

## Responses to editor:

We sincerely thank the editor and reviewer for the thorough evaluation of our manuscript and constructive suggestions provided. We have carefully considered each comment and made corresponding revisions to improve the clarity, accuracy, and overall quality of the work. Below, we provide a detailed, point-by-point response to all comments.

The reviewers find the study conceptually strong but agree that substantial revisions are required. Both emphasize that while you provided useful clarifications in your responses, these must be explicitly integrated into the manuscript. Key issues include the need for a clearer discussion of atmospheric feedbacks and temperature responses as well as the omission of how the land carbon sink responds to OAE. In addition, the figures and presentation require revision to improve clarity, and the novelty of the river-based OAE framing should be articulated more strongly. Please address these points thoroughly in your revision and demonstrate how changes were incorporated. The revised manuscript will be sent back to the reviewers for reassessment.

We thank you for the careful review of our manuscript and the valuable comments and suggestions that you have provided. Your professional insights have been instrumental in helping us improve the quality and rigor of the paper, and we greatly appreciate the time and effort you have dedicated to this process.

Key issues include the need for a clearer discussion of atmospheric feedbacks and temperature responses as well as the omission of how the land carbon sink responds to OAE.

Indeed, both reviewers raised similar concerns. We have addressed these points in detail in our reply letter and provide a summary of the questions and our responses below.

Reviewer #2, for example, highlighted the following issue:

“269-282: The DIC decrease in the Southern Ocean and equatorial Pacific is not mentioned? This is an apparent phenomenon, and overlooking it is weird. This may be due to the atmospheric feedback effects present in the ESM, for example, the ALK injection in the northern oceans reducing PCO<sub>2</sub>atm, which could have led to net outgassing in the Southern Ocean. However, further analysis is needed to confirm this. A more detailed analysis of the atmospheric and surface ocean PCO<sub>2</sub> outputs for both the CTRL and experimental groups is necessary to determine whether the DIC decrease is due to atmospheric feedback or other mechanisms.”

Our analysis shows that in the Southern Ocean, the difference between atmospheric and oceanic surface ocean *p*CO<sub>2</sub> is smaller in the OAE simulations than in the control run (Fig. S2), indicating enhanced outgassing under OAE. This mechanism likely

explains the observed DIC decrease and becomes more pronounced with higher levels of alkalinity addition (Fig. S3), consistent with the reviewer's expectation.

However, this explanation applies only where the atmospheric CO<sub>2</sub> decrease exceeds the corresponding seawater *p*CO<sub>2</sub> decrease. In the equatorial Pacific, the OAE-induced reduction in seawater *p*CO<sub>2</sub> is comparable to that in atmospheric CO<sub>2</sub>, resulting in only a slight reduction in outgassing and a small net increase in DIC inventory. We have added these clarifications to Section 3.3 of the revised manuscript in line 296-302.

*"A slight reduction of DIC inventory is observed in the Southern Ocean under the three continuous OAE simulation relative to the control, with the intensification of this reduction under higher alkalinity addition levels (Fig. 6b-d and Fig. S3). This phenomenon is attributable to the fact that OAE effectively lowers atmospheric CO<sub>2</sub> concentrations, thereby inducing an enhanced outgassing in the Southern Ocean and ultimately leading to a net DIC inventory loss there (Fig. S4)."*

Reviewer #1 raised the following concerns on the temperature responses:

L334-335 Does this mean the reductions in atmospheric air temperatures are not proportional to OAE? This is an important finding and requires discussion which appears to be absent. Why do the authors think this is the case? Is this because of internal variability? Are larger ensemble sizes of each experiment required?

We think these disproportional reductions of temperature are relative to the smaller atmospheric CO<sub>2</sub> declines which only lead to a 10% decrease of temperature compared to the temperature increase under esm-SSP585 scenario. Thus, the interannual temperature cover up the temperature decrease induced by riverine OAE. We have added these discussions in our discussion section in line 507-512.

*"We also find the reductions in surface air temperature are not proportional to alkalinity addition. This is because the slight cooling induced by OAE is smaller than the interannual variability simulated by the model, and is therefore obscured by internal climate variability (Lenton et al., 2018). We believe this phenomenon warrants further investigation with larger ensembles or longer simulations to confirm its robustness."*

Reviewer #1 also asked how the land carbon sink responds to OAE. To answer this question, we have integrated the total column carbon in land as the land carbon sink. We find the land carbon sink decreases by 4.31, 7.05 and 9.20 PgC in the simulation of OWE5, OWE75 and OWE10 respectively. We have added these results in discussion section in line 493-498.

*"Moreover, the increase in ocean carbon uptake is partially offset by a corresponding decrease in the land carbon sink of -4.31, -7.05 and -9.20 PgC in the OWE5, OWE75*

*and OWE10 simulations, respectively. These results underscore the importance of considering terrestrial carbon dynamics when evaluating the net effectiveness of OAE. To avoid offsetting the benefits of OAE, complementary strategies to preserve or enhance land carbon sequestration may be necessary.”*

In addition, the figures and presentation require revision to improve clarity, and the novelty of the river-based OAE framing should be articulated more strongly.

We have revised all the figures, enlarged the size of the legends to make the figures clearer.

The revised manuscript and responses to all reviewers are attached to this letter. We believe these revisions will enhance the overall quality of the manuscript.

1    **Response to Reviewer #1**

2    We sincerely thank the reviewer for their insightful and constructive comments. We  
3    appreciate the acknowledgment that expanding the diversity of OAE simulation  
4    studies is important. Below, we provide a point-by-point response to the main  
5    concerns raised.

6    **General Comments**

7    The following article addresses the impact of river-focused ocean alkalinity enhancement  
8    on carbon dioxide removal. It present's findings that mCDR broadly scales with OAE as  
9    other studies have similarly shown. While I believe that it's important to expand the  
10   number of OAE simulation studies and varying the means of alkalinity delivery is critical,  
11   the article is not particularly interesting. The authors could do more to differentiate their  
12   contribution, particularly given their use of an emissions-driven ESM. I was particularly  
13   surprised that they focus so little on changes in atmospheric temperatures, which appear  
14   counterintuitive. Moreover, there is no description at all of the land carbon sink and how  
15   it responds to OAE (one of the principal advantages of using a fully-coupled ESM). I  
16   would like to see both of these aspects developed in a revised manuscript. In my opinion,  
17   several of the current figures need cutting or revising to be useful to the reader.

18    **In the following, we address the general comments individually, providing  
19   responses to each point.**

20    **Reviewer Comment:** “The article is not particularly interesting. The authors could do  
21   more to differentiate their contribution, particularly given their use of an emissions-  
22   driven ESM.”

23    **Response:**

24    We appreciate the suggestion and have revised the manuscript to better emphasize the  
25   novelty of our work. Specifically, our study:

26       • Implements *river-based* alkalinity enhancement, reflecting a natural and  
27        spatially realistic pathway of alkalinity delivery that differs from the  
28        commonly assumed uniform ocean-wide input.

29       • Uses an *emissions-driven*, fully coupled Earth System Model (CESM2), which  
30        allows for two-way interactions between climate, ocean chemistry, and carbon  
31        fluxes—features not captured in prescribed-CO<sub>2</sub> simulations.

32       • Explores *termination effects* of OAE (OWE0) in addition to scaling scenarios,  
33        providing insights into persistence and reversibility of OAE-induced changes.

34    We have added more discussion on the temporal changes of air temperature and land  
35        carbon sink. We also reemphasize the novelty and highlight the contributions of the  
36        current work in the revised manuscript and also as follows.

37 In line 108-115, we emphasize the novelty of our study:

38 “...To mimic this mechanism, we use an emission-driven, fully coupled Earth System  
39 Model to evaluate a riverine-based, global-scale OAE scenario under a high-emission  
40 pathway (Shared Socioeconomic Pathway 5-8.5, SSP585), which reflects a natural  
41 and spatially realistic pathway of alkalinity delivery that differs from the commonly  
42 assumed uniform ocean-wide input. The responsive CO<sub>2</sub> concentration configuration  
43 in our simulation allows the interactions between climate, ocean chemistry and  
44 carbon fluxes and captures the features not captured in prescribed-CO<sub>2</sub> simulations.”

45 In line 120-123, we highlight the contributions of this work:

46 “This study provides the transient responses of ocean system to OAE and insights into  
47 persistence and reversibility of OAE-induced changes, as well as the suggestion to  
48 future study and deployment of OAE.”

49 In line 507-512, we discuss the changes of air temperature:

50 “...We also find that reductions in surface air temperature are not proportional to the  
51 level of alkalinity addition. This is because the slight cooling induced by OAE is  
52 smaller than the interannual variability simulated by the model, and is therefore  
53 obscured by internal climate variability (Lenton et al., 2018). We believe this  
54 phenomenon warrants further investigation with larger ensembles or longer  
55 simulations to confirm its robustness.”

56 In line 493-498, we calculate and discuss the land carbon sink:

57 “Moreover, the increase in ocean carbon uptake is partially offset by a corresponding  
58 decrease in the land carbon sink of -4.31, -7.05, and -9.20 PgC in the OWE5,  
59 OWE75, and OWE10 simulations, respectively. These results underscore the  
60 importance of considering terrestrial carbon dynamics when evaluating the net  
61 effectiveness of ocean alkalinity enhancement. To avoid offsetting the benefits of OAE,  
62 complementary strategies to preserve or enhance land carbon sequestration may be  
63 necessary.”

