nature portfolio

Peer Review File

Ventilation and buffering capacity effects on ocean acidification in low oxygen environments

Corresponding Author: Professor Wei-Jun Cai

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

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Review of: "Ocean acidification in low-oxygen environments: ventilation versus buffering 1 capacity," by Liang Xue, Christopher Sabine, Jianfang Chen, Qinsheng Wei1, Kuiping Li, Wei-Jun Cai5
General Comments
Xue and coauthors take a fresh new look at the controlling mechanisms behind the rapid acidification of subsurface waters in the global ocean. They suggest that anthropogenic CO2 invasion, changing buffer capacity, and ventilation processes contribute to the amplification of the acidification processes in the subsurface waters. The authors used existing GLODAP partial pressure of CO2 (pCO2), hydrogen ion concentration ([H+]), pH, and aragonite saturation state (Ωar) data sets to show that in the well-ventilated regions the amplification process is dominated by anthropogenic CO2 input and buffer capacity changes. However, in low-oxygen regions, particularly within the ocean's permanent oxygen minimum zones (OMZ), they show that ocean acidification is negligible in the least-ventilated, poorly buffered lower OMZs, but is detectable in the moderately ventilated upper OMZs. In upper OMZs, pH and Ωar decline slowly while pCO2 and [H+] first increase more rapidly than in adjacent well-ventilated waters. Their results suggest that in the least buffered, lowest-oxygen waters, acidification is ultimately constrained by the limited delivery of anthropogenic CO2 through ventilation. This significant new perspective on the acidification process in the interior ocean is sufficient justification for publication in Nature Communications after some specific comments provided below have been adequately addressed.

Specific Comments
Lines 70-75. Change to read…. Conversely, the acidification in the poorly ventilated OMZ would be in sharp contrast to that in coastal hypoxic regions, where ocean acidification can be greatly amplified.

Lines 28-29 and Table 1. If the changes in ΔCant, ΔpCO2, ΔH+, ΔpH and ΔΩar are relative to their respective preindustrial values, then it would seem to be very appropriate to report the corresponding ΔRF as well. If there is no change in RF from the preindustrial, then RF is most likely not a controlling factor of the enhanced acidification in the subsurface waters. But if ΔRF values are positive then it may well be an important factor in contributing to the enhanced acidification. Consequently, I believe you should be documenting ΔRF changes, along with the RF values, in text, tables, and figures.

Figure 2. It would seem to be useful to have a plot of ΔRF here. It might indeed identify where changes in RF make a significant contribution to the changes in ΔpCO2 and Δ[H+].

Table 1. I suggest adding a column of ΔRF values and associated uncertainties.

Lines 165-169. The values for ΔpCO2 and Δ[H+] are higher in each OMZu than in Ventu while the water mass ages are higher and the oxygen concentrations are lower. I submit that these differences are due to buffer capacity changes in this portion of the water column. I suggest that you add the ΔRF values to Table 1 and Figure 2.

Lines 178-185. This statement is correct. But these statements directly contradict the statements made in lines 165-168, where the authors state that ΔpCO2 and Δ[H+] are either lower than or comparable to those in well-ventilated waters and the upper 50 meters of the ocean. This contradiction must be rectified.

Figure 3. Shows that ΔpCO2 and Δ[H+] are enriched in subsurface waters down to depths of approximately 800m,

particularly in the Pacific Ocean. It would be. Very helpful to show a similar plot of ΔRF in each ocean basin. These additional plots would help delineate the depth range where buffer capacity changes are effective.

Lines 258-260. I suggest that the correlation between ΔCant and water age indicates that ΔCant is predominantly governed by the balance between air-sea exchange of CO2 and water age or ventilation), suggesting that ventilation may play a significant role in influencing the changes of acidification metric. In my opinion, both processes are important here.
Lines 307-308. A word appears to be missing here. I suggest that the phrase should read,,, In contrast, as ΔCant decreases, the absolute values of ΔΩ decline with depth and water-mass age due to less Cant supplies and a weakened influence from buffering capacity.
Lines 358 -368. It would be very helpful for the readers if the authors can expand on this paragraph a bit more and provide a summary of the key environmental conditions that are in place when the transition occurs between buffer-capacity controlled conditions and ventilation-controlled conditions in subsurface waters. Are they nearly the same in the three major ocean basins or are they very different? Perhaps a table of those conditions would be helpful for the reader.
Lines 443-465. How were the threefold future ΔCant increase FU calculated? What CO2 emission scenario was used? What assumptions were used for the ΔpCO2 and Δ[H+] calculations for the FU?

