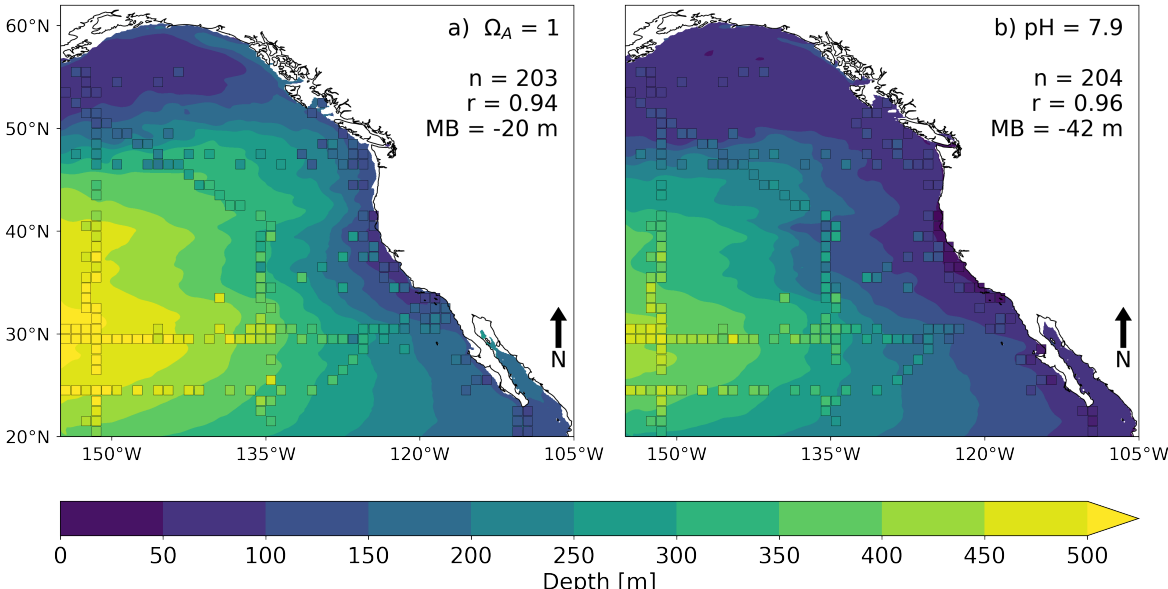
Figure 6: Evaluation of the model (HCast) simulated annual mean depths of (a) the Ω_A saturation horizon ($\Omega_A = 1$) and (b) the pH=7.9 isosurface compared to the corresponding observational estimates based on the 1°× 1° gridded GLODAPv2 climatology [Lauvset et al., 2016]. The model simulated results are shown as filled contours, while the (gridded but not mapped) observations are shown as filled squares. Each square stands for the corresponding 1°× 1° bin of the gridded product. The corresponding spatial Spearman's correlations (r), spatial mean biases (MB), and number of points (n) used for the calculation are indicated at the top.

We address this question by adding the following sentences in the methods of the revised manuscript:

Text added:

Lines 115-120: "Our HCast simulation uses slightly different initial conditions than employed by Desmet et al. [2022] as a result of a change in the forcing used for the model spin up. While Desmet et al. [2022] used daily fields from the year 1979 as the forcing for the spin up, we use a normal year forcing (apart from atmospheric CO_2, which is transient). The normal year forcing is created by adding daily anomalies of the year 2001 to the climatological mean surface fields of wind stress, short and long-wave radiations, and freshwater fluxes derived from ERA-5 [Hersbach et al., 2020; Copernicus Climate Change Service (C3S), 2017]."

Lines 138-140: "Although our HCast simulation is not numerically equivalent to the simulation employed by Desmet et al. [2022] owing to the different initial conditions (cf. Section 2.1), they present very similar evaluation results (not shown). Here we further evaluate the surface OA trends in pH and Ω_A of the model against observations (Table 1)."

L210: The authors mention the strong year-to-year variability and abrupt transition in the subsurface layer. However, there is no explanation of mechanisms for the strong variability and abrupt transition.

Authors: We thank the reviewer for this valuable comment and agree with the reviewer that it is worthwhile exploring the mechanisms for the strong variability and abrupt transition. We shortly discussed the potential mechanisms in the discussion of the original manuscript, but we decided to address those questions in a separate manuscript, in order to not overload the current one. Further investigations of the mechanisms involved in the strong year-to-year and decadal variability can be found in the Chapter 3 of Desmet [2022]. In the revised manuscript we refer to this chapter, and added further explanation in the discussion as follows:

Text added:

Line 405: "While it is beyond the scope of this work to assess the mechanisms driving the strong year-to-year variability in OAXs in the coastal regions (Section 3.1), this variability largely correlates with the El-Niño-Southern-Oscillation, particularly impacting OAX in coastal regions of the Northeast Pacific, as shown in Desmet [2022]."

Line 427: "the occurrence and intensity of OAXs in the CCons simulation correlate with decadal climatic modes such as the North Pacific Gyre Oscillation [Desmet, 2022]."

Line 431: "The timing of the step increases in OAXs in our study may therefore relate to the atmospheric forcing, and would probably vary if we were to run a coupled model, which would have its own decadal and year-to-year variability.

L315: It would be helpful to specify which figure corresponds to the statement being made.