64 **Reviewer Comment:** “I was particularly surprised that they focus so little on changes  
65 in atmospheric temperatures, which appear counterintuitive.”

66 **Response:**

67 We thank the reviewer for highlighting this important and counterintuitive aspect of  
68 our results. In the revised manuscript, we have expanded the Discussion section to  
69 address the changes in atmospheric temperature under riverine OAE scenarios.

70 Our results show that reductions in surface air temperature are not proportional to the  
71 amount of alkalinity added. This disproportionality is primarily due to the relatively  
72 modest declines in atmospheric CO<sub>2</sub>, which lead to only a ~10% decrease in  
73 temperature relative to the projected warming under the baseline esm-SSP585  
74 scenario. As a result, the temperature reductions associated with OAE are small and  
75 largely masked by interannual variability in the Earth system model.

76 We have added the discussion about surface air temperature change in line 507-512

77 *“...We also find that reductions in surface air temperature are not proportional to the  
78 level of alkalinity addition. This is because the slight cooling induced by OAE is  
79 smaller than the interannual variability simulated by the model, and is therefore  
80 obscured by internal climate variability (Lenton et al., 2018). We believe this  
81 phenomenon warrants further investigation with larger ensembles or longer  
82 simulations to confirm its robustness.”*

83 **Reviewer Comment:** “There is no description at all of the land carbon sink and how  
84 it responds to OAE (one of the principal advantages of using a fully-coupled ESM).”

85 **Response:**

86 We appreciate this insightful comment. In response, we have added more discussion  
87 in the revised manuscript that quantifies changes in the terrestrial carbon sink under  
88 each OAE scenario.

89 To evaluate the land carbon sink, we calculated the total column-integrated carbon  
90 over land areas. Our results show that the land carbon sink declines by 4.31, 7.05, and  
91 9.20 PgC in the OWE5, OWE75, and OWE10 simulations, respectively. These values  
92 have also been incorporated into the revised Discussion section in line 493-498, where  
93 we state:

94 *“...Moreover, the increase in ocean carbon uptake is partially offset by a  
95 corresponding decrease in the land carbon sink of -4.31, -7.05, and -9.20 PgC in the  
96 OWE5, OWE75, and OWE10 simulations, respectively. These results underscore the  
97 importance of considering terrestrial carbon dynamics when evaluating the net  
98 effectiveness of ocean alkalinity enhancement. To avoid offsetting the benefits of OAE,  
99 complementary strategies to preserve or enhance land carbon sequestration may be  
100 necessary.”*

101 **Reviewer Comment:** “Several of the current figures need cutting or revising to be  
102 useful to the reader.”

103 **Response:**

104 Thank you for this helpful suggestion. In response:

105 • We have removed Figure 1.  
106 • We have redrawn Figure 3 to make it clear.  
107 • Font sizes and color schemes have been adjusted throughout for better  
108 readability for figure 5.

109 We hope that these revisions improve the manuscript's readability and impact.

110

111 Specific Comments:

112 L26 Is this true? Wouldn't afforestation-based mCDR also absorb CO<sub>2</sub> and reduce acidification?

113 We agree with the reviewer that afforestation-based mCDR can also contribute to CO<sub>2</sub> removal and,  
114 indirectly, to the mitigation of ocean acidification. Afforestation enhances atmospheric CO<sub>2</sub> uptake  
115 through biological carbon sequestration, which in turn reduces the partial pressure of CO<sub>2</sub> in surface  
116 waters, thereby decreasing CO<sub>2</sub> dissolution and alleviating acidification (N'Yeurt et al., 2012). In  
117 contrast, OAE reduces acidification more directly by adding alkaline substances that chemically  
118 neutralize H<sup>+</sup> ions in seawater. To reflect this distinction and avoid overstating the uniqueness of  
119 OAE, we have revised the sentence as follows in line 26-27:

120 “...is one of the promising Carbon Dioxide Removal methods that can simultaneously absorb CO<sub>2</sub>  
121 and alleviate ocean acidification.”

122 L34-35 These are surface atmospheric temperature increases not SST increases I believe.

123 We are grateful to the reviewer for pointing out the mistake. We have revised this sentence  
124 accordingly as follows in line 34-37:

125 “...Global average surface atmospheric temperature has already increased by 1.1 °C relative to the  
126 1850–1900 baseline (IPCC, 2023) and continues to rise, approaching the Paris Agreement's target  
127 of limiting warming to below 1.5 °C by the end of this century (UNFCCC, 2015).”

128 L53 I would use a more recent estimate of this consistent with the latest scenarios (e.g. (Smith et al.,  
129 2024))

130 Thank you. The numbers have been updated according to estimate by Smith et al. (2024) in line 50-  
131 52:

132 “...However, an additional CO<sub>2</sub> sequestration requirement of -5.3 GtCO<sub>2</sub> per year is needed on the  
133 base of -2.1 GtCO<sub>2</sub> per year in 2011-2020 even under 76% greenhouse gas emission reduction  
134 (Smith et al., 2024).”

135 L59 Excluding geological reservoirs.

136 We sincerely thank you for pointing out the inaccurate expression in our manuscript. We have  
137 revised this sentence and describe the ocean as the largest carbon reservoir on Earth surface in line  
138 57-59.

139 *“...As the largest carbon reservoir at the Earth’s surface, the ocean holds substantial potential for*  
140 *enhanced CO<sub>2</sub> uptake.”*

141 L65-67 See previous point, other techniques could potentially also do this.

142 Agreed. We have adjusted the tone accordingly, both in our response and in the revised manuscript  
143 in line 64-66:

144 *“...Among these, OAE is promising because it offers the dual benefit of reducing atmospheric CO<sub>2</sub>*  
145 *and direct effect on alleviating ocean acidification, making it an ideal candidate for mitigating CO<sub>2</sub>-*  
146 *driven climate impacts through mCDR.”*

147 L68-70 This definition is a bit inaccurate. Alkalinity is perhaps better defined as the excess of H<sup>+</sup>  
148 accepters over donors.

149 Agreed. We have modified the definition accordingly, both in our response and in the revised  
150 manuscript in line 67.

151 *“Alkalinity is defined as the excess of proton acceptors over proton donators in seawater.”*

152 L70-71 This alkalinity decline may also be due to biotic feedbacks, (Barrett et al., 2025;  
153 Kwiatkowski et al., 2025).

154 Agreed. we have modified the sentence accordingly as follows and also in the revised manuscript  
155 in line 69-71:

156 *“...A decline in surface alkalinity, driven by enhanced upper-ocean stratification and bio-activity,*  
157 *has been shown to reduce oceanic carbon uptake (Barrett et al., 2025; Kwiatkowski et al., 2025).”*

158 L73 I’m not sure what excess H<sup>+</sup> is in this context.

159 We appreciate the reviewer’s comment. Our original intention was to describe the removal of  
160 additional protons resulting from ocean acidification. However, we agree that the term “excess H<sup>+</sup>”  
161 is potentially misleading and redundant with the accompanying description of rising pH. Therefore,  
162 we have removed this phrase in the revised manuscript.

163 In line 71-74, the revised sentence now reads:

164 “OAE works by introducing carbonate, bicarbonate, or other  $H^+$  acceptors into surface waters,  
165 thereby increasing carbonate ion concentrations, raising pH, and reducing the partial pressure of  
166  $CO_2$  ( $pCO_2$ ) in seawater.”

167 L74-75 Disequilibrium is not always enhanced. In areas of natural carbon outgassing, such as  
168 eastern boundary upwelling systems, it would likely be reduced. The net effect would be the same  
169 however, enhanced ocean carbon storage.

170 We thank the reviewer for this helpful clarification. We agree that air-sea  $CO_2$  disequilibrium is not  
171 uniformly enhanced across all regions, particularly in natural outgassing areas such as eastern  
172 boundary upwelling systems, where disequilibrium may actually be reduced. To improve clarity, we  
173 have revised the sentence accordingly in line 74-76:

174 “By altering the air-sea  $CO_2$  disequilibrium, OAE can enhance oceanic  $CO_2$  uptake in  
175 undersaturated regions and reduce outgassing in oversaturated regions, thereby increasing net  
176 ocean carbon storage and ultimately lowering atmospheric  $CO_2$  concentrations.”

177 L103-104 There are a growing number of regional OAE simulation studies that go beyond this,  
178 some of which the authors go on to cite.

179 Thank you for your suggestion. Now we have modified this sentence as follows in line 103-105:

180 “...Although there are a growing number of regional OAE simulations in recent years (e.g. Burt et  
181 al., 2021; Feng et al., 2017; He & Tyka, 2023), we still lack research using more practical delivery  
182 methods, such as river-based OAE.”

183 Figure 1. I don't find this figure particularly useful. The link between weathering and atmospheric  
184  $CO_2$  is unclear to me. Is this due to intensification of the hydrological cycle? And the role of sources  
185 and sinks of alkalinity in ocean sediments and marine biota is absent.

186 We have removed this figure.

187 L130 This equation is unnecessary (and is unnumbered).

188 Agreed. We have removed this equation.

189 L141 Add equation number.

190 Added.

191 L145-149. The language used here is not clear. Prescribed  $CO_2$  can still be transiently changing. Are  
192 simulations concentration-driven or emissions-driven? If emissions-driven, with dynamic  
193 atmospheric  $CO_2$  this needs to be explicit here.