Reviewer #2

(Remarks to the Author)
This manuscript makes a significant contribution to the literature by examining acidification rates in oxygen minimum zones (OMZs), which, although uninhabitable for many species, remain an important component of marine ecosystems. The manuscript is generally well written: the authors clearly state the main findings at the outset and guide the reader more or less smoothly through the results. The study shows that the OMZ regions experience relatively slow rates of ocean acidification, as poor ventilation limits exposure to anthropogenic carbon despite their higher concentrations of biologically produced CO2 and lower buffering capacities. The paper also discusses the mechanisms of how different carbonate system parameters can easily become decoupled, underscoring the importance of considering all four together. This point is relevant not only for experimental studies, but also for process studies in the ocean and for modeling efforts. Overall, I enjoyed reading the manuscript, and I have a few suggestions that could help clarify certain points and further improve the reading experience.
To avoid confusion for readers, it would be helpful to clarify the basis of Figure 1. Is it derived from data or intended as a conceptual illustration? If it is meant as a thought experiment to illustrate the hypothesis, please consider specifying this in the figure caption.
Lines 99-102: It would be helpful to clarify whether the reported changes in pCO_2 and H^+ are faster compared to neighboring well-ventilated areas, or only faster relative to pH and aragonite saturation state. I understood it as the latter, but revising the sentence to make this distinction explicit would avoid possible confusion.
Lines 116–122 were a bit confusing. The text states that water in the upper boundary of the OMZ shows pCO_2 and H^+ deviations from changes in anthropogenic carbon and water age, but this point is not elaborated on until later in the next paragraph. To avoid confusing the reader, I suggest getting rid of this sentence here and addressing it fully when it is discussed later. In addition, the following sentence states that the focus is on changes within the OMZ. Will the authors also address what happens at the upper boundary, or is that beyond the scope? It might also be helpful to indicate important locations in Figure 2 and to refer more directly to the figure in the text so that readers can clearly follow the reasoning behind the conclusions. For example, use figure letters throughout the manuscript.
In the paragraph starting on line 165, it might be helpful to briefly remind the reader that OMZs are often assumed to automatically have strong ocean acidification. While this point was explained in the introduction, restating it here would set up the findings in this paragraph more clearly and emphasize how the results contrast with that common expectation.
Lines 193-196: “In contrast, 193 in the upper OMZs, moderate ventilation drives significant acidification, characterized by slower declines in pH and Ωara but more rapid rises in pCO2 and [H+] compared to neighboring well- ventilated waters.” This section currently reads as if pCO_2 and H^+ are changing faster than in neighboring well-ventilated waters. Is that correct? This seems related to the earlier point I raised, and I found it difficult to identify the basis for this statement. Are you referring to Figure 3? If so, it would help the reader to be guided through the relevant panels more explicitly to see how you arrived at the different conclusions. In addition, could you clarify how the rate of change of pH and aragonite saturation state was compared with that of H^+ and pCO_2? Were the variables normalized in some way?
Similarly, from line 269 onward, it would be helpful to refer directly to the figure and its subpanels so the reader can more easily follow the text.
In Figure 4, the black dashed arrow is difficult to see.
Line 288: with higher RF usually leading to the enhancement of sensitivity in pCO2, [H+] and pH, and the reduction of sensitivities in Ωara (Supplementary Table 2 289 and Supplementary Fig. 3).
Please check Orr’s chapter in the OA book (chapter 3), as some of this was already nicely described in there.

Line 325: Therefore, when RF values are higher, pCO2 and $[H^+]$ show greater 325 sensitivity to ΔCant additions compared to that of Ωara – explained in Orr Chapter 3, OA book.

overestimated by 20% globally, but later says that since this mainly affects the Southern Ocean it will not influence the results presented here. I suggest clarifying or rewriting this passage so that the reasoning is easier to follow.
Were the biases mentioned in the methods, for example overestimation of water age, discussed in relation to the results somewhere?
Can you elaborate on sentence 482? I cannot follow…

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

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Re: Thanks very much for the recognition of our work.

Specific Comments
Lines 70-75. Change to read…. Conversely, the acidification in the poorly ventilated OMZ would be in sharp contrast to that in coastal hypoxic regions, where ocean acidification can be greatly amplified.

Re: As suggested, in the revised manuscript, the sentence has been revised.

Lines 28-29 and Table 1. If the changes in $\Delta Cant$, ΔpCO_2, ΔH^+, ΔpH and $\Delta \Omega ar$ are relative to their respective preindustrial values, then it would seem to be very appropriate to report the corresponding ΔRF as well. If there is no change in RF from the preindustrial, then RF is most likely not a controlling factor of the enhanced acidification in the subsurface waters. But if ΔRF values are positive then it may well be an important factor in contributing to the enhanced acidification. Consequently, I believe you should be documenting ΔRF changes, along with the RF values, in text, tables, and figures.

Figure 2. It would seem to be useful to have a plot of ΔRF here. It might indeed identify where changes in RF make a significant contribution to the changes in ΔpCO_2 and $\Delta[H^+]$.

Re: Thanks for your suggestion. In the revised manuscript, we have computed the RF changes (ΔRF) since the Industrial Revolution and added its presentation in main text, Table1, and Figs. 2-3.

However, we find that ΔRF almost can not influence ocean acidification, though RF reflects the buffering capacity. Rather, ΔRF is also determined by ΔC_{ant}, like $\Delta[H^+]$ and $\Delta\Omega_{ara}$, reflecting the results of acidification. This can be verified by the fact that the enhanced changes in pCO_2 and $[H^+]$ in the subsurface waters are not associated with ΔRF, but mainly associated with RF values (Fig. R1).

