Response to Reviewer

We sincerely thank the reviewer for their insightful and constructive comments. We appreciate the acknowledgment that expanding the diversity of OAE simulation studies is important. Below, we provide a point-by-point response to the main concerns raised. We have not included specific line numbers where revisions have been done, as these may be changes following the incorporation of comments from other reviewers.

General Comments

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

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

Reviewer Comment: "The article is not particularly interesting. The authors could do more to differentiate their contribution, particularly given their use of an emissions-driven ESM."

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

- Implements river-based alkalinity enhancement, reflecting a natural and spatially realistic pathway of alkalinity delivery that differs from the commonly assumed uniform ocean-wide input.
- Uses an emissions-driven, fully coupled Earth System Model (CESM2), which allows for two-way interactions between climate, ocean chemistry, and carbon fluxes—features not captured in prescribed-CO_2 simulations.
- Explores termination effects of OAE (OWE0) in addition to scaling scenarios, providing insights into persistence and reversibility of OAE-induced changes.

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

"…To mimic this mechanism, we use an emission-driven, fully coupled Earth System Model to evaluate a riverine-based, global-scale OAE scenario under a high-emission pathway (Shared Socioeconomic Pathway 5-8.5, SSP585), which reflects a natural and spatially realistic pathway of alkalinity delivery that differs from the commonly assumed uniform ocean-wide input. The responsive CO_2 *concentration configuration in our simulation allows the interactions between climate, ocean chemistry and carbon fluxes and captures the features not captured in prescribed-*CO_2 *simulations."*

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

"…We also find that reductions in surface air temperature are not proportional to the level of 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."

"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 ocean alkalinity enhancement. To avoid offsetting the benefits of OAE, complementary strategies to preserve or enhance land carbon sequestration may be necessary."

Reviewer Comment: "I was particularly surprised that they focus so little on changes in atmospheric temperatures, which appear counterintuitive."

Response:

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

Our results show that reductions in surface air temperature are not proportional to the amount of alkalinity added. This disproportionality is primarily due to the relatively modest declines in atmospheric CO_2, which lead to only a ~10% decrease in temperature relative to the projected warming under the baseline esm-SSP585 scenario. As a result, the temperature reductions associated with OAE are small and largely masked by interannual variability in the Earth system model.

"…We also find that reductions in surface air temperature are not proportional to the level of 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 Comment: "There is no description at all of the land carbon sink and how it responds to OAE (one of the principal advantages of using a fully-coupled ESM)."

Response:

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

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

"…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 ocean alkalinity enhancement. To avoid offsetting the benefits of OAE, complementary strategies to preserve or enhance land carbon sequestration may be necessary."

Reviewer Comment: "Several of the current figures need cutting or revising to be useful to the reader."

Response:

Thank you for this helpful suggestion. In response:

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

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

Specific Comments:

L26 Is this true? Wouldn't afforestation-based mCDR also absorb CO_2 and reduce acidification?

We agree with the reviewer that afforestation-based mCDR can also contribute to CO_2 removal and, indirectly, to the mitigation of ocean acidification. Afforestation enhances atmospheric CO_2 uptake through biological carbon sequestration, which in turn reduces the partial pressure of CO_2 in surface waters, thereby decreasing CO_2 dissolution and alleviating acidification (N'Yeurt et al., 2012). In contrast, OAE reduces acidification more directly by adding alkaline substances that chemically neutralize H^+ ions in seawater. To reflect this distinction and avoid overstating the uniqueness of OAE, we have revised the sentence as follows:

"…is one of the promising Carbon Dioxide Removal methods that can simultaneously absorb CO_2 and alleviate ocean acidification."

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

We are grateful to the reviewer for pointing out the mistake. We have revised this sentence accordingly as follows:

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

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

Thank you. The numbers have been updated according to estimate by Smith et al. (2024):

"…However, an additional CO_2 sequestration requirement of -5.3 $GtCO_2$ per year in the Paris-consistent scenario based on the baseline of -2.1 $GtCO_g$ per year in 2011-2020 even under 76% greenhouse gas emission reduction (Smith et al., 2024)."

L59 Excluding geological reservoirs.

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

"…As the largest carbon reservoir at the Earth's surface, the ocean holds substantial potential for enhanced CO_2 uptake."