194 We agree that in a prescribed CO<sub>2</sub> configuration CO<sub>2</sub> concentration will transiently change in  
195 atmosphere module. In such a setting, the atmospheric CO<sub>2</sub> forcing driving the ocean module  
196 changes in a fixed trajectory. Whereas, in a prognostic CO<sub>2</sub> configuration, atmospheric CO<sub>2</sub>  
197 concentration is dynamically changed according to the net strength of sources (e.g., emission) and  
198 sinks (e.g., land and ocean sinks). We expended the clarification of prognostic CO<sub>2</sub> in line 148-151:

199 *“...We use prognostic CO<sub>2</sub> settings to explore the responses of climate to OAE. In such a setting,  
200 dynamic atmospheric CO<sub>2</sub> forcing is used to drive the ocean and biogeochemistry module to avoid  
201 the uncertainty that stems from the difference between responsive and prescribed atmospheric CO<sub>2</sub>  
202 forcing to ocean (Tyka, 2025).”*

203 L153 “concentration” should be “emissions” as emissions not concentrations are prescribed in esm-  
204 hist.

205 Thank you for pointing this out. We have changed the “concentration” to “emissions”. In line 153-  
206 156:

207 *“When the climate is balanced with forcing, the historical simulation is performed as an emission-  
208 driven simulation using the historical atmospheric CO<sub>2</sub> emissions (esm-hist) prescribed by CMIP6  
209 protocol till the year of 2014.”*

210 L155 I don’t know what an SSP-based RCP is. You either ran an SSP or an RCP or is this some  
211 hybrid forcing I am not aware of.

212 Thank you for catching this mistake. We indeed used the emissions-driven SSP5-8.5 forcing  
213 scenario (esm-ssp585), not the concentration-driven variant. We have corrected the sentence in the  
214 revised manuscript to reflect this accurately. In line 156-157:

215 *“After that, the system is forced by an emission-driven SSP5-8.5 future scenario (esm-ssp585; Jones  
216 et al., 2016) till 2100.”*

217 L162-164 These simulation descriptions are confusing. What is meant by “based on... from 2050”?

218 In our simulation setup, we first ran the OWE5 scenario continuously from 2020 to 2100. Based on  
219 the conditions and outputs from the first 30 years of the OWE5 simulation, we then initialized three  
220 additional scenarios—OWE75, OWE10, and OWE0—starting from the year 2050 and continuing  
221 through 2100. In these latter simulations, the riverine alkalinity flux was modified relative to OWE5  
222 beginning in year 2050, corresponding to year 30 of the OWE5 run. In line 162-168:

223 “...

224 *Exp2 (OWE75): A 5-fold enhancement of riverine alkalinity flux is applied from 2020 to 2049,  
225 followed by an increase to a 7.5-fold enhancement from 2050 to 2100.*

226 *Exp3 (OWE10): A 5-fold enhancement of riverine alkalinity flux is applied from 2020 to 2049,*  
227 *followed by an increase to a 10-fold enhancement from 2050 to 2100.*

228 *Exp4 (OWE0): A 5-fold enhancement of riverine alkalinity flux is applied from 2020 to 2049,*  
229 *followed by complete cessation of alkalinity enhancement from 2050 to 2100.”*

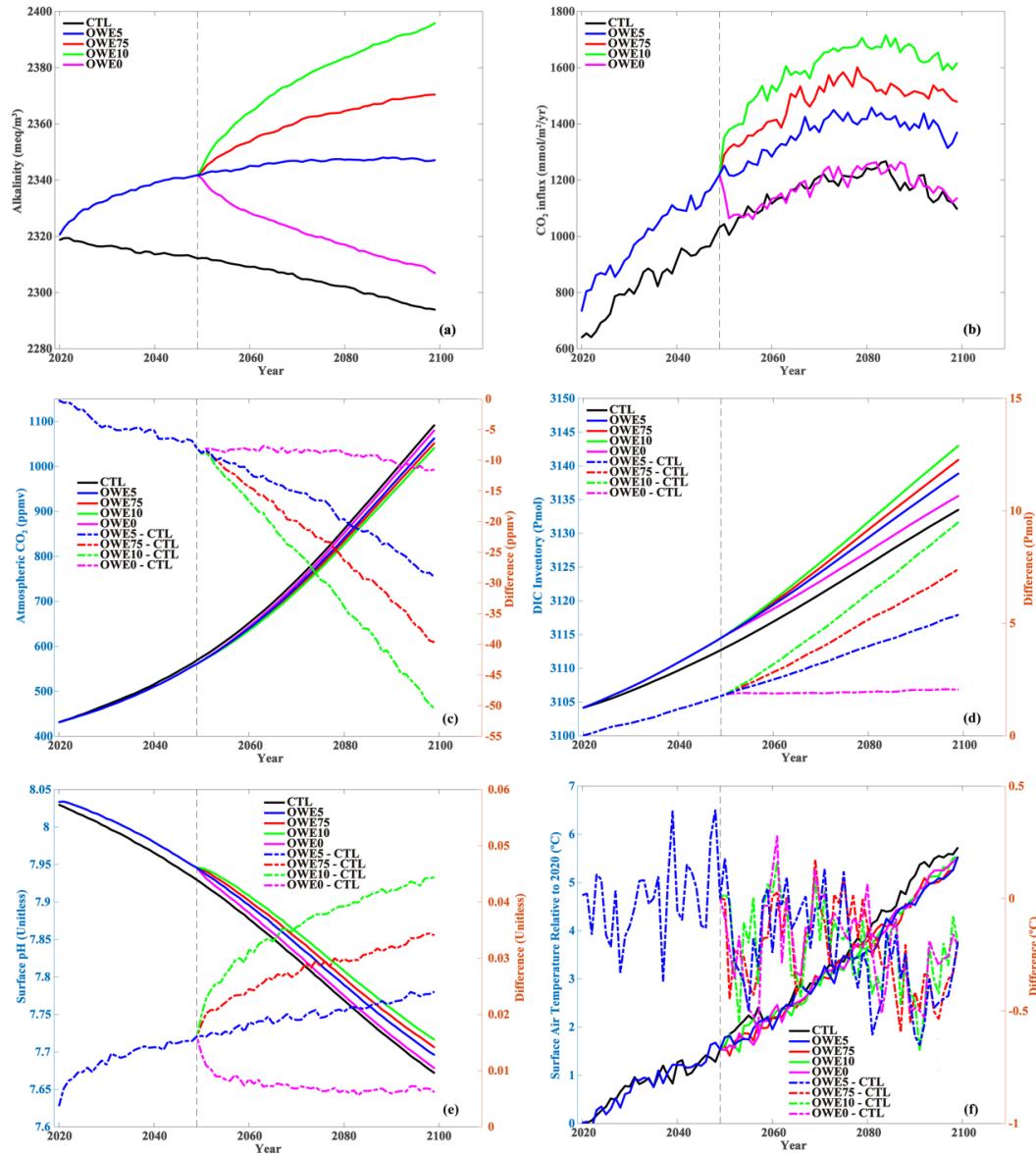
230 L165-169 Is the ocean alkalinity inventory balanced in the control run? Or is there some drift?

231 The model was spun-up by the community. In the spin-up runs, the burial of  $\text{CaCO}_3$  was tuned to  
232 balance the alkalinity input from rivers (Long et al., 2021). We do not rerun the spin-up phase and  
233 used the the restart files of the year 2020 obtained from data manager in CESM forum  
234 (<https://bb.cgd.ucar.edu/cesm/>). There may be still a trivial drift in these restart files, but it should  
235 not have a significant impact on our simulation because we conducted the control run and OAE  
236 simulations using the same restart file. Therefore, any drift should be canceled.

237 Figure 3 In printed format it is impossible to see any of the detail of this figure. Fonts are too small,  
238 lines to thin and legends impossible to read.

239 The image quality might be compressed when generating the PDF. In any case, we have redrawn  
240 the figure and made it clear. And now it is Fig.2.

241 “...



242

243 *Figure 2: Temporal changes of (a) mean alkalinity in the upper 100 m (unit: meq/m<sup>3</sup>), (b) CO<sub>2</sub> influx*  
 244 *(unit: mmol/m<sup>2</sup>/yr), (c) atmospheric CO<sub>2</sub> (unit: ppmv), (d) integrated DIC inventory (unit: Pmol),*  
 245 *(e) surface pH, (f) surface air temperature (unit: °C). Perpendicular grey dash lines in the year of*  
 246 *2050 denote the onset of the 7.5×, 10× alkalinity enhancement scenarios (OWE 75 and OWE10,*  
 247 *respectively), as well as the termination of alkalinity addition (OWE0). The coloured dash lines in*  
 248 *(c), (d), (e), (f) are the anomaly between OAE simulations and the control run.”*

249 L220 Clarify in the legend whether these are global zonal means or a specific transect.

250 Thank you. It is zonal mean. We have modified the legend of the Fig. 4 in our revised manuscript  
 251 as follows:

252 “...Figure 4: Vertical distribution of zonal mean alkalinity anomaly (upper 1500 m). (a) differences

253 *between OWE5 and CTL, (b) differences between OWE75 and CTL, c) differences between OWE10*  
254 *and CTL, (d) differences between OWE0 and CTL, (e) differences between OWE0 and OWE5. All*  
255 *the comparisons are based on the average of the last 10 years of simulation.”*

256 L225-226 See earlier point. OAE does not always enhance disequilibrium. If it does, I would like  
257 to see a plot of this.