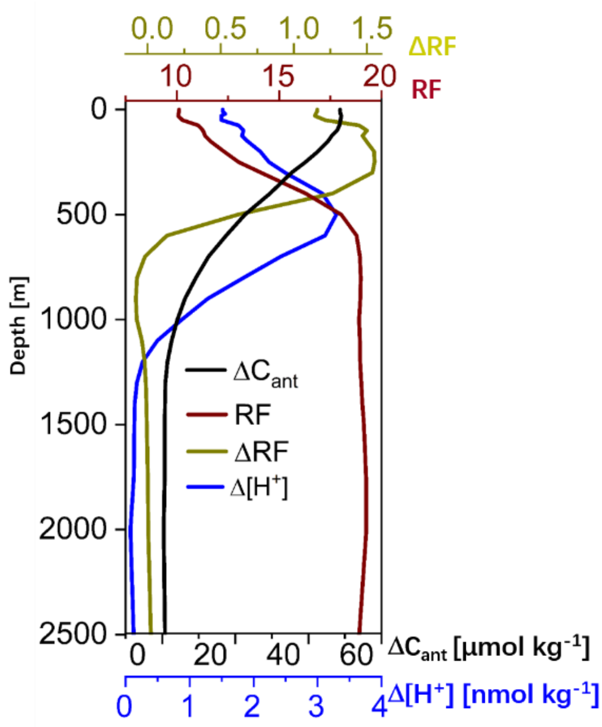

Fig. R1 Profile of ΔC_{ant}, RF, $\Delta[H^+]$ and ΔRF in a typical OMZ station located in the North Pacific (42.5°N, 152.5°W). Fig. R1 is revised on the basis of Fig. 3 in the main text.

In addition, previous studies and our analysis show that whether acidification metrics are enhanced or weakened mainly depends on the buffering capacity (Cai et al., 2011; Fassbender et al., 2023; Müller and Gruber, 2024; Orr, 2011), specific changes in pCO_2 (pCO_{2uc}), $[H^+]$ (H_{uc}), pH (pH_{uc}), and Ω_{ara} (Ω_{uc}) per unit change in ΔC_{ant}. We find that ΔRF cannot reflect the buffering capacity (Fig. R2). For example, ΔRF shows a significant negative correlation with H_{uc}, i.e., the buffering capacity for $[H^+]$ become stronger (smaller $[H^+]$ changes) with increasing ΔRF, inconsistency with our knowledge that the buffering capacity for $[H^+]$ become weaker with increasing RF. Similarly, ΔRF shows a significant negative correlation with Ω_{uc}, i.e., the buffering capacity for Ω_{ara} become weaker (larger Ω_{ara} changes) with increasing ΔRF, inconsistency with our knowledge that the buffering capacity for Ω_{ara} become stronger with increasing RF.

In contrast, we find that RF can well reflect the buffering capacity and shows good correlations with pCO_{2uc}, H_{uc}, pH_{uc} and Ω_{uc} (Fig. R3). Note that the relationship between RF_{uc} and RF is not monotonic, since RF can increase to a maximum and then decline (Egleston et al., 2010).

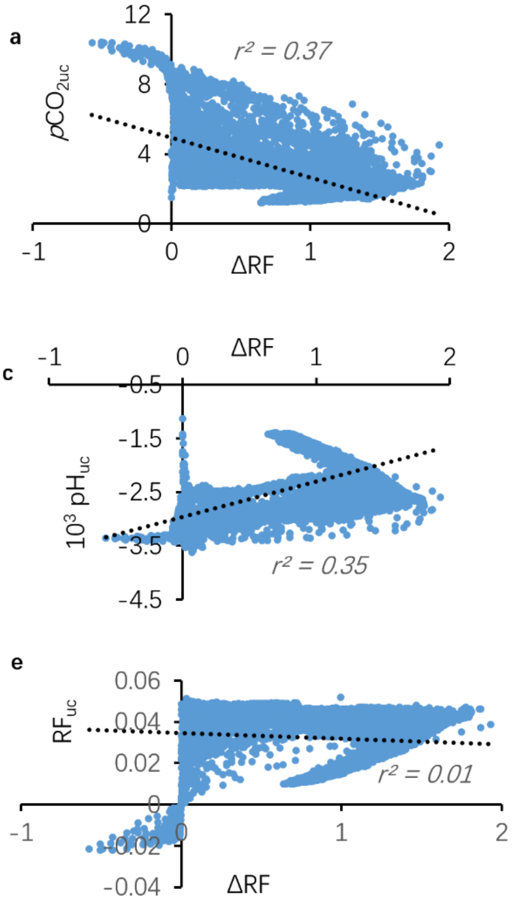

Fig. R2 Relationships of Revelle factor change (ΔRF) since the preindustrial era with per unit oceanic CO_{2ant} increase induced changes in pCO_2 (pCO_{2uc}, a), $[H^+]$ (H_{uc}, b), pH (pH_{uc}, c), Ω_{ara} (Ω_{uc}, d), and RF (RF_{uc}, e).