Authors: We agree with the reviewer and specified the corresponding figures in the revised manuscript as follows: Line 331: Figures 2,3,4,5

L326: Also, there is no description of explanation in strongest step increases in subsurface of the CNP, not merely mentioning the occurrence of the strongest step.

Authors: We interpreted this comment as the fact that a discussion on the strongest step increase, found in the subsurface of the CNP and described line 341 in the result section, was missing in the original manuscript. We added the reference to the corresponding Figure in the revised manuscript (Line 341) and discussed more explicitly the reason for this strongest increase in the revised manuscript as follows:

Line 419: "[...], the abruptness of the change also varies spatially, with the strongest step increase in OAX occurring in the subsurface CNP (Section 3.5, Figure 6f).

Line 424: "[...] in low variability regions, such as the subsurface CNP, [...], the non-linearities (step increases) found in those same regions (Section 3.5, Figure 6f) may result from the concurrent effect of OA trends and synergistic low frequency (decadal to multi-decadal) climate variability, as illustrated in Figure 8b"

L357-361: It is advisable to compare the results of Burger et al. 2020 and provide supplementary with similar analysis by using GFDL model results or other Earth system models. Alternatively, if the explanation relies on a specific figure, please indicate which figure elucidates the increase in the number of days as per Burger et al. 2020.

Authors: We thank the reviewer for pointing out that a reference to the specific figure from Burger et al. [2020] used for this comparison was missing. In the revised manuscript, we increased clarity by adding the number of the specific figures from Burger et al. [2020] used to compute the increase rate in number of OAX days and in OAX duration:

L388: It would be helpful to specify which figure corresponds to the statement being made.

Authors: We thank the reviewer for pointing out that clarity could be enhanced by specifying the figures that correspond to the statement made. In the revised manuscript, we increased clarity by dividing Figure 8 into 3 panels (a,b,c) and by specifying that Figure 8c, Figure2h,i and 6e correspond to the statement made as follows:.

Line 417: "This skewness delays the emergence of OA trend over the threshold (e.g., Figure 8c), which explains the weaker increase in OAX (Figures 2h,i and 6e)."

L400, L411: Provide additional details regarding the marine environment, such as temperature, salinity, or other influential factors.

Authors: We thank the reviewer for pointing out that the use of the term marine environment requires to give details about other variables than $[H^+]$, such as temperature or salinity. In the revised manuscript, we were more precise and replaced the term "marine environment" by "ocean carbonate chemistry" (Lines 434 and 445).

L412: How to suggest the emergence of near-permanent OAXs from this figure? A more comprehensive explanation is needed to clarify this point.

Authors: We thank the reviewer for pointing out that the manuscript needs a more comprehensive explanation of how Figure 7 suggests the emergence of near permanent OAXs. As above in response to major comment 2, we explicitly defined the term near permanent OAX in the revised manuscript, in order to increase clarity about this statement. Furthermore, we added a reference to the figure corresponding to the statement made as follows:

Line 447: "(cf. white areas in Figure 7)."

References

Burger, F. A., J. G. John, and T. L. Frölicher, 2020: Increase in ocean acidity variability and extremes under increasing atmospheric CO2. *Biogeosciences*, 4633–4662, doi:https://doi.org/10.5194/bg-17-4633-2020.

Copernicus Climate Change Service (C3S), 2017: ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. *Copernicus Climate Change Service Climate Data Store (CDS),29/08/2020*.

Desmet, F., 2022: *Ocean acidity extremes and their spatiotemporal evolution, a high-resolution modeling study in the northeast Pacific*. Ph.D. thesis, ETH Zürich.
URL https://doi.org/10.3929/ethz-b-000598701

Desmet, F., N. Gruber, E. E. Köhn, M. Münnich, and M. Vogt, 2022: Tracking the space-time evolution of ocean acidification extremes in the California Current System and Northeast Pacific. *Journal of Geophysical Research: Oceans*, 1–30, doi:10.1029/2021jc018159.

Franco, A. C., D. Ianson, T. Ross, R. C. Hamme, A. H. Monahan, J. R. Christian, M. Davelaar, W. K. Johnson, L. A. Miller, M. Robert, and P. D. Tortell, 2021: Anthropogenic and Climatic Contributions to Observed Carbon System Trends in the Northeast Pacific. *Global Biogeochemical Cycles*, **35**, 1–21, doi:10.1029/2020GB006829.

Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. De Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R. J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. de Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J. N. Thépaut, 2020: The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146**, 1999–2049, doi:https://doi.org/10.1002/qj.3803.

Lauvset, S. K., N. Gruber, P. Landschützer, A. Olsen, and J. Tjiputra, 2015: Trends and drivers in global surface ocean pH over the past 3 decades. *Biogeosciences*, **12**, 1285–1298, doi:https://doi.org/10.5194/bg-12-1285-2015.

Lauvset, S. K., R. M. Key, A. Olsen, S. Van Heuven, A. Velo, X. Lin, C. Schirnick, A. Kozyr, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, M. Ishii, F. F. Perez, T. Suzuki, and S. Watelet, 2016: A new global interior ocean mapped climatology: The 1° × 1° GLODAP version 2. *Earth System Science Data*, doi:https://doi.org/10.5194/essd-8-325-2016, iSBN: 1866-3591.