258 We now have modified this part as follows in line 246-249:

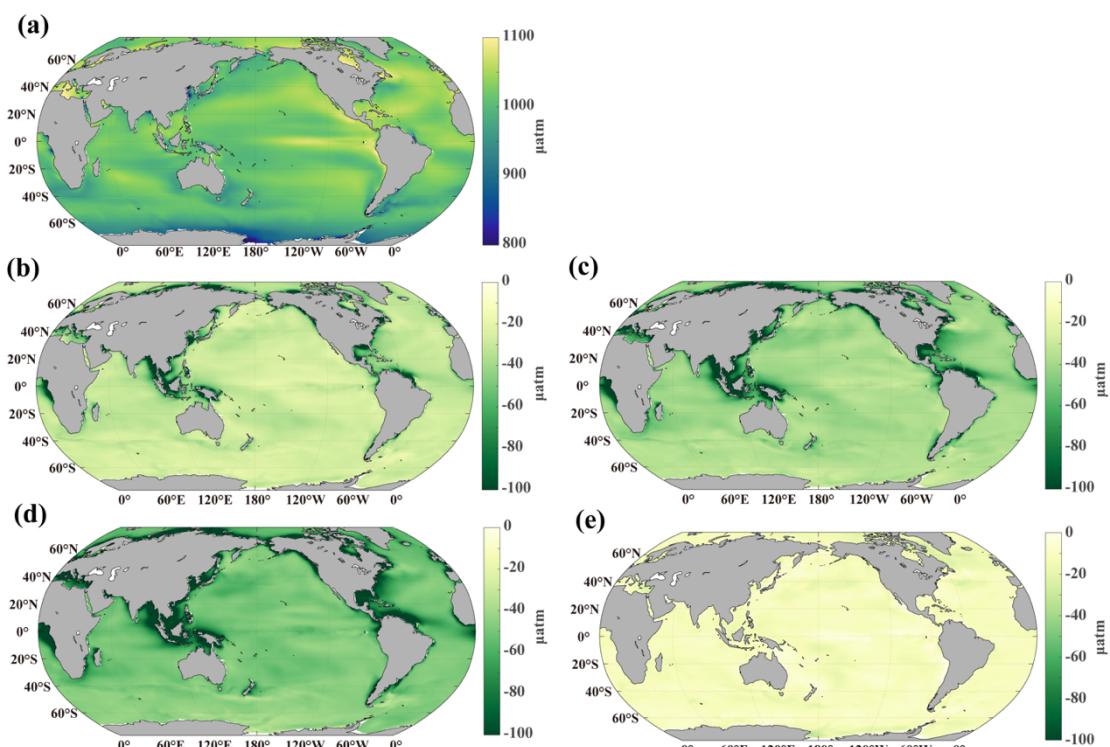
259 *“...OAE modifies the air-sea CO<sub>2</sub> gradient, promoting greater CO<sub>2</sub> absorption in areas where the*  
260 *ocean is undersaturated and diminishing CO<sub>2</sub> release in regions where it is supersaturated. This*  
261 *results in a net increase in ocean carbon storage and contributes to a reduction in atmospheric CO<sub>2</sub>*  
262 *levels.”*

263 L235 I think uatm units should be used for partial pressures.

264 Thank you for your suggestion. We have changed the units to uatm in line 254-257 and in Fig. 6:

265 *“In OWE5, OWE75, and OWE10, surface pCO<sub>2</sub> decreases by more than 20 µatm compared to the*  
266 *control, with OWE10 showing the greatest reduction. Although alkalinity addition is halted in 2050,*  
267 *surface pCO<sub>2</sub> remains slightly lower by ~10 µatm than in the control run even 50 years later*  
268 *(Fig. 5e).”*

269 “



270

271 **Figure 5: Distribution of surface pCO<sub>2</sub>. (a) control simulation, (b) difference**  
272 **between OWE5 and CTL, (c) difference between OWE75 and CTL, (d) difference**  
273 **between OWE10 and CTL, (e) difference between OWE0 and CTL. All the**  
274 **comparisons are based on the average of the last 10 years of simulation.**

275 "

276 L245 How much later? Give the year.

277 We have added the year in revised manuscript in line 266-267.

278 "...the CO<sub>2</sub> influx rapidly returns to the same rate as in the control simulation at the 5th year after  
279 termination (Fig. 2b).

280 L258 This seems like a trivial equation to provide, it's just a depth integral.

281 Agreed. The equation has been removed.

282 L308 I would avoid describing a global pH level as "healthy".

283 Thank you. We have changed the words as follows in line 338-340.

284 "... Under the high-emission SSP585 scenario, surface pH declines rapidly from a relatively high  
285 level (pH = 8.03) to a more acidic state (pH = 7.67) by 2100."

286 L332 The figure ordering is strange with respect to the text.

287 We double checked the ordering of all the figures and their appearance in the text, and have made  
288 sure that they are consistent.

289 L334-335 Does this mean the reductions in atmospheric air temperatures are not proportional to  
290 OAE? This is an important finding and requires discussion which appears to be absent. Why do  
291 the authors think this is the case? Is this because of internal variability? Are larger ensemble sizes  
292 of each experiment required?

293 Please reply to this comment in "General Comments" parts and have copied the  
294 content as follows:

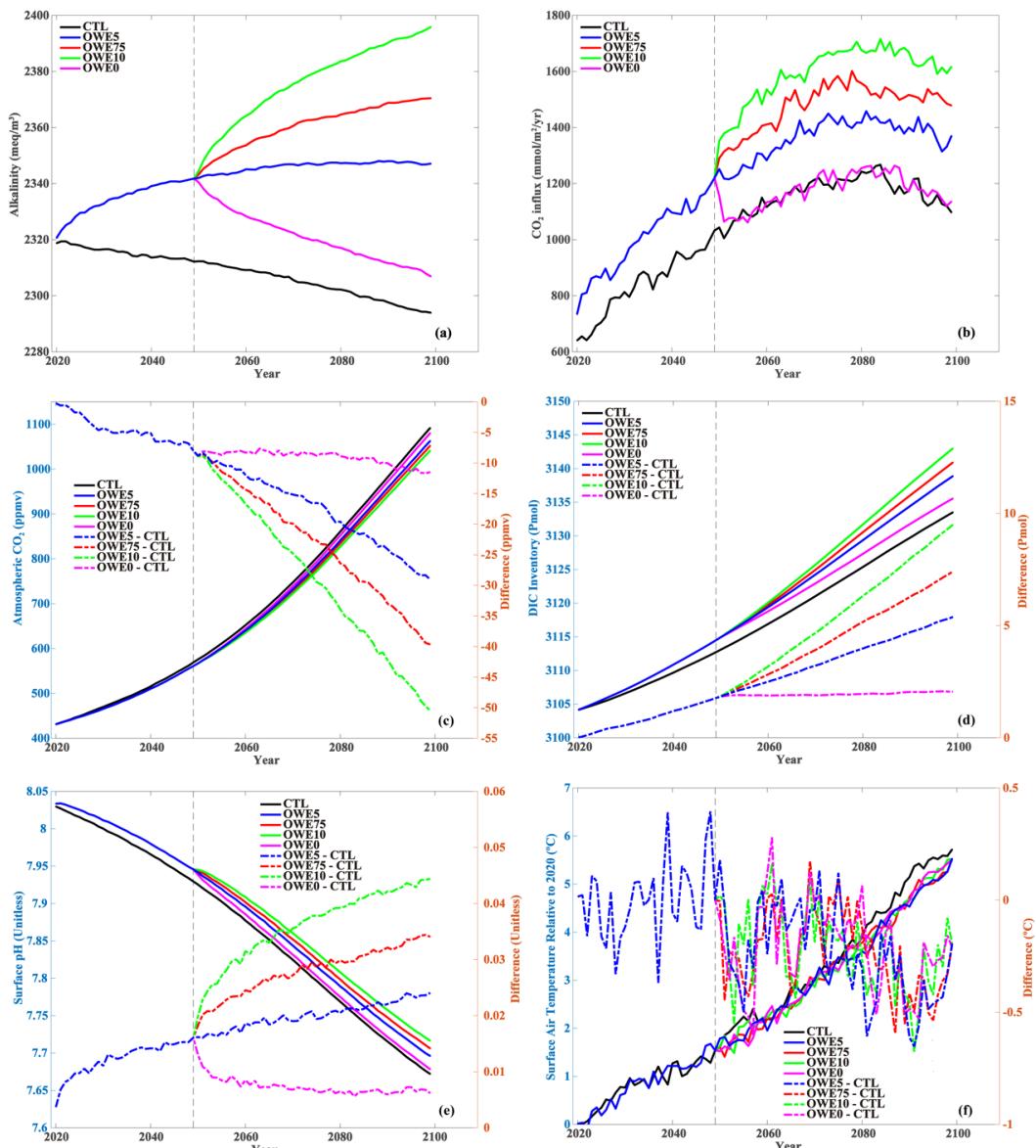
295 "...We also find that reductions in surface air temperature are not proportional to the  
296 level of alkalinity addition. This is because the slight cooling induced by OAE is  
297 smaller than the interannual variability simulated by the model, and is therefore  
298 obscured by internal climate variability (Lenton et al., 2018). We believe this

299 phenomenon warrants further investigation with larger ensembles or longer  
 300 simulations to confirm its robustness.”

301 L342 So the reductions in atmospheric CO<sub>2</sub> are consistent with the extent of OAE but not the  
 302 reductions in surface temperatures? Please discuss, perhaps the temperature values are type errors,  
 303 it's hard to see differences in figure 3.