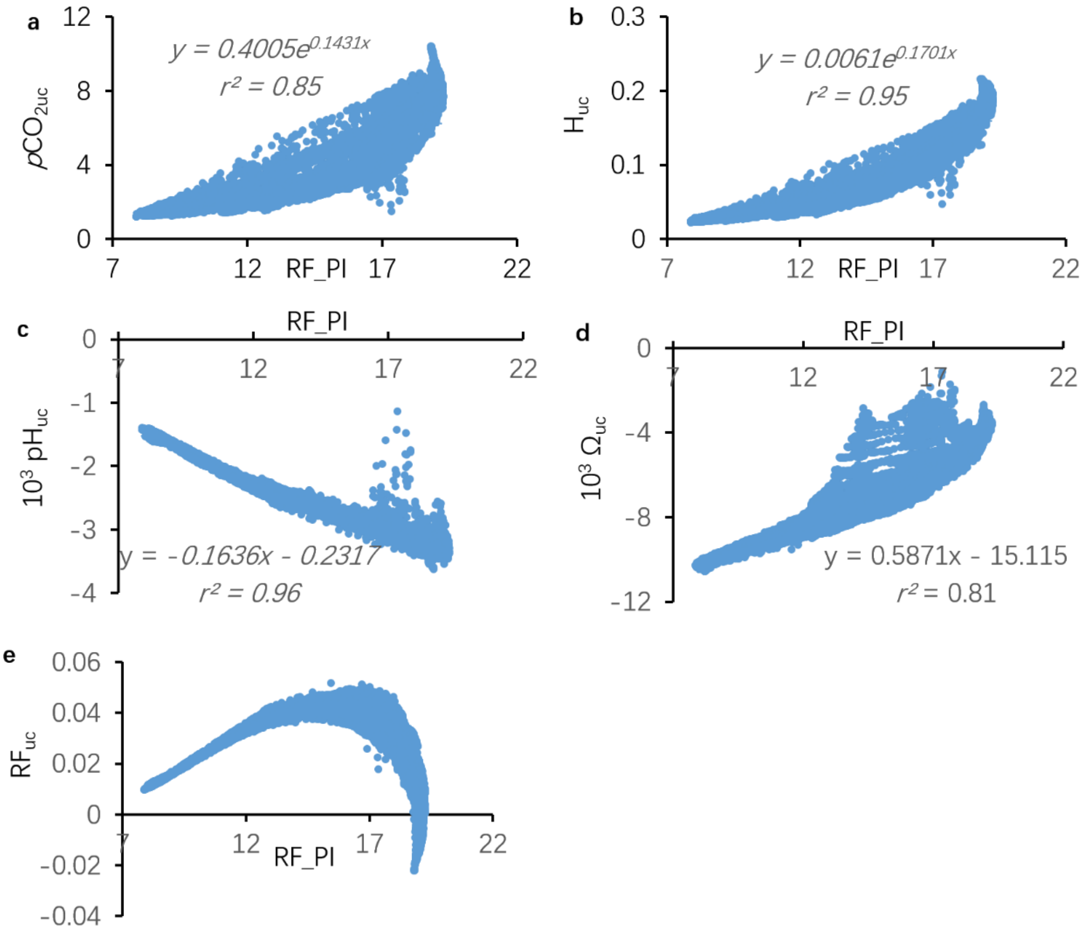

Fig. R3 Relationships of Revelle factor during the preindustrial era (RF_PI) with per unit oceanic CO_{2ant} increase induced changes in pCO_2 (pCO_{2uc}, a), $[H^+]$ (H_{uc}, b), pH (pH_{uc}, c), Ω_{ara} (Ω_{uc}, d), and RF (RF_{uc}, e).

Overall, how buffering capacity influences changes in acidification metrics since the Industrial Involution can not be captured by ΔRF, but by RF values. RF is nonlinear, and its change can approach zero (at its peak value) and then it may change negative. Given that rising anthropogenic CO_2 uptake has increased RF in most regions, which would further reduce the ocean's buffering capacity, thus in the revised manuscript we calculated ΔRF and reported the results in main text, Table1, and Figs. 2-3. In addition, this study concentrates on how spatial variations in RF or buffering capacity — driven by natural processes such as biological respiration affects ΔpH, $\Delta\Omega_{ara}$, ΔpCO_2 and $\Delta[H^+]$, and thus we do not deeply analyze the controlling processes of RF changes like the other four acidification metrics.

Table 1. I suggest adding a column of ΔRF values and associated uncertainties.

Re: In the revised manuscript, we add a column of ΔRF in Table 1 and associated uncertainties in Supplementary Table 1.

Lines 165-169. The values for ΔpCO2 and Δ[H+] are higher in each OMZu than in Ventu while the water mass ages are higher and the oxygen concentrations are lower. I submit that these differences are due to buffer capacity changes in this portion of the water column. I suggest that you add the ΔRF values to Table 1 and Figure 2.

Re: In the revised manuscript, we have added the ΔRF values in Table 1 and Fig. 2. As stated before, how buffering capacity influences changes in acidification metrics since the Industrial Involution can not be captured by ΔRF, but by RF values. This also can be seen from Table 1, showing that RF increased by 0.2±0.4 in the upper OMZ along section P16, while RF increased by1.3±0.2 in the upper ventilation region. That is to say, the enhanced acidification in the upper OMZ is due to the high RF values, not due to ΔRF.