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

Agreed. We have adjusted the tone accordingly, both in our response and in the revised manuscript:

"…Among these, OAE is promising because it offers the dual benefit of reducing atmospheric CO_2 and direct effect on alleviating ocean acidification, making it an ideal candidate for mitigating CO_2-driven climate impacts through mCDR."

L68-70 This definition is a bit inaccurate. Alkalinity is perhaps better defined as the excess of H^+ accepters over donors.

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

"Alkalinity is defined as the excess of proton acceptors over proton donators in seawater."

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

Agreed. we have modified the sentence accordingly as follows and also in the revised manuscript:

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

L73 I'm not sure what excess H^+ is in this context.

We appreciate the reviewer's comment. Our original intention was to describe the removal of additional protons resulting from ocean acidification. However, we agree that the term "excess H^+" is potentially misleading and redundant with the accompanying description of rising pH. Therefore, we have removed this phrase in the revised manuscript.

The revised sentence now reads:

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

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

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

"By altering the air–sea CO_2 disequilibrium, OAE can enhance oceanic CO_2 uptake in undersaturated regions and reduce outgassing in oversaturated regions, thereby increasing net ocean carbon storage and ultimately lowering atmospheric CO_2 concentrations."

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

Thank you for your suggestion. Now we have modified this sentence as follows:

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

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

We have removed this figure.

L130 This equation is unnecessary (and is unnumbered).

Agreed. We have removed this equation.

L141 Add equation number.

Added.

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

We agree that in a prescribed CO_2 configuration CO_2 concentration will transiently change in atmosphere module. In such a setting, the atmospheric CO_2 forcing driving the ocean module changes in a fixed trajectory. Whereas, in a prognostic CO_2 configuration, atmospheric CO_2 concentration is dynamically changed according to the net strength of sources (e.g., emission) and sinks (e.g., land and ocean sinks):

"…We use prognostic CO_2 settings to explore the responses of climate to OAE. In such a setting, dynamic atmospheric CO_2 forcing is used to drive the ocean and biogeochemistry module to avoid the uncertainty that stems from the difference between responsive and prescribed atmospheric CO_2 forcing to ocean (Tyka, 2025)."

L153 "concentration" should be "emissions" as emissions not concentrations are prescribed in esm-hist.

Thank you for pointing this out. We have changed the "concentration" to "emissions".

"When the climate is balanced with forcing, the historical simulation is performed as an emission-driven simulation using the historical atmospheric CO_2 emissions (esm-hist) prescribed by CMIP6 protocol till the year of 2014."

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

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

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

L162-164 These simulation descriptions are confusing. What is meant by "based on… from 2050"?

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

"…

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

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

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

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

The model was spun-up by the community. In the spin-up runs, the burial of $CaCO_3$ was tuned to balance the alkalinity input from rivers (Long et al., 2021). We do not reran the spin-up phase and used the the restart files of the year 2020 obtained from data manager in CESM forum (https://bb.cgd.ucar.edu/cesm/). There may be still a trivial drift in these restart files, but it should not have a significant impact on our simulation because we conducted the control run and OAE simulations using the same restart file. Therefore, any drift will be canceled.

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

The image quality might be compressed when generating the PDF. In any case, we have redrawn the figure and made it clear.