304 Please see our reply to your previous comment. We have also redrew figures and rewording the the  
 305 legend.

306 “...



308 Figure 2: Temporal changes of (a) mean alkalinity in the upper 100 m (unit: meq/m<sup>3</sup>), (b) CO<sub>2</sub> influx  
 309 (unit: mmol/m<sup>2</sup>/yr), (c) atmospheric CO<sub>2</sub> (unit: ppmv), (d) integrated DIC inventory (unit: Pmol),

310 (e) surface pH, (f) surface air temperature (unit: °C). Perpendicular grey dash lines in the year of  
311 2050 denote the onset of the 7.5×, 10× alkalinity enhancement scenarios (OWE 75 and OWE10,  
312 respectively), as well as the termination of alkalinity addition (OWE0). The coloured dash lines in  
313 (c), (d), (e), (f) are the anomaly between OAE simulations and the control run.”

314 L367-368 It’s primarily due to the transport of water masses into the subsurface prior to full-  
315 equilibration.

316 Agreed. The characteristics of the water mass is also related to the location where the OAE is  
317 deployed. And different deployment methods of OAE also affect the dissolution rate of alkalinity,  
318 thereby influencing the efficiency of OAE. In this section, we have included information about water  
319 masses, thus making the discussion more comprehensive. In line 402-404:

320 “...*The wide range in previous studies is probably due to spatial and temporal variability, as well*  
321 *as differences in OAE application methods, which will influence the contact time between the water*  
322 *mass and the atmosphere and the time for water mass to reach equilibrium.*”

323 L383-375. Can the authors explain the role of the simulation time? Is this because of sediment  
324 feedbacks? Most ESMs lack such feedbacks anyway (see Planchat et al., 2023) so I’m not sure  
325 running the models for longer would make a difference.

326 Köhler (2020) demonstrate that the calcite saturation horizon and lysocline transition zones in  
327 sediment will deepen under OAE, which finally lead to an increase of CaCO<sub>3</sub> accumulation. This  
328 process extracts alkalinity from the ocean and reduces the efficiency of OAE. However, as you  
329 mentioned, most of the Earth System models did not consider the sediment processes in alkalinity  
330 cycle. We have added some discussions in this part.

331 In line 412-415:

332 “...*Most ESMs do not take into account sediment processes, or they treat sediment processes as a*  
333 *part of the closed calcium carbonate cycle without considering the complex processes of*  
334 *sedimentation (Planchat et al., 2023). The absence of sedimentation processes may lead to an*  
335 *overestimation of the efficiency of OAE on a longer time scale.*”

336 And in line 424-426:

337 “...*Although the short simulation in He and Tyka (2023) and our study likely missed the decline*  
338 *stage in adsorption efficiency in Köhler (2020), but the lack of sediment processes will overrate the*  
339 *efficiency later than 2100.*”

340 L386-389 Are these differences in efficiency robust? Have similar effects been detailed in other  
341 studies and if so, can the authors explain the mechanism controlling this?

342 We believe these differences in efficiency are robust. In previous studies, the efficiency of OAE  
343 along the coastal regions would show a rapid increase in the initial years, and then the growth rate  
344 would slow down, reaching a relatively slow efficiency growth rate or a stable efficiency level (e.g.  
345 He & Tyka, 2023). We believe that the lower efficiency in OWE10 is due to the increased magnitude  
346 of OAE. It has not yet reached a relatively stable efficiency stage by the end of this century, and  
347 thus its efficiency is slightly lower compared to the other two groups of experiments. However, we  
348 did not run the simulation from later than 2100, thus we cannot give the final efficiency.

349 L398-400 Be clear that Zhou et al perform OAE locally in all grid cells and don't rely on rivers for  
350 delivery.

351 Thank you. We have clarified the applying method of OAE in Zhou et al. (2024) in line 439-451.

352 “...Moreover, Zhou et al. (2024) reported that absorption efficiency is higher when OAE is applied  
353 in the equatorial Pacific than in subtropical regions. In contrast, our simulations show low  
354 absorption efficiency in the equatorial Pacific and only minimal increases in DIC inventory. We  
355 attribute this discrepancy to differences in the calculation methods. Zhou et al. (2024) applied OAE  
356 regionally, adding alkalinity to all grid cells within selected regions, and defined efficiency as the  
357 ratio of the global increase in DIC inventory to the total alkalinity added. Their finding of high  
358 efficiency in the equatorial Pacific is intuitive, as upwelling there spreads additional alkalinity  
359 across the surface ocean, enhancing CO<sub>2</sub> uptake. By contrast, in the subtropical gyres, which is  
360 characterized by convergence, added alkalinity is more readily subducted into the deep ocean,  
361 reducing efficiency. In our approach, however, efficiency is calculated locally as the ratio of the  
362 increase in DIC inventory to the increase in alkalinity within the same region when compared the  
363 regional efficiency. Under this definition, strong upwelling in the equatorial Pacific promotes CO<sub>2</sub>  
364 outgassing, resulting in lower efficiency.”

365 L458 How do these rates of acidification and carbon uptake compare to those in the CTL simulation?

366 We have calculated the pH decrease rate as the indicator of the acidification rate. We find the  
367 acidification has accelerated in OWE0 simulation after the termination of OAE with a rate of 0.0054,  
368 faster than 0.0047 (from 2020 to 2100) and 0.0053 (from 2050 to 2100) in control run. However,  
369 the carbon uptake rate (the influx of CO<sub>2</sub>, see Fig. 2b) decrease to the similar rate with control run  
370 under OWE0 at the 5th year after OAE termination.

371 L487-489 Indicative that even riverine OAE results in loss of non-equilibrated water masses from  
372 the surface ocean, which are equilibrated of ocean circulation timescales of centuries.

373 Thank you for your suggestion. We have added these discussions in our revised manuscript in line  
374 533-534:

375 “This indicates that water masses altered by OAE and not in equilibrium with the atmosphere will

376 *return to the surface through ocean circulation on centennial timescales.”*

377

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429

430

431    **Response to Reviewer #2**

432    We sincerely thank the reviewer for the thorough evaluation of our manuscript and  
433    constructive suggestions provided. We have carefully considered each comment and  
434    made corresponding revisions to improve the clarity, accuracy, and overall quality of  
435    the work. Below, we provide a detailed, point-by-point response to all comments.

436    Reviewer comment: “Zhu et al. (2025) discussed river-based ocean alkalinity  
437    enhancement (OAE) for carbon dioxide removal in Earth system models. The main  
438    innovation of this paper lies in its specific focus on river-based OAE, distinguishing it  
439    from previous studies that typically assumed OAE on a broader scale, such as in open  
440    ocean basins (i.e., Lenton et al., 2018) or coastal areas (He and Tyka, 2023).  
441    Additionally, in contrast to global studies that cover estuarine regions (e.g., Zhou et  
442    al. 2024), this study uniquely utilizes an emission-driven Earth System Model (ESM),  
443    which provides an opportunity to further investigate atmospheric feedback effects  
444    (Tyka, 2025). However, the manuscript appears to capture such feedback but does not  
445    yet attempt to further distinguish and discuss these atmospheric feedback effects.  
446    Refining this section would enhance the scientific significance of the paper.  
447    Furthermore, there is still room for improvement in the figures and presentation. I will  
448    provide specific suggestions for improvement in the following sections. Overall, the  
449    conceptual foundation of this research is solid, and revisions and improvements  
450    would make this paper a valuable contribution to the growing body of literature on  
451    ocean alkalinity enhancement models.”

452    We sincerely thank the reviewer for the thoughtful and encouraging comments  
453    regarding the novelty and conceptual foundation of our work. We appreciate the  
454    recognition of our study’s specific focus on river-based OAE and its use of an  
455    emission-driven Earth System Model (ESM), and we agree that further clarification  
456    and discussion of atmospheric feedback effects would enhance the manuscript’s  
457    scientific value.

458    Reviewer comment: “However, the manuscript appears to capture such feedback but  
459    does not yet attempt to further distinguish and discuss these atmospheric feedback  
460    effects. Refining this section would enhance the scientific significance of the paper.  
461    Furthermore, there is still room for improvement in the figures and presentation. I will  
462    provide specific suggestions for improvement in the following sections.”

463    We appreciate this suggestion and have expanded the discussion on atmospheric  
464    feedback effects in the Results and Discussion sections. Specific points are addressed  
465    in our responses to your individual comments.

466    In addition, we have improved the figures and their presentation by adding anomalies,  
467    enlarging labels and legends, and implementing other enhancements in line with the  
468    reviewer’s recommendations.

469 Reviewer comment: “Additionally, I would like to share an idea with the authors:  
470 Given that both Zhu et al. (2025) and Zhou et al. (2024) used the CESM2 framework  
471 but with different atmospheric components, and considering that Zhou et al. (2024)  
472 provide an OAE efficiency budget for various global regions, converting Zhou et al.  
473 (2024)’s open-source results to the same OAE injection areas as in Zhu et al. (2025)  
474 would not require significant additional work. However, this approach could provide  
475 potential insights into the differences in OAE budgets due to atmospheric forcing and  
476 feedback effects. Please note that this is beyond the scope of this review, and the  
477 authors are not required to address this suggestion in the revision.”