Lines 178-185. This statement is correct. But these statements directly contradict the statements made in lines 165-168, where the authors state that ΔpCO2 and Δ[H+] are either lower than or comparable to those in well-ventilated waters and the upper 50 meters of the ocean. This contradiction must be rectified.

Re: We have rectified the contradiction by revising the expression on lines 166-168, page 7: "In the upper OMZs, due to moderate ventilation and thus moderate CO_{2ant} accumulation, acidification occurs, but the magnitudes of acidification metrics are either lower or higher than those in well-ventilated waters and the upper 50 meters of the ocean (Fig. 2g-x and Table 1)."

Figure 3. Shows that ΔpCO2 and Δ[H+] are enriched in subsurface waters down to depths of approximately 800m, particularly in the Pacific Ocean. It would be. Very helpful to show a similar plot of ΔRF in each ocean basin. These additional plots would help delineate the depth range where buffer capacity changes are effective.

Re: We agree with you. In the revised manuscript, we have added ΔRF profiles for the three meridional sections in the Pacific, Atlantic and Indian Oceans in Fig. 2. Also, we have added changes in RF for the present and the future scenarios in Fig. 3

Lines 258-260. I suggest that the correlation between ΔCant and water age indicates that ΔCant is predominantly governed by the balance between air-sea exchange of CO2 and water age or ventilation), suggesting that ventilation may play a significant role in influencing the changes of acidification metric. In my opinion, both processes are important here.

Re: We agree with you very much that both processes are very important. With increasing atmospheric CO_2, air-sea exchange is responsible for transferring CO_{2ant} from the atmosphere into the ocean, while the ventilation is responsible for redistributing the absorbed CO_{2ant} within the ocean interior. And water age well indicates the strength of ventilation spatially. So in the revised manuscript, the sentence is changed to "The correlation between ΔC_{ant} and water age indicates that ventilation, which carries surface waters rich in CO_{2ant} into the ocean interior, predominantly governs the spatial pattern of ΔC_{ant} in the ocean interior (see the insert in Fig. 4a), consistent with previous reports[3,4,29], even though air-sea exchange initially transfers CO_{2ant} from the atmosphere into the ocean." on lines 233-236, page 9.

Lines 307-308. A word appears to be missing here. I suggest that the phrase should read,,, In contrast, as ΔCant decreases, the absolute values of ΔΩ decline with depth and water-mass age due to less Cant supplies and a weakened influence from buffering capacity.

Re: We have changed it as suggested in the revised manuscript.

Lines 358 -368. It would be very helpful for the readers if the authors can expand on this paragraph a bit more and provide a summary of the key environmental conditions that are in place when the transition occurs between buffer-capacity controlled conditions and ventilation-controlled conditions in subsurface waters. Are they nearly the same in the three major ocean basins or are they very different? Perhaps a table of those conditions would be helpful for the reader.

Re: Thanks for the good suggestion. In the revised manuscript, we provide a summary on when the transition occurs between buffer-capacity controlled conditions and ventilation-controlled conditions in subsurface waters: "Furthermore, we propose that in the water column, if the increase in acidification caused by a weaker buffering capacity is larger than the decrease in acidification caused by weaker ventilation, then the observed trends in pCO_2, $[H^+]$, and pH will track changes in RF or buffering capacity (Supplementary Fig. 8). Otherwise, the observed trends in these acidification metrics will instead track changes in ΔC_{ant} or ventilation. We can apply this principle to determine whether rates of changes in acidification metrics are driven mainly by buffering capacity or by ventilation." on lines 348-354, page 13.

We think this basic principle applies to the global oceans, and whether the trends of change in acidification metrics are dominated by buffering capacity or ventilation depends on the specific sites.