"…

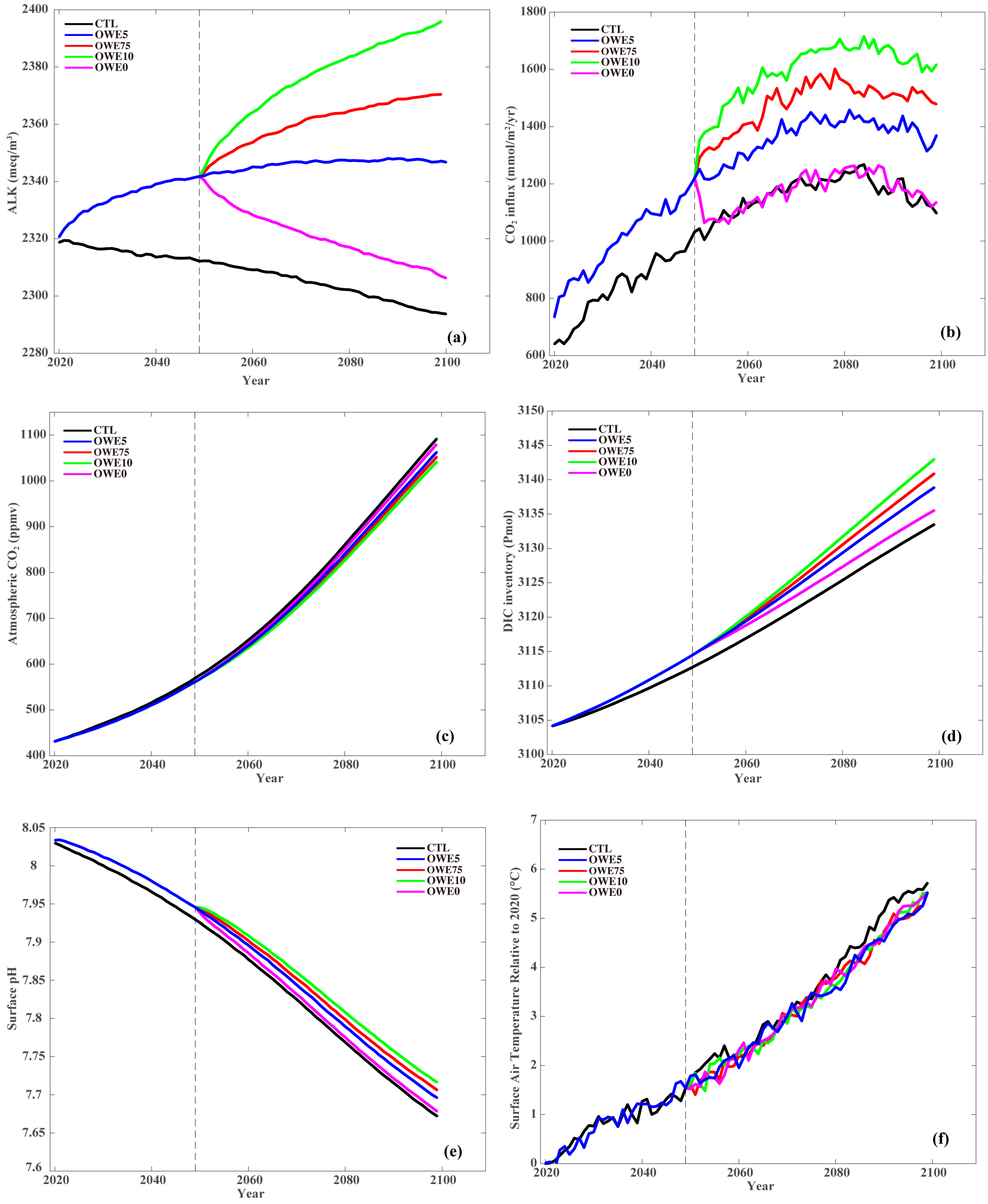

Figure 3: Global changes of (a) upper 100 m mean alkalinity (unit: meq/m^3), (b) CO_2 influx (unit: mmol/m^2/yr), (c) atmospheric CO_2 (unit: ppmv), (d) integrated DIC inventory (unit: Pmol), (e) surface pH, (f) surface air temperature (unit: ºC). Dash lines starting from in the year 2050 denote the onset of the 7.5×, 10× alkalinity enhancement scenarios, as well as the termination of alkalinity addition via rivers."

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

Thank you. It is zonal mean. We have modified the legend of the figure as follows:

"…Vertical distribution of zonal mean alkalinity anomaly. (a) differences between OWE5 and CTL, (b) differences between OWE75 and CTL, c) differences between OWE10 and CTL, (d) differences between OWE0 and CTL, (e) differences between OWE0 and OWE5."

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

We now have modified this part as follows:

"…OAE modifies the air–sea CO_2 gradient, promoting greater CO_2 absorption in areas where the ocean is undersaturated and diminishing CO_2 release in regions where it is supersaturated. This results in a net increase in ocean carbon storage and contributes to a reduction in atmospheric CO_2 levels."