478 We thank you for this insightful suggestion. Indeed, we used the same CESM2  
479 framework as Zhou et al. (2024). However, Zhou et al. (2024) forced their model with  
480 historical atmospheric CO<sub>2</sub> concentrations from the Japanese 55-year Reanalysis  
481 dataset (JRA55) and assumed that the OAE perturbation in their simulations was too  
482 small to generate significant changes in atmospheric CO<sub>2</sub>. In contrast, our simulation  
483 employed a fully coupled, emission-driven CO<sub>2</sub> forcing under the esm-ssp585  
484 scenario. This key difference in model configuration means the two studies are not  
485 directly comparable. Nevertheless, we will consider your suggestion and endeavor to  
486 incorporate such comparative analyses in future work.

487 195: The subtropical gyres seem to contribute to two distinct ventilation regions in  
488 around 30°N and 30°S, which are analyzed in the Discussion section (paragraph at  
489 406) but are not mentioned in the Results. Furthermore, Fig. 3 shows that the  
490 distribution of ALK across global ocean basins is inconsistent. For example, the ALK  
491 excesses in the North Atlantic is significantly stronger than in the North Pacific.  
492 Therefore, it would be helpful to calculate the contents in Fig. 4 separately for the  
493 Atlantic, Pacific, and Indian Oceans. The same approach is also recommended for the  
494 DIC analysis in Fig. 8.

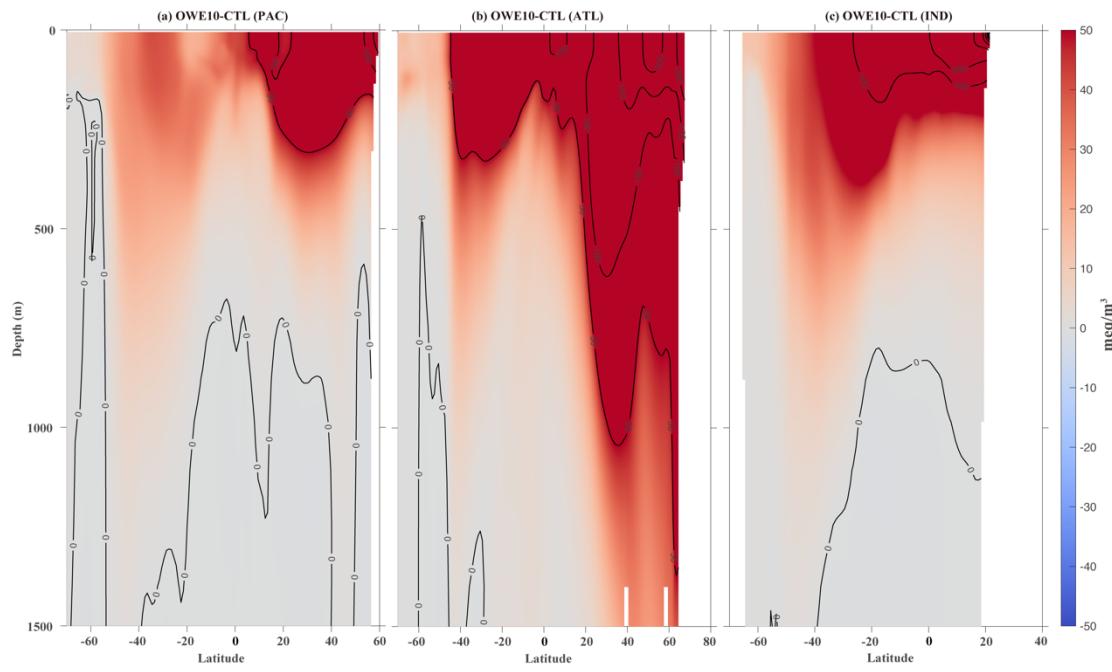
495 We thank the reviewer for this helpful suggestion. We have added the corresponding  
496 results in the section 3.1 and discussed more on the vertical anomaly of alkalinity  
497 along 150°W (PAC), 30°W (ATL) and 90°E (IND) transects under OWE10  
498 simulation as a case in this reply and revised manuscript. Figures are shown in this  
499 reply and in a supplementary file. In line 211-218 in our revised manuscript:

500 “...

501 *The distribution of alkalinity across global ocean basins exhibits heterogeneity. In the  
502 Pacific Ocean, a positive anomaly of alkalinity is observed within the upper 300-400  
503 m and penetrates deeper in both north and south subtropical gyres (Fig. S2a). The  
504 increase in alkalinity is greater in the north Pacific than in the south Pacific. The  
505 alkalinity anomaly in the Atlantic dominates the vertical distribution of zonal mean  
506 alkalinity anomaly, as there has the highest alkalinity increase and deepest  
507 penetration especially in SPNA as well as in subtropical gyres (Fig. S2b). In the*

508 Indian Ocean, the positive alkalinity anomaly also extends to greater depths within  
509 the subtropical gyres (Fig. S2c). ”

510

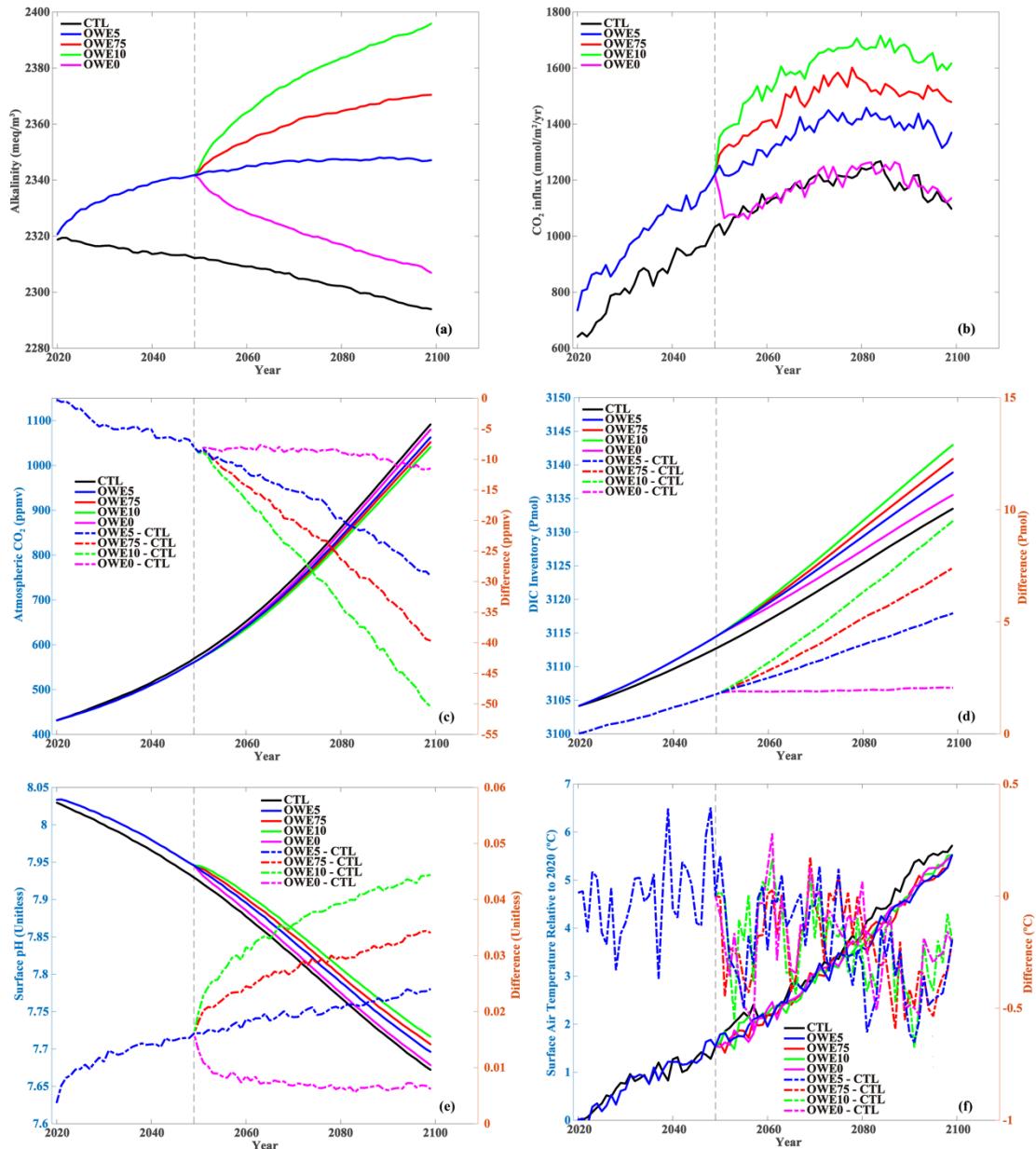


511 Figure S2. Vertical distribution of alkalinity anomaly along specific transects. (a)  
512 Differences between OWE10 and CTL along 150°W, represent the changes in the  
513 Pacific Ocean; (b) Differences between OWE10 and CTL along 30°W, represent the  
514 changes in the Atlantic Ocean; (c) Differences between OWE10 and CTL along 90°E,  
515 represent the changes in the Indian Ocean.

516 Fig. 3: It is recommended to use the anomaly for panels c-f, especially panel f. The  
517 differences between the curves in the current version are too small, which affects  
518 readability.

519 Thank you. We have added the anomaly in panels c-f and updated the figure in the  
520 revised manuscript.

521 “...