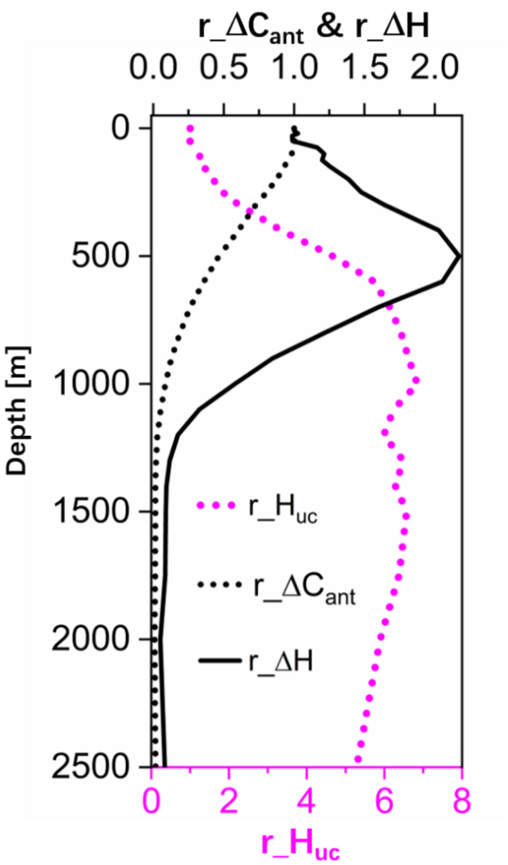

Fig. R4 (also Supplementary Fig. 8) Ratios of H_{uc}, ΔC_{ant} and $\Delta[H^+]$ in ocean interior relative to the surface. This figure shows the ratios of H_{uc} (r_ H_{uc}, pink dashed line), ΔC_{ant} (r_C_{ant}, black dashed line) and $\Delta[H^+]$ (r_ΔH, black solid line) in a typical OMZ station located in the North Pacific (42.5°N, 152.5°W). Here we use r_ H_{uc} to denote the increase in acidification by a weaker buffering capacity and r_ΔC_{ant} to denote decrease in acidification by weaker ventilation.

Lines 443-465. How were the threefold future ΔCant increase FU calculated? What CO2 emission scenario was used? What assumptions were used for the ΔpCO2 and Δ[H+] calculations for the FU?

Re: In the revised manuscript, we have added it on lines 439-456, pages 15-16: "In a similar manner, i.e., holding TA, S, T and nutrients constant and solely considering the effect of oceanic CO_{2ant} increase on DIC, we assessed the changes in acidification metrics at a single station in the North Pacific, when atmospheric CO_2 concentrations reach 560 ppm (twice the preindustrial value, Fig. 3), a level projected around 2075 under SSP2-4.5 and around 2050 under SSP5-8.5[86]. To do this, we first estimated the oceanic CO_{2ant} accumulation when atmospheric CO_2 concentrations reach 560 ppm, using the "transient steady state" concept[87] together with the "atmospheric perturbation" formulation[88]. Following Lauvset et al.[40], we assume the ocean's sensitivity to an atmospheric CO_2 perturbation—expressed as the oceanic CO_{2ant} change per unit change in atmospheric CO_2 (μmol kg^{-1} ppm^{-1})—remains constant. Under that assumption, the oceanic CO_{2ant} increase scales directly with the atmospheric increase[40,89,90]. Such that the increase in atmospheric CO_2 from 280 ppm (pre-industrial) to 373 ppm in 2002 (Δ = 93 ppm) corresponds to a known oceanic CO_{2ant} increase, ΔC_{ant_2002}; a further rise from 373 to 560 ppm (Δ = 187 ppm), being ~2× the earlier perturbation, would therefore add ~2·ΔC_{ant_2002} and yield a cumulative CO_{2ant} at 560 ppm of ~3× ΔC_{ant_2002} (~ three times the 2002 level). We note this approach likely overestimates future CO_{2ant} uptake because the oceanic sensitivity to atmospheric CO_2 diminishes at higher atmospheric CO_2 concentrations[40]. In addition, here we just perform a simplified estimate of how acidification metrics within OMZs will change under future atmospheric CO_2 increase, assuming no change in ocean circulation or ventilation over time."

Reviewer #2 (Remarks to the Author):

This manuscript makes a significant contribution to the literature by examining acidification rates in oxygen minimum zones (OMZs), which, although uninhabitable for many species, remain an important component of marine ecosystems. The manuscript is generally well written: the authors clearly state the main findings at the outset and guide the reader more or less smoothly through the results. The study shows that the OMZ regions experience relatively slow rates of ocean acidification, as poor ventilation limits exposure to anthropogenic carbon despite their higher concentrations of biologically produced CO2 and lower buffering capacities. The paper also discusses the mechanisms of how different carbonate system parameters can easily become decoupled, underscoring the importance of considering all four together. This point is relevant not only for experimental studies, but also for process studies in the ocean and for modeling efforts. Overall, I enjoyed reading the manuscript, and I have a few suggestions that could help clarify certain points and further improve the reading experience.

Re: Thanks very much for the recognition of our work.

To avoid confusion for readers, it would be helpful to clarify the basis of Figure 1. Is it derived from data or intended as a conceptual illustration? If it is meant as a thought experiment to illustrate the hypothesis, please consider specifying this in the figure caption.

Re: Figure 1 is a conceptual illustration and focuses on how seawater pCO_2 and $[H^+]$ change at different RF values when oceanic CO_{2ant} uptake occurs. So in the revised manuscript, the caption changed to "Fig. 1 Conceptual schematic of the combined influences of ΔC_{ant} and buffering capacities on acidification in terms of pCO_2 and $[H^+]$ changes. This conceptual schematic focuses on how seawater pCO_2 and $[H^+]$ change at different RF values when oceanic CO_{2ant} uptake occurs." on lines 78-80, page 4.

Lines 99-102: It would be helpful to clarify whether the reported changes in pCO_2 and H^+ are faster compared to neighboring well-ventilated areas, or only faster relative to pH and aragonite saturation state. I understood it as the latter, but revising the sentence to make this distinction explicit would avoid possible confusion.