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

Thank you for your suggestion. We have changed the units to uatm in line 238-239 and in Fig. 6:

"In OWE5, OWE75, and OWE10, surface pCO_2 decreases by more than 20 µatm compared to the control, with OWE10 showing the greatest reduction. In contrast, OWE0 achieves only a ~10 µatm decrease by 2100."

"

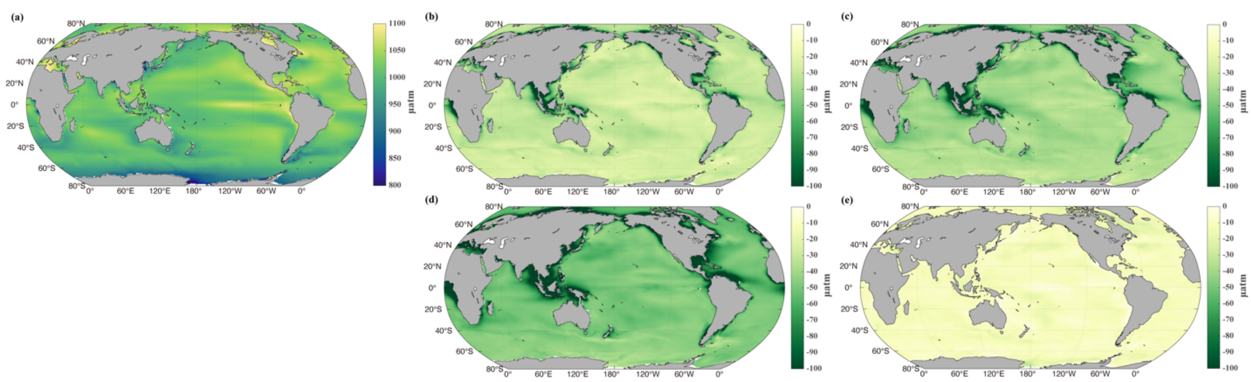

Figure 6: Distribution of surface pCO_2. (a) control simulation, (b) difference between OWE5 and CTL, (c) difference between OWE75 and CTL, (d) difference between OWE10 and CTL, (e) difference between OWE0 and CTL.

"

L245 How much later? Give the year.

We have added the year in revised manuscript.

"…the CO_2 influx eventually returns to the same rate as in the control simulation at the 5th year after termination (Fig. 3b).

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

Agreed. The equation has been removed.

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

Thank you. We have changed the wroding as follows.

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

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

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

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?

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

"…We also find that reductions in surface air temperature are not proportional to the level of 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."

L342 So the reductions in atmospheric CO_2 are consistent with the extent of OAE but not the reductions in surface temperatures? Please discuss, perhaps the temperature values are type errors, it’s hard to see differences in figure 3.