522

523 *Figure 2: Temporal changes of (a) mean alkalinity in the upper 100 m (unit:*  
 524 *meq/m<sup>3</sup>), (b) CO<sub>2</sub> influx (unit: mmol/m<sup>2</sup>/yr), (c) atmospheric CO<sub>2</sub> (unit: ppmv), (d)*  
 525 *integrated DIC inventory (unit: Pmol), (e) surface pH, (f) surface air temperature*  
 526 *(unit: °C). Perpendicular grey dash lines in the year of 2050 denote the onset of the*  
 527 *7.5×, 10× alkalinity enhancement scenarios (OWE 75 and OWE10, respectively), as*  
 528 *well as the termination of alkalinity addition (OWE0). The coloured dash lines in (c),*  
 529 *(d), (e), (f) are the anomaly between OAE simulations and the control run.”*

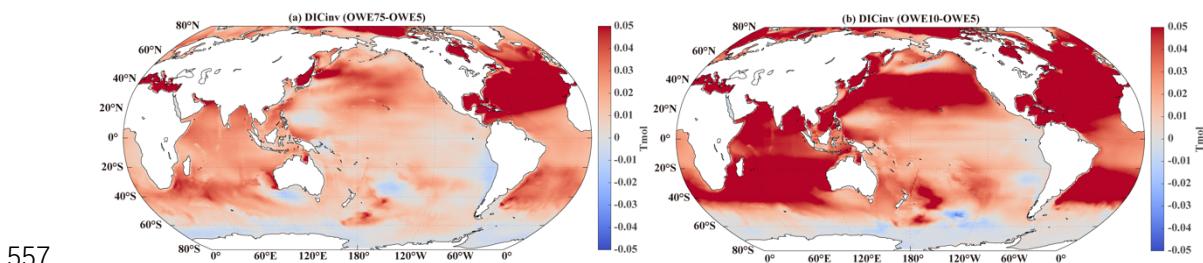
530 269-282: The DIC decrease in the Southern Ocean and equatorial Pacific is not  
 531 mentioned? This is an apparent phenomenon, and overlooking it is weird. This may  
 532 be due to the atmospheric feedback effects present in the ESM, for example, the ALK  
 533 injection in the northern oceans reducing PCO<sub>2atm</sub>, which could have led to net  
 534 outgassing in the Southern Ocean. However, further analysis is needed to confirm

535 this. A more detailed analysis of the atmospheric and surface ocean PCO<sub>2</sub> outputs for  
536 both the CTRL and experimental groups is necessary to determine whether the DIC  
537 decrease is due to atmospheric feedback or other mechanisms.

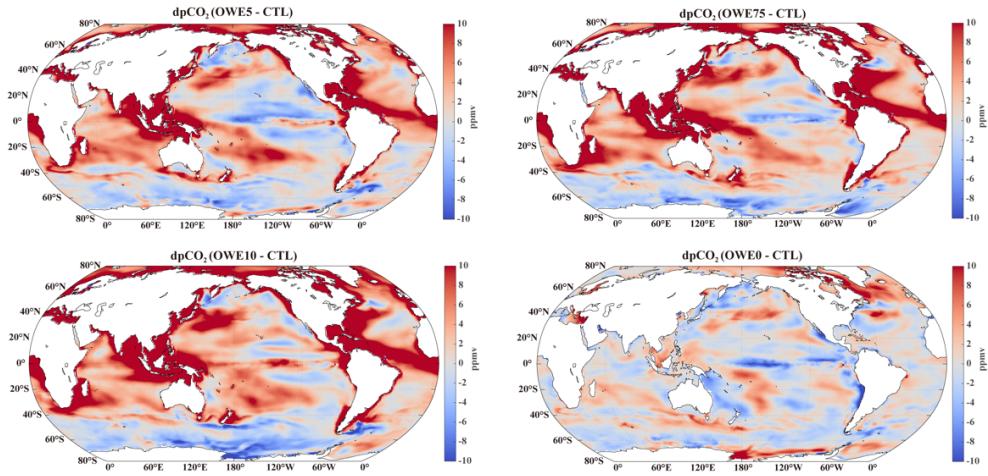
538 We thank the reviewer for highlighting this important point. Our analysis shows that  
539 in the Southern Ocean, the difference between atmospheric and surface ocean  $p\text{CO}_2$  is  
540 smaller in the OAE simulations than in the control run (Fig. S4), indicating enhanced  
541 outgassing under OAE. This mechanism likely explains the observed DIC decrease  
542 and becomes more pronounced with higher levels of alkalinity addition (Fig. S3),  
543 consistent with the reviewer's expectation.

544 However, this explanation applies only where the atmospheric CO<sub>2</sub> decrease exceeds  
545 the corresponding seawater  $p\text{CO}_2$  decrease. In the equatorial Pacific, the OAE-  
546 induced reduction in seawater  $p\text{CO}_2$  is comparable to that in atmospheric CO<sub>2</sub>,  
547 resulting in only a slight reduction in outgassing and a small net increase in DIC  
548 inventory. We have added these clarifications to Section 3.3 of the revised manuscript  
549 in line 296-302.

550 “...In contrast, the Southern Pacific exhibits only a modest increase. A slight  
551 reduction of DIC inventory is observed in the Southern Ocean under the three  
552 continuous OAE simulation relative to the control, with the intensification of this  
553 reduction under higher alkalinity addition levels (Fig. 6b-d and Fig. S3). This  
554 phenomenon is attributable to the fact that OAE effectively lowers atmospheric CO<sub>2</sub>  
555 concentrations, thereby inducing an enhanced outgassing in the Southern Ocean and  
556 ultimately leading to a net DIC inventory loss there (Fig. S4).”



558 Figure S3. Anomaly of DIC inventory. (a) difference between OWE75 and OWE5;  
559 (b) difference between OWE10 and OWE5.



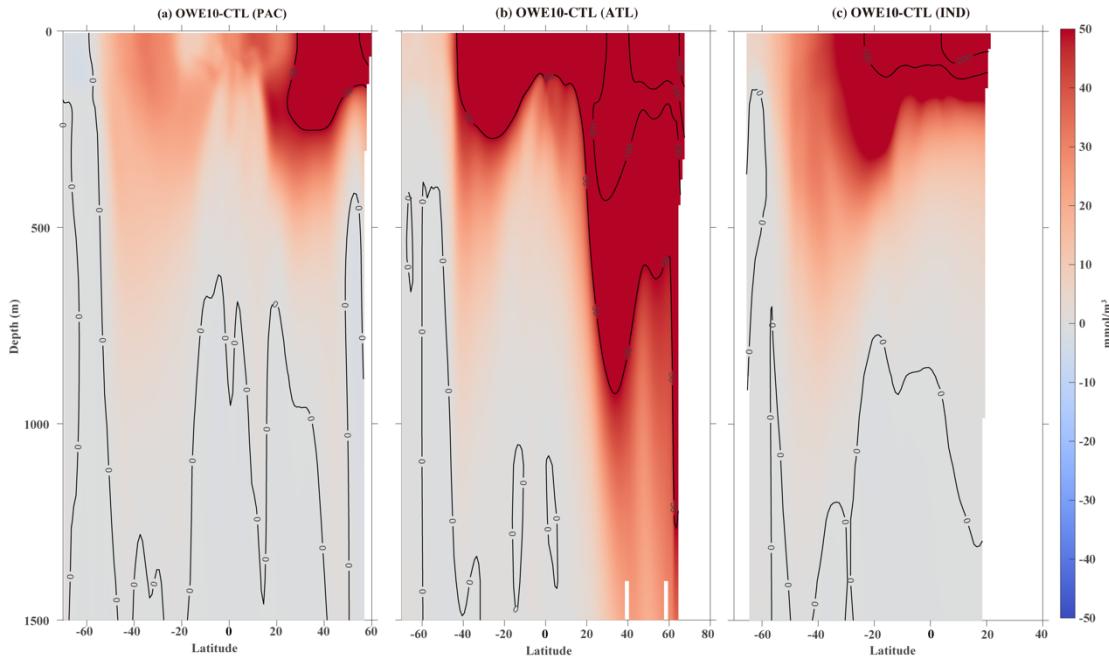
560

561 Figure S4. Anomaly of partial pressure of CO<sub>2</sub> between OAE simulations and the  
 562 CTL in the last 10 years of the end of simulation. The partial pressure difference  
 563 between the ocean and atmosphere is calculated by subtracting the pressure of CO<sub>2</sub> in  
 564 the ocean from the pressure of CO<sub>2</sub> in the atmosphere.

565 **Fig8: See suggestion for 195.**

566 Thank you. We have added further discussion on the vertical anomaly of DIC  
 567 concentration along 150°W (PAC), 30°W (ATL) and 90°E (IND) transects in this  
 568 reply and revised manuscript in line 312-318.

569 *“...from the surface to 200–300 m depth. The vertical anomaly of DIC concentration  
 570 across global ocean basins generally mirror the pattern of alkalinity anomaly. The  
 571 net CO<sub>2</sub> uptake induced by alkalinity injection results in DIC increase in most of  
 572 ocean basins. The subtropical gyres in all three basins facilitate the downward  
 573 transport of newly absorbed DIC, leading to the positive DIC anomalies in deeper  
 574 layers (Fig. S5a-c). However, unlike alkalinity, a reduction in DIC concentration is  
 575 evident in the high-latitude regions of the Southern Hemisphere, consistent with the  
 576 DIC inventory changes.”*



577

578 Figure S5. Vertical distribution of DIC concentration anomaly along 150°W (PAC),  
 579 30°W (ATL) and 90°E (IND) transects. (a) Differences between OWE10 and CTL  
 580 along 150°W, representing the changes in the Pacific Ocean; (b) Differences between  
 581 OWE10 and CTL along 30°W, representing the changes in the Atlantic Ocean; (c)  
 582 Differences between OWE10 and CTL along 90°E, representing the changes in the  
 583 Indian Ocean.