Re: Here we want to show that changes in acidification metrics within the upper OMZs are detectable, with pH and Ω_{ara} declining more slowly than neighboring well-ventilated waters at similar depths but pCO_2 and $[H^+]$ rising more rapidly than neighboring well-ventilated waters. So to avoid possible confusion as suggested, this sentence has been revised to "Our results reveal that since the Industrial Revolution, changes in acidification metrics are negligibly minor in the lower OMZs, whereas within the upper OMZs, they are detectable, with pCO_2 and $[H^+]$ rising more rapidly but Ω_{ara}, pH, and RF showing slow changes than those in neighboring well-ventilated waters at similar depths." on lines 103-107, pages 4-5.

Lines 116–122 were a bit confusing. The text states that water in the upper boundary of the OMZ shows pCO_2 and H^+ deviations from changes in anthropogenic carbon and water age, but this point is not elaborated on until later in the next paragraph. To avoid confusing the reader, I suggest getting rid of this sentence here and addressing it fully when it is discussed later. In addition, the following sentence states that the focus is on changes within the OMZ. Will the authors also address what happens at the upper boundary, or is that beyond the scope? It might also be helpful to indicate important locations in Figure 2 and to refer more directly to the figure in the text so that readers can clearly follow the reasoning behind the conclusions. For example, use figure letters throughout the manuscript.

Re: We agree with you. Thus, in the revised manuscript, we have moved part of them to the last paragraph of the section: "From the sea surface down to the OMZ upper boundary, the magnitudes of ΔC_{ant}, $\Delta\Omega_{ara}$, and ΔpH generally decrease with depth, whereas the magnitudes of ΔpCO_2 and $\Delta[H^+]$ generally increase (Fig. 3f-i)." Also, this sentence "In this work, we focus primarily on the changes occurring within the OMZs compared to well-ventilated regions of similar water depth." has been changed to "In particular, we compare changes occurring within the OMZs with those in well-ventilated regions at similar water depth."

In addition, in Fig. 2a-c, we have indicated the locations of the OMZs and well-ventilated regions. The dashed purple line (water age contour of 300 years) shows the separation between upper and lower OMZs and well-ventilated regions. Also, we use figure letters through the revised manuscript.

In the paragraph starting on line 165, it might be helpful to briefly remind the reader that OMZs are often assumed to automatically have strong ocean acidification. While this point was explained in the introduction, restating it here would set up the findings in this paragraph more clearly and emphasize how the results contrast with that common expectation.

Re: Thanks for the good suggestion. In the revised manuscript, we add a sentence "Despite previously reported low-oxygen waters being more vulnerable to acidification due to lower buffering capacity[11,16-21], we find that changes in all acidification metrics remain negligibly minor in the lower OMZs (Fig. 2j-x and Table 1)." on lines126-128, pages 5.

Lines 193-196: "In contrast, 193 in the upper OMZs, moderate ventilation drives significant acidification, characterized by slower declines in pH and Ωara but more rapid rises in pCO2 and [H+] compared to neighboring well- ventilated waters." This section currently reads as if pCO_2 and H^+ are changing faster than in neighboring well-ventilated waters. Is that correct?

This seems related to the earlier point I raised, and I found it difficult to identify the basis for this statement. Are you referring to Figure 3? If so, it would help the reader to be guided through the relevant panels more explicitly to see how you arrived at the different conclusions. In addition, could you clarify how the rate of change of pH and aragonite saturation state was compared with that of H^+ and pCO_2? Were the variables normalized in some way?

Re: Thanks for the comments. We indeed compared the changes in acidification metrics in the OMZs with those in well-ventilated regions from the preindustrial era to the present. And we find that changes in acidification metrics within the upper OMZs are detectable, with pH and Ω_{ara} declining more slowly than neighboring well-ventilated waters at similar depths but pCO$_2$ and [H$^+$] rising more rapidly than neighboring well-ventilated waters. However, for the future case we did not compare the changes in acidification metrics in the OMZs with those in well-ventilated regions. So in the revised manuscript the previous sentence changed to "within the lower OMZs, in the future limited ventilation would still lead to minor and even negligible changes in all acidification metrics, while in the upper OMZs, moderate ventilation would drive significant acidification." on lines 202-204, pages 8. Thus, we did not compare the rates of change of pH and aragonite saturation state with those of H^+ and pCO$_2$.

Similarly, from line 269 onward, it would be helpful to refer directly to the figure and its subpanels so the reader can more easily follow the text.

Re: Thanks for the good suggestion. In the entire revised manuscript, we have added figure letters for corresponding subpanels.

In Figure 4, the black dashed arrow is difficult to see.

Re: Thanks. In the revised manuscript, these arrows have been bolded.

Line 288: with higher RF usually leading to the enhancement of sensitivity in pCO2, [H+] and pH, and the reduction of sensitivities in Ωara (Supplementary Table 2 and Supplementary Fig. 3).

Please check Orr's chapter in the OA book (chapter 3), as some of this was already nicely described in there.

Line 325: Therefore, when RF values are higher, pCO2 and [H^+] show greater sensitivity to ΔCant additions compared to that of Ωara – explained in Orr Chapter 3, OA book.