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

“…

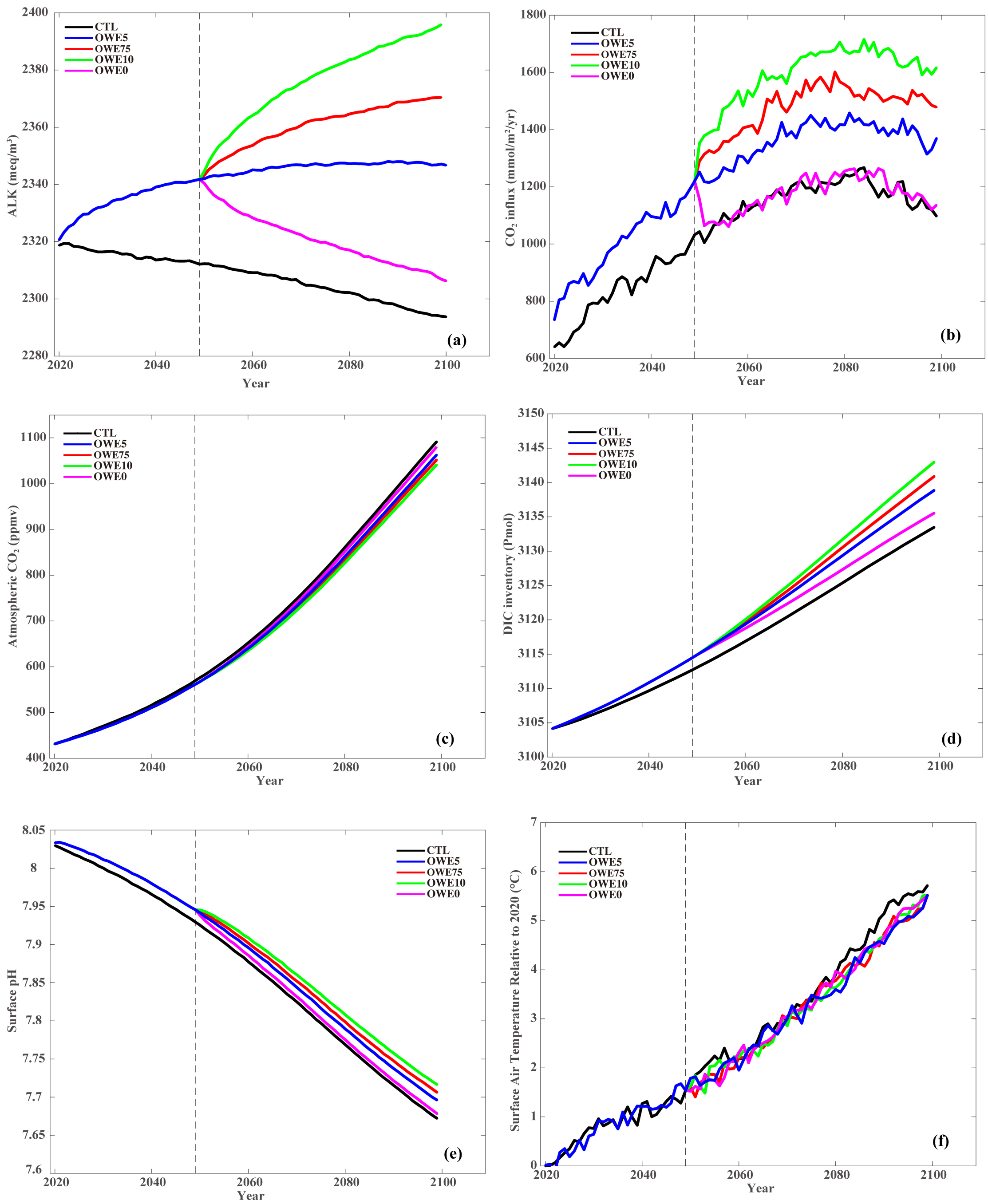

Figure 3: Global changes of (a) upper 100 m mean alkalinity (unit: meq/m^3), (b) CO_2 influx (unit: mmol/m^2/yr), (c) atmospheric CO_2 (unit: ppmv), (d) integrated DIC inventory (unit: Pmol), (e) surface pH, (f) surface air temperature (unit: ºC). Dash lines starting from in the year 2050 denote the onset of the 7.5×, 10× alkalinity enhancement scenarios, as well as the termination of alkalinity addition via rivers."

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

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

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

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

Köhler (2020) demonstrate that the calcite saturation horizon and lysocline transition zones in sediment will deepen under OAE, which finally lead to an increase of $CaCO_3$ accumulation. This process extracts alkalinity from the ocean and reduces the efficiency of OAE. However, as you mentioned, most of the Earth System models did not consider the sediment processes in alkalinity cycle. We have added some discussions in this part:

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

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

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

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

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

Thank you. We have clarified the applying method of OAE in *Zhou et al. (2024)*.

"…Moreover, our findings differ from those of Zhou et al. (2024), who perform OAE locally in all grid cells and found that absorption efficiency is higher in the equatorial Pacific compared to the subtropical regions."

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

We have calculated the pH decrease rate as the indicator of the acidification rate. We find the acidification has accelerated in OWE0 simulation after the termination of OAE with a rate of 0.0054, faster than 0.0047 (from 2020 to 2100) and 0.0053 (from 2050 to 2100) in control run. However, the carbon uptake rate (the influx of CO_2, see Fig. 3b) decrease to the similar rate with control run under OWE0 at the 5th year after OAE termination.

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

Thank you for your suggestion. We have added these discussions in our revised manuscript:

"This indicates that water masses altered by OAE and not in equilibrium with the atmosphere will return to the surface through ocean circulation on centennial timescales."

Reference:

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