584 320: It is recommended to provide a more detailed explanation for the increase in the  
 585 North Atlantic in OWE0, particularly in Hudson Bay and the Northwestern Channel.  
 586 Additionally, a noticeable pH increase is also observed in the Ross Sea. Is this related  
 587 to sea ice or outgassing? Further analysis and clarification would be beneficial.

588 We thank the reviewer for this valuable suggestion. In Hudson Bay and the  
 589 Northwestern Channel, alkalinity accumulates during the first 30 years of OAE (Fig.  
 590 S1). The narrow passages in these regions restrict exchange with the open ocean,  
 591 allowing alkalinity to persist locally. After OAE termination, this accumulated  
 592 alkalinity acts as a residual “source” that is advected to the SPNA, sustaining elevated  
 593 alkalinity and pH in both Hudson Bay and the SPNA relative to the control run.

594 In the Ross Sea, the observed pH increase also reflects higher alkalinity. The model  
 595 shows a modest alkalinity rise in the 2090s (Fig. S1), likely due to upwelling of water  
 596 masses carrying excess alkalinity originating from earlier OAE. This upwelled  
 597 alkalinity is the most plausible driver of the elevated pH in this region.

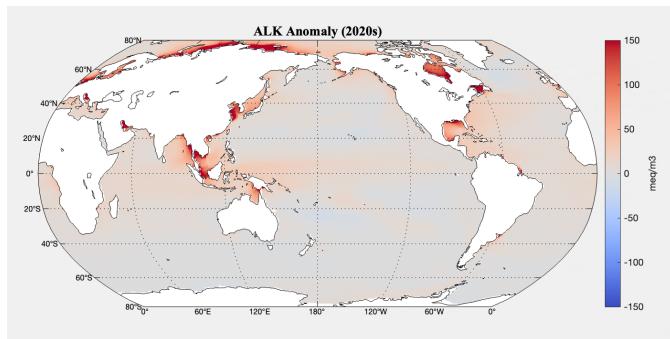
598 We have incorporated these explanations into Sections 3.1 and 3.4 of the revised  
 599 manuscript in line 198-203, and will include the supporting figures in the  
 600 supplementary material:

601     “...The accumulation and later release of alkalinity in the Hudson Bay is a potential  
602     reason why alkalinity in the SPNA remains relatively high even after alkalinity  
603     enhancement has ceased. During the first 30 years of OAE, alkalinity is accumulated  
604     and retained in this region due to the narrow passages in Northwestern Channel and  
605     Hudson Bay. When the OAE terminated, this accumulated alkalinity becomes a new  
606     “source”, which is transported to the SPNA and effectively maintains the alkalinity  
607     compared to the control group (Fig. S1).”

608     And in section 3.4, we have explained the increase of pH in SPNA and Ross Sea. In  
609     line 352-357:

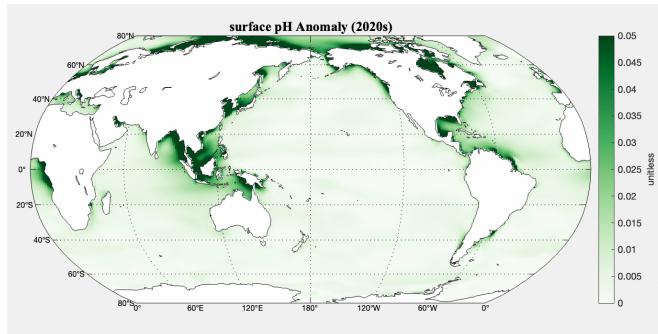
610     “...As expected, greater alkalinity additions correspond to stronger pH buffering.

611     Although alkalinity input ceases in OWE0, this scenario still shows a slight increase  
612     in surface pH compared to the control, particularly in the SPNA (Fig. 8e) where there  
613     are pronounced alkalinity increase compared to the control. However, this increase is  
614     considerably smaller than those observed in the continuous OAE treatments. We also  
615     find an increase of pH in the Ross Sea by the end of this century, which is attributable  
616     to the upwelling-mediated return of OAE-induced alkalinity to the surface, thereby  
617     elevating surface pH (Fig. S6).”



618

619     Figure S1. Alkalinity anomaly in OWE0 compared to CTL during simulation phase.



620

621     Figure S6. Surface pH anomaly in OWE0 compared to CTL during simulation phase.

622 332-334: The result is reasonable, but comparing the temperature values at a single  
623 time point is not appropriate. It is recommended to use the average temperature over  
624 the last 10 years or a similar metric for the analysis.

625 We appreciate the reviewer's comment. We actually compared the average  
626 temperature of the last 10 years between CTL and other OAE simulation. We have  
627 revised our manuscript in line 367-369 and make this comparison much clearer.

628 *"All the four OAE treatments show a slight decrease of temperature in the last 10  
629 years of this century, with 0.45 °C in OWE5, 0.39 °C in OWE75, 0.34 °C in OWE10,  
630 and 0.31 °C in OWE0 compared to CTL (Fig. 2f)."*

631 417-438: Recommend to streamline this section, as it currently appears more like a  
632 literature review rather than a targeted discussion.

633 We thank the reviewer for this constructive suggestion. In the revised manuscript, we  
634 have streamlined the paragraph to focus on the key challenges relevant to our study,  
635 while retaining only the most essential contextual references. The revised text now  
636 emphasizes the implications of alkalinity loss and material constraints for river-based  
637 OAE, rather than providing an extended literature survey. This change makes the  
638 discussion more concise and targeted. In line 463-472:

639 *"One of the most critical challenges in OAE is alkalinity loss through precipitation,  
640 which can rapidly reduce efficiency (Moras et al., 2022). The extent of this loss  
641 depends on the type and form of added material, solution state, and presence of  
642 particles (Hartmann et al., 2023). For riverine OAE, substantial losses may occur in  
643 estuaries, making it essential to regulate addition rates. CO<sub>2</sub>-equilibrated alkaline  
644 solutions and certain Mg-rich minerals can help limit precipitation (Jones, 2017; Pan  
645 et al., 2021), though some, like olivine, may still be less efficient due to particle-  
646 induced losses (Fuhr et al., 2022). Using finely ground particles can improve  
647 dissolution but increases energy costs, while particles in river plumes can promote  
648 heterogeneous precipitation (Wurgauf et al., 2021). These factors highlight the need  
649 for careful material selection and delivery design to minimize losses in real-world  
650 applications."*

651 Minor comments:

652 Figures 3-8: The numbering of the subplots, the legend, and the labels have fonts  
653 that are too small and need to be enlarged. Figures suffer from low image resolution,  
654 which affects readability. Please ensure that the images in the final published version  
655 are clear.

656 We have enlarged the labels and legends in our revised manuscript. And we will make  
657 sure the images clear in our final version.

658 203:50-70N? There is a difference with Fig. 5d.

659 Agreed. We have revised the latitude range in line 219-220.

660 “...Although alkalinity addition ceases after 2050 in the OWE0 simulation, a positive  
661 alkalinity anomaly persists through 2100, reaching depths of 1500 m near 50°–  
662 70°N.”

663 226: It is suggested to indicate the time of comparison here or in the caption of Fig. 6.  
664 Although it is provided later, it has not been explained earlier.

665 Agreed. We have revised our manuscript accordingly in 246-249:

666 “...OAE modifies the air-sea CO<sub>2</sub> gradient, promoting greater CO<sub>2</sub> absorption in  
667 areas where the ocean is undersaturated and diminishing CO<sub>2</sub> release in regions  
668 where it is supersaturated (Fig. 5). This results in a net increase in ocean carbon  
669 storage and contributes to a reduction in atmospheric CO<sub>2</sub> levels.”

670 245: Considering that the rate of rebound is rapid, "rapidly returns" would be more  
671 appropriate than "eventually returns".

672 We appreciate for your suggestion. We have changed “eventually returns” to “rapidly  
673 returns” in revised manuscript in line 265-267.

674 “...When alkalinity addition ceases in 2050 (OWE0), the CO<sub>2</sub> influx rapidly returns to  
675 the same rate as in the control simulation (Fig. 2b).

676 392: Fig 4, not 3.

677 Thank you. We have corrected this. We have deleted the Fig.1 in our revised  
678 manuscript according to the Reviewer #1, thus it finally is Fig. 3. In line 432-433

679 “...Although alkalinity is introduced via rivers, its effects extend to the open oceans,  
680 with more pronounced impacts observed in the Atlantic and Indian Oceans compared  
681 to the Pacific (Fig. 3).”

682 395: The logic seems unclear. It is recommended to rephrase as: Compared to the  
683 North Atlantic, the western boundary current of the North Pacific occurs outside the  
684 island chains, and a large amount of ALK excess is enriched inside the island chains,  
685 preventing it from spreading to the wider Pacific.

686 Thank you for the helpful recommendation. We have clarified our expression in line  
687 434-439.

688 “...For instance, in the Atlantic, excess alkalinity from the Caribbean Sea can be  
689 transported to the North Atlantic by the Gulf Stream, a strong western boundary

690     *current. Compared to the North Atlantic, the western boundary current of the North*  
691     *Pacific occurs outside the island chains, and a large amount of ALK excess is*  
692     *enriched inside the island chains, preventing it from spreading to the wider Pacific. ”*

693

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