Re: Thanks for the good suggestion. In the revised manuscript, we have cited the work by Orr (2011) to explain the differences in sensitivities of these four acidification metrics. Thus, in the revised manuscript, the corresponding parts have been changed to "We find that these acidification metrics have different sensitivities, with higher RF usually leading to the enhancement of sensitivity in pCO_2, [H^+], and pH, and the reduction of sensitivity in Ω_{ara} (Supplementary Table 2 and Supplementary Fig. 5), similar to previous studies[21,47,51,52]." on lines 266-269, pages 10-11 and "As analyzed by Orr[52], we find that these differences stem from the fact that waters with higher RF values have lower initial concentrations of CO_3^{2-} and borate ions ($B(OH)_4^-$), and vice versa[54] (see Supplementary Fig. 7). In waters with higher RF, less CO_3^{2-} is available to neutralize the incoming CO_2 and thus more CO_2 is available to produce H^+." on lines 294-297, page 11.

overestimated by 20% globally, but later says that since this mainly affects the Southern Ocean it will not influence the results presented here. I suggest clarifying or rewriting this passage so that the reasoning is easier to follow.

Were the biases mentioned in the methods, for example overestimation of water age, discussed in relation to the results somewhere?

Can you elaborate on sentence 482? I cannot follow…

Re: Thanks for the good suggestion. In the revised manuscript, we have deleted this sentence "However, this overestimation in the Southern Ocean does not affect our results, as this study does not focus on those regions.", which could be misleading. In fact, the uncertainties in ΔC_{ant} from these assumptions and from other biases such as in measurement and mathematical mapping of the input data have been considered in calculating ΔC_{ant} by Lauvset et al. (2016). And we further calculated the total uncertainties in ΔC_{ant} induced changes for each acidification metric, which are presented in Supplementary Table 2 and Supplementary Fig. 2 in the Supplementary materials. Also, the previous sentence in line 482 has been rewritten as: "Specifically, the uncertainties in ΔpCO_2 ranged from 25 to 150 μatm, the uncertainties in Δ[H^+] ranged from 0.5 to 3.5 nmol kg^{-1}, the uncertainties in ΔpH ranged from 0.02 to 0.07 units, the uncertainties in $\Delta\Omega_{ara}$ ranged from 0.1 to 0.3 units, and the uncertainties in ΔRF ranged from 0.1 to 0.8 units." on lines 472-475, page 16.

References:

Broecker, W.S. and Peng, T.H., 1982. Tracers in the sea. The Lamont-Doherty Geological Observatory, Palisades, New York, 1-690 pp.

Cai, W.J. et al., 2011. Acidification of subsurface coastal waters enhanced by eutrophication. Nature Geoscience, doi:10.1038/ngeo1297.

Clement, D. and Gruber, N., 2018. The eMLR(C*) Method to Determine Decadal Changes in the Global Ocean Storage of Anthropogenic CO_2. Global Biogeochemical Cycles, 32, 654 – 679. https://doi.org/10.1002/2017GB005819.

Egleston, E.S., Sabine, C.L. and Morel, F.M.M., 2010. Revelle revisited: Buffer factors that quantify the response of ocean chemistry to changes in DIC and alkalinity. Global Biogeochem. Cycles, 24(1): GB1002.

Fassbender, A.J. et al., 2023. Amplified Subsurface Signals of Ocean Acidification. Global Biogeochemical Cycles, 37, e2023GB007843. https://doi.org/10.1029/2023GB007843.

Gammon, R.H., Cline, J. and Wisegarver, D., 1982. Chlorofluoromethanes in the northeast Pacific Ocean: Measured vertical distributions and application as transient tracers of upper ocean mixing. Journal of Geophysical Research: Oceans, 87(C12): 9441-9454.

Lauvset, S.K. et al., 2016. A new global interior ocean mapped climatology: the 1° × 1° GLODAP version 2. Earth Syst. Sci. Data, 8(2): 325-340.

Lauvset, S.K. et al., 2020. Processes Driving Global Interior Ocean pH Distribution. Global Biogeochemical Cycles, 34,e2019GB006229. https://doi.org/10.1029/2019GB006229.

Meinshausen, M. et al., 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci. Model Dev., 13(8): 3571-3605.

Müller, J.D. and Gruber, N., 2024. Progression of ocean interior acidification over the industrial era. Science advances, 10(48): eado3103.

Orr, J.C., 2011. Chapter 3 Recent and Future Changes in Ocean Carbonate Chemistry. In: J. Gattuso and L. Hansson *Ocean Acidification. Oxford University Press, pp. 41-66.

Ríos, A.F., Velo, A., Pardo, P.C., Hoppema, M. and Pérez, F.F., 2012. An update of anthropogenic CO_2 storage rates in the western South Atlantic basin and the role of Antarctic Bottom Water. Journal of Marine Systems, 94: 197-203.

Tanhua, T., Körtzinger, A., Friis, K., Waugh, D.W. and Douglas, W.R.W., 2007. An Estimate of Anthropogenic CO_2 Inventory from Decadal Changes in Oceanic Carbon Content. Proceedings of the National Academy of Sciences of the United States of America, 104(9): 3037-3042.